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The topics of former workshops on Pellet Fueling or Pellet Injection, starting with the first meeting at Princeton in 1977, were injector development and ablation. In recent years there has been a shift of emphasis. Pellet injection has now become a method of improving plasma confinement. Experiments have been conducted on numerous tokamaks, but also on other plasma devices, e.g. stellarators and reversed field pinches. The discussion of pellet-fueled plasmas is concentrated at present on particle and energy confinement and impurity transport. This workshop was therefore held to provide an overview and a discussion of the present experimental and theoretical status of confinement and transport during and after pellet injection. Pellet ablation and injector development also featured at the meeting, but, unlike on previous occasions, they were not the main topics. The conclusions derived from the workshop by qualified speakers sum up the present status of pellet injection. The significance of pellet injection for future experiments was treated in an additional paper.

The three-day IAEA Technical Committee Meeting, held at a picturesque location on Lake Chiemsee in Bavaria, was attended by 55 participants. It was sponsored by IAEA, Vienna, and Max-Planck-Institut für Plasmaphysik (IPP), Garching, FRG. IAEA also covered the cost of printing the proceedings, and IPP were responsible for organizing the event, also contributing to the cost of organization, transport of the participants, and the banquet.

The meeting owed its success to the good interaction of all persons involved. Appreciation is due to the authors for their presentations and to the chairmen and the organizing committee for their excellent work. Special thanks must also go to the authors of the conclusions. Finally, we wish to thank the management of Hotel Gut Ising, who did so much to ensure their guests a pleasant stay.
EDITORIAL NOTE

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SUMMARY REPORT

Owing to the substantial plasma parameter improvement recently observed at different laboratories in pellet-fuelled tokamak discharges, this meeting was primarily devoted to discussion and analysis of the confinement properties of pellet-fuelled tokamak and stellarator discharges. Further topics discussed included pellet injector development, ablation phenomena, and pellet application in future devices. Fifty-four participants, representing practically all major magnetic fusion laboratories (with the exception of those in the USSR) developing or applying cryogenic hydrogen isotope pellet injectors, presented 33 papers in six topical sessions: General Phenomena, Future Devices, Particle and Energy Transport, Impurity Transport, Pellet Ablation, and Pellet Injectors. An extra session was devoted to Conclusions.

The major topics and ideas presented in these sections are summarized below. A comprehensive report on the meeting has appeared in the February 1989 issue of Nucl. Fusion (29, 2, 325).

General Phenomena

Results of measurements pertaining to pellet penetration depth, confinement characteristics, density and beta limits, MHD activities, etc., were reported in this session.

The pellet injection results obtained in JT-60 have shown that in ohmic divertor discharges \(I_p = 1 \text{ to } 2 \text{ MA}\) an optimum target plasma density exists for pellet injection. If the initial density is too low, peripheral ablation may result because of the presence of runaways. At high initial density (associated with low initial temperature) the pellet may quench the plasma, this resulting in disruption. The increase of the stored diamagnetic energy \(W_{dia}\) following pellet injection was 70 to 90 % in target plasmas of low and medium densities. In NB-heated (L-mode) and pellet-fuelled plasmas with an absorbed power \(P_{abs} < 15 \text{ MW}\), \(W_{dia}\) was found to increase with the absorbed power without saturation. Saturation was observed at higher beam powers. The saturation threshold was increased by increasing \(I_p\) from 1.5 MA to 1.8 MA. A moderately heated target plasma proved to be the optimum for pellet injection with subsequent application of the full beam power. Pellet injection usually triggered MHD \((m=1)\) and sawtooth activities. These activities were suppressed by producing density profiles with sufficiently strong peaking by means of injecting 3 pellets. In the case of LHRF heating of pellet-fuelled plasmas, a marked increase of the stored energy was observed without the occurrence of parametric instability.
The results of pellet injection experiments reported for ASDEX cover OH, NBI (beam power up to 3 MW), and ICRH (power 1.4 MW) discharges. All discharges described are marked by high recycling and centrally peaking density profiles. To reach enhanced confinement, it was necessary to inject pellets into target plasmas of medium density and to apply gas-puff during pellet injection. The maximum stored energy in an L-mode (NBI) discharge was \( \sim 100 \text{ kJ} \), this corresponding to \( \beta_t \approx 0.65\% \) and a Troyon factor of 1.5. The density limit could be increased (over the values obtained with gas-puff) by a factor of 1.5 (NBI) to 2.0 (OH). The respective Murakami parameter values are 10.5 and 8.

High recycling seems to support improved confinement. Furthermore, under the peaked density profile conditions, \( \tau_E \) was found to increase monotonically with \( \bar{n}_e \) and reach approximately double the saturated value characterizing gas-puff-fuelled discharges. The confinement was found to deteriorate with increased auxiliary heating in this case too. Regarding sawtooth activity, it was found that after injecting a string of 5 pellets into an L-mode (NB) discharge the sawteeth vanish and a quiescent period of \( \sim 0.1 \text{ s} \) duration follows. The plasma energy (\( \beta_p \)) reaches its maximum and the radiative losses steeply increase during this period. Simultaneously, strong MHD oscillations appear until, finally, sawteeth reappear as well and enhanced impurity radiation appears in the plasma centre.

In the case of pellet-fuelled ICRH discharges, two sawtooth phases can be distinguished: a regular sawtooth period is followed by a phase in which the density sawtooth is only accompanied by weak modulation of the electron temperature. In the second phase, \( \tau_E \) increases by 36% in relation to ICRH without pellet injection. Regarding particle transport, the highest peaking of the \( n_e \) profile (~2.6) was obtained in a sawtooth-free NBH discharge.

With regard to JET discharges, sufficiently deep pellet penetration was a prerequisite for producing peaked density profiles. In the case of high target plasma temperatures, the plasma first had to be cooled with a string of pellets before injecting the pellet that could produce a peaked density profile. A maximum peaking factor of about 3 was reported. The achievement of the 'enhanced performance mode' was coupled with the production of strongly peaked density profiles and the subsequent application of central ICRH. In such a case, \( T_e(o) = 11 \text{ keV}, T_i(o) = 8 \text{ keV} \) were obtained after injecting a 4 mm dia. pellet into the early flat-top phase of an ohmic plasma and subsequently applying an 8 MW central ICRH heating pulse. The central electron density at the moment of \( T_{e,\text{max}} \) was \( 6 \times 10^{19} \text{ m}^{-3} \). The enhanced confinement phase (lasting \( \sim 1.2 \text{ s} \) ) ended with a sudden loss of the energy in the plasma centre and the simultaneous appearance of the m=3, n=2 MHD mode. The maximum plasma pressure (with \( \beta_T(0) = 5\% \)) approached \( \sim 40\% \) of the critical Troyon value of optimized profiles (e.g. profiles without pellet), and the stability limit of the ideal ballooning mode may have been approached or even exceeded. Also the \( \eta_t \)-mode may have played a role in the confinement deterioration: \( \eta_e \approx \eta_t \approx 1.5 \) was estimated to prevail during the initial enhancement phase in the inner
half of the discharge. The application of additional NB heating to these discharges did not lead to any performance improvement.

The specific characteristics of pellet-fuelled discharges in large tokamaks such as JET and TFTR were analyzed in a separate presentation (G. L. Schmidt, PPPL). Strong electron temperature perturbation can be tolerated also in these machines, which allows the current profile and $q$-values in the central plasma region to be modified. Sawtooth activities may be suppressed by means of pellets. Measured penetration depths are generally in agreement with calculated values when pellet heating by thermal electrons dominates. However, the local mass deposition profiles may differ from those predicted. Enhanced particle deposition at the plasma edge was observed as compared with theoretical predictions. With regard to transport processes, if pellet injection is applied, the thermal diffusivities both in beam heated TFTR discharges and in RF heated JET discharges are reduced in the plasma core as compared with discharges without pellet injection. In JET discharges with central RF heating, the thermal diffusivities at the plasma centre can be a factor of 2 to 3 lower than in comparative discharges without pellet fuelling.

In JFT-2M, the injection of sufficiently large pellets into OH, NB, and ICR-heated plasmas in conjunction with central deposition was found to be a prerequisite for enhanced confinement. Pellet injection during the early phase of a NB pulse (L-mode) produced plasmas with $\langle \beta_t \rangle \approx 1.6\%$ and a Troyon factor of $\sim 2.2$. The highest densities obtained in OH and NB-heated discharges corresponded to Murakami parameter values of 8.7 and 10, respectively, these values being 1.5 and 1.2 times as large as the best ones obtained with gas-puff. The discharges usually terminated with disruptions: the stability limits of kink and ideal ballooning modes were apparently approached. In discharges with ICRH and central particle deposition (large $D_2$ pellets injected) enhanced confinement was observed in both L-mode and H-mode discharges. The global energy confinement time in pellet-fuelled L-mode discharges (NB and ICRF-heated) was found to be higher, by a factor of 1.4 to 1.7, than the H-mode $\tau_E$ values. MHD oscillations were found to be suppressed by pellet injection, resulting in quiescent discharges. No impurity accumulation was observed during the quiescent phase.

In NB-heated Heliotron-E plasmas, optimum results were obtained when pellets were injected in an initially low-power heating phase with a subsequent rise of the beam power. Pellet injection during ECH pulses only resulted in weak density increase (peripheral ablation) as compared with the substantial density increase associated with pellet injection after ECH pulses. Regarding the MHD behaviour of pellet-fuelled Heliotron plasmas, it was noted that in current-free discharges with high-beta ($\sim 2\%$) flat pressure profiles were found to be stable, whereas peaked pressure profiles are suspected to induce pressure-gradient-driven interchange modes ($m=1, n=1$ fluctuations were observed). In
this context, gas-puffing is suggested as a means of profile modification and hence stabilization. In the JIPP-TIU tokamak, the sawtooth oscillations were found to be strongly modulated by pellet injection.

The major results presented in this section are summarized as follows:

1. Pellet penetration. The proper selection of the target plasma parameters and timing of the pellet injection require special care if central deposition and peaked profiles are desired: optimum results were reported from pellet injection in moderately heated medium-density discharges (pellet injection during the current ramp-up phase, at low initial NB power, etc.) with a subsequent rise of the heating power.

2. Improved energy confinement. A peaked density profile combined with a medium target plasma density seem to be prerequisites for obtaining significant improvement of the confinement characteristics of pellet-fuelled plasmas. Density profile peakednesses (maximum to average density ratios) of 2.5 to 5.0 have been reported. High recycling may also be a factor improving confinement. The energy content of the plasma may be significantly increased by means of pellet injection: $\Delta W/W = 0.4$ to 1.0 was reported in OH and auxiliary-heated L-mode discharges. In large machines, the plasma remained in the enhanced confinement phase for a relatively long period of time ($\sim 1.2$ s in the case of JET). The energy confinement time increment deteriorates with increasing auxiliary heating. Enhancement of the energy confinement was also observed in an H-mode discharge (JFT-2M) under central ICRF heating conditions.

3. Density and beta limits. In some experiments the density and beta limits were approached. Average toroidal beta values of up to 1.6 to 2.0 % were obtained in pellet-fuelled discharges. The corresponding Troyon factors lie between 1.5 and 2.2. The Murakami parameters reported range up to 8 to 10.

4. MHD and sawtooth activities. With regard to sawtooth and MHD activities, as a result of the high central density and beta values, most of these discharges ended with disruption. Ballooning and kink modes are suspected to trigger the disruptions. The $\eta_i$-mode may also have become important in some cases. In the currentless Heliacon discharge, peaked pressure profiles were suspected to trigger the $m=1$, $n=1$ interchange mode. In discharges where sawtooth or MHD oscillations were present prior to pellet injection, they became strongly modulated or completely suppressed upon pellet injection. Sawteeth were shifted to lower frequencies while their amplitudes increased. In large machines where larger temperature perturbation may be tolerated, pellet injection seems to allow modification and perhaps control of the current profile and central $q$-values.
F. Engelmann (NET) reviewed the physical characteristics of reactor-grade devices such as NET, ITER, FER, etc., with particular attention to their particle exhaust and refuelling requirements under various operating conditions. To simulate the working conditions of the plasma-facing components, such a machine will most likely be operated in a high-recycling mode characterized by low fractional burn-up and correspondingly high fuel throughput. Fuelling is viewed not only as means of supplying the necessary particle fluxes, but also as a method of active density profile control.

The requirements imposed on the density profile by considerations related to different operational conditions are sometimes conflicting: a peaked profile might be required during startup to reach good confinement and thus to minimize the power needed to reach ignition, as well as if steady-state operation at high core density and reduced edge density proves to be necessary. On the other hand, a flat density profile may be needed for high-beta operation and is a prerequisite for high-recycling divertor operation. Flat density profile may also be desirable for minimizing impurity accumulation in the core of the plasma. For the purpose of active burn control, deliberate degradation of the confinement characteristics in the plasma core will be necessary. In addition to replenishing the fuel particles burnt, the fuelling method applied must supply particle fluxes covering the D,T particles exhausted with the helium ash and, if needed, for profile control. Hence the number of D,T particles to be injected is considerably larger than that required for fuelling alone. Hence, as possible areas for the application of pellet injection in reactor-grade plasmas Engelmann put forward startup scenarios with fast density ramp-up, the production of peaked density profiles when required, and, under high-density operation conditions, reduction of the edge density. The full potential of pellet fuelling will remain uncertain as long as questions of tokamak and pellet physics, such as the effect of the particle source distribution on the plasma transport properties, the magnitudes of the ablation rate and pellet penetration depth in reactor-grade plasmas, etc., have not been definitely clarified.

Particle and Energy Transport

In transport simulations applied to pellet-fuelled TFTR discharges, the evolution of the electron density profile could be simulated with an anomalous time-independent diffusion coefficient of the form \( D(r) = D(o) + (D(a) - D(o))(r/a)^2 \) supplemented by the neo-classical Ware pinch term for a remarkably broad range of initial plasma conditions: (a) peaked density profile with broad pedestals; (b) a hollow density profile corresponding to incomplete (non-central) pellet penetration and evolving into a peaked profile that after
some decay period was finally terminated by sawtooth oscillations; (c) the post-sawtooth period of the above profile; (d) NB-heated pellet discharges (with a weak source term, representing deposited NB particles, added). It is noteworthy that the neoclassical Ware pinch term was sufficient for simulating the transition from hollow to peaked profiles. The range of $D(o)$ values applicable to cases (a) to (d), 0.005 to 0.02 $m^2/s$, is rather low, whereas the corresponding values of $D(a)$ are 0.4 to 0.7 $m^2/s$.

Similar results were reported also for JET discharges. Two types of pellet-fuelled discharges with centrally peaking profiles could be distinguished in JET: discharges with long post-pellet decay times (OH and some ICRH shots) and discharges with auxiliary heating (ICRH) characterized by rapid central density decay and an ultimately flat density profile. In the first case, the post-pellet profile evolution could readily be modelled by a time-independent $D(r)$ profile of the type $D \approx 0.1 m^2/s$ for $r/a \leq 0.5$ and $D \approx 0.25$ for $r/a \geq 0.5$ (with slightly higher numerical values for the ICRH shots) supplemented by the neoclassical Ware pinch term. In the second case, the ohmic $D(r)$ profile had to be multiplied by a temperature function, $(1 + \text{const} \times T_e^{2/3})$, which is time-dependent. The rapid density profile flattening observed in this second case was attributed to the onset of MHD activities in the plasma centre. Discharges with non-central pellet penetration in JET could not be modelled with the same transport coefficients as those displaying an initially peaked density profile.

The fundamental similarities of different discharge types with centrally peaked density distributions such as pellet-fuelled, ctr-NB-heated and IOC (improved ohmic confinement) discharges were analyzed in a separate presentation (O. Gruber, IPP). All cases considered were characterized by density-independent (“profile-consistent”) temperature distributions and markedly improved energy confinement characteristics. The results of local transport analyses applied to these discharges were compared with those corresponding to flat density profiles. It was found that the confinement characteristics of discharges with both flat and peaked density profiles (ohmic discharges) could be simulated by assuming the same $\chi_e(r) \propto 1/n_e(r)$ dependence and adjusting the value (i.e. the radial variation) of $\chi_e$. For the cases with peaked density profiles considered, the value of $\chi_e$ was found to reduce in the central plasma region to values close to neoclassical ones. In the same region, $\eta_i \equiv d \ln T_i/d \ln n_i$ was found to satisfy the condition $\eta_i < 1$ simultaneously, i.e. the $\eta_i$-mode became suppressed. It was further found that with additional heating the impairment of confinement characteristics is primarily due to the increase of $\chi_e$. At the plasma edge, $\chi_e$ was found to exceed $\chi_i$ in all discharges investigated.

The experimental results reported for TEXT provided evidence of the concurrence of the improvement of the energy confinement and the suppression of the ion-gradient-driven ($\eta_i$) microinstabilities in pellet-fuelled TEXT discharges. The energy confinement cha-
racteristics and the associated microturbulence fluctuation spectra were recorded and compared for gas and pellet-fuelled discharges at three average density levels: low, medium, and high, $n_e(10^{19} \text{ m}^{-3}) = 2, 4, \text{ and } 8$, respectively. In gas-fuelled discharges at low average densities, $\tau_E$ was observed to increase linearly with $\bar{n}_e$ and the observed microturbulence (large-amplitude broad-band peak at each wave vector investigated) was found to propagate in the electron diamagnetic (ED) drift direction. At the medium density level, where $\tau_E$ was observed to saturate with increasing $n_e$, the density fluctuations observed to propagate in the ED drift direction were accompanied by a small-amplitude peak propagating in the ion diamagnetic drift direction, which signaled the onset of ion modes. At the highest average density tested, a distinct ion mode was observed in gas-fuelled discharges with amplitudes comparable to those of the electron modes also present in these discharges, which indicates the relevance of energy losses through ion channel at the density level considered. Finally, in pellet-fuelled discharges of comparable (high) average density, only the fluctuation component propagating in the ED drift direction could be detected, the component propagating in the ID drift direction being absent. These pellet shots were characterized by considerably reduced density gradient scale lengths in the central plasma region yielding $\eta_i \leq (1 \text{ to } 2)$ there, and an unsaturated $\tau_E \propto \bar{n}_e$ proportionality. Time-dependent transport simulations applied to the gas-fuelled discharges at the different density levels tested could only reproduce the experimentally observed $\tau_E$ behaviour if the local enhancement of $\chi_i$ due to the ion-gradient-driven microinstabilities was taken into account whenever the condition $\eta_i \geq 1.5$ was fulfilled.

In modelling particle transport in the ICRF-heated JET shot #16211 that displayed the enhanced confinement characteristics previously discussed, the neoclassical diffusion and Ware pinch terms were supplemented by an anomalous diffusion term based on the diffusion coefficients $D = 0.08 \text{ m}^2/\text{s}$ for $0 \leq r/a < 0.4$ and $0.2 < D(\text{m}^2/\text{s}) < 0.4$ in the region $0.4 \leq r/a < 1$. Essential was the numerical value of $D$ assumed for the central plasma region. Analogous expressions were used for the electron and ion heat fluxes: the neoclassical expressions were supplemented by anomalous electron and ion heat conduction terms with $\left(\chi_e/D_e\right)_{an} = 13/4$ and $\left(\chi_i/\chi_e\right)_{an} = 1$ assumed. With this set of transport coefficients, the dynamics of the discharge evolution as well as the magnitudes of all essential parameters of it could be simulated with sufficient accuracy.

The major results presented in this session are summarized as follows:

(1) Particle transport. Centrally peaked density profiles with broad pedestals were produced by injecting pellets into large machines. In OH discharges, rather long decay times were associated with the peaked profiles produced. The time evolution of the electron density distribution following pellet injection was successfully modelled in such cases by a strongly reduced time-independent and, within the region of large
density gradients, spatially constant diffusion coefficient value \( D_e(< 0.1 m^2/s) \) with a sharp increase at the edge of the gradient domain (to 0.3 to 0.4 \( m^2/s \)), supplemented by purely neoclassical terms. Neoclassical inward drift (Ware pinch) was found to suffice to explain the density evolution in the plasma centre even in cases of originally hollow density profiles associated with incomplete pellet penetration (TFTR). An anomalous inward drift term had to be postulated in the case of ASDEX.

(2) Energy transport by electrons. In OH discharges of low average plasma densities, energy losses through the electron channel dominate. In such discharges \( \chi_e \) and \( \tau_E \) were found to change proportionally to \( n_e^{-1} \) for both flat and peaked density profiles. However, in the case of flat profiles, \( \tau_E \) saturates at some medium density level, i.e. energy losses through the ion channel become dominant. No saturation is observed in the case of peaked density profiles; the limits for confinement improvement are set in this case by the density limit. If additional heating is applied, transport simulations indicate enhanced electron conductivity.

(3) Energy transport by ions. Energy losses through the ion channel gain weight with increasing average plasma density. In the case of flat density profiles combined with the usual bell-shaped temperature distributions, ion-density-gradient-driven microturbulence (\( \eta_i \)-mode) appears in the plasma at some intermediate density level that impairs the energy confinement characteristics. According to the observations and some systematic measurements (TEXT), the production of peaked density profiles by pellet injection may lead to the suppression of the \( \eta_i \)-mode and may render access to regimes with improved energy confinement. In the central plasma domain with peaked density distribution, the ion thermal conductivity \( \chi_i \) was found to approach the neoclassical value.

Impurity Transport

In ALCATOR-C, improved energy and particle confinements triggered by pellet injection were always accompanied by impurity accumulation in the plasma centre. Both low (C) and high (Mo) Z impurities were observed to accumulate, in agreement with neoclassical transport theory. The same tendency was observed in the case of non-intrinsic (injected) impurities. The carbon accumulation profile during the post-pellet phase could be described by means of inward drift and outward diffusion rates of the order of \( v_{in} \approx 10 \, m/s \) and \( D \approx 0.03 \, m^2/s \), respectively. Another feature of pellet-fuelled discharges was the disappearance of sawteeth: their period was found to increase and their amplitude to diminish upon pellet injection. With the impurity profile being strongly peaked, the plasma resistivity increases in the centre and the current profile flattens. A hollow current profile may result. The central \( q \)-value was found to rise, in agreement with the
observation of sawtooth disappearance, from a value below unity to $q(o) = 1$. The suppression of sawteeth was usually followed by large-amplitude $m=1, n=1$ oscillations. The appearance of this mode, possibly a pressure-gradient-driven interchange mode that periodically drives cold plasma blobs into the plasma centre, was accompanied by an abrupt stop to further impurity accumulation.

Also in pellet-fuelled OH discharges in ASDEX with weak additional ctr-NB heating, pellet injection and the associated improved confinement regime were accompanied by the disappearance of sawtooth oscillations. Simultaneously with the decay of sawteeth, the radiation power emitted from the plasma centre began to rise steeply in about 100 ms after the injection of the last pellet, and, after another 100 ms, it exceeded the OH power input by about 50%. Both light (C, O) and heavy (Cu) impurities were present, light impurities being dominant. The central value of $Z_{eff}$ rose from initially 1.6 (ohmic phase) to about 2.8 during the impurity accumulation phase. The impurity transport was successfully modelled by a combination of classical, neoclassical, and anomalous terms. No anomalous inward drift term was necessary for explaining impurity accumulation at the plasma centre. (However, anomalous terms had to be postulated for the background plasma.) At the time of sawtooth disappearance, the anomalous impurity diffusion coefficient had to be abruptly reduced to a value $(0.05 \, m^2/s)$ equal to the (reduced) diffusion coefficient of the background plasma particles over the plasma region $r/a \leq 0.75$.

With regard to impurity transport in pellet-fuelled JET discharges, both light and medium Z impurities accumulated at the plasma centre and, in full agreement with neoclassical particle transport theory, had a profile width considerably narrower than the electron density. In OH discharges, the decay time of the peaked impurity profiles extended over several seconds. Sawteeth were suppressed by pellets and only reappeared after the density profile became flat again. Good confinement, i.e. peaked density profile combined with the absence of sawteeth, seems to be a prerequisite for impurity accumulation at the plasma centre. In the course of impurity accumulation, the soft X-ray emission increased by a factor of 10. The emission profile remained narrow for some time and then, concurrently with the appearance of MHD activities, rapidly flattened. When ICRH or NBH was applied, the same initial impurity behaviour was observed as in OH discharges. However, the accumulation and the subsequent depletion of the impurities at the discharge axis occurred on a notably shorter time scale than in OH discharges. Transport analysis applied to OH or otherwise heated JET discharges revealed that impurity transport can be described in terms of a combination of neoclassical and anomalous transport, the latter being, in general, dominant: $D_{an} \approx 1 \, m^2/s$. Typical neoclassical diffusion coefficients and drift velocities at the plasma centre are of the order of (0.1 to 0.5) $m^2/s$ and (1 to 4) m/s for carbon, and (0.05 to 0.1) $m^2/s$ and (1 to 2) m/s for Ni. Following pellet injection, the anomalous diffusion coefficient assumed for the plasma core had to be reduced to values of the order of 0.001 $m^2/s$. In the outer region, anom-
lous transport continued to dominate. The low-diffusivity plasma core region initially extending to $\sim a/2$ was found to shrink practically to $r \approx 0$ during the post-pellet phase.

In TEXT, pellet-fuelled discharges exhibited considerably higher impurity concentrations and stronger peaking at the plasma centre than their gas-fuelled counterparts, and relatively constant impurity densities over the broad pedestals. The impurity peak was substantially narrower than the associated electron density peak. Since the edge characteristics showed no significant difference for the two discharge types, the differences in impurity behaviour in the plasma center were not caused by boundary (source) effects. The observed impurity distributions were compared with results stemming from neoclassical theory. Classical Pfirsch-Schlüter and banana-plateau fluxes were taken into account, thus covering all collisionality regimes. The measured diffusion coefficients and inward drift velocities, $D \approx 0.15 \, m^2/s$, $v_{in} \approx 25 \, r[m] \, m/s$, were found to be higher than the neoclassical values, $D \approx 0.02 \, m^2/s$ and $v \approx 6 \, r[m] \, m/s$. The discrepancy was attributed to the existence of an anomalous inward pinch during the time following pellet injection.

The results presented on impurity transport are summarized as follows:

1. Impurity accumulation. In agreement with neoclassical transport theory and as a consequence of improved confinement, both low- and high-Z impurities accumulate in the plasma centre, substantially increasing the radiation intensity there (by a factor of 10 to 40).

2. Impurity profile. Impurities acquire peaked profiles with broad constant-density pedestals. The impurity peakedness is notably higher than that of the plasma particles. Comparisons of gas-fuelled and pellet-fuelled discharges (TEXT) with equal edge conditions indicate that the peakedness is due to transport and not to wall (source) phenomena. In JET, the decay time of peaked impurity profiles is measured in seconds.

3. Sawtooth and MHD activities. In all experiments reported, impurity accumulation and the associated drastic increase of radiation emission from the plasma centre were concurrent with the disappearance (suppression) of sawteeth oscillations. After the impurity profile became again flattened, MHD oscillations (usually $m=1$, $n=1$ oscillations; a pressure-gradient-driven interchange mode is suspected in ALCATOR) set in and eventually sawteeth reappeared (JET). Impurities may be removed from the plasma centre by the reappearing sawteeth (declining central impurity concentration was observed in this discharge phase in JET, never radiation collapse).

4. Transport analyses. The impurity transport could usually be described by a combination of classical, neoclassical, and anomalous terms (neoclassical description suf-
ficed in the case of ALCATOR). No anomalous inward drift term was necessary for interpreting impurity transport observed in ASDEX. The anomalous diffusion coefficients and inward drift velocities arrived at usually exceeded the neoclassical values: \( D_{an} \approx O(1 \, m^2/s) \) as compared with \( D_{neo} < 0.1 \, m^2/s \). During the improved confinement regime, the impurity transport is also drastically reduced in the plasma centre (\( D_{an} = 0.05 \, m^2/s \) in ASDEX, \( 0.001 \, m^2/s \) in JET, the value being a function of the diffusion coefficient inward drift velocity combination anticipated). The anomalous impurity inward drift velocities reported vary from 1 \( m/s \) to 10 \( m/s \).

**Pellet Ablation**

Results of theoretical and experimental investigations were reported and compared in this session. A comparison of pellet penetration depths observed in TFTR with computational results based on the neutral gas plasma shielding (NGPS) ablation model yielded, in the absence of suprathermal electrons, reasonable agreement for both OH and NB-heated discharges. In the case of NB-heated discharges, it was found that for the range of beam energies applied, NB particles have a substantial effect on the ablation rate only at thermal electron temperatures below 4 keV. Above this temperature, ablation caused by electrons dominates.

The basic characteristics of the neutral gas plasma shielding (NGPS) ablation model were reviewed by W.A. Houlberg (ORNL): multi-group treatment of the plasma electrons, allowance for both neutral gas and plasma shielding, option for NB ions as energy carriers. He compared the velocity scalings of the pellet penetration depth obtained for two different models: neutral gas shielding and plasma shielding approximations. In the former case, the semi-analytical expression for the ablation rate can be integrated, yielding a penetration depth proportional to \( (v_{pel})^{1/3} \). For the second case, it was assumed that the ablated particles are funnelled into a flux tube whose radius is equal to the pellet radius (instantaneous ionization and confinement of the ablated particles). Under this condition, the ablation rate equation could again be integrated, yielding a penetration depth that is independent of the pellet injection velocity. Houlberg noted that the velocity range in which the validity of the NGPS ablation model has been experimentally verified is not sufficiently large.

A self-consistent MHD model has been developed at IPP-Garching for the time evolution of the ablatant cloud. The model shows that the cloud represents a massive high-\( \beta \) disturbance for the background plasma. It may become partially diamagnetic, thus reducing the electron flux affecting the pellet (magnetic shielding). The ionization and confinement radii of the ablated particles increase with increasing number of particles
locally deposited. Owing to the slow-down of the ionized particles at the ionization radius, a shell-structure may result. The magnitude of the confinement radius show significant variation, depending upon the tokamak plasma parameter ranges and magnetic field strengths considered. The spherically symmetric expansion velocity of the initially neutral pellet particles may considerably exceed the translational velocity of the pellet. Hence the pellet flies through its own ablant. The resulting additional shielding may gain importance for reactor-grade plasmas. Stopping length calculations applied to the evolving ablant cloud show that, as soon as the bulk ionization degree of the cloud exceeds a few per cent, the incident electron energy flux is depleted predominantly by e-e collisions.

Results were presented on pellet penetration depths and striation structures observed in TFR discharges. In ohmic discharges, striations were practically always present in the $H_\beta$ emission pattern. However, the radial positions of the striations were not reproducible for otherwise identical discharges, nor could they be related, in a unique manner, to the positions of rational $q$-surfaces of reasonably small $m$ and $n$ values. In the case of ECRH discharges, neither peaks in the $H_\beta$ emission nor striations in the pellet wake were observable. In this case, the pellet ablation was always completed in the peripheral plasma region.

The results presented on ablation phenomena are summarized as follows:

(1) Pellet heating and ablation modelling. As has been known for some time, pellet ablation in thermal plasmas is primarily due to electrons residing in the high-energy wing of the electron distribution function. This fact is now taken into account in the NGPS ablation model (ORNL), in which a multi-energy-group option (up to 20 energy groups) is now available. Computational results show significant differences in ablation rates depending on whether the single or multi-energy group is used. In the same ablation model, an option is available for determining the ablation caused by NB-produced non-thermal ions. Again, the results show that the effect of NB ions on the local ablation rate may be significant in plasma regions with low and moderate temperatures. At high electron temperatures, ablation due to electrons dominates. There is no quantitative model available yet to describe the effect of suprathermal electrons on the ablation rate.

(2) Ablant cloud expansion. A model has been developed for calculating the evolution of the high-density low-temperature cloud surrounding an ablating pellet from the moment of neutral particle release up to full ionization and radial confinement of the ablatant. The cloud expansion velocity may significantly exceed the pellet velocity, thus producing a thermal buffer zone ahead of the pellet. This cloud represents a temporary high-beta disturbance for the confining magnetic field and the recipi-
ent plasma and, at the same time, determines the time evolution of the shielding characteristics affecting the pellet.

(3) Pellet shielding. Two shielding mechanisms are taken into account in the NGPS ablation model: neutral gas shielding due to particles locally released by the pellet and shielding by the ionized and magnetically confined fraction of the ablatant. An essential parameter in this model is the confinement radius of the ionized ablatant fraction. This radius may be guessed, or calculated by means of the cloud expansion model. Additional shielding may result from the partial expulsion of the magnetic field lines from the ablatant cloud and the associated reduction of the thermal electron flux.

(4) Penetration depth and velocity scaling. Good correspondence between observed penetration depths and those calculated by means of the NGS model was reported for low plasma temperatures. Apparently, the neglect of plasma shielding is fully compensated in this case by the neglect of the high-energy wing effect in the single electron energy group approximation applied. At medium plasma temperature (ASDEX, JET, etc.) the experimentally observed penetration depths can readily be reproduced by the NGPS if a realistic ablatant ionization radius value is guessed, and the multi-energy-group option is used for the electrons. The accuracy of the penetration depth calculations performed for reactor-grade plasmas is uncertain. The range of plasma parameter and particularly pellet velocity variations used in validation calculations is not sufficiently large. Scaling law considerations applied to simplified versions of the NGS and NPGS ablation models indicate that the NPGS model in its present form yields a rather weak dependence, if any, of the penetration depth on the pellet injection velocity.

(5) Pellet wake structure. The origin of the striations observed in pellet wakes and the associated peaks in the $H_\alpha$ or $H_\beta$ emission patterns is not yet fully understood. They are most likely coupled with fluctuations in the ablation rate. There exist various hypotheses regarding the origin of the striae: (a) differences in the energy reservoirs and thus the energy fluxes affecting the pellet at flux surfaces with rational and irrational q-values; (b) instabilities associated with the ablation and/or radial confinement processes; and, finally, (c) the slow-down of the ionized material at the ionization radius and the formation of a shell structure consisting of a cold core and a hot outer region. The pellet may pass periodically through regions of higher and lower temperatures and densities thus undergoing modulation of the ablation rate as well.
Pellet Injectors

The injectors developed at ORNL can be classified as follows: (a) single-barrel pneumatic injectors delivering single or multiple pellets, (b) multiple-barrel pneumatic injectors with single ("pipe gun") or multiple pellets, (c) centrifugal injectors. Typical velocities of the order of (1 to 2) km/s have been obtained with these devices. The injector installed at JET is a three-barrel multiple-pellet gun that produces pellet velocities of up to 1.2 to 1.5 km/s. The injectors to be installed at PBX and ATF represent an improved version of the 8-barrel gun operated at TFTR. This latest 8-barrel pipe gun (pellets are formed inside the gas barrel by direct condensation from the gas phase) is to be capable of delivering 8 pellets of different sizes (1 m to 3 mm) in a preprogrammed sequence with velocities of up to 1.3 km/s. A further device under development is an arc-discharge-supported pneumatic pellet accelerator of the pipe-gun type in which the rate of pressure rise is increased from 30 to 100 bar/ms and the corresponding pellet velocity from 1.3 to 2.0 km/s. A two-stage light gas gun is being developed for high pellet velocities. Velocities of up to 4.5 km/s have already been obtained with plastic pellets. Feasibility tests are under way with a facility envisaged for T\textsubscript{z} pellet injection. It is planned to produce and accelerate \textit{T}_2 and \textit{DT} pellets to velocities of \sim 1.5 km/s. In addition to problems posed by radioactivity (shielding and automation), problems are created by the presence of \(^3\textit{He}\) in \textit{T}_2 (condensation difficulties). A pipe-gun-type device is used. Pellet velocities of up to 1.82 km/s have already been obtained with \textit{D}_2 pellets, and velocities of up to 1.4 km/s with \textit{T}_2 pellets.

Another two-stage high-speed pellet launcher is being developed at JET. With the help of this gun, plastic pellets 50 mg in weight were accelerated to velocities of up to 4.6 km/s. The maximum unsupported ice pellet velocity attainable with this launcher is limited by the pellet strength, friction, and erosion effects to about 3 km/s (velocities of up to 2.7 km/s were actually achieved with pellets 6 mm in dia.). Supporting the pellets with separable cartridges ("sabots") during the acceleration phase seems to be a practical way of overcoming this difficulty. (The sabots are separated from their payloads at the end of the acceleration phase, a process that poses some technical problems.) Obviously, the mass to be accelerated by this method is much larger than the pellet mass (by a factor of 6 to 30), which makes the installation large. Sabot-supported ice pellets 5 mm in dia. have been accelerated to velocities of up to 3.8 km/s. In addition to the two-stage gun, an advanced launcher is being developed for repetitive injection of high speed pellets into JET.

Pellet injectors are being developed at Risø National Laboratory for the RFX reversed field pinch experiment at Padova and the FTU upgraded tokamak at Frascati. Both injectors are of the multi(8)-barrel type, employing pipe guns. \textit{H}_2 and \textit{D}_2 pellets (\textit{10}^{20} to \textit{10}^{21} atoms/pellet) are to be accelerated to velocities of \sim 1.2 km/s. With a
prototype single pipe gun, velocities of 1.3 km/s ($D_2$ pellets) to 1.5 km/s ($H_2$ pellets) have already been obtained. As prototype for the 8-barrel gun, a 3-barrel injector has been built and tested. Velocities of up to 1.35 km/s have been achieved with $H_2$ pellets. A rotating disc-type six-pellet injector is being developed for HELIOTRON-E at Kobe Steel, Ltd. The pellet sizes envisaged are 1.2 mm to 2 mm in diameter. The pellet velocities (400 m/s to 1.4 km/s) as well as the time delay between two successive pellets (0 to 100 ms) can be preselected. cycle time of the injector itself is 10 min or longer. An electromagnetic railgun attached as a booster or second stage to a conventional gas gun is under development at University of Illinois. A pellet leaving the gas gun barrel (first stage) enters the railgun through a coupling piece in which the pressure behind the pellet is reduced to a preselected value. When the pellet enters the railgun, electric breakdown is produced behind the pellet, which ensures that the plasma arc of the railgun current triggered at this moment forms behind, and not in front of, the pellet. With this system, solid hydrogen pellets 3.2 mm in dia. and 4 mm in length were accelerated to velocities of up to 2.2 km/s (arc voltage and current 10 kV and 18.8 kA, respectively). Velocities of up to 4 km/s are envisaged, without using sabots, by increasing the length of the railgun barrel from 1 m (currently used) to 3 m.

The centrifugal pellet accelerator being developed at ORNL for TORE SUPRA is to deliver pellets at a frequency of 10 to 30 Hz for a discharge pulse length of 30 s. The pellet velocities planned are between 0.8 and 1.2 km/s. The pellet dispersion at the plasma surface should not exceed ± 30 mm. Also the design principles of an electron-beam-driven rocket-type pellet accelerator to be developed at ORNL were presented. According to the estimates, the exhaust velocity of the pellet particles leaving the high-density shielding cloud surrounding the pellet and irradiated by the E-beam is of the order of $8 \times 10^3$ m/s. Under this condition, it should be possible to accelerate a pellet initially 12 mm long ($r_p = 2$ mm) with an intense beam ($E = 20$ keV, $I = 20$ A) to velocities of up to ~ 10 km/s over an acceleration length of ~ 5.5 m within ~ 1.26 ms. The residual pellet length at this time would be 3 mm. Mass loss from the lateral (radial) surface has not been estimated by the authors. Keeping a long cylindrical pellet in a stable position (without tumbling) during the acceleration phase may also pose some problems. Experimental tests are about to start.

The major performance characteristics of the injector types presented are summarized as follows:

(1) Pneumatic single-stage accelerators with driver gas pressures of 50 to 100 bar:

- **JET:** ORNL 3-barrel injector, pellets 2.7/4.0/6.0 mm in dia., pellet frequencies 5.0/2.5/1.0 Hz, respectively; pellet velocities of up to 1.5 km/s.
- **TFTR, PBX, ATF:** ORNL 8-shot pellet injectors, pellets 3 to 4 mm in dia., programmed time sequence, velocities of up to 1.5 km/s.
RFX, FTU: pellets 1.5 to 3 mm in dia., with velocities of up to 1.2 km/s.
HELIOTRON-E: revolving disc-type six-pellet injector, pellets 1.2 to 2 mm in dia.,
velocities of up to 1.4 km/s.

(2) Centrifugal accelerators:
TORE SUPRA: pellets 1 to 2 mm in dia. at 10 to 30 Hz, velocities up to 1.2 km/s.

(3) Advanced two-stage pneumatic guns under development:
ORNL: driver gas pressure 55 bar, pumpe tube and gun barrel diameters and lengths
25.4 mm, 4 mm, 1 m, and 1 m, respectively; 35 mg plastic pellets were accelerated
to \( v \sim 4.5 \text{ km/s} \); (5 to 20) mg \( H_2 \) and \( D_2 \) pellets envisaged.
JET: driver gas pressure 200 bar, pumpe tube and gun barrel diameters and lengths
35 mm, 6 mm, 1.5 m, and 1 m, respectively; 50 mg plastic pellets were accelerated
to \( v = 4.6 \text{ km/s} \), 6 mm unsupported \( H_2 \) pellets to \( v = 2.7 \text{ km/s} \), and 5 mm sabot
supported pellets to \( v = 3.8 \text{ km/s} \); pellets velocities in the range of 5 to 10 km/s are
envisaged.

(4) \( T_2 \) pellet injector installation (ORNL):
In the test runs, \( D_2 \) pellets 4 mm in dia. were accelerated to \( v = 1.85 \text{ km/s} \), \( T_2 \) (DT)
pellets can be accelerated to velocities of up to 1.4 km/s.

(5) Electromagnetic railgun accelerator (Univ. Illinois):
Pellets 3.2 mm in dia. \( \times 4 \text{ mm in length} \) were accelerated to velocities of up to 2.2
km/s, velocities of up to 4 km/s being envisaged.

(6) E-beam-driven rocket-type accelerator (ORNL):
Experiments are planned, envisaged are velocities of up to 10 km/s.
I. GENERAL PHENOMENA
RESULTS OF PELLET INJECTION EXPERIMENTS IN JT-60

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Abstract

This paper presents recent experimental results of pellet injection to joule plasmas and heating experiments of pellet injected plasmas by NB, LHRF, and ICRF. Especially clear improvement in confinement has been obtained in NB heating of pellet injected plasma up to 10-15MW in Ip=1.5-1.8MA lower-side X-point divertor configuration.

1. INTRODUCTION

Control of density profile is one of the method to improve confinement, and pellet injection is the powerful method to make a peaked density profile.

JT-60 installed a multi-barrel pneumatic H₂ pellet injector in March 1988. Sizes of the pellets are 2.7mm x 2.7mm and 3.8mm x 3.8mm, and pellet velocity is about 1500m/sec. As shown in Fig.1 pellets are injected with an angle of 47 degree from the midplane with off-axis injection, where the chord of Thomson scattering exists at R=2.95m and two chords of submillimeter interferometer exist at R=2.53m(U₂₃) and 3.55m(U₆). Pellet ablation profile can be monitored by multi-channel measurement of Hα light.

Fig.1 Configuration of lower-side X-point divertor plasma.
Experiments of pellet injection were started from June 1988, and two 2.7mm pellets and one 3.8mm pellet were successfully injected. Optimization in pellet injection has been performed for getting a peaked density profile with joule plasma and 1.8MW NB heated plasma. Then 3.5-17MW NB heating of pellet injected plasma has been performed in lower-side X-point divertor configuration. Furthermore ion heating of pellet injected plasma has been performed with LHRF of 1.0-2.0MW or ICRF of 0.7-3.1MW.

2. PELLET INJECTION TO JOULE PLASMAS

Experiments in pellet injection to joule plasma has been performed to make a peaked density profile and to get an improved confinement in both of limiter and lower-side X-point divertor plasma with Ip=1.0-2.0MA.

First of all plasma density just before pellet injection was scanned to find out the optimum target plasma density for increasing stored energy as shown in Fig.2, that presents three cases of plasma density in 1.5MA limiter plasma as follows. (a) Low density; Ablation of pellet occurs at the plasma periphery for the sake of low plasma density and/or runaway electrons. Increase in line integral density at U6 chord is high, that locates about 0.66 of minor radius, however decay time of that is short. Increase in stored energy ($W_{DIA}$) is only 180 kJ.

Where $W_{DIA}$ is measured by diamagnetic loop. (b) High density; Passing-through of pellet occurs for the sake of low plasma temperature. Radiation of main plasma increased at this moment and plasma becomes disruptive. Therefore no increase in stored energy is observed. (c) Medium density; Pellet penetrates near the plasma center, and increase in radiation power is small. The maximum increase in stored energy of 240 kJ is obtained. These experimental results suggest control of target plasma density is the key issue to get the optimum pellet penetration and the large increase in plasma stored energy. Optimum target plasma density depends on number and time interval of pellets, plasma current, and the configuration of plasma. Therefore feedback control of plasma density is adopted to search optimum density and to increase reproducibility of pellet injection.
Highly peaked density can be obtained in the case of (a). Figure 3 shows the density profile 50msec after the last pellets injection $n_e(0)$ is about $1.7 \times 10^{19}/m^3$ and $n_e(0)/\langle n_e \rangle_\gamma$ is 5.0. This peaking factor decreases to about 3.0-4.0 at the time of maximum stored energy, that is 300-400msec after the last pellet injection.

In limiter plasma stored energy of pellet injected plasma is almost the same level with that of gas puffed plasma and improvement in confinement has not been obtained yet. On the other hand improvement is observed in divertor plasma, where increase in increases in $\tau_E$ is about 10%.

![Fig.3 Profile of density and temperature at 50msec after the pellet injection.](image)

3. NB HEATING OF PELLET INJECTED PLASMAS

NB heating of pellet injected plasma has been performed in lower-side X-point divertor configuration with $P_{NB}=1.8-17$MW and $I_p=1.5,1.8$MA. First of all we have combined pellet injection and low power NB heating of 1.8MW (1-unit of NBI in JT-60) for getting stable and reproducible pellet injection. Figure 4(a) shows the plasma stored energy of (i) this combination, comparing with (ii) pellet injection alone. Stored energy of (i) is 100kJ higher than (ii) with almost same increase in stored energy of around 420kJ. Profile of density and temperature at 300msec after the pellet injection is almost same between (i) and (ii) as shown Fig.4(b). Therefore power scan of NB heating has been performed raising NB power up to 17MW at 50msec after the last pellet injection.

Time evolutions of $W^{DIA}$ after the pellet injection are presented in Fig.5 for each NB power, in the case of 1.5MA divertor plasma. At low power level of 1.8-3.5MW improvement in confinement lasts for about 1sec. Then large sawtooth activity terminates this improvement, the time points of that are presented by arrows in Fig.5. This improved phase becomes shorter with higher NB power. In the case of $P_{NB}>15$MW this improvement terminated at 200msec after the pellet injection, then plasma enters in the improved divertor confinement (IDC) phase and stored energy increases without saturation.
Fig. 4(a) Stored energy of pellet injected joule plasma and 1.8MW NB heated plasma.

Fig. 4(b) Profile of density and temperature at 300msec after the pellet injection. E7471: pellet + joule plasma, E7999: pellet + 1.8MW NB heated plasma.

Fig. 5 Stored energy in 1.8-17MW NB heating of pellet injected plasma. Arrows present the time point of the occurrence of large sawtooth activity.
Figure 6(a) shows the plasma stored energy against total absorbed power in the case of 1.5MA lower-side X-point divertor plasma. Clear increase in stored energy can be observed in NB power of <15MW. At $P_{abs}=10$MW confinement time increases around 20% of NBheating alone. Figure 6(b) shows WDIA of 1.8MA divertor plasma against the absorbed power, and increase in stored energy by combination of NB heating and pellet injection is observed with $P_{NB}=15$MW. This suggests confinement can be improved by higher NB power at higher plasma current.

![Graph](image)

**Fig. 6(a)** Stored energy of 1.5MA lower-side X-point divertor plasma against absorbed power.

![Graph](image)

**Fig. 6(b)** Stored energy of 1.8MA lower-side X-point divertor plasma against absorbed power.

The increase in stored energy is attributed to a peaked density profile. Because peaking factor of density profile decreases with higher NB heating power and increase in stored energy becomes small. The other reason of the improvement may be increase in density. However density dependence of stored energy at $P_{abs}>5$MW is small.
In the combination of NB heating and pellet injection, internal m=1 mode and sawtooth oscillation is frequently observed in Soft X-ray emission. Increase in stored energy is suppressed by this MHD activity. However extremely peaked high density profile produced by multi-pellets injection suppresses this activity and raise the stored energy. Figure 7 shows this phenomena and increase

Fig. 7(a) Stored energy in 10MW NB heating of pellet injected plasma. E8009;NB heating only, E8005;2 pellet injection+NB heating, and E8007;3 pellet injection+NB heating.

Fig. 7(b) Soft X-ray emission from the center plasma.
in stored energy is locked by the occurrence of sawtooth activity and internal $m=1$ mode in E8005. On the other hand no such MHD activity exists in the case of E8007 and stored energy increases up to 15% higher without saturation until the sudden decrease at $t=6.2$ sec, that might be caused by radiation collapse.

The difference between E8007 and E8005 is number of pellets. Three pellets are injected in E8007 and density at the plasma center is about 40% higher with slightly lower electron temperature than that of two pellets injection in E8005. This suggests current profile can be controlled by pellet injection and improvement in confinement can be obtained by that.

4. LHRF HEATING OF PELLET INJECTED PLASMAS

For getting ion heating by LHRF in the high density regime, combination of pellet injection and LHRF heating has been performed in lower-side X-point divertor configuration with $P_{LH}=1.0-2.5$ MW, $f_{LH}=1.74$ GHz, $I_p=1$ MA, $B_T=4.5$ T and hydrogen plasma). Figure 8 shows the time evolution of the typical case. Three pellets were injected at 50msec intervals into a low density plasma. At 80msec after the third pellet injection, RF powers with pulse length of -0.15 sec were injected during the density decay phase. Hard X-ray emission with an energy of larger than 200 KeV is not observed in the first pulse of RF and seems to increase at the second and third pulse. Ion temperature measured by charge exchange of neutral particles rises largely in the first pulse. This suggests the first RF pulse does ion heating.

![Fig.8 LHRF heating of pellet injected plasma.](image)
Incremental energy confinement time defined by $\Delta W_{\text{LH}}/(P_{\text{LH}} + \Delta P_{\text{OH}})$ increases with line averaged density at high density regime of $>4 \times 10^{19}/m^3$, and parametric instability is not observed. Peaked density profile with low edge plasma density produced by pellet injection is preferable for suppressing parametric instability at plasma periphercy and getting ion heating in the plasma core.

5. ICRF HEATING OF PELLET INJECTED PLASMAS

ICRF heating of pellet injected plasma has been performed with 0.7-3.1 MW in (0,0) mode. Increase in Ti(0) is about 0.5 keV at ne of $5.6 \times 10^{19}/m^3$ and $\tau_{\text{INC}} = (\Delta W_{\text{corrected}}/P_{\text{IC}} + \Delta P_{\text{OH}})$ is 50 msec, that is almost the same level at low density of $1-2 \times 10^{19}/m^3$.

6. SUMMARY

Pellet experiments started from June in 1988, and peaked density profile of $n_e(0)/<n_e> = 5.0$ with $n_e(0) = 17 \times 10^{19}/m^3$ has been obtained in joule plasma for the sake of the optimization in the target plasma density. Furthermore pellet injection to low power NB heated (1.8 MW) plasma has been performed, and more increased stability in pellet injection has been obtained.

Power scan of NB heating of pellet injected plasma has been performed in lower-side X-point divertor configuration with $I_p = 1.5$ MA and 1.8 MA. Clear increase in stored energy has been observed at NB power of <10-15 MW. Increase in threshold power for getting improved confinement is observed with raising plasma current. Suppression of internal m=1 mode and sawtooth activity has been observed in extremely peaked and high density profile with three pellet injected plasma and confinement has been improved about 15% of two pellet injected plasma. This suggests current profile can be controlled by pellet injection improvement in confinement can be obtained by that.

LHRF heating of pellet injected plasma has been performed, and increase in stored energy without the occurrence of parametric instability and Hard-Xray emission has been observed. This suggests peaked density profile with low edge plasma density is preferable for ion heating by LHRF.

ICRF heating of pellet injected plasma has been performed and no decrease in heating efficiency observed.

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IMPROVED PLASMA PERFORMANCE BY REPETITIVE PELLET INJECTION IN ASDEX

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Abstract

Experiments with repetitive pellet injection were performed in ASDEX divertor discharges under purely Ohmic as well as with NBI and ICRH heating. The pellets used were of two different sizes each contributing 1 or 3 \(10^{19}\text{m}^{-3}\), respectively, to the volume averaged plasma density. The parameter scans concentrated on discharges with \(B_t = 2.2\ T\), \(I_p = 380\ kA\), and covered a line-averaged electron density range between \(n_e = 1.4 \times 10^{20}\text{m}^{-3}\) (2.6 MW NBI). Both latter values constitute increases by approximately \(n_e = 5.5 \times 10^{19}\text{m}^{-3}\) over the respective limits in gas-puff discharges and correspond to Murakami parameters of \(n_e R/B_t = 8 \times 10^{19}\text{m}^{-2}\text{T}^{-1}\) and \(10.5 \times 10^{19}\text{m}^{-2}\text{T}^{-1}\). Additional heating powers applied so far to these discharges ranged up to 2.6 MW of NBI and 1.3 MW of ICRH.

Pellet injection is found to give rise to density peaking also inside the deposition radius of the pellet particles. It leads to a long lasting increase of \(n_e(0)/<n_e>_{\text{vol}}\) from 1.5 to 2.6 which can be explained only by an increase in the ratio of the inward pinch velocity to the particle diffusion coefficient \(-V/D\). In Ohmic deuterium discharges, this increase is typically a factor of 1.5. In addition the diffusive mixing process caused by sawteeth is normally reduced and sometimes eliminated by pellet injection. With additional heating the global peaking parameter \(n_e(0)/<n_e>_{\text{vol}}\) is gradually reduced. Additionally to the transport on the typical diffusive time scale a fast inward transport of particles on a time scale of <2 ms is sometimes observed immediately following the pellet deposition.

1. Introduction

In tokamak fusion research the most important objective is to improve the plasma characteristics to reach the Lawson criterion. In many tokamaks, e.g. JET, TFTR, DIII, TFR, JT-60, JFT-2M, Alcator-C, PLT, ISX and PDX, pellet injection experiments have been performed to explore their potential for improving the plasma performance. It is found in both ohmically and auxiliary heated discharges that pellet injection can lead to extended operational regimes with respect to the density limit and the global energy confinement time. In ASDEX divertor discharges \((R = 1.65\ m, a = 0.40\ m, \text{carbonized walls})\) experiments with pellet injection were performed with purely ohmic heating as well as with NBI and ICR heating. A centrifuge accelerated typically 5 to 30 deuterium or hydrogen pellets into a single discharge at time intervals of between 30 to 100 ms. The pellets were of two different sizes, each contributing 1 and \(3 \times 10^{19}\text{m}^{-3}\), respectively, to the volume-averaged plasma density. Penetration depths of half the plasma radius, incre-
asing with pellet size, were yielded with the injection velocity of \( \approx 600 \) m/s. Injection of deuterium pellets into deuterium and of hydrogen pellets into hydrogen discharges was studied. Extensive optimization studies and parameter scans concentrated on discharges with \( B_t = 2.2 \) T, \( I_p = 380 \) kA \( (q_a = 2.7) \) and covered a line-averaged density range between \( n_e = 1 \times 10^{19} \) and \( 1.2 \times 10^{20} \) (OH) and \( 1.4 \times 10^{20} \) m\(^{-3}\) (2.6 MW). Additional heating power applied so far ranged up to 3 MW of NBI and 1.4 MW of ICRH. These plasmas are characterized by markedly centrally peaked electron density profiles, high edge recycling, reduced sawtooth activity, central impurity radiation, enhanced density limit and improved global energy confinement.

The studies were carried out with two divertor chamber configurations, the more recent one, DV-II [1], having a smaller volume of the immediate divertor chamber, but larger bypasses to the main discharge chamber.

2. Phenomenology

The plasma performance is substantially improved by injecting small pellets into OH discharges and large pellets into additionally heated discharges. Pellet injection started typically in the flat-top phase of the discharge at medium target electron densities. During the pellet injection phase sufficient gas-puff has to be provided to reach stationary high-density phases and enhanced energy confinement. The sawtooth dynamic is strongly reduced and sometimes completely suppressed by the pellets. This is accompanied by increased central radiation loss, sometimes to values comparable to the local power input. The total radiated power increases continuously during the density build-up but does not exceed 45 % of the total input power. The maximum plasma energy stored during the L-mode (NBI) is about 100 kJ, which corresponds to a volume-averaged toroidal beta of \( \beta_t = 0.65 \% \) and a Troyon factor of \( g = 1.5 \) (according to \( \beta_t = gI_p/aB_T \)).

In ohmically heated discharges nearly all the particles of the pellet are detected in the main plasma, whereas with NBI heating up to 50 % of the injected pellet mass is missing when the NBI power significantly exceeds the ohmic power level (\( \approx 0.5 \) MW). The pellet ablation and penetration are monitored by photodiodes with \( D_\alpha/H_\alpha \) line filtering and photography. The deduced penetration depths of the two diagnostics and theoretical calculations (see separate contribution to this workshop by L. Lengyel) agree well. Sometimes toroidal deflection of the injected pellets in the electron direction in OH as well as in auxiliary heated discharges is observed.

In a limited number of pellet-refuelled ICR heated discharges we have observed two phases of significantly different sawtooth behaviour and energy confinement [2]. In the first phase, regular sawteeth are visible on \( T_e \) and \( n_e \), whereas during the second phase a still strong sawtooth on the density signal corresponds to only a weak modulation in the electron temperature. The energy confinement increases about 16 % and 36 % in relation to that with ICRH alone in the first and second pellet-refuelled phases, respectively. The timing of the transition seems to be correlated to the closing of the external gas valve.
3. Density Limit

Figure 1 demonstrates the beneficial effects of pellet injection into ohmically and NBI heated L-mode deuterium discharges with respect to the density limit. The line-averaged density limit increases almost independently of the heating power by $n_e \approx 5.5 \cdot 10^{19} \text{ m}^{-3}$ over the respective limits in gas-puff discharges and corresponds to Murakami parameters of $n_e R/B_t = 8$ (OH) and $10.5 \cdot 10^{19} \text{ m}^{-2} T^{-1}$ (2.6 MW NBI). The density limit $n_{e,DL}$ of the common gas-puff and pellet refuelled discharges can be described by $n_{e,DL} = 7.1 \cdot P_{tot}^{0.25}$ and $n_{e,DL} = 12.7 \cdot P_{tot}^{0.1} \left[10^{19} \text{ m}^{-3}, \text{MW}\right]$, respectively. The enhancement of the density limit might be partly due to the decrease of $Z_{eff}$ and the change of the density profile shape during pellet injection. As shown earlier with the previous ASDEX divertor, DV-I, pellet injection cannot substitute sufficient recycling at the plasma boundary [3], and so the density limit even with pellet injection is usually coupled to high radiation at the plasma boundary.

![Fig. 1: Line-averaged density limit $n_e$ versus $P_{tot}$ of pellet (solid line) and standard gas-puff (dashed line) $D^+$ discharges at $I_p = 380 \text{kA}$. The density limit is increased with pellet injection by $n_e \approx 5.5 \cdot 10^{19} \text{ m}^{-3}$ at all heating powers.](image-url)
4. MHD Activity and Impurity Behaviour

In general, strongly increasing central radiation was observed in all cases of successful density build-up and peaking of the density profile. This results from the high $n_e(0)$ and from the accumulation of highly ionized metal impurities. The net inward motion of the impurities and protons depends sensitively on the details of the sawtooth dynamics [4]. For example, the time evolution of $n_e$, $n_e(0)$ and $T_e(a/2)$ of a 0.5 MW NBI heated discharge with five injected large pellets is shown in fig. 2a. Figure 2b describes the sawtooth behaviour. The radially shifting “sawtoothing zone” marks the region which is affected by the sawtooth activity according to the chord-integrated soft X-radiation. This radiation is also used to estimate the violence of the sawtooth activity $A_{st}$. With the start of pellet injection the inversion radius shrinks slightly. After the last pellet the sawtooth dynamics vanishes for about 0.1 s and simultaneously there is a dramatic increase of the central radiation. The plasma pressure $\beta_p$ reaches its maximum during this phase. Parallel to the rise of the central radiation strong MHD oscillations are observed around $r \approx 0.07$ m which disappear when the SX-radiation saturates. At $\approx 1.28$ s sawtooth-like behaviour starts affecting only the radial region between $r \approx 0.1$ m and 0.25 m, which apparently does not hinder the accumulation of impurities.

Fig. 2: Figure (a) shows the reconstructed $\bar{n}_e$-trace and the smoothed $n_e(0)$ and $T_e(a/2)$ information vs. time. Figure (b) indicates the radial zone affected by sawteeth according to SX-ray line integrals. The regions of dropping (-) and rising (+) amplitude are separately marked. Figure (c) shows the measured (by means of infrared bremsstrahlung) and the neoclassically calculated radius-averaged $Z_{eff}$ and the central radiation power density $P_{rad}(0)$.

The time period (fig. 2c) and the radial zone, where the bolometrically measured radiation increases, coincides well with the central zone of vanishing sawtooth activity in fig. 2b. Spectroscopic investigations of similar cases revealed the divertor plate material Cu to be responsible for the central radiation (see separate contribution to this workshop by G. Fußmann).
The measured (by means of infrared bremsstrahlung) and the neoclassically calculated radius-averaged $Z_{eff}$ agree well and show a continuous increase with time after a reduction at the start of pellet injection (fig. 2c), the latter being related to the dilution by the pellets.

5. Particle Transport
Pellet injection is found to lead to strong peaking of the electron density profile also inside the deposition radius of the pellet particles. Figure 3 presents the peaking factor $n_e(0)/\langle n_e \rangle$ as a function of the total heating power $P_{tot}$ for ohmically and neutral beam heated L-mode deuterium discharges. With gas-puffing only and with normal sawtooth activity, the peaking factor is below 1.5 and depends little on $P_{tot}$. When the sawteeth vanish in ohmic discharges, the peaking factor rises to 2 (only $D^+$ discharges tend to loose sawteeth). The highest peaking of about 2.6 was reached in sawtooth-free OH phases after pellet injection. With additional heating, the peaking parameter is gradually reduced from 2.6 to 1.6 (2.6 MW NBI) if one compares the peaking at the end of pellet injection; but if the sawtooth dynamics is completely suppressed, a maximum peaking of about 2.5 is attained after the last pellet also with strong NBI heating. This increase of the peaking parameter reflects a change of the particle transport properties. In parallel the electron temperature profile shape is not changed by the pellet injection.

![Figure 3: Density profile peaking factor $n_e(0)/\langle n_e \rangle$ as a function of $P_{tot}$ of pellet and gas-puff-fuelled $D^+$ discharges. The solid data point at $P_{tot} = 0.45$ MW corresponds to sawtooth-free standard gas-puff OH discharges.](image)

If we describe the particle flux by the ansatz $\Gamma_e = -D \cdot \nabla n_e + V_{in} \cdot n_e$, we consequently find - during nearly stationary density phases - a change of the ratio of inward velocity to diffusion coefficient $-V_{in}/D$ in the inner two-thirds of the plasma. This ratio of $5.4 \cdot r/a^2$ in pellet-refuelled sawtooth free OH discharges has to be compared with $3.5 \cdot r/a^2$ in the sawtooth-free gas-puff case. It is still an open question whether $|V_{in}|$ increases and/or D decreases.

Information about $V_{in}$ and $D$ can be separately gained by analyzing dynamic phases. Numerical simulation of the density evolution over $\approx 0.12$ s (fig. 4b) after the last pellet of discharge #25064 (fig. 2) reveal that the following transport coefficients can explain the measured density history (fig. 4a) inside $r < 3/4a$: $D(r) = 0.07 \cdot (1 + r/a)m^2/s$ and $V_{in}(r) = -1.1 \cdot (r/a)m/s$. The accuracy of the transport coefficients is estimated to be $\approx 25\%$. Similar calculations of OH pellet discharges indicate that both D and $|V_{in}|$ increase with rising NBI heating power.
Fig. 4: Density evolution of discharge # 25064 measured by Thomson scattering (a) and calculated (b) after pellet injection. The time between each plotted profile is $\approx 17$ ms. The electron flux $\Gamma_e$ deduced from the measured profile evolution is averaged over the whole time interval of 120 ms. The electron flux $\Gamma_{NBI}$ reflects the electron source due to the NBI.

6. Global Energy Confinement

We have investigated the dependence of the global energy confinement time $\tau_E$ on the externally controllable parameters $n_e$, $P_{tot}$, isotope type and fuelling method. Whereas, with purely ohmic heating, density scans for the usual gas-puff-fuelled discharges with flat density profiles show a saturation of $\tau_E$ at 60 and 85 ms for $H^+$ and $D^+$, respectively, pellet fuelling allows access to a regime with peaked $n_e(r)$ and monotonically increasing $\tau_E$.
cally increasing $\tau_E(\bar{n}_e)$, reaching values of 110 ms for $H^+$ and 160 ms for $D^+$. Also in this case, however, confinement deteriorates with heating power, and the gain factor of $\tau_E$ of these peaked density profile discharges in relation to the conventional gas-fuelled L-regime cases decreases from nearly 2 at ohmic powers to 1.3 at $P_{tot} = 2.7$ MW (fig. 5) (see separate contribution to this workshop by O. Gruber).

7. Future Aspects
We have demonstrated the advantage of operating in the high-density pellet regime with its genuinely enhanced confinement characteristics. To improve the flexibility of the pellet injection experiments a feedback system relating a central density measurement to the pellet centrifuge has been installed which allows the suppression of pellets. This opens the possibility of stationary operation at high densities for a long time ($>> \tau_E$). Additionally, the pellet mass and repetition time can now be varied during the injection procedure. Figure 6 shows one example of the first density-centrifuge feedback experiments.

Fig. 6: Time history of $\bar{n}_e$, density profile peaking factor and central chord-integrated SX-radiation of a density-centrifuge feedback experiment.

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The multiple injection of deuterium pellets into JET plasmas under various scenarios for limiter and X-point discharges with currents up to 5MA with pure ohmic, neutral beam and RF heating has been undertaken in a collaborative effort between JET and an USDoE team under the umbrella of the EURATOM-USDoE (US Department of Energy) Fusion Agreement on Pellet Injection using an ORNL built 3-barrel, repetitive multi-pellet launcher. The best plasma performance with pellet injection and additional heating so far has been obtained by injecting early into 3 MA, 3.1 T pulses while centrally depositing the pellet mass, with $n_{\text{eo}}$ initially well in excess of $10^{20}$ m$^{-3}$. Subsequent central heating of this dense and clean core by ion cyclotron resonance heating (ICRH) with H and $^3$He minorities in the 10 MW range yields $T_{\text{eo}}$ up to 12 keV and $T_{\text{io}}$ up to more than 10 keV, while $n_{\text{eo}}$ is decreasing (within up to 1.5s) decaying to $0.6 \times 10^{20}$ m$^{-3}$, suggesting an enhanced central energy confinement in limiter discharges with only modestly improved global L-mode confinement. In this plasma core electron pressures of more than 1 bar with gradients in the order of $4 \text{ bar} \times \text{m}^{-1}$ have been reached with the total pressure approaching ballooning stability limits. The resulting total neutron rate from D-D reactions of up to $4.5 \times 10^{15}$ s$^{-1}$ so far increases strongly with RF power and can exceed that of similar non-enhanced shots by factors of 3 to 5. $n_{\text{p}}(0)T_{\text{i}}(0)\tau_{\text{e}}(a)$ products in the range of 1 to $2 \times 10^{20}$ m$^{-3}$keVs are obtained but combined power with neutral beams (up to 28 MW total) generally degrades the performance though leading to higher neutron rates of up to $7 \times 10^{15}$ s$^{-1}$. 

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1. INTRODUCTION

Pellet Injection experiments on JET have started since 1986 with single pellet experiments establishing that peaked density profiles can be generated and that the central density is not closely tied to the global density limit experienced in tokamak operation [1]. With the installation of the multi-pellet injector, jointly built by JET and Oak Ridge National Laboratory (ORNL) the range of experiments could be enormously widened due to the flexibility of the injector capable of delivering 2.7, 4 and 6 mm pellets from three independent barrels (i.e. guns can be fired simultaneously) with up to 1.5 km s\(^{-1}\) speed and up to 5 s\(^{-1}\) repetition frequency. The number of pellets is at present limited to a maximum of 32 only by the control and monitoring system of the injector. More technical details are given in [2,3].

The experiments - jointly carried out and evaluated by the JET-US team - tried initially to probe predominantly ohmic plasmas in preparing the plasma for subsequent additional heating since it was known that at least the smaller pellets of the above choice would not penetrate far into very high temperature plasmas. However, a few experiments of the latter kind were also performed.

The paper will firstly give a short summary of these probing attempts and their (preliminary) results - for more information see [4,5] - and then turn to the more interesting phenomenon of a new confinement regime found in the plasma core when applying centrally deposited RF heating to particularly peaked density profiles in the early current flat-top phase. The very first indications of this effect came as a late entry to the EPS conference at Dubrovnik [4,6,7] and the newest results on the now broadened data base have been given at the recent IAEA conference at Nice [8].

2. SUMMARY OF PROBING RESULTS

2.1 2.7 and 4 mm deuterium pellets have penetration depths in line with previous single pellet results, and single pellets as a rule of thumb will reach the center of JET plasmas with central electron temperatures \(T_e(0)\) of 1.5 and 2.5 keV, respectively; according to our experience only then strong density peaking is to be expected. Fig. 1 shows the normalised peaking factor \(n_e(0)/\langle n_e \rangle\) (central over volume averaged electron density, ratio of this factor before - usually 1.5 - to that 0.2 s after the pellet event)
versus penetration depth as derived from the end of the Dα-trace (minor horizontal radii of JET plasmas are \( a = 1.15 \) to 1.25 m). As can be seen from the figure, pellets in the case of JET must reach the center within 0.3 m before significant peaking will occur.

2.2 Since JET plasmas of \( \geq 3 \) MA develop usually already higher \( T_e(0) \) than the ones quoted above, pellets are either injected at the beginning of the pulse into the current ramp or early flat top (these cases will be dealt with in chapter 4 more extensively) or a string of pellets preceeding the one to facilitate the peaking have to be applied to cool the plasma suitably. An example of the latter case (pulse \# 13572) is given in fig. 2 where a 4 mm pellet at 4.5 s controls the temperature such that a close (ca \( 10^{-3} \) s apart) combination of a 4 and a 2.7 mm pellet at 5.5 s leads to strong peaking of density, starting with a maximum of \( 1.3 \times 10^{20} \) m\(^{-3} \) decaying slowly in this ohmic shot to \( 0.9 \times 10^{20} \) m\(^{-3} \) within 2 s; the well confined core is still recognisable after 3 s and sawtooth activity is supressed well beyond the timescale of fig. 2.

![Diagram of pellet injection](image)

2.3 Multiple pellet injection in the current flat-top, early as well as late, has in limiter discharges quite often led to the excitation of quasi-stationary modes (QSM or locked modes) which usually destroy the density peakedness quite rapidly and can easily lead, in particular with subsequent heating attempts, to disruptions [9]. No general recipe has yet been found to avoid QSMs; they seem largely but not uniquely to depend on the conditioning of walls and limiters. In one of the few attempts to heat plasmas with RF (16 MW) after flat-top injection of three successive (2 s\(^{-1}\)) 4 mm pellets the neutron rate (\( 7 \times 10^{14} \) s\(^{-1}\)) came out higher than with comparable RF shots at that time: a hint for the higher deuterium contents despite the lack of central pellet deposition in this case.

2.4 Recently some preliminary attempts of fuelling into RF heated (ca 6 MW) limiter discharges have been performed in a quasi-centrifuge mode: in one case 32 pellets of 2.7 mm at 2.5 s\(^{-1}\) and in another six 4 mm pellets at 1 s\(^{-1}\) have not created any sign of peaking of the density profile which has rather exhibited the features of gas fuelled pulses.

2.5 Injection into single and double null X-point discharges can be dealt with like in limiter discharges: we have achieved strong peaking before the onset of the additional heating and an H-mode could be created thereafter. However, the limited penetration of the JET neutral deuterium
beams cannot heat this central dense core and RF antennae and plasma geometry in this configuration are incompatible at present. Also small pellets into an H-mode (without destroying it) and into supershots (with slightly increasing the highest neutron rate on JET so far) have been facilitated.

2.6 Most of the above experiments have been performed on plasma currents close to 3 MA for reasons of higher stability (i.e. higher safety factor q(a)) and less severe disruptions. The extension of the schemes to be described in item 4. to plasma currents of 4 and 5 MA proved quite tricky because it is difficult to control the T_e(0) appropriate for peaking by a suitably timed pellet string over the long time to reach the respective current (e.g. ca 7 s for 5 MA). Scenarios have been developed but until now there was insufficient time to perform the subsequent heating.

2.7 Suitable plasmas for the injection of 6 mm pellets (T_e(0) = 5-6 keV and total plasma energy > 5 MJ) have not readily been available and the few attempts made in marginal conditions have ended in disruptions.

3. EARLY INJECTION AND HEATING - ENHANCED MODE

3.1 The peaked density profiles with peaking factors around 3 (after 0.2 s) with injection into the current ramp and early flat-top can be facilitated as demonstrated in the two examples given in figs. 3 and 4: a string of 7 2.7 mm pellets leads to n_e(0) = 0.9*10^{20} m^{-3} when 8.5 MW of RF (H minority ICRH) and 5 MW of neutral beam (NB) are applied (# 14550) raising T_e(0) to 8 keV; in # 16211 a single 4 mm pellet created an initial n_e(0)=1.4*10^{20} m^{-3} before 8 MW of RF only (again H minority) boost T_e(0) and T_i(0) up to maximum values of 11 and 8 keV, respectively, while the central density is decaying towards 0.6*10^{20} m^{-3}. Both pulses - Fig. 4, lower - exhibit after an initially steep and smooth slope of T_e(0) some hesitation in this rise and end the increase in a sudden loss of electron temperature by several keV (still no sawtoothing present, and for # 16211 analysed to be accompanied by MHD modes, predominantly m=3, n=2). Fig. 4, upper shows the development of the central safety factor q(0) for both pulses as derived from Faraday rotation and shows it to be >1 (even through the crash of T_e(0) in # 16211) and to be higher for the multiple pellet shot which may be of advantage if ballooning instability is a problem. In the last period we concentrated on "single" pellet peaking (and achieved here the maximum value of n_e(0) = 2*10^{20} m^{-3}) but it will be of interest to return to the other scheme.
The comparison of a pellet shot (I = # 16211) with a non-peaking pellet shot (II = # 16206 resembling very much a gas fuelled one) in fig 6 (a to e) clarifies why we speak of enhanced performances: When central ICRH is applied the rates of electron and ion temperature rise as well as the obtained maximum values are superior to those of the shot lacking the density peaking. This is particularly evident from the neutron rate due to D-D reactions being increased by factors of 3 to 5 and that due to D-T reactions of the generated tritons being larger by an order of magnitude; it is important to note that the D-T reaction is maintained steadily through the $T_e$ crash documenting that the tritons are not expelled.

Fig. 7a shows a comparison of radial profiles of density from LIDAR Thomson scattering at the time of pellet injection and 1.2 s thereafter (the central density peaking still recognisable and shifted to a larger radius because of $\beta$-effects) for # 17749, marked (P), in comparison with the flat non-pellet profiles of # 17747, marked (NP). Underneath in fig 7b, the comparison is seen for $T_e$ from LIDAR and $T_i$ from charge exchange.
spectroscopy documenting that the temperatures for the enhanced performance are tracking each other well concerning the radial profiles and are well into the reactor relevant range. The resulting electron pressure (1.2 bar with a gradient of 4 bar m$^{-1}$) in fig. 7c leads to an plasma pressure estimate of close to 2 bar and poses the question of stability: Although this pressure approaches only 40% of the Troyon limit for idealised profiles more detailed calculations show that - taking into account the uncertainty for $q(0)$ - the stability limit is at least approached if not exceeded (fig. 8); This is one possible explanation for the deterioration of the enhanced performance. Fig. 9 presents $n_e = \delta \ln T_e/\delta \ln n_e$ values from LIDAR measurements whereby we assume that $n_i = n_e$ at least for the first 0.75 s because of the proximity of temperature profiles of electrons and ions and the low $Z_{eff}$; the indications that $n_i$ is below 1.5 for the central half of the plasma radius may contribute to the enhancement but the progression of the $n(r)$ curve with time towards the axis would then also point to the transient nature of this phenomenon. In transport modelling with a single fluid model the thermal conductivity for the central core had to be assumed to be 2 to 3 times lower than compatible with the modelling of other non-pellet shots (reduction also in $\chi_e$)[10]. With regard to the plasma stored energy and global energy confinement time these shots are only marginally (20% on average) better than the gross of the RF heated limiter discharges at the same current (L-mode); this is understandable since the markedly improved central energy density (by a factor of 2 to 3) fills only a small (10-20%) part of the total plasma volume.
3.4 Fig. 10 shows the peak neutron yields of peaked and non-peaked profile shots and the strong increase with the RF power. The neutron rate is usually at maximum before, and in decline when, the temperature maxima are reached and this is roughly in line with impurity accumulation encountered in these shots. At the moment of pellet injection global $Z_{\text{eff}}$ from Bremsstrahlung assumes values of 1.3 to 1.5 which increase on the time scale of about 1 s to values around 3-4 suggesting, supported also by conventional and charge exchange spectroscopy and neutron diagnostics, that $n_D/n_e$ may be of the order of 50% to 80% only at the temperature maximum. Total radiation is not yet terminal for the total power balance, but it is certainly a candidate to limit the core performance.

3.5 The $n_0(0) T_i(0) \tau_e(a)$ product rises up to maximum values in the order of $2-3 \times 10^{20} \text{ m}^{-3} \text{ keVs}$ for the better ones of these shots but the correlation with the D-D neutron peak is not unique and more detailed work has to be carried out to understand the plasma conditions in the central core.
3.6 The above shots have in common that the ICRH has to be centrally deposited (off-axis heating did fail to exhibit the enhancement signature); most of them have been heated using the H minority scheme but ³He minority heating can achieve the same effects suggesting that direct deuterium second harmonic heating does not seem to play a dominant role; also the choice of antenna configuration (most shots used dipoles, some however monopoles) does not seem to have a large influence.

3.7 The addition of neutral beams to the RF power does either little to boost the performance as judged from the $T_e$, $T_i$ behaviour (the injected beam cannot reach the central core of these high density plasmas) or even deteriorates the performance in relative terms (e.g. with respect to the $n_D(0)T_i(0)\tau_E(a)$ product). However, with the application of 28 MW of combined heating for this type of pulse (half of it RF, half of it NB) the highest neutron rates $7\times10^{15}$ s$^{-1}$ for these kind of shots have so far been obtained.

4. CONCLUSIONS

This enhanced regime, though transient on the time-scale of one second, is interesting because of its potential to permit in-sight into reactor relevant tokamak and plasma physics, and may provide an operational help of potentially igniting a tokamak. More work has to be done on the questions of stability in conjunction with appropriately tailored pellet deposition and heating profiles in space and time, and on impurity control.

Also work has to resume on the fuelling aspects of long-pulse high temperature plasmas, and it is hoped that the use of the 6 mm gun and the employment of a new high-speed launcher with pellet speeds around 5 kms$^{-1}$ will allow in the next year to make progress in this field.

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PELLETS IN LARGE TOKAMAKS TFTR AND JET*

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Abstract

In TFTR and JET experiments, pellet fueling has been extended to larger, higher temperature devices. We will review selected current results in the light of earlier experiments. Penetration depths are generally in agreement with modelling when ablation by thermal electrons dominates, but local deposition may differ from predictions based solely on the prepellet Te profile. Deposition at the plasma edge can be enhanced. Deposition near the plasma center may also be altered, particularly in JET. Fueling efficiency is high, but at present strongly peaked density profiles are obtained only with pellet penetration approaching or beyond the plasma center. Density achieved with pellets in ohmic plasmas is greater than that attainable with deuterium gas puffing in both these large devices as in previous experiments. Locked modes limit this density in JET but not yet in TFTR. Strong electron temperature perturbations can be tolerated in these large devices as on smaller machines allowing modification of the current profile leading to a change in the time evolution of the central q value and suppression of existing sawtooth relaxations or delay of their onset. In ohmic discharges plasma reheating is moderate, typically 1.5 keV. Axial voltage is maintained. Loss of central density can be extremely slow. Decay rates of 1.5 to 2 sec are observed. With heating, Te > 5 keV is rapidly achieved. Axial voltages may strongly decrease. Under these conditions central particle loss rates can be enhanced. Decay rates in JET at 5 - 8 keV are approximately 0.75 s. Energy confinement is observed to improve in TFTR ohmic discharges as was seen in earlier experiments. With beam heating in TFTR, central energy confinement was not degraded during the reheat following the pellet perturbation. However, central power deposition was low in these cases due to diminished beam penetration. In recent JET experiments, application of central RF heating following a pellet fueling sequence has shown strong central electron and ion heating.

1.0 Introduction: In the past 10 or more years, pellet fuelling experiments have been conducted over a wide range of machine geometry, pellet size and plasma parameters. With experiments on TFTR, JET and now JT60[1], pellet fuelling has been extended to larger, high current, high temperature devices. Figure 1 illustrates the range of machine geometry over which tokamak experiments have been conducted since the first results from Ormak[2] and ISX-A[3]. The range of minor radius and plasma volume is roughly one and three orders of magnitude respectively. The increase in plasma volume particularly has permitted use of pellets up to 4mm in diameter (4 x 10^{-1} D0), with a capability for injection of 6mm pellets in place at

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JET. In the large tokamaks, use of these size pellets has extended pellet ablation studies to electron temperatures approaching 4keV, has produced peaked density profiles at high density, and has improved plasma performance. In this paper we will discuss pellet experiments in TFTR and JET, contrasting results in these larger machines with those obtained earlier in smaller tokamaks. Pellet penetration and mass deposition, average and core density, particle and energy confinement, and finally high power operation will be discussed.

2.0 Penetration and Mass Deposition: The neutral gas shielding model for hydrogenic pellet ablation is generally correct in predicting pellet penetration in ohmic plasmas at moderate electron temperatures (<1keV) [4]. The large tokamak experiments provide a test of this model at higher electron temperatures (< 4keV). At these temperatures, the ablation model in its most recent form [5] remains in general agreement with measurements of pellet penetration when ablation by thermal electrons dominates [6,7], but local deposition may differ from predictions based solely on the pre-pellet electron temperature profile. In large machine geometry the time scale is long for the decay of the density profile established by a pellet during the ablation process (t_{decay}>>t_{ablation}). Details of that profile are therefore readily seen using local density measurements following pellet injection obtained with multi-point Thomson scattering systems. Fuelling efficiency is high (70%) in ohmic plasmas, but may degrade during auxiliary heating[7]. Compared to calculations, deposition of mass near the plasma edge appears to be enhanced. Deposition near the plasma center may also be altered, particularly in JET.

2.1 Non-Central Deposition: Figures 2.1 and 2.2 illustrates a JET pellet fuelling event leading to hollow density profiles. Pellet penetration to 3.18m is determined from the duration and spatial extent of the light present during ablation. Penetration to 3.26m is predicted by the ablation model. Formation of an inverted density profile is predicted by the ablation model and is observed. However, the measured density peak occurs at a larger minor radius than predicted, the two locations differing by some 0.5m. The discrepancy between measured and calculated profiles indicates that ablation and deposition can be more rapid at large minor radii than predicted. The agreement as to overall penetration depth implies that this higher ablation rate is in some way compensated deeper within the plasma. Such deposition would be consistent with enhanced energy flux to the pellet in the plasma outer region and diminished flux within the plasma interior. The profile of electron temperature shown gives some indication of this possibility. The post-pellet temperature profile still reflects in general terms the measured local pellet mass perturbation but the central value appears to reflect some additional radial energy flow. Alternatively, a temperature dependence for the ablation process which is stronger at low temperatures, $T_e$<1 to 1.5keV, and weaker above this temperature may be indicated.
Major Radius (m) 20 30

Figure 2: Pellet Deposition in JET. Figure 2.1: Non-Central Deposition - Density Profiles: a) before pellet injection, b) following pellet injection, calculated from the local ablation rate \(\frac{dN}{dt}\) distributed over a flux surface and added to local target density, c) approximately 20 ms after pellet injection, measured with the LIDAR Thompson Scattering system. Figure 2.2: Non-Central Deposition - Temperature Profiles: a) before injection, b) calculated following injection assuming adiabatic deposition, c) measured approximately 20 ms after injection. Figure 2.3: Central Deposition - Density Profiles: a) early injection limiter plasma, b) Late injection, x-point plasma, \(B_r=2.8\) and \(2.1T\). Profiles are measured approximately 20 ms after injection (LIDAR). Target density profiles are similar to figure 2.1.

As the figure indicates, rapid inward flow of significant pellet mass during or immediately following pellet ablation (\(t \rightarrow t_{ablation}\)) has not yet been observed in TFTR or JET, even for large pellet perturbations. If such rapid flow, observed in earlier experiments on Alcator[8] is associated with the pellet perturbation itself, then the time scale for, and potential speed of, mass flow during or shortly after the ablation process is likely to be similar in large and small devices. The magnitude of the pellet perturbation relative to the plasma target density is the same or possibly larger in the large devices; the resulting perturbed electron temperature and sound speed are therefore similar. The distance to the plasma core, however, has increased by an order of magnitude from 0.03 m to some 0.3 to 0.5 m, while mass deposition is possibly enhanced at large radius. If present, rapid mass flow to the plasma core under these conditions should be less in the larger devices. If the inward mass flow is associated with a strong convective flow on a longer time scale[9], such flows have not yet been produced in pellet fuelling experiments on TFTR and JET.

2.2 Central Penetration: In past experiments, penetration to or beyond the plasma magnetic axis led to deposition strongly peaked on axis in the region of small volume and highest pre-pellet temperature. In large tokamaks this effect is also observed. Strong peaking of the density profile is seen under these conditions in both TFTR (figure 3) and in JET (figure 2.3). However, in JET such strong peaking is not always observed. When pellets are injected late in the current flattop, the deposition peak can shift off axis, although measured penetration depth remains apparently beyond the magnetic axis. Figure 2.3 illustrates this result, comparing post-pellet density profiles for three injection events. The early injection event took place prior to sawtooth onset and the presence of a \(q=1\) surface in the plasma[10]. The late injection events took place long after sawtooth oscillations were present. The location of the density maximum is near the usual \(q=1\) radius and appears to shift outward with lower TF. This apparent change in deposition between early and late injection may be associated with a vertical deflection of the pellet trajectory not present early in the discharge. This possibility can not be eliminated until the trajectory itself is photographed, but a significant deflection would be required. An alternative explanation may be associated with enhanced ablation at, or just outside, \(q=1\) due to a collapse of energy content within the \(q=1\) surface triggered by the pellet [11]. Such an enhancement in ablation rate near the \(q=1\) surface might also be associated with the formation of the helical structures "snakes" observed on JET following some pellet events[12].

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Production of highly peaked density profiles has been most easily achieved in TFTR and JET by pellet penetration to the plasma core early in the discharge using either a single pellet event (single pellets or multiple pellets closely spaced in time) or a multiple pellet sequence with pellets timed so as to produce and maintain low central electron temperatures and central penetration during the pellet sequence.

3.0 Average and Central Density: Pellet fuelling as a mechanism to achieve high density operation has been well established by past experiments. In TFTR and JET density achieved with pellets in ohmic plasmas is also greater than that attainable with deuterium gas puffing. Both multiple pellet (5 pellets - TFTR, 32 pellets - JET) and single pellet fuelling experiments have been conducted. In both machines $n_e R Q_{cy} / B_T = 20$ has been achieved in ohmic discharges, extending by roughly a factor of 2 the value attained by gas puffing. In JET this limit corresponds to that attained with gas fuelling in auxiliary heated discharges and is associated with the formation of locked modes[13]. As in smaller devices, large perturbations in central density and electron temperature can be obtained without disruption by direct pellet fuelling of the plasma core, utilizing a single large pellet or simultaneous injection of multiple pellets forming a single pellet event. However, these experiments often approach the density limit. As in earlier experiments on other tokamaks, disruptions can occur with increased frequency when experimental conditions are not ideal. A central density of $4 \times 10^{20}$ m$^{-3}$ has been achieved in TFTR (figure 3) and $2 \times 10^{20}$ m$^{-3}$ on JET (figure 2.3). Peaking factors, $n_e(0)/\langle n_e \rangle_{vol}$, from 2.5 to 4 are attained. Even in these large tokamaks at high current (1.5 to 3MA) central electron temperatures can fall below 1keV immediately following the pellet event (figure 3). Under these conditions, the MHD behavior of the discharge can be modified. In particular, as in earlier experiments, sawtooth oscillations can be suppressed [14], or when pellet fuelling is employed prior to the onset of sawtooth oscillations, that onset time can be significantly delayed [10], allowing heating experiments to be conducted during a sawtooth free period.

4.0 Particle Confinement: Relaxation of the density profile in large devices following a pellet perturbation occurs on time scales longer than those observed in previous experiments. Decay times of 100ms in Alcator C[8] are extended to 1 to 2 seconds on TFTR and JET. The general evolution of the profile shape appears to be similar however. Figure 4 shows the evolution of the density profile and the diffusion coefficient inferred from the
measured particle fluxes in PDX [15]. Modeling of the profile evolution on TFTR and JET yields coefficients of similar or lesser magnitude. Figure 5 illustrates the profile evolution for a TFTR discharge[14]. The diffusion coefficient obtained during the density decay, assuming diffusive flow alone, or including the neoclassical (Ware) pinch, shows a strong radial dependence with values of approximately 0.05 m² s⁻¹ obtained within the plasma core. In JET this radial dependence has been modeled using an abrupt transition from a low value within the core to a larger edge value, suggesting a separation of the plasma into a weakly anomalous core region and more strongly anomalous outer region. Figure 6 shows the transport coefficient inferred from two JET cases, one ohmic, the other with strong core RF heating[16]. In TFTR this radial variation has been modeled using an (r/a)² radial dependence[17].
High density operation obtained with pellet fuelling reduces $Z_{\text{eff}}$ immediately following pellet injection on TFTR and JET, as in past experiments. Values for $Z_{\text{eff}}<1.5$ have been obtained [18]. Low anomalous diffusive loss within the plasma core, the presence of strong density and temperature gradients at low collisionality, and the absence of sawteeth, all serve to accentuate neoclassical impurity transport effects seen in past experiments [19]. In TFTR and JET impurity transport is consistent with a neoclassical model incorporating a particle diffusivity similar to that used to model electron transport [17,20]. In JET, increased core impurity concentration can occur in both ohmic and auxiliary heated discharges, appearing on a 1 second time scale. In these large, high temperature devices with low Z limiters, such impurity accumulation leads to dilution rather than radiation collapse.

5.0 Energy Confinement: One of the primary reasons for applying pellet fuelling on large tokamaks has been in an effort to produce peaked density profiles and improved energy confinement, as was obtained in earlier experiments [8,21]. Improved confinement has been obtained following pellet injection for periods greater than 1 second in some cases. In TFTR ohmic discharges an enhancement from 1.5 to 1.8 times the saturated ohmic level was found, as illustrated in figure 7 [14]. In auxiliary heated discharges, TFTR results (figure 8) using beam heating showed reduced core thermal diffusivity, although in these discharges heating power profiles were peaked outside the plasma core due to poor beam penetration at high density [22]. In more recent JET experiments (figure 9), transport coefficients of similar magnitude within the plasma core have been obtained even in the presence of strong central RF heating (0.8MW/m$^3$), high temperatures ($T_i=T_e=10$keV) and low collisionality $\nu_i^*\nu_e^*<0.1$ [10,23,24,25,26]. These values of $\chi_i$ and $\chi_e$ are roughly 1/2 to 1/3 those obtained later in

![Figure 7: Variation of global confinement with line density in ohmic TFTR discharges. Saturated ohmic level obtained with gas puffing is roughly L-mode level [25].](image)

![Figure 8: Thermal diffusivity during beam heating in pellet fuelled and gas fuelled TFTR discharges. The radial variation in $\chi_e$ was obtained assuming an ion thermal diffusivity in the range from 1 to 3 times the neoclassical value (0.1 to 0.3 m$^2$s$^{-1}$ in the region 0.2 to 0.4m). The range of $\chi_e$ values shown in each case indicates the variation obtained for a multiplier of 1 and 3.](image)
Figure 9: Thermal diffusivity during on-axis RF heating in pellet-fuelled JET discharges. Variation with time of values at $r/a=0.2$ is plotted. Core value of $\chi_1$ is determined from measured $T_\|$. Radial variation similar to $\chi_\|_e$ is assumed. In this calculation total ion heating is assumed to be 50% of the RF input power at all times.

the discharge in the presence of broad density but similar heating profiles. When both the heating and density profiles were strongly peaked within the plasma core, global confinement 1.6x the L-mode[26] value (3MA and 10MW) was obtained. In large, high temperature devices fast ions can contribute significantly to the plasma energy content, and may have slowing down times greater than the thermal plasma confinement time, perhaps distorting the comparison with L-mode scaling. In the high density pellet case however, the thermal plasma energy content is the dominant global term.

6.0 High Power Operation: At high power, peaked profiles produced by beam fuelling lead to enhanced performance, which is often terminated by a strong carbon influx[27]. Pellet fuelling during the heating pulse has recently been used in such discharges, not to peak the density profile, but to introduce deuterium and delay the onset of high carbon influx[28]. Neutron rates in this case have been enhanced by a further 20%.

7.0 Summary: In TFTR and JET experiments, pellet fuelling has been extended to larger, higher temperature devices. Penetration depths are in general agreement with calculations when ablation by thermal electrons dominates, but local deposition may differ from predictions. Deposition at the plasma edge can be enhanced. Deposition near the plasma center may also be altered. Fueling efficiency is high, but at present strongly peaked density profiles are obtained only with pellet penetration approaching or beyond the plasma center. As in earlier experiments in smaller devices: density achieved with pellets in ohmic plasmas is greater than that attainable with deuterium gas puffing, significant electron temperature perturbations can be tolerated, suppression of existing sawtooth relaxations or delay of their onset is obtained, decay of the density perturbation is slow with density decay times of 1.5 to 2s observed, energy confinement is observed to improve and with core heating $T_\|_e(0)>5$keV is rapidly achieved. In addition pellet fuelling during low density high power beam heating has been used to delay onset of high carbon influx, and further enhance plasma performance.

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REFERENCES

Abstract

The main object of a pellet injection in JFT-2M is to improve the plasma March parameters, i.e. to achieve high confinement, high density and high beta plasmas. Neutral beam (NB) or ion cyclotron range of frequency wave (ICRF) heated JFT-2M discharges with gas fueling exhibit H-modes in divertor or limiter configuration. Deuterium pellets (speed: 0.7 - 1 km/s) were injected in the L- or H-mode phase of divertor discharges.

A very high confinement mode was achieved as the large pellet $\Delta n_e \approx 3 - 4.5 \times 10^{19} m^{-3}$ was injected in the L-mode phase. The maximum global energy confinement time ($\tau_E = \frac{W_0}{(P - dW/dt)}$) is 60 - 75 ms in NB heating and 55 - 60 ms in ICRF heating, which exceed $\tau_E$ in gas fueled H-mode by a factor of 1.4 - 1.7. In ICRF heating, $\tau_E$ was also improved as the pellet was injected in the H-mode phase. In this case, pellet penetration depth is the same as that of injection in the L-mode of NB heating. With a small pellet ($\Delta n_e < 1.5 \times 10^{19} m^{-3}$), large improvement of $\tau_E$ has not been obtained.

High density plasmas were easily obtained by injection of 4 pellets with time interval of 30 - 50 ms. Maximum line-averaged electron density was $8 \times 10^{19} m^{-3}$ ($\Delta n_e = 5 \times 10^{19} m^{-3}$) in Ohmic heated discharges ($6 \times 10^{19} m^{-3}$ for gas fueling) and $9.5 \times 10^{19} m^{-3}$ ($\Delta n_e = 7 \times 10^{19} m^{-3}$, Murakami factor = 9.7) in NB heated discharges.

These results indicate that pellet injection is useful to improve the plasma parameters.

The global energy confinement time was remarkably improved by injecting pellets into inner region of the plasma on the auxiliary heated discharges, and it was found that there was no remarkable difference of the global energy confinement time by the pellet materials. The high density was achieved by multi-pellets injection. The Fueling by pellet injection is useful to obtain the high beta value.

1. INTRODUCTION

Injection of a solid hydrogen-isotope pellet with high velocity is very powerful technique of fueling. Most of particles is deposited inner side of the plasma column, so the
fueling efficiency is high, recycling rate of the fueled particles on the wall and/or limiter is little and the plasma confinement is remarkably improved [1-6].

Main object of a pellet injection on JFT-2M is to improve the plasma properties, i.e. to achieve high confinement, high density and high beta plasma etc. The single-pellet injector (pneumatic-gun type) has been used for the period 1982-1986 (6). Since 1987, the pneumatic-gun type injector with 4 pellets has been used in fueling experiments. Maximum velocity is about 1.5 km/s. In usual experiments, the pellet velocity was fixed between 0.7 and 1.3 km/s. Deuterium or hydrogen pellets were injected into Ohmic-, L- or H-mode phase of divertor- or limiter discharges (5,6).

2. IMPROVEMENT OF PLASMA PROPERTIES

2.1 Energy confinement

The global energy confinement time \( T_E \) is calculated according to the energy balance equation, i.e.

\[
T_E = \frac{W_s}{(P_{total} - dW_s/dt)}
\]

where \( W_s \) is a plasma stored energy, \( P_{total} \) is a heating power.

In the Ohmic heated discharges, the improvement of \( T_E \) was little. When the additional deuterium was fueled by gas-puffing in the \( \text{H}_2/\text{D}_2 \) mixed plasmas \( (n_d/n_e < 40\%) \) with D-shaped limiter configuration, \( T_E \) was increased to 55-60 ms in the region of 2.5-4.5 \( 10^4 \) \( \text{m}^3 \). \( T_E \) in plasmas with puffing of the \( \text{H}_2/\text{D}_2 \) mixed gas was 45-50 ms. On the other hand, when the 4 \( \text{D}_2 \)-pellets with the time interval of 100 ms was injected into the mixed plasma, \( T_E \) increased to 60-70 ms and its values was about 22 \% higher than that in the additional \( \text{D}_2 \)-gas fueled discharges. These results may indicate that the deuterons are well confined inside the core region when the deuteriums are fueled in the more inner region.

A very high confinement state was obtained when the large single-pellet (rise of the line-averaged electron density \( \Delta n_e \approx 3-4.5 \times 10^4 \text{m}^{-3} \)) or 3-4 pellets were injected into L-mode phase. The large pellet can deeply penetrate. Figure 1 shows the parameters of NB \( (P_{NB} \approx 0.77 \text{ MW}) \) heated discharges \( (B_t=1.2 \text{ T}, I_p=220 \text{ kA}) \) with single-null divertor configuration. \( W_s \) increased linearly until the large MHD oscillation \( (\sim 5 \text{ kHz}) \) grew, and the plasma was disrupted. The increment of \( W_s \) is due to the increase of both electron and ion temperatures, which are recovered to the level before injection for 30-40 ms (Fig.2). Just before \( W_s \) is burst out, \( (\beta_t) \) value is about 1.6 \% and the Troyon factor \( g \) \( (g=C_{\beta_t})=g_{Ip}/(aBt) \) \) is about 2.2. These results agree with the range of theoretical limits due to kink and ballooning modes with free boundary. The plasma disruption may be due to the \( \beta \)-limit. Sometimes, \( (\beta_t) \) value touched close to the \( \beta \)-limit softly, so the discharges were not disrupted but \( W_s \) stopped increasing and \( T_E \) decreased to the level of the gas-fueled H-mode discharges as shown in Figs.1 and 3. In both cases, the maximum \( T_E \) is 60-75 ms (Fig.3). These values were only kept for about 20 ms. During maintaining high confinement, the radiation power loss \( (P_R) \), and intensities of highly ionized impurity ions \( (\text{Fe}^{3+}, \text{Ti}^{10+}, \text{O}^{6+}) \) and Balmer alpha line \( (\text{D}_{\alpha}) \) did not increase.
Fig. 1 Time evolutions of plasma parameters in NB ($P_{in} = 0.77$ MW) heated divertor discharges. (a) line-averaged electron density ($n_e$), (b) plasma stored energy ($W_p$) and half envelope of $B_0$ signal, (c) global energy confinement time ($\tau_E$), (d) intensities of FeXVIII, TiXI, OVI lines, (e) radiation power loss including charge-exchanged particles ($P_q$) and intensity of $Q_0$ line.

Fig. 2 Time evolutions of electron temperature $T_e$ (soft X-ray analysis) and ion temperature $T_i$ (charge-exchanged neutral particle analysis) in the discharges in Fig. 1.

Fig. 3 Global energy confinement time versus line-averaged electron density in single-null divertor discharges with NB ($P_{in} = 0.77$ MW) heating. The single-pellet ($Q_0$) was injected into L-mode phase. @:large pellet injection, \(\Delta\): small pellet injection, \(\Delta\): ohmic heated discharges with gas fueling.

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[Image of the diagrams and text as described above]
These facts indicate that impurities do not accumulate into the plasma core and particle recycling is very little compared with those in the H-mode discharges. When the pellet was injected after H-transition of NB heated discharges, the remarkable improvement was not obtained. It is due to enhancement of ablation (dash-dotted line in Fig. 5) near the peripheral region.

When the single-pellet was injected into the L-mode phase of the ICRF heated discharges (electron heating mode), the confinement time was improved ($\tau_E = 55-60$ ms) as shown in Fig. 4, and the pellet mainly ablated around $R_{\text{out}} - R \approx 0.13$ m ($R_{\text{out}}$ : major radius of outer magnetic surface) and passed through the center of the plasma column (solid line) as well as in the NB heated cases (dotted line) as shown in Fig. 5. The plasma center was near $R_{\text{out}} - R \approx 0.25$ m. Also, $\tau_E$ was improved when the large pellet was injected into the H-mode phase (triangles in Fig. 4). In this case, the ablation profile (broken line in Fig. 5) and penetration depth were similar to those of injection into L-mode phase.

![Fig. 4](image1.png) Global energy confinement time versus line-averaged electron density in ICRF ($P_B = 0.6-0.8$ MW) heated single-null divertor discharges ($D^*$). Single-pellet ($D^*$) was injected. △: pellet injection into L-mode phase, O: pellet injection into H-mode phase, ◦: Ohmic heated discharges with gas fueling.

![Fig. 5](image2.png) Ablation profiles of $D^*$-pellet. Solid and broken lines are profiles on pellet injection into L-mode phase and H-mode phase of ICRF heated discharges in Fig. 4. Dotted and Dash-dotted lines are profiles on pellet injection into L-mode phase and H-mode phase of NB heated discharges in Fig. 4.
Hydrogen-isotope effect on the global energy confinement was investigated by the $\text{D}_2$- or $\text{H}_2$-pellets injection into L-mode phase of NB ($P_{\text{NB}} = 1.2-1.6 \text{ MW}$) heated $\text{D}^+$- or $\text{H}^+$-plasmas ($B_t \approx 1.28 \text{ T}$, $I_p \approx 280 \text{ kA}$). In both gas-fueled $\text{H}^+$- and $\text{D}^+$-discharges with NB heating, the global energy confinement was nearly equal, e.g., 17-25 ms in the density range of $3.5-8.5 \times 10^{19} \text{ m}^{-3}$ as shown in Fig. 6. The 3-4 $\text{D}_2$-pellets were injected into $\text{D}^+$- or $\text{H}^+$-plasmas, and $\text{H}_2$-pellets were injected into $\text{H}^+$-plasmas. For all cases, $\tau_E$ was improved by a factor of 1.4-1.7 compared with that of gas-fueled discharges when the pellets were deeply penetrated crossing magnetic axis. However, $\tau_E$ was nearly the same value as that in H-mode discharges ($\odot$, +) as shown in Fig. 6 when the pellets ablated near the peripheral region of the plasma. Deep penetration of the pellet may be key-point to achieve very high confinement. On the NB heated discharges, it was found from Fig. 6 that there was no remarkable difference of the global energy confinement time by the pellet materials. Also, it was difficult to keep the long confinement time for long time.

![Fig. 6](image_url)

**Fig. 6** Global energy confinement time versus line-averaged electron density on multi-pellets injected single-null divertor discharges with NB heating ($P_{\text{NB}} = 1.2-1.6 \text{ MW}$). Pellets were injected into L-mode phase. O: small pellets injection, +: large pellets injection, $\odot$, +: gas fueling.

### 2.2 High density

On Ohmic heated $\text{H}^+$-divertor-discharges ($B_t \approx 1.25 \text{ T}$, $I_p \approx 249 \text{ kA}$), into which 4 $\text{D}_2$-pellets was injected with the time interval of 30-40 ms, the achieved $\bar{n}_e$ was about $8 \times 10^{19} \text{ m}^{-3}$ at maximum ($\bar{n}_e$ before the pellet injection was about $2.6 \times 10^{19} \text{ m}^{-3}$), $\Delta \bar{n}_e$ by 4 pellets was $5.8 \times 10^{19} \text{ m}^{-3}$. Murakami factor ($\bar{n}_e R / B_t$) is about 8.7, which is 1.5 times larger than that in gas-fueled discharges under the same discharge condition. Such a high density in Ohmic heated discharges could not be obtained by single-pellet injection (plasma was disrupted).

The line-averaged electron density increased up to $9.5 \times 10^{19} \text{ m}^{-3}$ by 4 $\text{D}_2$-pellets injection with time interval of 30-50 ms in NB ($P_{\text{NB}} \approx 0.72 \text{ MW}$, Co-injection) heated $\text{H}^+$-discharges with single-null divertor configuration ($\Delta \bar{n}_e \approx 7 \times 10^{18} \text{ m}^{-3}$). Murakami factor is 9.7. In the gas fueled NB ($P_{\text{NB}} \approx 0.89 \text{ MW}$) heated discharges, this factor is 8.9. Also, on the recent $\text{D}^+$-discharges injected 4 $\text{D}_2$-pellets simultaneously into the L-mode phase of NB ($\sim 1.3 \text{ MW}$) heated discharges, $\bar{n}_e$ of $10^{20} \text{ m}^{-3}$ was obtained, and the Murakami factor is about 10.
2.3 High beta

In order to improve the beta value, the 3-4 pellets were injected into single-null divertor H- or D- discharges (Bt=1.25-1.28 T, Ip=249-280 kA) heated by two neutral beams (P_{NB}=1.2-1.6 MW). The pellets were delivered at about 10 ms after the start of the NB (injection into L-mode phase). The line-averaged electron density increased from 3-4x10^{19} m^{-3} to 8.5x10^{20} m^{-3}. The MHD oscillation was suppressed to the low level and the discharges were very quiescent. The increase of radiation power loss by the pellets injection was little. In these discharges, (\beta_e) is 1.8% and the normalized beta value, e.i. Troyon factor g is 2.2-2.3 just before plasma disruption as shown in Fig.7. They may be within the theoretical limits as well as in subsection 2.1. Sometimes, (\beta_e) value may touch close to the \beta-limit softly, so the discharges were not disrupted. On the other hand, the g-factor was less than 2.0 in gas-fueled discharges. These results indicate that the pellet injection is a useful method to get the high beta value.

3. SUMMARY

The present experimental results are summarized as follows.

(1) The global energy confinement time was improved by a factor of 1.4-1.7 compared with that of H-mode (gas-puffing) by the pellet injection into L-mode phase of both NB and ICRF heated discharges. Also, on the pellet injection into H-mode phase of ICRF heated discharges, \tauE was improved, but on NB heating the remarkable improvement was not obtained.
(2) There was no remarkable difference of $\mathcal{E}_E$ by the pellet materials.

(3) The high density was obtained by the multi-pellets injection on both Ohmic and NB heated discharges.

(4) High beta value was achieved by multi-pellets injection, which was larger than that in gas-fueling.

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PELLET INJECTION IN THE RFP

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Abstract

Observation of pellets injected into the ZT-40M Reversed Field Pinch has allowed a new twist on the usual tokamak ablation physics modeling. The RFP provides a strong ohmic heating regime with relatively high electron drift parameter ($\xi_{\text{drift}} \sim 0.2$), in the presence of a highly sheared magnetic field geometry. In situ photos of the pellet ablation cloud using a gated-intensified CCD camera, as well as two-view integrated photos of the pellet trajectory show substantial modification of the original pellet trajectory, in both direction and speed. Depending on the launch geometry, increases in the initial 500 m/s pellet speed by 50% have been observed, and a ski jump deflector plate in the launch port has been used to counteract strong poloidal curvature. In contrast to the tokamak, the $D_\alpha$ light signature is strongest near the edge, and weaker in the plasma center. Additional information on ion temperature response to pellet injection with 20 µsec time resolution has been obtained using a 5-channel neutral particle analyzer (NPA). The energy confinement is transiently degraded while the beta is largely unchanged. This may be indicative of pellet injection into a high-beta plasma operating at fixed beta.

INTRODUCTION: Pellet injection refueling of the Reversed Field Pinch (RFP) is relatively new, and has been reported in ZT-40M at Los Alamos$^{1,2}$ and Eta-Beta II in Padova. The study of pellet ablation in RFP plasmas provides an opportunity for new and varied insights into tokamak-pellet experiments and modeling. The RFP provides a high-$\beta$ plasma with large ohmic heating power (5–20 MW) at high power density. The poloidal and toroidal magnetic fields are comparable in magnitude, which when combined with the rather high electron drift parameter found in present RFP devices, results in spectacular three-dimensional pellet trajectory curvature. Due to the coincidence of ablation, transit, particle and energy confinement timescales (~ 0.5 msec) however, the transient phenomena are more difficult to model. By combining information from a variety of diagnostics, we observe that the electron beta improves with increasing density, but infer that pellet injection momentarily degrades both the global particle and energy confinement as the pellet flies through the plasma edge region. A small population of suprathermal electrons is sufficient to explain the unusual ablation time-history and pellet track curvature, and may influence other RFP features (resistivity and dynamo) as well.

TRAJECTORY CURVATURE: Using a modified 4-shot gas gun, originally from Alcator C, the first pellets were injected into ZT-40M (R = 1.14 m, a = 0.20 m) along a “normal” midplane radial trajectory, with velocities of 400-700 m/sec, and a measured pellet content of $5 \times 10^{19}$ D atoms. Only 1/3 to at most 1/2 of the pellet could be observed directly as a density rise in the plasma, usually with initially hollow density pro-

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files. Top and tangential view time-integrated photography, as well as information from a fanned array of vertically-viewing tightly collimated Dα detectors (depicted schematically in Fig.1) showed that the pellets were being strongly deflected toroidally and poloidally. Fast pellets in low density plasmas can reach the back wall without being fully ablated, while slower pellets were deflected so strongly that they would miss the axis, sometimes even hitting the bottom of the torus, resulting in unsatisfactory deposition profiles.

By changing the launch position (port), and/or angle as denoted in Figure 1, we have been able to substantially improve the pellet trajectory, essentially using the curvature itself to pitch the pellet closer to the plasma axis. Figure 2 shows a tangential view of a pellet which finished its life very close to the plasma axis. It initially started out +13 cm above the plasma midplane in the horizontal high side launch position, and resulted in peaked plasma density profiles. In gen-

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Figure 1: Schematic layout of injection ports, and location of top viewing still camera, along with bottom D0 chordal array.

Figure 2: High side launch allows pellet to be deflected downwards near the plasma axis. Tangential side view using a hemispherical mirror, with three dark circles corresponding to the three outside ports.
eral, if a second pellet is launched within $\leq 0.5$ msec of the first, then its trajectory is straight and the velocity of the pellet in the plasma remains the same as it was in the gun. Pellets fired at time intervals of greater than two milliseconds behave largely independently, without any mutual shielding effects. For single pellet shots, other plasma parameters also recover (density, temperature, loop voltage, Carbon V emission) on several ms timescales, although the plasma soft x-ray emission is suppressed for timescales of 5-10 msec or longer.

Direct time-resolved imaging of the pellets in flight in the plasma show for midplane launch that the first curving pellet typically has an absolute speed increase of 30-50%. A small pellet may even double its initial speed, but measurements from photos are complicated as it moves out of the calibration plane (of the camera) toroidally, such that the measurement becomes only a lower bound on the velocity increase. As predicted by the rocket model, when a component of the electron drift direction is along (against) the trajectory of the pellet, the pellet speed increases (decreases). Pellets from the top barrels in the high side launch position at $+16$ cm above the plasma midplane have been observed to stop dead in their track, as they encounter (nearly head on) the (assumed) drifting electrons or suprathermals in the purely poloidal magnetic field at the reversal layer. Due to the largely poloidal field at 3/4 of the RFP minor radius, when the pellet is launched from the midplane, it is first deflected downwards (for the normal sense of ZT-40M plasma current and fields) and then if it survives to the opposite side of the plasma, it experiences an upward deflection. This can actually be seen in Figure 3, where a multiply-gated CCD image (A 5 $\mu$sec exposure every 100 $\mu$sec) of the torus cross section is shown. The first pellet is sharply deflected, and fully ablated. Typical cloud dimensions are measured to be 1 cm FWHM in light intensity, with a tendency to be larger in the outside edge region. The second pellet, shielded by the first, experiences a smaller downward deflection (and little change in speed), but is also seen to begin to curve upwards as it approaches the inner wall (on the right side of the photo). This corresponds on both sides of the poloidal cross section to electron impact in the counterclockwise sense in the photo above. In some cases a comet-like tail is observed to develop, both poloidally (in the edge) and toroidally (in the core), apparently corresponding to the local magnetic field direction.

ABLATION TIME HISTORY: In general, the ablation time history observed in the RFP is in striking contrast to the so-called "thermal ablation" history seen in ohmically heated tokamaks with normal profiles. Figure 4 shows the $D_\alpha$ time history of three successive hydrogen pellets, monitored by diffuse light reflected from the back torus wall across the plasma from the pellet launch port. This reproducible light signature is characterized by a rapid rise to maximum (ablation) rate, and then a gradual fall off.
The same behavior is seen with the CCD images, where the pellet is typically 3–4\times brighter in the outer edge region (in the vicinity of $17 \rightarrow 13$ cm radius), than in the core. Interestingly, this corresponds to the general region of field reversal in the RFP, and may be a clue to the location of a possible nonthermal electron population. As a further cross check, one can sum the response of the $D_\alpha$ array, and obtain an approximate time history (corresponding to a hypothetical wide angle $D_\alpha$ detector). This is done in Figure 5, and the associated density traces from the two-chord FIR interferometer (the central chord at +4 cm, and the “edge” chord at +16 cm) are also shown. In this example, two pellets were launched from the high side port location. The first with an initial speed of 500 m/sec, dropped down vertically to within ~ 7 cm of the axis while undergoing a 90° deflection toroidally, whereas the second slower (400 m/sec, 0.9 msec later) pellet did not curve down nearly as much...but was still fully ablated in the plasma. The first pellet experienced a higher edge ablation rate relative to the second, and the combination of two pellets maintained a centrally peaked density for almost two milliseconds. It is evident from the light time history, that the high edge ablation rate of the successive pellets is suppressed for short times by the action of the initial pellet. One may also speculate that better accountability of the pellet inventory is possible if the edge ablation is reduced.

**CONFINEMENT:** Pellet injection into a fixed beta plasma may be, in principle, intrinsically different in its effects on the plasma, than in the usual present-day tokamak pellet experiments. Over a wide range of operating conditions, it is empirically observed that ZT-40M, HBTX and Eta-Beta II usually have an electron beta in the range of 5–20%, depending on the electron density and plasma current, and/or the ratio of I/N. For a fixed current, the electron density and temperature can be traded off against each other, except as one approaches the highest I/N values, where the resistivity escalates even though the temperature is high. A cleaner denser regime of low I/N can be accessed through pellet injection.\(^8\) It is observed with pellet injection that the electron beta improves marginally with increasing density.\(^9,10\)

As the pellet is injected, there is a brief period when the density momentarily decreases in the plasma. Observations on ZT-40M show an actual de-
crease in line average density if a small (poorly formed), poorly penetrating pellet disturbs the plasma edge, or for a period of 150-200 $\mu$sec after a large pellet first enters the plasma. During this time before the pellet begins substantive refueling of the plasma, the core electron temperature has dropped, but the core electron density has not increased. Soft x-ray flux in the core drops rapidly within $<100$ $\mu$sec of the pellet entering the plasma edge, while the ion temperature decay is delayed by $\sim 400$ $\mu$sec (relative to the soft x-rays). The ion temperature is measured by the neutral particle analyzer (NPA) 150$^\circ$ toroidally removed from the pellet injector, and low energy time of flight (TOF) spectrometers. Figure 6 shows the line of sight NPA ion temperature response (from the slope of the spectrum) and corresponding electron density, soft x-ray, and one of the CX flux energy channels. The cooled electron temperature on axis at $t=7.00$ msec, was $T_e(0)=132\pm26$ eV, (ZT-40 Shot 31219). A second small pellet at 8.5 msec was responsible for the long density decay.

In addition, as the density builds, the plasma toroidal current drops, while the loop voltage typically increases slightly ($\sim 5\%$). A large increase in input power to the plasma can occur, not from the resistive input which is nearly constant, but from a weakening of the magnetic field reversal leading to a decrease in the stored magnetic energy (equivalent to a weak expansion of the plasma). This magnetic energy is then presumably available to heat the plasma, and represents a transient power increase in the range of 40–50% for Figure 6, and more generally is seen to range from 10–100 %, correlated with the magnitude of the density increase. An increase in resistivity due to cooler electron temperatures is partly compensated by a drop in $Z_{eff}$ and/or the resistive anomaly factor, by up to a factor of four for multiple pellets.

DISCUSSION: Reheat of the ions is observed to take place slowly, only on the timescale of the electron density decay. Because electron-ion equilibration timescales are long, and in light of the RFP's anomalous ion heating, a beta-limit is strongly suggested as being responsible for the general balance between density and temperature. On the other hand, in the face of the large increase in input power, it appears likely (even in the absence of temperature profile measurements) that the global energy confinement time is degraded by pellet injection.
However, "long term" beneficial effects in the sense of a suppression of the soft x-ray flux (initially likely due to a drop in $T_e$, but later perhaps due to a cleaner plasma and/or a reduction in suprathermal electrons), as well as a measure of density control, lead one to conclude that pellet injection is both beneficial and desirable in the RFP, although certainly not painless. Full profile measurements of the appropriate parameters are needed for further understanding. The opportunity exists for better pellet code modeling, incorporating non-Maxwellian distributions, and real-time energy input to the plasma during the pellet ablation process. Assumptions about the pellet velocity in the plasma should be checked in every case.

ACKNOWLEDGEMENTS

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PELLET INJECTION EXPERIMENTS ON HELIOTRON E

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Abstract

The overall feature of pellet injection experiments on Heliotron E, which does not need an external plasma current for plasma confinement in contrast with tokamaks, is described, including study of transport, MHD stability and ablation.

1. INTRODUCTION

Recently, a pellet injection method is widely used for refueling a plasma in toroidal magnetic confinement devices such as tokamaks and stellarators/heliotrons.\(^1\)\(^-\)\(^5\) The results are successful in most cases from view points of both refueling and confinement. A pellet injection is being used also for plasma diagnostics. This paper describes overall feature of pellet injection experiments on Heliotron E, which does not need an external plasma current for plasma confinement in contrast with tokamaks.

2. EXPERIMENTAL SETUP

2.1 Heliotron E

Heliotron E (R = 2.2 m, \(\langle a_p \rangle = 0.2 \text{ m} \)) is one of stellarator/heliotron devices, producing a current-free plasma. As to the winding law, \(l = 2\) and \(m = 19\). The cross section of a Heliotron E plasma is elliptical; the longest minor radius: \(a_\perp = 0.3 \text{ m}\) and the shortest minor radius: \(a_\parallel = 0.15 \text{ m}\). The rotational transform varies from 0.55 in the center to 2.5 at the plasma boundary. Thus, the device has a high shear. The plasma is produced and heated by ECRH using 53.2 GHz Gyrotrons with up to 650 kW, 100 ms pulse width. For cases of fundamental and second harmonic resonance heating, \(B = 1.9 \text{ T}\) and 0.94 T are used respectively. For additional heating, NBI (30 kV, 4 MW and 200 ms) and ICRF (27 MHz, 2 MW, 100 ms) are used. The pellets are injected in the horizontal direction along the long axis \(a_\parallel\).

2.2 Pellet Injector

In early experiments, a single pellet injector of disk gun type\(^6\) was used. There were various pellet sizes. It can be changed by replacing the cryostat head. The nominal pellet size is \(1-2 \text{ mmL} \times 1-2 \text{ mm} \phi\). The velocity ranges from 400 m/s to 1000 m/s. The differential pumping system is used for evacuating propellant gas, which is satisfactory even for a multiple pellet injector. Recently, a 6-pellet-injector has been installed to Heliotron E. The detail explanation is given in the separate paper.
3. STUDY OF TRANSPORT
3.1 Pellet Injection into NBI Plasmas

Achieved plasma energy by pellet injection depends on penetration depth of the pellet as shown in Fig.1. In this case, the deeper the penetration is, the more internal energy one can get. It is found that the mode of operation in which pellets are injected at relatively low-NBI-power followed by a higher-NBI-power phase as shown in Fig.2 is preferable to that in which pellets are injected during a constant high-power phase.

![Diagram](image_url)

Fig. 1. (a) Cosine coil signal increase $\Delta I(=I_a)$ due to pellet injection versus penetration depth $X_a$. (b) Chord averaged density increase $\Delta n$ due to pellet injection versus penetration depth $X_a$.

![Diagram](image_url)

Fig. 2. Temporal evolution of chord averaged density, electron temperature (ECE), ion temperature (NPA), ion saturation current, H_a intensity, and gas puff intensity in the 'staged NBI' case.
The pellet injected plasma is compared with the gas puffed one. In the central region, $T_e$ of the gas puffed case is by 150 eV lower than in the pellet case as shown in Fig. 3. The higher density at the plasma periphery in the gas puffed case causes a higher power deposition of NBI fast particles near the plasma boundary. As a result, orbit loss will increase.

Although pellet injection is effective for increasing both plasma density and energy, radiation loss increases especially in the central region of the plasma, as shown in Fig. 4. This indicates impurity accumulation in case of high density NBI plasmas.

Fig. 3 $T_e$ and $n_e$ profiles in the pellet fuelled discharge ('through NBI', solid line) and the solely gas fuelled discharge (broken line).

Fig. 4 Emissivity profile of the bolometric power in the case without pellet injection (broken line) and in the case with pellet injection ('through NBI', solid line).
3.2 Pellet Injection into ECH Plasmas

When a pellet is injected into an ECH plasma, the density increase is weak as shown in Fig. 5a). When the pellet is injected into the afterglow plasma just after turning off the RF power, the density increase is apparently larger than the former case as shown in Fig. 5b). The achieved density profile in case of the ECH-ON plasma is more flat. Thus, the high energy electrons produced by the RF power may increase pellet ablation much in the periphery of the plasma. The production of the high energy electrons is confirmed, although the quantitative measurement remains to be done.

![Fig. 5 Line density evolution in cases of pellet injection (a) into an ECH plasma, and (b) into an ECH afterglow plasma.](image)

3.3 High Density Achievement with Carbon Coating

As described in 3.1, the radiation loss is a dominant problem for obtaining a high density plasma. The dominant impurity in this case is identified as Fe. So, the Fe impurity is reduced by carbon coating on the inner wall of the vacuum chamber. Consequently, a high density plasma of $n_e \sim 1.8 \times 10^{14}$ cm$^{-3}$, $T_e \sim 300$ eV has been achieved as shown in Fig. 6. It is

![Fig. 6 High density operation by pellet injection into an NBI plasma under the condition of Carbon Coating on the wall.](image)
remarkable that the density is kept temporarily constant in contrast with no carbon coating case. The plasma energy, however, does not definitely increase by this pellet injection. The reason is not clear, but it may be attributed to poor penetration of NBI beam due to high density.

4. STUDY OF MHD STABILITY

4.1 Instability Induced by Pellet Injection

High $\beta$ current-free plasmas are studied by reducing $B$ to 0.94T. By gas puffing, the plasma density is increased to about $1 \times 10^{14}$ cm$^{-3}$. As a result, a plasma with a flat pressure profile is more stable (Q mode; $\beta$ is up to 2%), while a plasma with a peaked pressure profile is unstable (S mode; $m=1/n=1$ fluctuation). A peaked density profile is rather easily produced by pellet injection. Typical fluctuations of density, soft X ray, and magnetic probe signal induced by pellet injection$^{7}$ are shown in Fig.7. Because a gas fueled discharge of the similar density (Q mode) is stable$^{8}$, the fluctuations are induced due to a centrally peaked pressure profile, that is, presumably due to steeper pressure gradient at $\iota = 1$ (at $r = 0.7$ a), which can induce the pressure driven interchange mode$^{9}$.

![Fig.7 Typical fluctuations induced by pellet injection $B=0.94T$.](image)

4.2 Stabilization by Gas Puffing

Since a flat pressure profile is more favorable for a high $\beta$ plasma, the gas puffing is added to the plasma where the fluctuation is induced by pellet injection. Figure 8a)-c) shows the temporal behavior of the density: (a) gas fueled target discharge, (b) pellet induced unstable discharge, (c) gas puffing added discharge to the pellet injected plasma. The effect of additional gas puffing is clearly seen in reducing the amplitude of
density fluctuations with broadening the density profile. The density profiles at \( t = 367.5 \) ms are shown in Fig. 8 d)- f). Thus, this demonstrates the possibility of stabilization of the fluctuations by broadening the density profile. Therefore, the fine tuning of the density profile by pellet injection will be useful for high \( \beta \) experiments.

![Fig. 8](image)

**Fig. 8** Suppression of fluctuation by adding gas puff (c.f) to the pellet injected plasma (b,e).

5. MULTIPLE PELLET INJECTION

Recently, a six-pellet injector has been installed on Heliotron E, in order to increase flexibility of pellet injection experiments. Preliminary results in case of \( B = 1.9 \) T are shown in Fig. 9. The increase of the central chord of FIR is larger than that of the outer chords, which indicates the density profile be-

![Fig. 9](image)

**Fig. 9** Plasma parameters in case of six pellets injection.
comes peaked. The electron temperature after the last pellet injection is about 450 ev and it has a very broad profile. It is remarkable that the bolometer signal decreases just after each pellet injection while Fe X VI increases after each pellet injection. The signal of the neutral particle analyzer behaves like the bolometer signal. Thus, the dominant part of the bolometer signal in this case is probably due to charge exchanged fast neutral particles.

6. STUDY OF PELLET ABLATION

In case of low-density high-power ECH plasmas, sharp spikes of Hα signal are observed, which suggests the existence of localized heat source: high energy electrons. Hα signals in cases of an ECH plasma and an NBI plasma are compared in Fig.10, which shows the rapid increase of the ablation rate in the outer region of the plasma for the ECH case compared to the NBI plasma. The density increase in the central chord for the ECH case is smaller than the NBI case, while that of the outer chord is larger than the NBI case. Thus, the central particle deposition is relatively difficult for the ECH case as observed also in the other devices like TFR tokamak. The pellet ablation in case of NBI can be simulated by neutral shielding model including fast ions.

From observation of the trajectory of light emission in case of NBI plasmas, the trace is found to be curved, which indicates asymmetry of heat flow in the toroidal direction.

![Graph showing Hα intensity and density increase in cases of an ECH plasma and an NBI plasma.](image-url)
7. CONCLUSION

The pellet injection on Heliotron E carried out so far is found to be effective for refueling, and useful for the study of transport, MHD stability and pellet ablation. The multiple pellet injection experiments has just started successfully.

ACKNOWLEDGEMENTS

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STUDIES ON H$_2$/D$_2$ PELLET INJECTION IN JIPP-TIIU TOKAMAK

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Abstract

An ice pellet injector has been developed in order to study particle transport and confinement in the JIPP-TIIU tokamak. The pellet size is 1.0 and 1.4 mm and the speed is from 300 to 950 m/s. From an electron density perturbation by the pellet injection particle transport has been analyzed. The density profile factor $k$, defined as $n(r,t) = n(0,t)(1 - (r/a)^2)^k(t)$, changes rapidly by the injection and recovers gradually. Analysis is carried out in the recovery phase by using the integral form of the particle diffusion equation, where the source term at this phase is negligible around $r/a \sim 0.5$. The values $D$ and $v$ at $r/a \sim 0.5$ for ohmic plasmas are determined with good accuracy as $0.4 \text{ m}^2/\text{s}$ and $4 \text{ m/s}$, respectively. In addition, the particle confinement time is obtained from the measurement by fast neutral particle analyzers, and the result is consistent with the particle diffusion coefficient.

[1] Introduction

In these years pellet injection studies have been widely performed from the viewpoint of the improvement of confinement and the fueling of plasmas. On the other hand, the ice pellet injection is also useful for the study of particle transport and confinement of plasmas.

An ice pellet injector of pneumatic type has been developed and installed with JIPP-TIIU tokamak in order to study particle transport and confinement of torus plasmas. From an electron density perturbation by the pellet injection the particle transport coefficient has been obtained through the analysis of particle diffusion equation. Also, the particle confinement time has been analyzed from fast neutral particle measurements, and the result is consistent with that of the transport coefficient.


A schematic drawing of the injector head is shown in Fig.1. A disk type pellet carrier has a hole with the size of $1.0 \text{ mm} \times 1.0 \text{ mm}$/$1.4 \text{ mm} \times 1.4 \text{ mm}$, inside which an ice pellet is produced. The H$_2$/D$_2$ gas feeding
Fig. 1. Schematic drawing of the pellet injector head.

System is controlled properly to have a suitable pressure and temperature in order to introduce the solid pellet into the hole of the disk successively. This operation has made the system reproducible one.

High speed framing photograph is utilized to measure sizes of pellets in flight. An example is shown in Fig. 2. Actual sizes are usually a little less than that of the disk hole.

Fig. 2. High speed framing photograph of a pellet in flight.

[3] Properties of Plasmas with the Pellet Injection

(1) General

A set of typical results of the experiment is shown in Fig. 3. Here, a pellet is injected at \( t = 162 \) ms with the speed of 650 m/s. A loop voltage rapidly increases with the injection and returns gradually. A total radiation loss from the plasma starts to increase, and a stored energy from diamagnetic measurement gradually increases to the level of almost twice as much as that before the injection. These indicate improvement of the confinement of the plasma.
A soft X-ray signal which looks at the center code of the plasma exhibits a change in period of sawtooth oscillation from 1 ms to 2.3 ms (to 4 ms in maximum case) as shown in Fig. 4. The amplitude of this signal also increases by a factor of more than two.

An electron cyclotron emission (ECE) measurement by a polychromator shows the time evolution of temperature profile after the injection as shown in Fig. 5, where the initial profile is assumed to be a parabolic one. These characteristics will include the effect of pellet penetration into the plasma as well as the heat transport effect inside the plasma.
A particle confinement has been studied with a hydrogen pellet injection into a deuterium plasma. A neutral hydrogen flux is measured by using the fast neutral analyzer for the ion temperature measurement.

A time evolution of the neutral hydrogen flux of the energy range of $1.1 \pm 0.05$ keV is shown in Fig.6. Also, the fluxes of $H^0$ [(a), (b), (c)], $D^0$ [(d), (e), (f), (g)] and the ratio $H^0/(H^0+D^0)$ in the energy range of 1.0 keV [(h)] are shown in Fig.7. Two charge exchange processes just after the injection are as follows.

\[
H^0_{\text{pellet}} + H^+_{\text{plasma}} \rightarrow H^+_{\text{pellet}} + H^0_{\text{plasma}} \quad (1)
\]

\[
H^0_{\text{pellet}} + D^+_{\text{plasma}} \rightarrow H^+_{\text{pellet}} + D^0_{\text{plasma}} \quad (2)
\]

where $H^+_{\text{plasma}}$ is as a minority species in D-plasma. After the ablating of the pellet, $H^0$ from the pellet exchanges a charge with $H^+$ (process (1)), the time scale of which is about 5 $\mu$s. This seems to correspond to a in Fig.6. On the other hand,
the decay time of $\theta$ in Fig. 6 is of the order of 100 ms. This seems to imply the particle confinement time, although the flux may exhibit overlapping of the component from various places in the plasma. Slight differences among the values in (a), (b) and (c) in Fig. 7 also suggest this overlapping. From these considerations, the decay time of neutral hydrogen flux in high energy range [i.e., (c) in Fig. 7] seems to represent the actual particle confinement time. Here, the effect of the neutral flux from wall is negligible, since the value of the ratio $H^0/(H^0+D^0)$ recovers to that before the injection as shown in Fig. 7(h).

Particle transport studies have been done by introducing a small $D_2$ pellet as a source of an electron density perturbation. Figure 8 shows the time evolution of the density profile and the profile factor, $k$, defined by the fitting of the density as $n(r,t) = n(0,t)(1-(r/a)^2)^k(t)$, respectively. The integral form of the particle diffusion equation is written as

$$\frac{\partial}{\partial t} \int_0^r n(r')dV_p = 4\pi R_0 (r\frac{\partial n}{\partial r} + rvn), \quad (3)$$

where the source term at the density relaxation phase is negligibly small around $r/a = 0.5$. The values $D$ and $v$ have been determined with a good accuracy by evaluating the above equation at two different times $t_1$ and $t_2$ in Fig. 8; i.e., $D = 0.4$ m$^2$/s and $v = 4$ m/s at $r/a = 0.5$ for ohmic plasmas.

Using a 1-D transport code, the time evolution of the density profile has been analyzed. The experimental data just after the pellet
injection have been employed into the computer code as the initial density profile. The diffusion coefficient and the inward velocity are assumed as

\[ D(r) = \frac{D(0)}{\{n(r)/n(0)\}} , \quad (4a) \]

\[ v(r) = v(a)(r/a)^n . \quad (4b) \]

A good agreement with experimental data has been obtained in the case of \( n = 3, D(0) = 0.5 \text{ m}^2/\text{s} \) and \( v(a) = 35 \text{ m/s} \), which gives the values of \( D = 0.6 \text{ m}^2/\text{s} \) and \( v = 4 \text{ m/s} \) at \( r/a = 0.5 \).

Fig. 8. Time evolution of the density profile \( n_e(r,t) \) with a small pellet injection, and the profile factor, \( k \), defined as \( n_e = n_e(0)(1-(r/a)^2)^k \).

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II. FUTURE DEVICES
PROSPECTIVES OF PELLET INJECTION IN NET-LIKE DEVICES

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Abstract

The prospectives of pellet injection in NET-like devices are discussed in the light of anticipated requirements for the control of the plasma density.

1. Introduction and Summary

Pellet injection is a means to influence the profile and the time dependence of the plasma density. In this paper, upon characterizing NET-like devices, the general operational requirements of experimental tokamak reactors are summarized on the basis of Refs.1 to 3 mainly in view of displaying the role of the density profile. The particle fluxes needed for various functions are analyzed and estimated, and the relations between them are discussed. The properties of pellet injection are recalled. It is concluded that pellet injection at moderate velocity should be included in the concepts of NET-like devices to enhance their operational flexibility. More detailed knowledge on tokamak physics and pellet ablation is needed for a full appreciation of the potential of pellet injection in NET-like devices.

2. Characteristics of NET-Like Devices

NET-like devices, in the context of the present paper, are meant to be experimental tokamak reactors with the objective of demonstrating controlled burn of DT plasma, reliable and safe operation of the apparatus, and testing of blanket modules and plasma-facing components. Apart from NET itself, ITER, FER, OTR, TIBER etc. belong to this category. As far as plasma operation is concerned, these devices can be considered to be proto-typical for electricity-producing tokamak reactors.

Typical parameters of NET-like devices are listed in Table 1. The duration of the burn pulse will have to be a few 1000 s with steady-state operation as an ultimate target. Under such conditions, the startup of the discharge can be comparatively slow: reaching burn conditions after 50 to 500 s is anticipated. Using noninductive current drive to assist current rampup and to maintain (part of) the current during burn, as well as for current profile control, is under consideration. It is important to note that the most promising schemes for these functions, namely current drive by lower hybrid and/or electron cyclotron waves, involve the generation of a highly energetic
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<tbody>
<tr>
<td>plasma minor radius $a [m]$</td>
<td>1.5 to 2.5</td>
</tr>
<tr>
<td>plasma major radius $R [m]$</td>
<td>5.5 to 6.5</td>
</tr>
<tr>
<td>aspect ratio $A=R/a$</td>
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</tr>
<tr>
<td>plasma elongation $b/a$</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>magnetic field in plasma $B [T]$</td>
<td>5 to 6</td>
</tr>
<tr>
<td>average plasma density $&lt;n&gt; [10^{20} \text{ m}^{-3}]$</td>
<td>0.7 to 1.5</td>
</tr>
<tr>
<td>peak plasma density $n(o) [10^{20} \text{ m}^{-3}]$</td>
<td>1 to 2.5</td>
</tr>
<tr>
<td>average plasma temperature $&lt;T&gt; [\text{keV}]$</td>
<td>10 to 15</td>
</tr>
<tr>
<td>peak plasma temperature $T(o) [\text{keV}]$</td>
<td>20 to 30</td>
</tr>
<tr>
<td>fusion power $P_{\text{fus}} [\text{GW}]$</td>
<td>0.5 to 1</td>
</tr>
<tr>
<td>average neutron wall load $Q_n [\text{MW/m}^2]$</td>
<td>$\approx 1$</td>
</tr>
</tbody>
</table>

electron population. For ensuring power and helium exhaust, manageable working conditions of the plasma-facing components and satisfactory plasma cleanliness, a divertor configuration with enhanced recycling in front of the divertor target is anticipated to be necessary.

3. General Operational Requirements

The operation conditions of a NET-like device are strongly influenced by the plasma profiles and, in particular, by the density profile. However, at the moment full information on these relations is not yet available. The following points are of importance in the present context:

3.1. Energy confinement and burn control

While ensuring good energy confinement is of general importance to be able to reach ignited burn for plasmas having the size anticipated, this is particularly important during the phase of heating to ignition, to minimize the external heating power needed. Furthermore, to be able to control a burning plasma and to operate within a range of fusion powers, active control of confinement is essential; this effectively implies the necessity of being able to progressively degrade energy confinement with increasing fusion power. A possible scenario for this is to provide a more peaked density profile during heating to ignition than during the burn phase. In addition, affecting the reactivity during plasma burn by a fast transient increase of the plasma density may be useful as part of a control scheme to stabilize the burn temperature if the working point desired is thermally unstable.

3.2. Avoidance of impurity accumulation in the core plasma

In relation with the necessity of avoiding excessive radiation losses from and dilution of the core DT plasma, a sizeable accumulation of impurities and helium in the plasma core cannot be tolerated. This points to flat density profiles being preferable, at least during plasma burn.
3.3. High beta operation

Although definitely conclusive results are still lacking, it appears that operation at high average beta, or more appropriate high fusion power density, requires a quite flat pressure profile \[4\] such as

\[ p(r) \sim [1-(r/a)^2]^{\alpha} \quad \text{with} \quad \alpha \approx 0.7 \text{ to } 1. \]  

(1)

This implies that both the density and the temperature profile have to be rather flat. Such a situation is consistent with the additional requirement that also the current profile has to be comparatively flat although additional current profile control by noninductive current drive may still be necessary. Note in this context that in an ignited plasma only control of the density profile provides a direct way of influencing the profile of the heating power which is approximately given by

\[ w_\alpha(r) \approx n^2(r) T^2(r). \]  

(2)

This again indicates that globally flat density profiles will be needed during burn.

3.4. High density operation

Conventional density limits in tokamaks tend to be more stringent limitations for the accessible working conditions than beta limits for the parameters of NET-like devices. Since the density limit rather imposes a bound on the plasma density at the edge than on the average plasma density, peaked density profiles are known to allow operation at higher average density \[5\] and hence are favourable in enhancing the accessible core plasma densities. Due to the high heating power present in tokamak reactors, this may however not be a crucial point if the density limit is a consequence of the heat flux into the edge region becoming too small. In fact, if one assumes that up to 70\% of the available heating power can be lost by radiation from the plasma within the \( q=2 \) magnetic surface without the density limit being reached \[2\], the latter will not present a critical constraint for NET-like devices even if the density profile is rather flat.

3.5. Plasma edge conditions

Optimum helium pumping condition are achieved for high-recycling conditions in front of the divertor plate, that is low temperature and high density of the divertor plasma. In this regime also erosion of the divertor target is minimized (except if chemical erosion and/or sublimation enhanced by the impinging particle flux is an issue, as it would be for a graphite target). To enter well into this regime, the highest possible edge plasma density is required. Since the average densities needed (see Table 1) tend to approach the edge densities compatible with a low temperature (\( \leq 15 \text{ keV} \)) divertor plasma, flat density profiles (up to beyond the separatrix, if possible) are optimum from this point of view (see also Fig.1).
Obviously, in this case the DT flux pumped (and to be recycled back into the discharge via the fuelling system) is rather high and, equivalently, the fractional burnup is low; this is an obvious disadvantage of this regime.

These considerations indicate that during the burn pulse a rather flat density profile will be needed. A peaked density profile, if it allows to improve energy confinement without excessive impurity accumulation in the plasma core, could be useful to ease reaching ignited conditions. For burn temperature control purposes producing a transient increase of the plasma density may be useful.

4. Particle Fluxes for Fuelling, Density Profile Control and Burn Temperature Control

4.1. Steady-state conditions

As there is a simple relation between the fusion power $P_{\text{fus}}$ and the rate of helium production, one has for the helium exhaust flux

$$\Gamma_{\text{He}}(\text{out}) \times 10^{20} \text{ s}^{-1} = 3.6 \times P_{\text{fus}} \text{ (GW)}. \quad (3)$$

The D and T fluxes needed to replace the DT atoms burnt obviously are

$$\Gamma_{D}(\text{in}, b) = \Gamma_{T}(\text{in}, b) = \Gamma_{\text{He}}(\text{out}). \quad (4)$$

These fluxes, hence, just depend on the fusion power.

Quantifying the D and T exhaust for fluxes $\Gamma_{D}(\text{out})$ and $\Gamma_{T}(\text{out})$ for a given $\Gamma_{\text{He}}(\text{out})$ is much more complex. In fact, these fluxes also depend on the divertor plasma conditions (which in turn depend on the plasma edge density and the power exhausted through the divertor) as well as on the configuration of the divertor and pumping duct and the pumping speed available. In practice, one expects that under all circumstances
\[
\Gamma_{D,T}^{\text{out}} \gg \Gamma_{\text{He}}^{\text{out}}
\]
so that the total DT fuelling fluxes
\[
\Gamma_{D,T}^{\text{in, tot}} = \Gamma_{D,T}^{\text{in, b}} + \Gamma_{D,T}^{\text{out}} \tag{6}
\]
that are needed are much larger than \(\Gamma_{D,T}^{\text{in, b}}\). This implies that the fuelling requirements effectively are determined by the exhaust conditions rather than the fusion power.

Density profile control is possible within the constraints imposed by the exhaust conditions (since these are affected by the density profile that is adopted, as discussed in Sect.3.6), the total DT exhaust flux being the sum of the particle fluxes deposited in the plasma core \((\Gamma_{D,T}^{(P, c)}))\), in the outside layers of the hot plasma \((\Gamma_{D,T}^{(P, s)})\) and in the scrape-off layer \((\Gamma_{D,T}^{(sc)}))\), i.e.
\[
\Gamma_{D,T}^{\text{out}} = \Gamma_{D,T}^{(P, c)} + \Gamma_{D,T}^{(P, s)} + \Gamma_{D,T}^{(sc)}; \tag{7}
\]
this situation is visualized in Fig.2. Obviously, the highest density peaking is achieved maximizing \(\Gamma_{D,T}^{(P, c)}\), while the flattest density profile possible is obtained for pure edge fuelling (see Fig.1); while these limits provide absolute constraints to the range in which the density can, in principle, be varied, in practice the allowable working conditions of the divertor target (see Sect. 3.6) strongly restrict this range.

![Diagram showing particle exhaust and fuelling fluxes for different deposition requirements; the various fluxes are defined in the text.](image)

To illustrate the situation, let us consider a device having a fusion power of \(P_{\text{fus}}=0.8\) GW. Then, \(\Gamma_{\text{He}}^{\text{out}} = \Gamma_{D}^{\text{in, b}} = 3 \times 10^{20}\) atoms/s. In a high-recycling divertor regime (i.e., for a comparatively flat density profile) DT exhaust fluxes \(\Gamma_{T}^{\text{out}} \approx \Gamma_{T}^{\text{out}}\) of about \(5 \times 10^{21}\) atoms/s are expected. On the other hand, for achieving a significant peaking of the plasma density profile, assuming that the characteristic time for a particle to travel from the plasma...
centre to the edge is of the order of 10 s and taking into account that the plasma typically contains $5 \times 10^{22}$ D and T ions, one would need $\Gamma_{D,T}(P) + \Gamma_{D,T}(P) \approx 5 \times 10^{21}$ atoms/s. This shows that, even apart from the additional constraints deriving from the divertor target working conditions, only a limited amount of profile peaking may be possible for the operation conditions anticipated (if profile peaking is not increased by the presence of an enhanced particle "pinch", which is by now uncertain). Similar constraints are expected to apply to power reactors.

4.2. Startup

During the startup of the discharge the fuelling flux needed is mainly determined by the desired density rampup rate. Since density rampup is anticipated to be on the time scale of 10 s or more, fuelling fluxes $\Gamma_{D,T}(\text{ramp}) \approx 5 \times 10^{21}$ atoms/s will be the upper limit of what is needed. Again, significant profile peaking probably requires particle deposition close to the core of the discharge.

4.3. Burn temperature control

The particle fluxes needed for affecting the reactivity to suppress a possible thermal instability of the operation point during burn are appreciably smaller than those needed for density profile control and rampup.

5. Features of Pellet Injection

Pellet injection can provide a means for the deposition of high average particle fluxes, of the order of those required for particle fuelling and density profile control, as well as density rampup (see Sect.4), beyond the plasma edge region. However, for reactor-grade temperatures the penetration depth of pellets is expected to be limited ("shallow particle deposition") so that density profile steepening (provided there is no effect on the density profile beyond the penetration depth of the pellet) can only be achieved in the outside part of the discharge. This is illustrated in Figs.3 where the penetration depth is given for various velocities, pellet sizes and plasma temperatures; two different temperature profiles are considered and two different ablation models are used [6-8]. In particular for flat temperature profiles as anticipated for the burn phase of NET-like devices and power reactors, pellet penetration exceeding 20% of the minor radius $a$ appears to be difficult to obtain even if pellet velocities larger than $10^4$ m/s were achievable. A further limitation is that in the presence of fast electrons, i.e., when current drive by lower hybrid and/or electron cyclotron waves is used adjacent to the plasma edge, pellets will not be able to penetrate at all. Hence, especially for full or partial current drive in the outer plasma layers by one of these methods during the burn pulse, sophisticated scenarios (consecutive phases of current drive and pellet injection) would have to be considered. Finally, pellet injection tends to generate strong momentary plasma perturbations. In order to keep these within acceptable
Peaked Temperature

Flat Temperature

a) normalized penetration depth as a function of pellet velocity for $T(0)=25$ keV and a pellet radius of 4 mm.

b) normalized penetration depth as a function of the central temperature $T(0)$ for a pellet velocity of $5\times10^3$ m/s and a pellet radius of 4 mm.

c) normalized penetration depth as a function of the pellet radius for $T(0)=25$ keV and a pellet velocity of $5\times10^3$ m/s.

---

Fig. 3: Pellet penetration depth normalized to the horizontal minor radius $a$ for various conditions; the density profile is $n(r)=n(0)\left(1-(r/a)^2\right)^{\alpha}$ with $n(0)=2\times10^{20}$ m$^{-3}$; an electron temperature profile $T(r)=T(0)\left(1-(r/a)^{\alpha}\right)^{\alpha}$ is adopted with $\alpha=2$ ("peaked temperature") and $\alpha=1$ ("flat temperature"); two ablation models have been used: model 1 is the NGPS model [6] with a constant shielding cloud radius of 5 mm, in model 2 this radius is calculated according to Lengyel [7].
limits, pellets with a radius smaller that about 4 mm will have to be used.

6. Overall Conclusions

The preceding discussion shows that pellet injection in NET-like devices may be useful for achieving a fast density rampup and a certain degree of plasma density peaking, in particular during heating to ignition to improve plasma confinement in this phase. During the burn phase, density profile peaking, necessarily accompanied with a reduction of the plasma density in the scrape-off layer, rather appears to be undesirable. On the other hand, pellet injection could be useful as part of a burn temperature control scheme. In order to fully appreciate the potential of pellet injection in NET-like devices and power reactors, a better knowledge of tokamak physics is needed, especially on the impact of a varying particle deposition profile (with emphasis on shallow particle deposition) on the plasma transport properties [9], as well as on the pellet ablation process (in particular, the sensitivity of pellet penetration with respect to the pellet velocity). This information will have to be obtained from experiments on present tokamaks. A definite conclusion is that pellet injection into plasmas containing a fast electron population as generated during current drive by lower hybrid and electron cyclotron waves, is not possible.

In conceptual designs of NET-like devices pellet injection should be included to provide additional operational flexibility. However, on the basis of present knowledge a need for high pellet velocities (above about $5 \times 10^3$ m/s) achievable only if a great technical development effort is made, cannot be justified.

Acknowledgements: Fruitful discussion with many colleagues during the INTOR and ITER activities and in the NET Team are greatly acknowledged. Figures 3 were provided by L.L. Lengyel and P.J. Lalousis; this help in preparing the material for the paper is very much appreciated.

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III. PARTICLE AND ENERGY TRANSPORT
PARTICLE TRANSPORT IN PELLET-FUELED
TFTR PLASMAS

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Abstract

Analysis of electron and ion particle transport in TFTR pellet-fueled plasmas has been carried out by detailed modeling of time-dependent electron density profiles and impurity radiation.

TRIUMPH electron transport code results show the entire 1 to 2 seconds of post-pellet electron density evolution in ohmically heated, pellet-fueled plasmas to be reasonably well modeled using a time-independent \( D(r) = D(0) + [D(a) - D(0)](r/a)^2 \), together with the neoclassical electron particle flux. The derived \( D(0) \) is very low, in the range 50 ~ 200 cm\(^2\)/s, while \( D(a) \) rises to 1000 ~ 5000 cm\(^2\)/s. The development of centrally peaked density profiles on broad pedestals is seen to be the result of edge particle loss and replacement by edge sources after the pellet deposition. Sawtooth disruptions can dramatically flatten the central density profile, with observed re-peeking of the density between sawteeth consistent with the pre-sawtooth \( D(r) \) and neoclassical flux model. In these same ohmic discharges, MIST impurity transport code modeling of VUV, X-ray, and bolometric data for injected and intrinsic impurities indicates that adopting essentially the same \( D(r) \) for the impurity ions, together with their neoclassical flux, is a viable hypothesis. Given the low \( D(0) \) for these models, this results in strong on-axis peaking for the impurity ions.

Similar modeling is currently being used to study the role of a reduced Ware pinch and enhanced diffusion in producing the density pump-out observed in similar neutral beam heated plasmas.

INTRODUCTION - Detailed modeling of electron density profile evolution and impurity behavior in TFTR pellet-fueled plasmas has been carried out in order to develop a comprehensive picture of particle transport in these plasmas.

Analysis of electron particle transport relies primarily upon modeling of the time-dependent electron density profile data available from the MIRI 10-chord far-infrared interferometer. The TRIUMPH 1-dimensional radial electron particle transport code is initialized with the measured electron density profile immediately after the pellet deposition, and the post-pellet development of the profile is calculated using specified transport coefficient and source models. Time-independent anomalous diffusion coefficient profiles with the parameterized form \( D(r) = D(0) + [D(a) - D(0)](r/a)^2 \) have been found in a previous survey of candidate \( D(r) \) profiles to be successful in modeling particle transport in pellet-fueled plasmas\(^1\), and are used in the work presented here. To this anomalous diffusive flux is added the neoclassical electron particle flux\(^2\), of which the Ware pinch is the most significant term in the present results. While the broader features of the post-pellet
electron density evolution can be modeled with some success without the neoclassical flux\(^1\), more detailed modeling supports its presence in the electron transport, as will be shown. An electron particle source rate due to wall-evolved neutrals is determined using a feedback loop based on tracking the total number of particles in the model versus the experimental data. The edge particle source radial profile shape is based on a neutral deposition calculation from the TRANSP code\(^3\). For neutral beam-heated plasmas, an additional source is specified, using now both the absolute rate as well as source profile shape from the TRANSP beam deposition calculation.

Analysis of the transport of injected and intrinsic impurities relies on modeling of VUV and X-ray PHA spectroscopic line brightness time evolutions using the MIST 1-dimensional radial impurity transport code\(^4\). Time-dependent \(T_e(r,t)\) and \(n_e(r,t)\) profile data are used by the code in order to correctly model impurity behavior in these evolving plasmas. Impurity transport modeling is subject to considerably greater uncertainties than the electron density profile analysis, due in part to uncertainties in the atomic rate coefficients required. Therefore, the approach here is to begin the impurity transport analysis assuming the same \(D(r)\) as was found for the electrons for the plasma in question, but now combined with the impurity neoclassical flux\(^5\), and seek to test the hypothesis that the impurity ions are subject to the same anomalous \(D(r)\) as the electrons.

The three pellet-fueled plasmas discussed here all have \(B_T \sim 48\text{kG}, I_p \sim 1.8\text{MA}\). The first is a typical high density ohmic plasma, with a centrally peaked pellet deposition profile. The next ohmic plasma has more complex dynamics, beginning with a slightly hollow initial deposition profile, and followed by sawtooth activity. Finally, results for a neutral beam-heated pellet-fueled plasma are presented.

RESULTS - Pellet-fueled high-density ohmic plasmas are typically characterized by long central density confinement times, as seen in Figure (1) for shot 25697. Also seen here is the typical development from an initially centrally peaked deposition profile, to a profile with a narrower central peak on a broader density pedestal. A model with \(D = 50 + 3950(r/a)^2 \text{cm}^2/\text{s}\) plus the electron neoclassical flux is shown as reproducing these features of the experimental density profile evolution. The feedback model source

![Figure 1. Ohmically-heated shot 25697 electron density profiles at t = 0, 0.5, 1.0, and 2.0 s after pellet deposition. Model (solid lines) has D = 50 + 3950(r/a)^2 (cm^2/s) plus electron neoclassical flux.](image-url)
rate derived by the code compares well with the neutral hydrogen influx calculated from Hα measurements for this shot. The inset figure demonstrates the role of post-pellet fueling by this edge source in producing the typical peaked-on-pedestal profile development. Here, the \( t=2s \) model profiles with \( (S \neq 0) \) and without \( (S=0) \) the edge particle source are compared. The relatively well confined centrally deposited particles remain peaked at the center, augmented by the Ware pinch, while the edge profile is determined by refueling and the relatively higher value of \( D(a) \).

Impurity transport in this same plasma was investigated using scandium injection at 2.5s, 0.5s after the pellet deposition. Figure (2) shows the spectroscopic brightness time evolution for the VUV 279.8Å line from Li-like Sc XIX and the X-ray PHA Kα line at 2.87Å. The model results have \( D = 100 + 3900(r/a)^2 \text{ cm}^2/\text{s} \) plus the impurity neoclassical flux, showing that a small variation from the nominal electron particle transport \( D(0) \) result succeeds in fitting the data. The two figures have been separately scaled, with the experimental PHA/VUV line ratio agreeing within a factor of \( \sim 2 \) with that from the model shown. A similar fit to the data can be achieved with a purely diffusive model using the electron transport \( D(r) \), however for this result the line ratio factor rises to \( \sim 5 \). Within the usual uncertainties accompanying impurity injection transport analysis, the scandium transport can be considered consistent with the electron \( D(r) \) together with the impurity neoclassical flux.

![Graphs showing brightness time evolution for Sc XIX and Kα lines](image)

In such dynamically evolving plasmas as this, the study of intrinsic impurity transport is both more complex and potentially more fruitful than is the case for near-equilibrium plasmas. Figure (3) shows the VUV spectral line brightness time behavior and modeling for intrinsic nickel in 25697 following the pellet. These spectral lines are weak and typically not well isolated in the available spectra, hence data quality is a significant consideration in this analysis. However, the model shown, using the same \( D = 50 + 3950(r/a)^2 \text{ cm}^2/\text{s} \) as found for the electron transport, plus the impurity neoclassical flux, provides a reasonable fit to the data. The pre-pellet nickel equilibrium is assumed purely diffusive (flat) with \( D=10^4 \text{ cm}^2/\text{s} \); the results are not particularly sensitive to the exact pre-pellet equilibrium profile. A constant nickel source rate is assumed at the pre-pellet equilibrium value. Figures 3(a,b) show that such a continued nickel source is required in order to reproduce the low nickel charge state NiXVIII behavior, by contrast with a zero source model \( (S=0) \). Figure (3c) shows good agreement for the detailed time development of the centrally-peaked Be-like Ni XXV, which has the highest-quality data of the five lines. Data from the adjacent and also centrally peaked Li-like NiXXVI emission lines show somewhat different time development, while the model predicts similar behavior to the adjacent NiXXV state. The scandium injection at 2.5s is an obvious source of contamination in the experimental measurement of these NiXXVI lines, although the effect on the neoclassical part of the nickel transport itself should be small (\( \Delta Z_{\text{eff}} \approx 0.01 \)). The continually evolving plasma density and temperature at still have a marked effect on the physics even at 3.5s, with a decreasing nickel neoclassical pinch (lower by a factor of 5 from \( t=2.5 \) to 4.0 s), continuing ionization to the He-like state, and decreasing \( n_e(0) \), all combining to produce the slow decay in the modeled high nickel charge state brightnesses.
Perhaps the strongest evidence for the presence of the neoclassical flux here is in the central to edge charge state line brightness ratios shown in Figure (3f). Plotted are the scale factors used for each spectral line brightness plot to produce the quantitative agreement at 3.5s seen in figures (3a-e), versus the approximate peak radius for the corresponding charge state density. Perfect agreement between the model and the experimental data would have all these scale factors equal; the model shown with the neoclassical flux included roughly achieves this, while the scale factors for an identical model without the neoclassical flux show a much larger discrepancy.

An example of more complex electron density profile dynamics is seen in figure (4) for shot 28970. The initially hollow profile fills in by 0.2s, and approaches the usual peaked-on-pedestal form by 0.6s. Between 0.6 and 0.61 s, a sawtooth relaxation is seen to dramatically re-distribute the central density. This evolution from hollow to peaked profile, together with the recovery after sawtooth disruptions, provide particularly interesting tests of the transport. The model shown has \( D = 200 + 4800(r/a)^2 \text{ cm}^2/\text{s} \), with the neoclassical flux. In figure (5), the density at four radii is followed after the sawtooth activity has
begun. In the code, the density profile is empirically re-distributed at each sawtooth disruption consistent with the observed form of the post-disruption profile, and the usual radial transport then continues. The pre-sawtooth transport model works well even after the sawtooth activity has begun, and in particular the Ware pinch is seen as clearly adequate to produce the observed profile re-peeking between sawteeth. In contrast, the inset figure shows how a purely diffusive model cannot re-peak $n_e(0)$.
Particle confinement in neutral beam heated plasmas is an issue of particular interest. In figure (6) we consider electron particle transport for the beam heated shot 31612, beginning at the last of three pellets and the coincident start of 10MW of coinjected neutral beam power. The evolution to the characteristic peaked-on-pedestal form is still apparent, and can be well reproduced by the $D = 200 + 6800(r/a)^2$ cm$^2$/s plus neoclassical flux model shown. New features in this neutral beam heated model relative to the previous ohmic plasmas include the presence of electron sources associated with the neutral beam injection. In the case shown, while this beam source is over an order of magnitude smaller in total particles per second rate than the feedback model calculated edge particle source, it is nevertheless of some importance due to its relatively deep penetration. It is also interesting to note that the diminished loop voltage in the hotter neutral beam plasma reduces the Ware pinch contribution to the particle confinement, although the anomalous diffusive flux also seems to be increased as well.

CONCLUSIONS - The entire 1 to 2 seconds of post-pellet electron density evolution in these ohmic and neutral beam heated plasmas can be reasonably well modeled using a time-independent anomalous $D(r) = D(0) + [D(a) - D(0)](r/a)^2$, together with the neoclassical electron particle flux. The derived $D(0)$ is very low, in the range of 50 to 200 cm$^2$/s, while $D(a)$ rises to the range of 4000 to 7000 cm$^2$/s for the plasmas shown. The development of centrally peaked profiles on broad density pedestals can be seen as the result of particle loss and refueling at the plasma edge after the pellet deposition. Sawtooth disruptions are seen to be capable of dramatically re-distributing the central density; re-peaking of the profile after the disruption is consistent with the pre-sawtooth anomalous $D(r)$ and the neoclassical flux. Analysis of injected and intrinsic impurity behavior indicates that adopting similar anomalous $D(r)$ for all plasma particles, together with the appropriate neoclassical flux, is a viable hypothesis for these plasmas. For the impurity ions the neoclassical flux is a major factor in their dynamics, given the low $D(0)$ of these models, and results in strong on-axis peaking of the impurity ions.
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PARTICLE TRANSPORT ANALYSIS OF PELLET FUELED JET PLASMAS

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Abstract

The analysis is carried out using a 1 - 1/2 D radial particle transport code modelling the experimental density evolution for given particle transport coefficients. These analyses are carried out in ohmic, RF heated, and NBI heated plasmas in both limiter and X-point configurations. We find that ohmic cases are generally characterized by hollow radial diffusion coefficients and can be satisfactorily modelled without any anomalous convective (pinch) term. Auxiliary heated cases show rapid pump out of density which can be explained by changes in the transport coefficients. Initial analysis of pellet and non-pellet fueled H-mode plasmas also can be explained by changes from the ohmic X-point case. In all cases neoclassical transport diffusion coefficients are substantially smaller than the determined values.

1. INTRODUCTION

An understanding of the mechanism controlling particle transport in tokamaks is of crucial importance in projecting the fueling requirements and performance of such devices. Multiple pellet injection experiments have been carried out on JET to determine heating and confinement characteristics of pellet fueled plasmas [1,2,3]. We report in this paper on the analysis of electron particle transport in these multi-pellet fueled JET plasmas under ohmic heating, ICRF heating, and NBI heating conditions in primarily limiter configurations. The study of particle transport in JET plasmas is based on measurements by a 6-channel far-infrared interferometer for density profile evolution and Hα detectors for edge source magnitude.

Fluctuation induced transport is frequently suggested as the mechanism responsible for the anomalous particle and heat fluxes observed in tokamaks. As part of our analysis, we compare the determined electron particle and heat fluxes with fluctuation induced transport calculations using electron and ion drift wave mechanisms as the dominant fluctuation spectrum. The Onsager symmetry found in the neoclassical transport theory of fluctuations [4] can be used to determine a connection between the anomalous electron particle and heat flux.

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³ The members of the JET/USDOE Pellet Collaboration are the authors of the paper entitled ‘JET multi-pellet injection experiments’ in these proceedings.
2. ANALYSIS

An interpretive particle transport analysis code (PTRANS) has been written at JET to analyze particle transport in pellet fueled plasmas. This transport code is used to compare the measured density evolution with calculations using a number of different transport models to determine which ones may apply. We also analyze the data using a version of the QFLUX [5] interpretive code to integrate the continuity equation directly using the experimentally determined time-dependent density profiles. This analysis gives a particle balance determination of the diffusion for a given convective flux model.

2.1 PTRANS Particle Transport Code

PTRANS is a 1-1/2 D (non-circular geometry) radial transport code that calculates the evolution of density by solving the continuity equation for up to 32 different particle flux models \((D(p), v(p))\) independently and in parallel [6]. The calculations are initialized with the experimental profile shortly after the pellet deposition. A finite differencing method is used to solve the continuity equation with both implicit and explicit terms (Crank-Nicholson scheme).

The flux-surfaced-average continuity equation is

\[
\frac{\partial n_a(\rho, t)}{\partial t} + \frac{1}{V'(\rho, t)} \frac{\partial}{\partial \rho} \left[ V'(\rho, t) \Gamma_a(\rho, t) \cdot \nabla \rho \right] - s_a(\rho, t) = 0, \tag{1}
\]

where the radial particle flux \(\Gamma\) is defined by

\[
\Gamma = -D(\rho, t) \frac{\partial n(\rho, t)}{\partial \rho} (|\nabla \rho|) + n(\rho, t)v(\rho, t). \tag{2}
\]

Transport coefficients used in the models may have neoclassical [7] and anomalous parts. The neoclassical electron particle flux is given by

\[
\Gamma_{e}^{NC} = -D_n^{NC} \frac{\partial n_e}{\partial \rho} - D_T^{NC} \frac{\partial T_e}{\partial \rho} - v_p^{NC} n_e, \tag{3}
\]

where the last term is the Ware pinch whose velocity is given by

\[
v_p^{NC} = K e^{1/2} \frac{E_{||}}{B_p}, \quad K \sim \frac{2.30}{[1 + \nu_e^{1/2} + \nu_e^3][1 + \nu_e^{3/2}]}. \tag{4}
\]

The radial shape of the edge source \(s(\rho, t)\) is obtained from external neutral deposition calculation (QFLUX) using H\(_\alpha\) edge measurement to determine the magnitude. There is optional source feedback built into the code which can adjust the magnitude of the source profile for each model to keep the number of particles in the plasma the same as that determined from the experimental density profiles. This is used in ICRF heated plasmas when the RF is initially turned on since the H\(_\alpha\) detectors used to measure the source magnitude are located away from the antennae and do not see the particle source from the antennae until a particle confinement time later.
2.2 Anomalous Transport Calculations

An enhanced version of the time slice interpretive transport code QFLUX [5] has been developed at JET to perform calculations of anomalous fluctuation driven transport using the neoclassical transport theory of fluctuations [4]. This code is run for a number of time slices through the discharge and calculates the coefficients of the Onsager transport matrix and the thermodynamic forces that drive the transport. Assumptions are made that there is no plasma rotation for non beam heated discharges and that the ion temperature profile is the same shape as the electron profile (but scaled from central measurements). Initial calculations have been done using electron and ion drift waves as the fluctuation mechanisms. In analyzing discharges with this code, we calculate the fluctuation amplitude needed to explain the anomalous particle flux as determined from a particle balance calculation. This amplitude is then used to calculate the resultant anomalous electron heat flux from the transport matrix. This fluctuation driven heat flux is then compared to the anomalous electron heat flux as determined by power balance calculation.

3. RESULTS

Peaked electron density profiles are generated in JET discharges from pellet injection with central penetration. These density profiles are frequently found to slowly decay to a peaked profile on a broad pedestal. The decay of the peaked profile is sometimes accelerated by the application of ICRF on axis and NBI. In the cases where accelerated profile decay is seen, a broad flat density profile quickly appears that is characteristic of auxiliary heated limiter discharges. It is found that the neoclassical pinch velocity is reduced when the auxiliary heating is applied due to the change in electric field and collisionality. This reduced pinch appears to play a role in the peaked profile decay.

The period of the peaked density profile in sawtooth free limiter discharges has been analyzed and the electron profile evolution modeled by the use of a neoclassical pinch velocity and a time independent diffusion coefficient with a strong increase at the radial position of the density pedestal formation as shown in Fig. 1. The diffusion model used is more than an order of magnitude larger than the neoclassical value. 

![Fig. 1.](image)

Electron diffusion coefficient for ohmic and ICRF heated cases. Measured (solid) and calculated (dashed) density at four radii for ohmic and ICRF heated cases.
This same transport model is found to be applicable in both ohmic and ICRF heated discharges although the heated case shows slightly higher diffusion. Calculations of the density evolution using the $\left(\frac{r}{a}\right)^2$ dependent diffusion coeffient suggested by Hulse [6] for TFTR ohmic cases does not yield the observed density pedestal on the outer half of the minor radius.

In cases where the peaked density profile rapidy redistributes to a flat one, the diffusion coeffient can be modeled as a function of local electron temperature [8] such that the central diffusion rapidly evolves from the ohmic post pellet case to a diffusion coeffient profile which is more nearly flat as shown in Fig.2. This rapid change in diffusion suggests that another mechanism is present in these discharges that further accelerates the central electron density decay. In a discharge where a clear transition from the ohmic like transport to one in which central MHD activity is seen from Soft X-rays, the profile evolution can be modeled by a transition from the ohmic like diffusion to the temperature dependent diffusion. The diffusion coeffient determined from particle balance calculations of the electron flux agree well with the best case diffusive models used in the discharges that have been modeled.

A large number of particle transport models have been used to analyze a variety of JET pellet fueled discharges including a model that has been used to predict CIT performance [9]. This model uses $D = \frac{n_e (m^{-3})}{10^{19}}$ and $v = -2Dr/a^2$. The results from this model as shown in Fig.3 typically yield peaked density profiles when the measured profile is seen to remain flat in the center. If these JET results scale down to smaller ignition machines such as CIT, the currently predicted performance may be over estimated.
Fluctuation induced transport calculations have been performed for over 10 pellet fueled discharges and have typically shown that electron drift wave driven electrostatic fluctuations in the quasilinear approximation show some correlation in the determined anomalous electron particle and heat transport. The power balance heat flux is typically a factor of 3-10 higher than the calculated fluctuation driven heat transport but shows a qualitatively similar profile shape.

4. CONCLUSIONS

The analysis done on JET sawtooth free discharges has shown that the density evolution following peaked profiles from pellet injection can be modeled with a neo-classical pinch velocity and a diffusion coefficient with a steep gradient at the radius of the density plateau which is near the $q=2$ surface. This type of transport model works in both ohmic and central ICRF heated discharges. Some of the auxiliary heated cases show rapid central density decay which may be due to MHD related turbulence. The profile evolution in these discharges can be modeled with a temperature dependent diffusion coefficient with the neo-classical pinch velocity. Discharges with non-central pellet penetration show no significant density peaking and cannot be modeled with the same transport coefficients as the peaked profile cases.

Transport calculations utilizing neoclassical fluctuation theory indicate that electrostatic fluctuations driven with an electron drift wave spectrum are not sufficient alone to fully explain the resulting anomalous particle and heat transport. Other mechanisms driving magnetic fluctuations presumably exist in parallel that may contribute more to the anomalous heat transport.

ACKNOWLEDGEMENTS

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REFERENCES


CORRELATION OF HEAT AND PARTICLE TRANSPORT IN JET

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Abstract

Radial thermal and particle diffusivities have been measured using transient methods, yielding $\chi$ and $D$ simultaneously in the plasma interior at $0.5<r/a<0.7$. $\chi_e = 2.7 \pm 0.4 \text{ m}^2\text{s}^{-1}$ and $D_e = 0.4 \pm 0.1 \text{ m}^2\text{s}^{-1}$ have been measured in OH plasmas, giving $\chi_e/D_e = 6.8 \pm 2.7$. NBI heated H-mode plasmas are indistinguishable from OH plasmas in respect of $\chi_e$, $D_e$ and $\chi_e/D_e$. The ion thermal diffusivity has also been measured in H-mode plasmas, giving $1<\chi_i(\text{m}^2\text{s}^{-1})<3$, simultaneously with $\chi_e = 3 \pm 0.5 \text{ m}^2\text{s}^{-1}$, thus $0.3<\chi_i/\chi_e<1$. The large value of $\chi_e/D_e$ would suggest that micro-magnetic stochasticity, rather than ExB convection, may be the key mechanism in anomalous transport.

1. INTRODUCTION

An important objective in tokamak research is to find suitable descriptions for the measured radial thermal and particle fluxes, and to identify the underlying mechanism of transport. Many models for transport in tokamaks have been developed which make specific predictions for correlations between thermal and particle transport\cite{1}. Correlations amongst the transport coefficients arise due to mutual interference between the simultaneously occurring processes in the system, which is described by some form of Onsager relations. In order to exclude some of the contending models, accurate measurements of the correlations are required. To reduce uncertainties arising from shot-to-shot and spatial variations it is necessary to determine these coefficients simultaneously in the same spatial region of the plasma. We expect that static experiments involving steady-state analysis for the determination of correlations between transport coefficients will be inconclusive, and that transient methods which do not strongly perturb the plasma are more appropriate.

We present simultaneous measurements of radial thermal and particle transport coefficients by analysis of inward propagation of temperature and density perturbations produced when a small pellet is injected into the plasma. The results are compared with those from other transient techniques (a) measurements of the velocity and damping of electron temperature and density pulses propagating outwards following a sawtooth collapse, (b) time dependent transport analysis applied to non-stationary plasmas. This paper incorporates results from earlier publications\cite{2}, where details of the applied methods are given. Other transient methods to measure electron density and thermal transport, by modulating the sources, have been used in JET\cite{3,4}. However those methods cannot be applied simultaneously.

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In the following we contrast thermal and particle transport behaviour in Ohmically heated (OH) deuterium plasmas in the outer-limiter configuration in the parameter range $I_a=3\text{MA}$, $2.8<\beta(T)<3.4$, $T_e(0)=3\text{keV}$, $T_i(0)=1.5\text{keV}$ and $1.5<\bar{n}_e(10^{19}\text{m}^{-3})<2.7$, with that in H-mode deuterium plasmas limited by a magnetic separatrix formed during single-null x-point operation, in the parameter range $I_a=3\text{MA}$, $\beta=3\text{T}$, $T_e(0)=T_i(0)=5\text{keV}$, $\bar{n}_e=5\times10^{19}\text{m}^{-3}$, and $\sim8\text{MW}$ of NBI heating, in the same spatial region. Table I summarizes the measurements.

Table I: Some Elements of the Transport Matrix

<table>
<thead>
<tr>
<th></th>
<th>OH limiter plasma</th>
<th>NBI heated H-mode plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_e(\text{m}^2/\text{s})$</td>
<td>$D_e(\text{m}^2/\text{s})$</td>
<td>$Q_p(\text{kW/m}^2)$</td>
</tr>
<tr>
<td>(a) 2.8±0.3</td>
<td>0.4±0.1</td>
<td>-</td>
</tr>
<tr>
<td>(b) 2.9±0.4</td>
<td>0.4±0.2</td>
<td>-</td>
</tr>
<tr>
<td>(c) 2.5±0.5</td>
<td>0.5±0.1</td>
<td>4.3±0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\chi_i(\text{m}^2/\text{s})$</th>
<th>$D_i(\text{m}^2/\text{s})$</th>
<th>$r/a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 3±0.5</td>
<td>0.3-0.6</td>
<td>1-3</td>
<td>$=0.5$</td>
</tr>
<tr>
<td>(b) 3±0.6</td>
<td>-</td>
<td>-</td>
<td>$=0.6$</td>
</tr>
<tr>
<td>(c) 2(d)</td>
<td>0.2-0.3</td>
<td>-</td>
<td>$=0.5$</td>
</tr>
<tr>
<td></td>
<td>0.3-0.4</td>
<td>-</td>
<td>$=0.7$</td>
</tr>
</tbody>
</table>

where
(a) Pellet Injection.
(b) Analysis of sawtooth density and heat pulse[2,16,17].
(c) Time dependent transport analysis, 'flux-gradient' method[2,7].

Thermal flux model

\[ Q(r) = -\chi_e(r)n_e(r)v(T_e(r)) + Q_e(r) \]

Particle flux model

\[ r_e(r) = -D_e(r)n_e(r) + \Gamma_e(r) \]

Assumed $T(r) = T_e(r)$. Inferred $\chi_e$ is for a single fluid plasma.

(d) H-mode at $I_a = 2\text{MA}$, $\beta = 2\text{T}$, different from the other data.

2. DETERMINATION OF $\chi_e$, $D_e$, AND $\chi_i$ BY PELLET INJECTION

Local thermal and particle diffusivities are determined by analysis of propagation of perturbations of temperature and density. The perturbation is caused by a small pellet injected in the horizontal mid-plane, penetrating to a radius $r_p$ such that $r_p/a<0.7$, where $a$ is the minor radius. The propagation is analyzed in the region $r_c<r<r_p$, where $r_c$ is the sawtooth inversion radius. Typically, in the investigations reported here, $0.3<r_c/a<0.5$ for the OH and $r_c/a<0.35$ for the H-mode cases. Previously we have shown[5,6] that the radial propagation of electron temperature and density perturbations caused by pellet injection may be representative of the local transport properties of the target plasma in the region $r_c<r<r_p$.

2.1 ELECTRON THERMAL DIFFUSIVITY

$\chi_e$ is determined by comparing the measured temporal evolution of $T_e(r)$ at $r_r<r<r_p$ with a simulation using a diffusive model including sources,

\[ (3/2)n_e(r)d(kT_e(r))/dt = -\text{div}Q_e + S(r) \]

where $Q_e = -\chi_e(r)n_e(r)v(kT_e(r))$, $S(r)$ the thermal source, and $k$ is the Boltzmann constant. A convective term in the expression for $Q_e$ is suggested by steady-state power balance analysis[7], but is ignored here; a negative flux term(pinch) will increase the inferred $\chi_e$, and a positive flux will
decrease it. The initial condition for solving eq.1, $T_e(r,t=0)$ and $n_e(r,t=0)$, the temperature and density profiles instantly after pellet injection, are determined from measurements of $T_e(r)$, $n_e(r)$, pellet mass, ablation rate and penetration depth. Fig.1 shows $T_e(r)$ and $n_e(r)$ immediately before and after pellet injection. The pellet deposition profile is calculated using the neutral gas and plasma shielding model of pellet ablation[8,9]. The model reproduces both the pellet penetration, as seen by the soft x-ray cameras viewing the pellet trajectory, and the maximum in the density deposition, as seen in the measurement of $n_e(r)$.

During evolution of $T_e(r)$ the perturbed density profile is assumed to be stationary. This is justified because the density perturbation travels much more slowly than the temperature perturbation, as will become clear in the following. $S(r)$ is calculated for the equilibrium pre-pellet plasma, and is assumed to remain stationary thereafter; the pellet injection events analyzed are such that perturbations in total heating power and in radiation and charge-exchange losses may be neglected. The modelled evolution of $T_e(r)$ is found to be sensitive only to the local value of $\chi_e$, which is iterated until good agreement with the measured $T_e(r,t)$ is obtained. Fig.2 shows a representative comparison between measured and modelled $T_e(r,t)$ at four radii. $\chi_e=2.8\pm0.3$ m$^2$/s for the OH plasmas, and $\chi_e=3\pm0.5$ m$^2$/s for the H-mode plasmas are obtained.
2.2 ELECTRON PARTICLE DIFFUSIVITY

$D_e$ is determined analogously by comparing the temporal evolution of $n_e(r)$ with a simulation using a diffusive model including sources.

$$\frac{dn_e(r)}{dt} = -\text{div} \Gamma_e(r) + S_e(r)$$

where $\Gamma_e(r) = -D_e(r) \nabla n_e(r) + \Gamma_p(r)$, and $S_e(r)$ is the electron source. The diffusion coefficient is represented as $D_e(r) = D_0(1 + 2r^2/a^2)$ and the pinching flux $\Gamma_p(r) = n_e(r)V_p(r)$. This form for $D_e(r)$ is justified by our previous measurements of density profile dynamics in JET [3,8,10]. $D_e(r)$ is specified for the equilibrium $n_e(r)$ and with the appropriate total $S_e(r)$, the pinch velocity $V_p(r)$ is self-consistently calculated. Using these, the temporal evolution of $n_e(r)$ is calculated. $D_0$ is iterated until a match with the measured $n_e(r,t)$ is achieved. For the OH plasmas $D_e = 0.4 \pm 0.1$ m$^2$/s, and for the H-mode plasmas $D_e = 0.3 - 0.6$ m$^2$/s. The large uncertainty in $D_e$ for the H-mode arises due to uncertainties in determining the particle source.

2.3 ION THERMAL DIFFUSIVITY

$\chi_i$ is similarly determined by analyzing propagation of an ion temperature perturbation. Since the ion temperature cannot at present be measured with the required spatial and temporal resolution, we have employed propagation of perturbations of thermonuclear neutron emission, as evidenced by a multi-chord neutron camera, viewing a poloidal cross-section of the plasma from above, to deduce $\chi_i$. In OH plasmas $T_i$ is not high enough to give sufficient neutron flux to the camera for high quality neutron emission profile analysis. Therefore only the NBI heated H-mode plasmas have been analysed for the $\chi_i$ determination. Fig.3 shows the temporal evolution of line-integrated neutron emission in five of the chords viewing the outside half of the plasma cross-section. The pellet is injected at $t = 54.8$ s, which reduces $T_i$ for $r \approx r_p$. Fig.3 shows that the neutron emission on the chord passing through the cold plasma (chord 19) also
instantaneously drops, whereas the neutron emission on the chords viewing the plasma further inside drops more slowly. In fig.3 we observe a neutron emissivity perturbation due to an ion temperature 'cold' front travelling diffusively into the plasma. We have modelled this process as follows. The equilibrium (pre-pellet) deuteron density profile, \( n_d(r) \), is constructed from the measured profiles \( n_e(r) \) and \( Z_{\text{eff}}(r) \). The pre-pellet deuteron temperature profile, \( T_d(r) \), is assumed to be Gaussian with the measured peak value \( T_d(0) \). The width of the Gaussian is adjusted to match the thermonuclear part of the measured neutron yield, taking into account the proportion of beam-plasma and thermonuclear neutron yield which is deduced from a model calculation of neutral beam dynamics within the TRANSP code[11]. The model calculation also gives spatial emissivity profiles for neutrons from each of the two reactions.

After pellet injection the beam-plasma neutron emissivity profile is assumed to remain unchanged, which is reasonable since the pellet produces only a small perturbation of the plasma parameters, and the NBI power remains constant. The observed perturbations in the total neutron yield are attributed to perturbations of ion temperature and its consequences for the thermonuclear neutrons. The initial condition for solving the diffusion equation for \( \chi_e \), analogous to eq.1, is the deuteron density and temperature profiles immediately after pellet injection. \( n_d(r,t=0) \) is deduced as in sec.2.1, and \( T_d(r,t=0) \) is derived by assuming adiabatic response of the ion temperature. The temporal evolution of \( T_d(r) \), the corresponding thermonuclear neutron emissivity, and the total line-integrated neutron emission observed in each cord of the neutron camera are calculated. The perturbed \( n_d(r) \) is assumed to be stationary during evolution of \( T_d(r) \). The value of \( \chi_e \) in the measurement region is iterated until a match is obtained with the observed temporal evolution of the emission, fig.4. This procedure yields \( 1<\chi_e(\text{m}^2/\text{s})<3 \), simultaneously with \( \chi_e=3\pm0.5 \text{ m}^2/\text{s} \), giving \( 0.3<\chi_e/D_e<1 \) for the H-mode plasma.

3. CONCLUSIONS

Table I summarizes the observations. Simultaneous direct measurements of thermal and particle transport yield \( \chi_e=2.7\pm0.4 \text{ m}^2/\text{s} \) and \( D_e=0.4\pm0.1 \text{ m}^2/\text{s} \), giving \( \chi_e/D_e=6.8\pm2.7 \) at \( 0.5\leq r/a\leq 0.7 \) in the OH plasmas. The H-mode plasmas, with \( \approx 6 \text{ MW} \) of NBI heating, are indistinguishable from the OH plasmas in respect of \( \chi_e \), \( D_e \), and \( \chi_e/D_e \). The ion thermal diffusivity has also been
determined in the specified region for the H-mode plasmas, giving $1 < \chi_e (m^2/s) < 3$, thus $0.3 < \chi_e / \chi_T < 1$. An aim of our future work is to incorporate impurity transport into this scheme.

The large value of $\chi_e / D_e$ would suggest that micro-magnetic stochasticity, rather than $E \times B$ convection, may be the primary contributing mechanism in the observed anomalous transport. The above observations are contrary to those reported from other experiments$^{[12,13]}$, where thermal and particle diffusivities of equal magnitude are deduced. The measurements presented here appear to be consistent with expectations of the critical temperature gradient model of anomalous transport$^{[14,15]}$. The similarity of OH limiter plasmas and NBI heated H-mode plasmas in respect of the electron thermal and particle transport behaviour in the plasma interior suggests that the same underlying mechanism of anomalous transport is operative in the two cases, although they are quite different in respect of magnetic configuration, temperature range, and density profile shape. The intrinsically better particle (vs thermal) confinement witnessed here, which will similarly affect recycled impurities and helium ash, may pose the more severe barrier to future reactor-oriented tokamak experiments.

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REFERENCES


COMPARISON OF LOCAL TRANSPORT STUDIES WITH THE PROFILE CONSISTENCY CONCEPT FOR ASDEX PELLET-REFUELED DISCHARGES

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Abstract

Strongly peaked electron density profiles have been obtained in ASDEX by different refuelling methods: pellet fuelling, NBI counter-injection and recently by reduced gas puff fuelling scenarios. These discharges show in common increased density limits, a canonical electron temperature profile independent of the density profile and an improvement of the particle and energy confinement.

Whereas the changes in particle transport are not fully understood, local transport analyses point out that the improved energy transport can be explained by reduced ion conduction losses coming close to the neoclassical ones. The different results for the ion transport with flat and peaked density profiles are quantitatively consistent with that expected from \( n_J \)-driven modes. So all cases showing confinement improvement through density peaking correspond to \( n_J \) (and \( n_e \)) < 1 over a large part of the plasma cross-section. With the ion transport behaviour emerging from our analysis, the saturation of \( \tau_E \) with \( n_e \) for flat density profiles and the extension of the linear dependence for peaked ones in OH discharges then fits with a continuing inverse density dependence of the electron thermal diffusivity \( \chi_e \) is also in agreement with \( \tau_E \) enhancement when going from \( D^+ \) to \( H^+ \) ions. With additional heating \( \chi_e \) is largely responsible for the confinement degradation in the L-mode and again the improvement at the H-mode transition. Near the plasma boundary \( \chi_e \) is higher than \( \chi_i \) in all cases investigated.

I. Introduction

Strongly peaked electron density profiles have been obtained in ASDEX by different refuelling methods: pellet fuelling (ohmic and co-injection heating), NBI counter-injection and recently by reduced gas puff fuelling scenarios. These discharges show in common increased density limits, a canonical relative electron temperature profile independent of the density profile and an improvement of the particle and energy confinement times \( \tau_E \) with respect to the values in standard ohmically heated or L-regime discharges at the same line averaged density \( \bar{n}_e \) and total heating power \( P_{tot} \). Standard gas puff-fuelled OH discharges with flat density profiles show the roll-over from the linear dependence \( \tau_E = \bar{n}_e \) to a saturated \( \tau_E \) regime, whereas ohmically heated discharges transiting into the peaked density (IOC) regime show an extension of the linear \( \tau_E(\bar{n}_e) \) behaviour and are up to 60% above the comparison cases. An even higher gain is shown by the pellet-fuelled OH-cases, with values of \( \tau_E = 160 \text{ ms} \) (110 ms for \( H^+ \))/1.3/4 being reached and sustained for times much longer than \( \tau_E \) in the post-pellet phases. With additional heating the gain in \( \tau_E \) diminishes with increasing power. As the density peaking is reduced at the same time from 2.6 to 1.6/4, a further dependence of \( \tau_E = \tau_E(\bar{n}_e, P_{tot, A}) \) on the density peaking factor \( n_e(0)/\langle n_e \rangle \) can be inferred from these results. This is illustrated in Fig. 1 showing \( \tau_E \) as a function of the density peaking factor and the heating power for different confinement regimes. With pellet
Fig. 1. Energy confinement time \( \tau_E \) versus density peaking factor \( n_e(0)/<n_e> \) as a function of heating power (ohmic and NBI) for pellet-fuelled (full, dashed and dot-dashed lines, \( q=2.8 \)), IOC (crosses, \( q=2.8 \)) and Ctr-injection (dots, \( q=2.2 \)) discharges. In the region right to the wavy lines confinement is dominated by radiation.

Local transport analyses, presented in section II, indicate that the improved energy transport can be explained by reduced ion conduction losses coming close to the neoclassical ones. The different results for the ion transport with flat and peaked density profiles agree with those expected from \( n_i \)-driven modes. So all cases showing confinement improvement through density peaking correspond to \( t_{\text{ij}} \) and \( T_{\text{ie}} \) over a large part of the plasma cross-section.

Another possible explanation of the global confinement results involves the \( T_e \) profile consistency concept - assuming \( T_e(r)/T_e(0) \) to depend only on \( q_a \) and a strong correlation of the global confinement with transport processes in the plasma boundary zone. The roll-over of \( \tau_E \) vs. \( n_e \) in ohmically-heated GP-fuelled discharges results then from a decrease of \( T_e(0) \) and the concomitant increase in ohmic heating, whereas the pellet discharges gain in \( \tau_E \) owing to a more favorable weighting of the fixed \( T_e \) profile with the peaked density profile. As the analyses of section II revealed electron transport to be dominating the global energy confinement in the outer plasma region a statistical investigation of the dependencies of the electron temperature profile was started and its consequences for the \( \tau_E \) scaling will be given in section III.

II. Local analysis of ion and electron thermal transport

The global confinement results suggest that the peaking of the density profile removes the cause of the \( \tau_E \) saturation observed in ohmic discharges and also improves the behaviour of additionally heated plasmas. To improve our understanding of transport processes, we performed detailed analyses with the TRANSP code using the measured radial profiles of \( n_e, T_e, \beta_0, \text{ and } Z_{\text{eff}} \).

The ion energy balance was solved in a predictive form as an equation determining \( T_i(r) \) under different model assumptions for \( \chi_i(r) \), attempting to fit results of active and passive CX-analyzers and the integral constraints given by \( \beta_0, \beta = \beta_0^\text{eff}, Z_{\text{eff}} \) and neutron flux measurements.

For the purely ohmically heated \( D^+ \) and \( H^+ \) pellet discharges it can be unequivocally shown that the ion energy transport in the central plasma region \( r/a \leq 0.5 \) cannot be enhanced above the neoclassical one given by Chang and Hinton, named \( \chi_{\text{OH}} \) in the following, since already this hypothesis leaves practically no energy to be conducted by the electrons (Fig. 2a). Further conclusions suffer from the fact that under many relevant conditions electron and ion energy transport cannot be sufficiently well separated owing to the error bars in the plasma parameter measurements especially in ohmic discharges. Our analysis can therefore only establish that a uniform
hypothesis explains qualitatively and quantitatively all ion energy balance features considered: the conductive ion energy transport is only due to \( XQ^+ \) and an additional contribution from \( \eta_l \)-modes /1/.

![Image](image_url)

**Fig.2a.** Radial dependence of heating power and loss power fluxes resulting from TRANSP analysis of a post-pellet phase in a Ohmically heated D+ discharge (\( q_a=2.7 \)).

![Image](image_url)

**Fig.2b.** Profiles of \( X_e \) and \( X_i \) of pellet-fuelled, ohmically heated discharges in deuterium and hydrogen. Pellets injected were of the same isotope as the recipient plasma. For more than 0.15 s the \( T_e \) and \( n_e \) profiles develop very similarly except of a 20% higher density in the D+ discharge.

According to drift wave theory peaked density profiles may lead to reduced anomalous heat transport if the threshold condition of the 'ion temperature gradient' mode is not violated /8,9/. This threshold is determined by the temperature and density gradients according to \( \eta_l = \left( \frac{L_T}{L_n} \right) = \frac{(d\ln T_i/dr)/(d\ln n_i/dr)}{1} \geq 1 \). The measured \( \eta_e \) and - as \( T_i = T_e \) at high densities - \( \eta_i \) values of the high confinement discharges indeed decrease to values below 1 over a large part of the plasma radius (see Fig. 3).

![Image](image_url)

**Fig.3.** \( \eta_e(r) \) for different discharge conditions. Profile for the counter-injection case truncated at small \( r/a \) as \( T_e \)-profile becomes hollow.
In the discharge phases with $\eta_i<1$ of the ohmically heated pellet-fuelled discharges, $\eta_i$-modes should be either quenched or make only a small contribution to $\chi_i$ over the whole plasma cross-section, so that our model would also predict $\chi_i = \chi_{CH}$ in the outer discharge region. Anomalous electron energy transport has thus to be dominant there and to be of sufficiently large magnitude even to determine the scaling of global $TE$. This conclusion also allows one to reconcile the predicted increase of $\chi_i = \chi_{CH}$ with the square root of the isotope mass $A$ and the observation that $TE$ values in D+ are larger than in H+ pellet discharges. A resulting decrease of the formally defined electron heat diffusivity $\chi_e = -q_e/(kn_eVT_e)$ with $A$, which here can only be shown to be consistent with our basic hypothesis (see Fig. 3), could be clearly established in lower-density discharges with separable energy balances for ions and electrons. Ohmically heated pellet-fuelled discharges only allow a test of the threshold conditions of $\eta_i$-modes. A similar conclusion can be drawn from the IOC discharges which again show a reduction of $\eta_e$ and $\eta_i$ to a value close to 1 in parallel to confinement improvement and $\chi_i = \chi_{CH}$. The $\chi_i$ reduction going from a flat to a peaked density profile within a single discharge results in peaking of the $T_i$ profile as observed in IOC discharges (2).

A quantitative comparison of $\eta_i$-modes with their predicted contribution to $\chi_i$ can be made for the flat density profile discharges. To describe the influence of the ion temperature gradient mode on the ion energy transport in flat density profile discharges, we use the formula

$$\chi_{\eta_i} = F(\eta_i, \eta_i, \chi_{CH}) \rho_s^2 c_s / (c_L n_i^{0.3})$$

with the Larmor radius $\rho_s$ and the sound speed $c_s$ determined by $TE$ and the ion mass. The switch-on function $F$ is 0 for $\eta_i < \eta_i, \chi_{CH}$ and equal to 1 for $\eta_i > \eta_i, \chi_{CH} + 0.8$. A value of 1.1 is taken for $\eta_i, \chi_{CH}$ according to our experimental results and includes an enhanced threshold for regions with a long density decay length $(L_n)_{\eta_i; \chi_{CH}} = \max\{1.1, 1.1 + 2(n_L/R - 0.2)\}^2$. As, for measured ASDEX profiles, different theoretical models for the function $G$ result only in a variation of $\chi_{\eta_i}$ by a factor of less than 2, we chose in a first step the G expression given by ref. /8/ multiplied by a factor of 0.5.

An analysis of purely ohmically heated cases in fact show the compatibility of $\chi_i = \chi_{CH} + \chi_{\eta_i}$ with $T_i$ measurements but cannot -within the error bars and owing to the sensitivity of the electron ion energy transfer on $(T_e, T_i)$ - uniquely discriminate against the assumption $\chi_i = \alpha \chi_{CH}$ with $\alpha = 2-4$. As the $T_i$ profile is flatter than that of $T_e$, $\eta_i$ is somewhat smaller than $\eta_e$ (cf. Fig. 2) and is clamped to values between 1 and 2. The ion and electron energy balances can, however, be well separated in NBI-heated discharges at the same electron density. For the L-regime case of Fig. 4 the assumption $\chi_i = \chi_{CH}$ would clearly give much too high $T_i$ values, whereas our present hypothesis yields agreement. The average or peak ion temperature could, of course, also be brought into agreement by enhancing $\chi_{CH}$, but this theoretically unjustified procedure would give a worse fit to the profile shape. Enhanced ion energy transport from $\eta_i$-modes are also expected to persist in H-regime discharges still having $\eta_i, \chi_{CH} > 1$ and in fact our analysis gives good agreement with the measured $T_i$ profiles.

**The improvement in confinement with density profile peaking in additionally Co-beam-heated pellet-fuelled and Ctr-beam-heated GP discharges is also in agreement with the expected behaviour of $\eta_i$-modes, although the gain diminishes with increasing power together with the density peaking (see Fig. 1). Correspondingly the region with suppressed $\eta_i$-modes is limited to the inner zones (see Fig. 3) which can explain the failure to recover the full gain - as obtained with ohmic heating - in global confinement over the corresponding flat density case. In fact, a plot of $\chi_i(r)$ as follows from our model (Fig. 5) shows a hump in the outer regions stemming from residual $\eta_i$-activity. The increase in the centre is due to the neoclassical contribution, which becomes significant there owing to the high peak density. The ion conduction losses are therefore the dominant loss channel up to $r=0.8a$, which explains the large error bars of $\chi_e$ in the inner parts of the plasma minor radius. This neoclassical ion confinement zone shrinks towards the plasma centre with increasing additional heating as the density peaking is reduced.**

These results bring low- and high-density OH results into one consistent picture with a continuing inverse density dependence of the electron thermal diffusivity, which dominates the power balance at low densities. At medium densities ($n_e > 3 \times 10^{19} m^{-3}$) and with flat density profiles $\chi_i$ is larger than $\chi_e$ and enhanced ion conduction losses cause the $TE$ saturation. With peaked density profiles (pellet, see also /5/ and IOC discharges) $\chi_i$ is decreased to the neoclassical value and becomes comparable to $\chi_e$ in the confinement region. A similar density dependence was also derived for D and $\eta_i$ from gas oscillation experiments in ohmic discharges with flat density profiles. The iso-
Fig. 4. Profiles of temperatures, $\eta_{e, \theta}$ and heat diffusivities for gas puff-fuelled, flat density profile L-regime discharge (Co-NBI; $q_a = 2.5$; $\eta_n = 4.2 \times 10^{19}$ m$^{-3}$). $T_j$ is obtained by TRANSP analysis with $X_j = X_{CH} + X_{\eta_1}$ and has to be compared with the passive CX measurements ($\circ$). For comparison the neoclassical $X_{CH}$ values and $T_j$ calculated with $X_j = X_{CH}$ are shown too.

Fig. 5. Radial profiles of $X_e$ and $X_i$ resulting from TRANSP analysis of peaked density profile NBI(H$^+$)-heated L-regime pellet-fuelled deuterium discharge ($P_N = 1.2$ MW, $q = 2.8$).

tope dependence of $X_e$ is also in agreement with $\tau_E$ enhancement when going from D$^+$ to H$^+$ ions. Comparing $X_e$ of flat and peaked density profile discharges, i.e. Fig. 2b and 5, respectively, $X_e$ seems to be reduced in the 'peaked' discharges, owing either to a dependence of the electron diffusivity on $\eta_1$ or $\eta_e$, i.e. predictions of first-principle theoretical models, or to the favourable scaling with density.

III. Electron temperature profile 'stiffness' and confinement time

The electron temperature profile was statistically investigated by applying the SAS-code to about 1800 time points out of 70 deuterium discharges covering the following parameter range:

$0.25 \leq n_e \leq 1.2 \times 10^{20}$ m$^{-3}$, $0.3 \leq P_n \leq 2.6$ [MW] at fixed $I_p = 0.38$ MA and $B_t = 2.17$ T.

($P_n$ is the power flowing through the boundary determined as heating minus radiated power). The
analysis included pellet and non-pellet discharges in different modes of confinement (OH-SOC, -IOC, L-mode) and with different heating methods (OH, NI-Co, -Ctr, ICRH) /3/. At present the data set excludes to a large extent hydrogen and low density discharges and H-mode data as well. If the electron temperature profile is self-similar and 'stiff', respectively, in its relative shape, the absolute overall temperature is proportional to the boundary temperature. Precisely speaking it is the temperature at that location in the boundary where 'stiffness' stops, which for practical reasons was taken at r=35 cm, which means 5 cm inward from the separatrix. At this location reliable electron temperatures can be obtained from the YAG system. Following results are obtained:

The electron temperature at r=0.35m, called $T_{35}$, scales like $n_{35}^{-0.4} P_h^{0.2}$ and is only weakly reduced in hydrogen discharges. For simplicity we used ordinary least squares after a logarithmic transformation. The uncertainty of the exponents is typically ±0.1 and the root mean squared error (rmse) of the fit is 17%. In the investigated data set, $T_{35}$ ranges from .1 to .35 keV. The influence of pellet injection is small, with a $T_{35}$ being only 10% smaller immediately after injection while 10 ms later no significant difference can be found.

The $T_e$ profile shape was analysed in the term of the two ratios $T_0/T_{20}$ and $T_{20}/T_{35}$, where the reference radius $r=20$ cm was chosen as it is always outside the sawtooth region. No dependence on $n_{35}$ and $P_h$ was found, there exists however a weak inverse dependence on the corresponding density ratios with an exponent of $a=0.2$. The relative temperature gradient at the fixed q value is very 'stiff' and its original profile shape is recovered again within a few milliseconds after pellet injection /1/, although the pellet mass is very inhomogeneously deposited around half the minor radius (see Fig.6). This holds even for the extended periods of improved confinement after the last pellet injection. Other investigations on ASDEX confirm the high insensitivity of the relative electron temperature profile, especially in the outer part.

Taking this $T_e$ self-similarity at fixed q together with the assumption $T_e = 1.1 T_i$ we can rewrite the energy confinement time

$$\tau_E \sim \int \frac{n_e T_e \, dV}{P_h} \sim \int n_{35}^{-0.2} dV / P_h$$

With the scaling law for $T_{35}$ from above one gets (at fixed $q=2.8$)

$$\tau_E \sim n_T n_{35}^{-0.4} P_h^{-0.8} (n_{35}/n)^{0.2} dV.$$

A direct regression analysis with the first three parameters of this scaling yields

$$\tau_E \sim n_T^{0.6} n_{35}^{-0.3} P_h^{-0.6}.$$

Fig.6. Peak $(r=0)$ and volume averaged ($\langle \rangle$) electron density and temperature vs. time for a ohmic hydrogen pellet discharge. The data points measured by Thomson scattering are smoothed between adjacent pellet pop times and extrapolated to them.
The difference can be partly explained by the additional density weighting of the first scaling and the high correlation of $n^T$ and $n_{35}$ of our database. The $\tau_E$-values for all the investigated conditions are relatively well described by this scaling law with a rmse of 12% (see figure 7). The improvement of energy confinement in pellet and IOC discharges enters via the increased $n^T$-value, that means through the density peaking. The very unfavourable power dependence is partly a consequence of the assumption $T_e = 1.1 T_i$, which systematically tends to underestimate the increase in energy content with heating power.

![Graph showing measured $\tau_E$ versus fitted scaling $\tau_E \sim n^{0.6} n_{35}^{-0.3} P_{th}^{-0.6}$ for OH, Co- and Ctr-NBI, ICRH-discharges with and without pellet-refuelling.](image)

**Fig.7.** Measured $\tau_E$ versus fitted scaling $\tau_E \sim n^{0.6} n_{35}^{-0.3} P_{th}^{-0.6}$ for OH, Co- and Ctr-NBI, ICRH-discharges with and without pellet-refuelling.

**IV. Summary**

There exist four discharge conditions under which peaked density profiles are obtained on ASDEX: with pellet refuelling, with ctr-NBI, with reduced GP (IOC) and with spontaneous suppression of sawtooth activity. All show improved particle and energy confinement, with the latter partly offset by enhanced radiation.

Local energy transport analyses show that the temperature profile of the ions and their contribution to energy confinement depend on the density profile shape and can be explained by superposition of neo-classical and $\eta_i$-mode driven ion heat conductivities, the latter being present in all flat density profile cases (OH, L- and H-mode). The neoclassical ion confinement zone of the peaked density profile cases with $\eta_i$ (and $\eta_0$)<1 shrinks towards the plasma centre with increasing additional heating as the density peaking is reduced. With this ion transport behaviour a continuing inverse density dependence of $\chi_e$ in ohmic discharges is found. With additional heating $\chi_e$ is largely responsible for the confinement degradation in the L-mode and again the improvement at the H-mode transition. The physical reasons for the confinement improvement in the H-mode and in the peaked density mode are therefore quite different, coming mainly from reduced electron and ion losses, respectively.

The global energy confinement remains controlled by electron transport and the discharges are characterized by a nearly self-similar $T_e$ profile. This leads to a picture of a mechanism which provides temperature profile similarity and correlates the global confinement with transport processes in the plasma boundary zone, i.e. the boundary temperature. The additional changes of global confinement with changing density profiles are then connected to the altered particle transport and a $\tau_E$ scaling fitting discharges from different confinement regimes results.
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EXPERIMENTAL OBSERVATION OF $\eta_i$-MODE SUPPRESSION BY DENSITY PROFILE MODIFICATION THROUGH PELLET INJECTION

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Abstract

For high-density ohmic discharges in the TEXT tokamak, a distinct ion mode (i.e., density fluctuations propagating in the ion diamagnetic drift direction) is observed in the microturbulence spectra. The magnitude and spectral characteristics of the mode are identified. A microinstability based transport model is used for the purpose of interpreting anomalous confinement properties. Onset of the ion feature occurs at plasma densities where a clear saturation is evident in the global energy confinement time $\tau_E$. When the ion feature in the fluctuation spectra is strongest, agreement between predictions from the transport model and experimentally measured values of the global energy confinement time is only realized when anomalous ion effects due to the ion-pressure-gradient-driven ($\eta_i$) instability are included. By injecting pellets, a high-density plasma is created in which the density profile is sharply peaked. Under these conditions the ion feature in the fluctuation spectra is suppressed. Possible connection between this experimentally observed ion mode and the theoretically predicted properties of the $\eta_i$ instability is explored

Previous measurements on the Texas Experimental Tokamak (TEXT) have shown that the global energy confinement time ($\tau_E$) saturates with increasing plasma density. This trend, which has been observed in numerous other Ohmically-heated tokamaks, has been attributed to the increased dominance of the ion thermal loss channel over the electron channel at sufficiently high densities. If the ion losses are taken to be governed by neoclassical transport, then transport modeling calculations can provide predictions for the density at which $\tau_E$ saturates. However, in many discharges refueled by gas puffing (e.g., DOUBLET-III, ALCATOR-C, and ASDEX), the saturation of $\tau_E$ is actually observed to occur at densities considerably lower than the ion neoclassical estimates. As first proposed by Coppi et al., this "anomalous"
behaviour could be caused by the onset of enhanced ion thermal transport due to the excitation of ion-temperature-gradient-driven ($\eta_1$) drift instabilities. Using models based on the presence of these modes, recent transport code calculations have yielded results in reasonable agreement with the density saturation observed in a large number of tokamak experiments. Experimental results from ASDEX have shown significant improvement in the global energy confinement time for discharges with pellet injection and reduced neutral-gas fueling to recycling ratio. Strongly peaked density profiles are the common feature of all these operating regimes and transport code calculations indicate the increase in energy confinement time may be due to stabilization of the $\eta_1$ mode.

The preceding discussion provides ample motivation to search for direct experimental evidence of ion-pressure-gradient-driven instabilities. Along with anomalous ion thermal transport, theoretical analyses make specific predictions regarding the nature of microturbulence characterizing such modes. If the parameter $\eta_1 = L_p/L_T = \delta n T_e/d n$, where $\delta n$ is the perturbation density, exceeds a threshold value, $\eta_1 \geq 1$ to 2 then drift-type microinstabilities propagating in the ion diamagnetic drift direction are predicted to be present with a typical range of $k_p \rho_i \leq 1$. This is essentially the same $|k|$-space range characteristic of the usual electron drift wave turbulence with $k_p$ being the wave vector of the density fluctuation in the plane perpendicular to the toroidal magnetic field and $\rho_i$ being the ion gyroradius times $(T_e/T_i)^{1/2}$. The primary focus of the present study is to systematically examine the density fluctuation spectra at various plasma densities in the Ohmically-heated TEXT tokamak. A unique multichannel far-infrared laser scattering system is employed to measure the entire $S(k_p, \omega) = |\langle n(k_p, \omega) \rangle|^2$ spectra during a single discharge. Implementation of a heterodyne receiver allows the wave propagation direction of simultaneously-occurring counter-propagating modes to be resolved. In addition, a profile-consistent microinstability-based model is used in the BALDUR transport code (time dependent, one dimensional) for the purpose of interpreting the anomalous confinement properties of the plasma.

The scattering system, which is described in detail by Peebles et al., simultaneously collects the frequency-shifted scattered radiation at six discrete angles corresponding to $0 \leq k_p \leq 15$ cm$^{-1}$. A twin-frequency laser source and heterodyne receiver system permits resolution of the wave propagation direction. The portion of the far-infrared laser beam ($P_\nu = 14$ mW, $\lambda_\nu = 2 \pi/k_0 = 1222$ μm, $\Delta \omega/2\pi = 1$ MHz for the heterodyne receiver) utilized as the probe beam is weakly focused along a vertical chord to a waist of radius $a_0 = 2$ cm at the $e^{-2}$ point of the intensity distribution. The measured wavenumber resolution is independent of wave vector with $\Delta k = 0.01$ cm$^{-1}$. The length of the scattering volume (along $k_0$) varies as a function of wavenumber and ranges from ±11 cm ($e^{-2}$ point of scattered power) at $k_p = 12$ cm$^{-1}$ to a chord average as $k_p \rightarrow 0$.

Microturbulence poloidal frequency spectra for low ($n_e = 2 \times 10^{13}$ cm$^{-3}$), medium ($n_e = 4 \times 10^{13}$ cm$^{-3}$), and high ($n_e = 8 \times 10^{13}$ cm$^{-3}$) density gas-fueled TEXT discharges are shown in Fig. 1. The low density regime corresponds to conditions where $\tau_E$ is linear with varying density while the medium density discharge represents the transition region to high density where $\tau_E$ is saturated. Scattering volumes at each $k_0$ are located above the midplane along a vertical chord at the major radius $R = 1$m. The heterodyne receiver system permits resolution of the wave propagation direction with negative (positive) frequency corresponding to the electron (ion) diamagnetic drift direction. For each wave vector examined, there is a distinct large-amplitude broadbanded ($\Delta \omega/\omega = 1$) peak at negative frequencies which moves to higher (more negative) frequencies as $k_0$ increases indicating a dispersion for the fluctuations. In contrast, at low plasma densities [Fig 1(a)], only a low-level contribution to the total scattered power is observed from microturbulence propagating in the ion diamagnetic drift direction.
appears to peak at approximately zero frequency for all $k_\theta$. However, at medium plasma densities (Fig. 1(b)), a small-amplitude non-zero peak is observed at positive frequencies in addition to the microturbulence propagating in the electron diamagnetic drift direction. Finally, at the highest plasma densities (Fig. 1(c)), microturbulence propagating in the ion diamagnetic drift direction is seen to exist with magnitude comparable to that of its negative frequency counterpart and a clear dispersion is observed. The ion feature is observed in the same $k_\theta$ space as the electron drift wave type fluctuations with $0.1 \leq k_\theta \leq 0.3$. Since the fluctuations are measured in the laboratory frame of reference, it should be noted that plasma rotation effects resulting from $\nabla \times \mathbf{B}$ drifts induced by a negative plasma potential serve to shift the spectra (both the electron and ion features) to more negative frequencies (i.e., electron diamagnetic drift direction). Raising the plasma density acts to broaden $n_e(r)$ and increase the density scale length in the confinement zone which may drive $\eta_1$ above the threshold for instability.
The appearance of the ion feature in the fluctuation spectra also occurs simultaneously with the saturation of $\tau_T$ and is a signature of the ion-temperature-gradient-driven instability.

By injecting pellets into the plasma, it is possible to obtain high-density discharges with sharply peaked $n_e(r)$ when compared to a gas-fueled equivalent as shown in Fig. 2. This in turn reduces the density scale length $L_n$ and can potentially drive $\tau_T$ below the critical level for instability. Such a scenario has often been invoked to explain the improved energy confinement observed for high-density pellet-fueled discharges $^{11,18}$ To be consistent with fluctuation measurements, one would then expect the ion feature to be significantly reduced for the pellet-fueled case. Figures 3 (a) and (b) show the fluctuation frequency spectra at times before ($n_e = 3 \times 10^{13}$ cm$^{-3}$) and after ($n_e = 7 \times 10^{13}$ cm$^{-3}$) pellet injection. For each case, the fluctuations are observed to propagate predominantly in the electron diamagnetic drift direction suggesting contributions from $\tau_T$ instability are small. In contrast, a comparable high-density gas-fueled discharge ($n_e = 6 \times 10^{13}$ cm$^{-3}$) contains appreciable levels of the turbulence propagating in both directions, as shown in Fig. 3(c). The largest changes in the density scale length occur well away from the plasma edge (see Fig. 2) indicating the ion mode, which is not observed for the pellet-fueled discharge, comes from this region of the plasma. Pellet-fueled discharges on TEXT are characterized by suppressed sawtooth activity, peaked density profiles, increased radiated energy confinement, and generally lower fluctuation levels.

![Figure 2](image)

**Figure 2** Comparison of (a) density and (b) density scale length profiles for high-density gas-fueled and pellet-fueled discharges. The symbols denote (- - - -) gas-fueled, (---) pellet-fueled (+5 ms), and (-----) pellet-fueled (+50 ms) discharges.

![Figure 3](image)

**Figure 3** Microw turbulence poloidal frequency spectra for $k_{\perp} = 9$ cm$^{-1}$, $I_p = 250$ kA, $B_0 = 2$ T, and (a) pre-pellet, $n_e = 3 \times 10^{13}$ cm$^{-3}$, (b) post-pellet, $n_e = 7 \times 10^{13}$ cm$^{-3}$ and (c) high-density gas-fueled equivalent discharge, $n_e = 6 \times 10^{13}$ cm$^{-3}$. Negative (positive) frequency corresponds to the electron (ion) diamagnetic drift direction. Vertical axes are in arbitrary units.
power on axis, and improved particle confinement times. These properties are consistent with pellet-fueling experiments on other tokamaks which also report significant improvements to the measured global energy confinement time. However, on TEXT, energy confinement properties for the high-density (i.e. $n_e > 7 \times 10^{13} \text{ cm}^{-3}$) pellet-fueled discharge are not known.

In the preceding discussions, it has been pointed out that the presence of an ion feature in the measured fluctuation spectrum is consistent with theoretical predictions for the appearance of ion temperature gradient driven drift instabilities ($\eta_i$ modes). Moreover, the observed confinement properties for gas-fueled plasmas appear to exhibit significant degradation when the ion feature is present. These trends have motivated a systematic simulation study of the relevant TEXT discharges using microinstability-based models for the anomalous electron and ion thermal diffusivities, $\chi_e$ and $\chi_i$, in the BALDUR transport code. The trapped-electron modes in both collisional and collisionless regimes are represented in $\chi_e$ and, when the parameter $\eta_i$ exceeds $\eta_{ic}$, the toroidal ion temperature gradient modes account for enhancements to $\chi_i$. For $\eta_i < \eta_{ic}$, the ion losses are taken to be only neoclassical. The choice of $\eta_{ic}$ in the transport model was taken to be 1.5. An exact value is difficult to determine with various theoretical studies indicating a range of $\eta_{ic}$ from 1 to 2. As described in detail in Refs. 22 and 23, this model was calibrated on deuterium plasmas from TFTR and successfully applied to the simulation of numerous discharges from TFTR, ASDEX, and ALCATOR-C. In the present calculations, which deal with hydrogen plasmas, a scaling factor $Z_i^2/M$ was used in the expression for $\chi_i$ to accommodate the familiar empirical mass-charge dependence observed in most tokamak experiments which fall in the saturated Ohmic regime. Preliminary results from simulations of helium discharges on TFTR have also yielded good agreement when this empirical factor was utilized.

Results from the transport code simulations for $\tau_E$, $\tau_{Te}$, and $\tau_{To}$ (central electron and ion temperatures) are compared with corresponding experimental results displayed in Table I. The entries are representative cases from the database of Fig. 1 and Ref. 15, where the fluctuation properties in gas-fueled discharges were investigated. At low density, the anomalous ion thermal transport mechanism in the transport model produces only a minimal effect on the predicted confinement properties indicating that even though $\eta_i$ is marginally above the threshold for instability, the ion contribution to the total heat flux is small. The modeled and measured energy confinement times

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<th>CASE</th>
<th>SIMULATION</th>
<th>EXPERIMENT</th>
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<tr>
<td>$\bar{n}_e$</td>
<td>$\chi_i^T$</td>
<td>$T_{Te}$</td>
</tr>
<tr>
<td>$2 \times 10^{13}$</td>
<td>off</td>
<td>1.45</td>
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<tr>
<td></td>
<td>on</td>
<td>1.4</td>
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<tr>
<td>$4 \times 10^{13}$</td>
<td>off</td>
<td>1.25</td>
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<tr>
<td></td>
<td>on</td>
<td>1.1</td>
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<tr>
<td>$6 \times 10^{13}$</td>
<td>off</td>
<td>1.2</td>
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<td></td>
<td>on</td>
<td>0.8</td>
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are similar producing a picture consistent with fluctuation measurements which indicate ion pressure gradient driven turbulence is small. As the density is increased to \(4 \times 10^{15} \text{ cm}^{-3}\), the energy confinement time from the transport model without anomalous ion effects is 30% larger than \(\tau_E\) computed with \(\chi_i^0\). Including anomalous ion thermal transport produces better agreement with the measured confinement time. Under these conditions, fluctuation measurements indicate a distinct mode propagating in the ion diamagnetic drift direction. For the high density case, where the ion feature in the fluctuation spectra is strongest, agreement is possible only if the anomalous \(\chi_i^0\) is turned on in the simulation, thereby decreasing \(\tau_E\) by a factor of two. Hence, in the three separate tokamak operating regimes examined, transport model predictions are consistent with fluctuation and transport measurements provided the ion-pressure-gradient-driven instability is included. For the high density pellet fueled case, the transport model estimates \(\tau_i\) to be below the threshold for instability with \(\tau_E\) increasing to a level equivalent to an unsaturated linear density dependence. This is once again consistent with fluctuation measurements which do not show a significant ion feature for the high-density pellet-fueled discharge.

In conclusion, a distinct ion mode has been observed in the microturbulence fluctuation spectra occurring simultaneously with the high-density saturation of the global energy confinement time. The ion feature is seen in the same \(k_R\) space as electron drift wave type fluctuations, possessing the characteristic signatures of ion-pressure-gradient-driven turbulence. At high densities, where the ion feature in the fluctuation spectra is strongest, agreement between the microinstability-based transport model and experimentally measured values of the global energy confinement time is only realized when anomalous ion effects due to the \(\tau_i\)-mode instability are included. The measured properties of transport and fluctuations appear to be clearly linked to those theoretically predicted for the \(\tau_i\) instability. For high-density pellet-fueled discharges, the density profile is sharply peaked on axis thereby reducing the density scale length \(L_n\). Under these conditions, the ion feature in the fluctuation spectra is no longer prominent, demonstrating that the density profile can be actively used to control the instability.

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WHIST TRANSPORT ANALYSIS OF HIGH-NEUTRON-PRODUCTION, ICRF-HEATED, PELLET-FUELED JET PLASMAS*

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Abstract

The WHIST 1½-D predictive transport code is used to model the particle and energy transport in JET plasmas with pellet fueling and ICRF heating. Pellet injection during the current rise phase was used to produce strong central peaking of the particle density, followed by central ICRF heating; this led to a transient period of enhanced confinement [1]. The evolution of the density profile and of the electron and ion temperature profiles under strong ICRF heating conditions during this period of enhanced confinement is examined in the context of models for particle and energy transport.

Because WHIST is a predictive transport code, it requires models for particle and energy sources and transport coefficients. The analysis procedure thus consists of modeling the particle source terms (pellets, gas, and recycled neutrals), energy source terms (Ohmic and ICRF heating), and energy loss terms (primarily radiation) and then varying the transport models until the best qualitative and quantitative agreement is obtained between calculated and observed quantities. We find that plasma behavior during the first second of ICRF heating following pellet injection is well described by the same transport coefficients that describe the Ohmic plasma. The distinction between electron and ion thermal losses depends on the relative heating rates of electrons and ions as determined by the ICRH model and on the radiation losses.

ICRH MODEL

The ICRF heating model is an extension of the PPPL ray-tracing code [2] used as a subroutine of the WHIST transport code [3]. Input to the model from WHIST consists of plasma geometry, magnetic field, and plasma densities and temperatures. Typically, 20 rays are launched from the antenna and their propagation is followed using ray-tracing

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1 The members of the JET/USDOE Pellet Collaboration are the authors of the paper entitled ‘JET multi-pellet injection experiments’ in these proceedings.
equations for a warm-fluid, multi-species plasma [4]. The initial spatial coordinates, the mode numbers, and the power content along the antenna are assumed quantities. Wave damping is calculated using the quasi-linear diffusion operator of Kennel and Engelmann [5], as each ray propagates through the plasma. Then the distribution function for the resonant or minority species is evolved using a 1-D Fokker-Planck equation to represent the collisional transfer of power to the thermal species. This collisional heating is added to the direct wave damping profiles to obtain the net power deposition profiles for the electrons and all ionic species, which are then used as input heating source profiles in WHIST.

TRANSPORT MODEL

The possible variations of transport coefficients are virtually limitless; we decided to rely on input from interpretive analyses of JET pellet plasmas for the particle transport and extend these values to energy transport using a simple approximation to theoretical relationships. The particle transport coefficients are taken from interpretive analysis of JET for shot 16211 during the enhanced confinement period [6]. To the neoclassical diffusive and Ware pinch terms, we add an anomalous diffusive term of the form

$$\Gamma(\rho) = \Gamma^{nc} - D^{an}(\rho) \frac{\partial n(\rho)}{\partial \rho}$$

where $D^{an} = 0.08 \text{ m}^2/\text{s}$ in the core, rises sharply to 0.2 $\text{ m}^2/\text{s}$ at $\rho/a = 0.4$, and then increases as $\rho^2$ to 0.4 $\text{ m}^2/\text{s}$ at the plasma edge. The critical features are the low central value and the sharp rise. The increase in the outer portion of the plasma probably does not strongly affect the calculations.

The heat fluxes are constructed in the same way; to the neoclassical terms we add anomalous electron and ion conduction terms. The relationship between the anomalous electron conductivity and the anomalous particle diffusivity is taken as $\chi^{an}_e(\rho) = 13D^{an}(\rho)/4$, where the factor $13/4$ arises in the neoclassical quasi-linear theory of fluctuation-induced transport [7]. We retain only the diagonal terms for simplicity. For the anomalous ion contribution we select as a reference $\chi^{an}_i = \chi^{an}_e$.

We retain the same values of the anomalous transport coefficients throughout the Ohmic and heating phases, and both before and after pellet injection.

ANALYSIS OF JET SHOT 16211

JET shot 16211 exhibited the enhanced confinement characteristics and was selected as a reference shot for analysis. Figures 1 and 2 show the time history of many of the experimental discharge characteristics in the time interval from 42 to 44 s. The results from a WHIST calculation are shown as solid points in the time interval from 42 to 44 s.

The total plasma current (Fig. 1(a)) was a programmed input to the WHIST calculation and reached the 3 MA flattop value at $\approx 43.5$ s. The current profile was initialized such that the axial safety factor, $q_0$ (Fig. 1(a)), matched the value determined by the MHD equilibrium code IDENTC at 42 s; both $q_0$ and the loop voltage at the plasma boundary track well with the experimental values when evolved with neoclassical resistivity. The internal inductance shown in Fig. 1(b) is also a measure of the current profile shape, and the simulation matches the IDENTC result. The ICRH power, Fig. 1(c), was an input to the ray-tracing calculation; it rises abruptly to 5 MW at 43.2 s, then increases approximately linearly to 7 MW at 44 s. The calculated Ohmic power (Fig. 1(c)) shows an abrupt rise from 2 to 4 MW at the time of pellet injection, 43 s, and then decays exponentially to about 1 MW at 44 s. The Ohmic power from the magnetic analysis is somewhat smoothed over the pellet transient, but shows essentially the same behavior.
FIG. 1. The time evolution of JET discharge characteristics with WHIST simulation values shown as solid points: (a) plasma current, central safety factor, and loop voltage; (b) internal inductance; (c) ICRH and Ohmic power; (d) $Z_{\text{eff}}$; (e) radiative and charge-exchange power loss; (f) energy confinement time.

FIG. 2. The time evolution of JET discharge characteristics with WHIST simulation values shown as solid points: (a) total plasma particle content, (b) axial electron density, (c) axial electron temperature, (d) axial ion temperature, (e) total plasma kinetic energy, (f) D-D reaction rate.
Modeling impurities and radiation with a predictive transport code to match experimental values of $Z_{\text{eff}}$ and radiation is very difficult. We chose carbon, oxygen, and nickel in the density ratio 1.0:0.2:0.01 and the magnitude such that $Z_{\text{eff}} \approx 2$ at 43 s. Radiation losses were then evaluated with a coronal equilibrium model [8]. The impurity densities were kept constant through the WHIST simulation because no option existed to program them in time, but this can be remedied for future calculations. When the pellet is injected, $Z_{\text{eff}}$ decreases because of impurity dilution, as shown in Fig. 1(d). Both the visible bremsstrahlung and neoclassical resistivity analyses indicate the dilution effect but then show $Z_{\text{eff}}$ rising, indicating a subsequent buildup of impurities. The bolometer measurement of radiative and charge-exchange loss (Fig. 1(e)) also shows an impurity increase, and at 44 s the loss calculated by WHIST is low by about 1 MW. Impurity radiation also affects the assessment of global energy confinement time. The WHIST simulation shows the energy confinement time rising from a prepellet Ohmic value of 0.3 s to 0.75 s at 43.5 s and then holding there until 44 s. This increase is purely a geometric effect from the strongly peaked axial ICRF heating [9] because there is no density, temperature, or power scaling in the transport coefficients. On the other hand, the diamagnetic analysis indicates the confinement time dropping again to about 0.4 s at 44 s. This results, at least in part, from the increased radiation loss and may be amplified if that loss is strongly peaked in the plasma center.

The total plasma electron content (Fig. 2(a)) rises in the Ohmic phase even without gas puffing. We model this in WHIST with 70% direct particle recycle plus a virtual particle source representing a slow release of the wall particle inventory. The total source of $\approx 10^{21}$ s$^{-1}$ in the WHIST simulation is in reasonable agreement with $H_{\text{D}}$ measurements and exceeds the diffusive plus charge-exchange losses. The increase in particle content at 43 s was modeled with a deuterium pellet with an effective spherical radius $r_p = 2.23$ mm, representing 92% of the ideal mass of a cylinder 4.0 mm in diameter and 4.0 mm long. The initial decay of the particle content after pellet injection is modeled with the same 70% recycle and virtual source. The saturation at higher density can be modeled only with increased hydrogenic and impurity sources associated with the additional plasma heating. Pellet penetration and the resulting particle source profile were calculated with the neutral and plasma shielding model [10]. In the calculation, pellet penetration was short of the axis, whereas in the experiment, the pellet penetrated to the axis. Calculated ablation rates are not very reliable close to the axis because of the singularity in the plasma volume. The calculated axial density rise was slightly higher than that given by inversion of the FIR chords (Fig. 2(b)), but the decay was at the same rate as observed experimentally. The axial electron and ion temperatures show excellent agreement over the entire time interval from 42 to 44 s (Figs 2(c) and 2(d)). The ICRF ray-tracing calculation indicated comparable total electron and ion heating rates with an H minority fraction of $n_H/n_e \approx 2.5\%$; since $T_{e0}$ and $T_{i0}$ were observed to rise at the same rate, we chose to use the same anomalous conductivity for both electrons and ions. The relative ion and electron heating rates are sensitive to the minority fraction, which is not well known, so definitive conclusions about the split between anomalous electron and ion losses cannot be made. In simulations extending beyond 44 s, we found that the temperatures continued to rise. We expect that the experimental saturation is due to impurity accumulation, through both radiation and reduction in the deuterium fraction (the deuterium fraction is an important factor in deducing $T_{e0}$ from neutron signals). Until 43.5 s the calculated total kinetic energy content agrees with the diamagnetic value (Fig. 2(e)). Increased radiation losses of 1 MW over the next 0.5 s (Fig. 1(e)) can explain the 0.5 MJ difference at 44 s. The neutron signal saturates at $\approx 43.7$ s while the calculated value continues to rise (Fig. 2(e)); the saturation is probably due to a reduction in the deuterium content in the core, as discussed earlier.

Axial temperatures and densities and the evolution of the electron temperature and density profiles from the WHIST simulation are shown in Fig. 3. The bump in the axial temperatures (Fig. 3(a)) is an artifact of the frequency with which the ICRF deposition profile is recalculated. Initially the resonance is located exactly at the
FIG. 3. WHIST simulation of the time evolution of electron density and temperature with experimental values shown as solid points: (a) axial electron and ion temperatures, (b) axial electron density, (c) electron temperature profile, (d) electron density profile. The ion temperature profile is essentially the same as the electron temperature profile.

magnetic axis. This very strong axial heating profile is held for about 0.2 s before being recalculated. By that time, the outward shift of the axis has increased by ≈5 cm and the resonance no longer passes through the axis. The response of the axial density in the WHIST simulation is slower than that observed (Fig. 3(b)) because the pellet did not quite reach the axis in the calculation. Once filled in, the axial density overshoots the experimental value. This could indicate that the calculated deposition profile is skewed a little too much toward the end of the pellet life. The electron temperature is very narrow (Fig. 3(c)) because of the central heating and low conductivity in the core. The ion temperature profile (not shown) has essentially the same shape. The hole in the center of the density profile from incomplete pellet penetration can be seen in Fig. 3(d). The profile fills in rapidly and then exhibits the characteristic central hump of deep pellet fueling with a broad outer shoulder.

CONCLUSIONS

ICRF heating of plasmas with the highly peaked density profiles associated with deep pellet fueling leads to a period of enhanced confinement. During this period, the plasma behavior can be modeled with the same transport coefficients that apply in the Ohmic plasma. The enhanced confinement comes mostly from the geometric effect associated with strong central heating and begins to deteriorate as impurity radiation increases.
REFERENCES

IMPROVED CONFINEMENT WITH PEAKED DENSITY PROFILES IN OHMICALLY AND NEUTRAL BEAM HEATED PLASMAS IN ASDEX


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Abstract

New regimes of improved energy and particle confinement were found on ASDEX in gas fuelled ohmic discharges at high density and with neutral beam injection in counter direction (ctr-NI), respectively. In both cases the improvement in confinement is closely related to a peaking of the density profile. Peaking of $n_e(r)$ and a gradual rise of the energy content are triggered by a reduction of the external gas flux. In the improved ohmic confinement regime (IOC) the energy confinement time $\tau_E$ does not saturate with density up to the density limit. With ctr-NI, $\tau_E$ values up to 50% above the ohmic saturation level are obtained. With peaking of the density profile, the parameter $\eta_1=L_n/L_T$ drops to 1 or below. Therefore the improvement in confinement might be explained by stabilization of the $\eta_1$-modes.

Introduction

Particle and energy fluxes seem to be correlated to a large extent in the different operation regimes of a tokamak. In ohmic discharges the external gas flux required increases nonlinearly with density in the region where the energy confinement time saturates with density. In L-mode phases density clamping is encountered without enhanced gas puffing. In H-phases, on the other hand, the density rises together with the energy content. Change of the particle fuelling method also induces a change in energy confinement, as seen in pellet injection experiments. In ASDEX, the particle fluxes in gas fuelled discharges have been changed considerably by a reduction of the divertor volume and replacement of titanium by copper target plates /1/. The recycling coefficient increased leading to a reduction of the gas consumption by a factor of 2. The lower gas flux rates gave access to new regimes of improved confinement with ohmic and NI-heating.

The IOC Regime

The linear rise of the energy confinement time with density in ohmic discharges, $\tau_E \sim \bar{n}_e$, usually saturates at high density and $\tau_E$ then tends to decrease with increasing $\bar{n}_e$. In ASDEX, it was found that this degradation is connected with discharge conditions subject to large gas fluxes: The saturated ohmic confinement (SOC) prevails at high density in all discharges with fresh carbonized walls, releasing large amounts of gas. With hydrogen as working gas requiring high gas fluxes due to poor particle confinement, the energy confinement time always saturates at high density. With deuterium, $\tau_E$ saturates when $\bar{n}_e$ is continuously ramped up by applying large external gas fluxes. In steady state deuterium discharges, however - either with uncoated stainless steel walls or with carbonized walls conditioned by He-glow discharges - improvement of the confinement was found upon reduction of the gas puff rate to low levels /2/.
The transitions between the different ohmic confinement regimes are shown in Fig. 1 with a specifically tailored discharge in deuterium. The density is increased in 3 steps with long flat top phases at $n_e = 2.5 \times 10^{13}$, $n_e = 3.9 \times 10^{13}$ and $n_e = 4.8 \times 10^{13}$ cm$^{-3}$. The first plateau is chosen near the upper end of the linear ohmic confinement (LOC) regime in ASDEX where $\tau_E \sim n_e$ still holds. During the subsequent ramp-up phase, $\beta_p$ remains constant with the density rising. The discharge there passes into the regime of saturated ohmic confinement (SOC). Upon reduction of the external gas flux, $\Phi_{\text{gas}}$, $\beta_p$ starts to rise and about 300 ms after the transition a new steady state with improved ohmic confinement (IOC) is established. Further increase of the density by enhanced gas puffing leads to a decrease in $\beta_p$, and the discharge falls back into the SOC regime. A second transition to the IOC regime with recovery of $\beta_p$ is obtained again after reduction of the gas flux. The ohmic heating power $P_{\text{OH}}$ drops slightly during the IOC phases. The level of $D_\alpha$ emission is reduced in the

![Graph showing plasma parameters](image)

**Fig. 1:** Temporal evolution of plasma parameters in a deuterium discharge passing with 3 steps in $n_e$ through different ohmic confinement regimes. The density profile factor $Q_N$ is derived from the interferometric line integrals: $Q_N = N_e(0)/N_e(0.75a)$. $B_t = 2.17$ T, $q_a = 2.75$.

![Graph showing energy confinement time](image)

**Fig. 2:** Energy confinement time $\tau_E$ versus $n_e$ for the discharge of Fig. 1.
IOC regime. Also the particle outflux decreases according to measurements by a low energy neutral particle analyzer /3/. This indicates an improvement of the particle confinement. The evolution of the energy confinement time during the different phases of the discharge is seen from Fig. 2 where $\tau_E$ is plotted versus $n_e$. The confinement time improves from $\tau_E=88$ ms in the SOC regime at $n_e=3.8 \times 10^{13}$ cm$^{-3}$ to $\tau_E=131$ ms in the IOC regime at $n_e=4.8 \times 10^{13}$ cm$^{-3}$.

The changes in the confinement behaviour correlate closely with variations of the shape of the density profile. In Fig. 1 the form of $n_e(r)$ is monitored by the ratio of central to peripheral density, as given by the line integrated interferometer signals: $Q_N=N_e(0)/N_e(0.75a)$. This parameter $Q_N$ decreases during the SOC phases and starts rising with begin of the IOC phases. Flat density profiles therefore are characteristic for phases of degraded confinement. The transition to improved confinement correlates with a peaking of the density profile, occurring on the same long time scale as the improvement of the energy confinement time.

The link between the different ohmic confinement regimes has been further investigated in a discharge where first the density $n_e$ is ramped up by strong gas puffing from $n_e=2 \times 10^{13}$ cm$^{-3}$ in the LOC regime to $n_e=4.9 \times 10^{13}$ cm$^{-3}$ far in the SOC regime; then the external gas flux is switched off completely and the density is kept decaying to the starting value. The dependence of $\tau_E$ and $Q_N$ on $n_e$ for this discharge is shown in Fig. 3. During the ramp-up phase $\tau_E$ rolls over at $n_e=3 \times 10^{13}$ cm$^{-3}$ (phase 1). Upon switch-off of the gas valve the confinement time starts rising while the density now begins already to fall (phase 2). In this IOC phase $\tau_E$ rolls over towards lower densities at the approach of the line $\tau_E \sim n_e$ and returns

![Figure 3](image-url)

**Fig. 3:** Variation of $\tau_E$ and $Q_N$ with $n_e$ during the discharge #24448 ($I_p=380$ kA,$q_a=2.75$, D2).
along this line to the LOC values (phase 3). A similar hysteresis loop is obtained for $Q_N$ as function of $\bar{n}_e$, as shown in Fig. 3b. The increase in $Q_N$, indicating a peaking of $n_e(r)$ during the first IOC phase (2), correlates with the increase in $\tau_E$ after the IOC transition. The subsequent decrease of $Q_N$ with decaying $\bar{n}_e$ in phase 3 takes place in parallel with a decrease of $\tau_E$. The close correlation between the energy confinement time and the form of the radial density profile is summarized in Fig. 4. There both, $\tau_E$ and the ratio of central to volume averaged density, $Q_n=n_{e,0}/\langle n_e \rangle$, are plotted versus line averaged density $\bar{n}_e$. In the LOC regime, $\tau_E$ and $Q_n$ increase linearly with $\bar{n}_e$. At densities above $\bar{n}_e = 3 \times 10^{13}$ cm$^{-3}$ both, $\tau_E$ and $Q_n$ show a bifurcation into the SOC and IOC regimes.

![Graph](image)

**Fig. 4:** Energy confinement time $\tau_E$ and density profile factor $Q_n=n_{e,0}/\langle n_e \rangle$ versus $n_e$ for discharges in the different ohmic confinement regimes.

**Counter-Neutral Injection**

Improved energy and particle confinement were obtained in ctr-NI heated discharges, with $\tau_E$ a factor of two above L-mode values in co-NI /4/. Two discharges with co-NI and ctr-NI, respectively, into the same target plasma are compared in Fig. 5. In both discharges the density is feedback controlled until 1.2 s. Then the gas puff rate is reduced and kept constant at the same low level in both cases. During the phase of high gas flux, $\bar{n}_e$ and $\beta_p$ are similar for co- and ctr-NI.
With ctr-NI a lower external gas flux is required to maintain the same density as with co-NI, and also the level of D$_\alpha$ emission is lower. This indicates better particle confinement already during the initial phase of ctr-NI. Upon reduction of the gas feed, density and $\beta_p$ start decaying slowly in the case of co-NI. With ctr-NI, $n_e$ as well as $\beta_p$ are rising gradually after reduction of the external gas flux. The D$_\alpha$ intensity remains constant at a level lower than with co-NI. This demonstrates clearly the better particle and energy confinement with ctr-NI in this phase. Marked differences between the two discharges are seen in the behaviour of the density profile. With co-NI, a slight drop in the profile factor $Q_N$ and therefore a flattening of $n_e(r)$ is seen during the initial phase with stronger gas puffing. Later, $Q_N$ returns to the ohmic value. With ctr-NI, the density profile retains the form of the ohmic phase during feedback controlled gas feed in the beginning. During the phase of reduced gas flux, $n_e(r)$ is gradually peaking, as seen from the continuous rise of $Q_N$.

The sawtooth period increases gradually in the course of the density peaking phase with ctr-NI. From soft X-ray measurements an increase of the sawteeth inversion radius is seen during this phase. At the same time an increase of the internal inductance is derived from magnetic measurements and from the electron temperature profile as measured by laser light scattering. This indicates an expansion of the q=1 surface and a peaking of the current density profile. The same behaviour is observed also in ohmic discharges during the IOC transition. After rearrangement of the current profile, enhanced peaking of the density profile and a larger rise in $\beta_p$ may be obtained.

In the ctr-NI heated discharge shown in Fig. 5, sawteeth oscillations disappear completely at $t = 1.4$ s. This leads to a strong increase of the radiation losses due to progressive accumulation of metallic impurities in the plasma center /5/. The resulting drop in the electron temperatures causes the roll over of $\beta_p$. The

Fig. 5: Temporal evolution of plasma parameters in two discharges with co-NI and ctr-NI, respectively, into the same target plasma: $I_p=420$ kA, $B_t=2$ T, $q_a=2.26$, $P_{NI}=0.9$ MW, H$^0$ $\rightarrow$ D$^+$. 

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accumulation phase is terminated by a radiation collapse at $t = 1.55 \, \text{s}$. With increasing NI-power, the duration of the sawtoothing phase decreases. At high beam power, sawteeth are completely suppressed during ctr-NI. Therefore the maximum attainable $\beta_p$ values are limited by the rapidly rising radiation losses. Before the roll over of $\beta_p$, a close correlation between energy confinement time and the shape of the density profile is seen for the whole range of beam powers applied. In Fig. 6, $\tau_E$ is plotted versus the form factor $Q_n = \frac{n_e(0)}{\langle n_e \rangle}$ for ohmic and ctr-NI heated discharges. In LOC and SOC regimes, $Q_n$ is nearly invariant and no correlation with $\tau_E$ is seen. In the IOC regime, $n_e(r)$ is peaking and $\tau_E$ increases with $Q_n$. With ctr-NI, a similar correlation between $\tau_E$ and $Q_n$ is found in phases not yet dominated by large central radiation. At low NI-power, energy confinement times as high as in the IOC regime can be attained.

![Fig. 6: Energy confinement time $\tau_E$ versus density profile factor $Q_n = \frac{n_e(0)}{\langle n_e \rangle}$ for OH discharges (LOC, SOC, IOC: $I_p = 380 \, \text{kA}, B_t = 2.17 \, \text{T}, q_a = 2.75$) and for ctr-NI ($I_p = 420 \, \text{kA}, B_t = 2 \, \text{T}, q_a = 2.26$).](image)

**Discussion**

The flux of cold neutral particles across the plasma boundary seems to play a crucial role in the achievement of the new improved confinement regimes in OH and NI-heated discharges. With the modified divertor geometry of ASDEX, the recycling is enhanced. The resulting lower gas puffing rates appear to be a prerequisite for the development of improved energy confinement. It also benefits from the superior particle confinement of deuterium compared with hydrogen discharges and of ctr-NI compared with co-NI. The transitions to the IOC regime and to improved confinement with ctr-NI are triggered in both cases by a reduction of the external gas feed. After an initial drop of the density at the separatrix, the whole
$n_e(r)$ profile is gradually peaking, with the central density rising. The energy confinement time increases slowly and its temporal evolution is closely correlated with the changing form of the $n_e(r)$-profile. This has been shown also in the opposite direction: Raising of the gas puff rate in the improved state leads to a broadening of the density profile and a degradation of $\tau_E$. The shape of $n_e(r)$ therefore has to be considered an important parameter determining $\tau_E$.

With peaked density profiles, the scaling $\tau_E \sim \langle n_e \rangle$ is extended up to the density limit in the IOC regime. With ctr-NI, the L-mode degradation can be avoided, and $\tau_E$ stays close to the ohmic values. Peaking of the density profile therefore obviously leads to a suppression of the losses responsible for the confinement degradation in SOC and L-mode. The hysteresis experiment of Fig. 3 shows that $\tau_E$ and the shape of $n_e(r)$ are closely linked only for densities $\langle n_e \rangle > 3 \times 10^{13}$ cm$^{-3}$. Between $\langle n_e \rangle = 2 \times 10^{13}$ cm$^{-3}$ and $\langle n_e \rangle = 3 \times 10^{13}$ cm$^{-3}$ the confinement time still increases linearly with density while $n_e(r)$ starts already flattening with strong gas puffing. The roll over of $\tau_E$ at higher densities has been explained with enhanced anomalous ion heat conduction losses. Peaking of $n_e(r)$ has then to suppress these losses in order to restore the linear scaling seen in the upper branch of the hysteresis curve (phase 3).

An instability sensitive to the observed profile changes is the ion temperature gradient driven mode. The critical parameter for excitation of this mode is the ratio of density to ion temperature decay length: $\eta_I = L_n/L_{T_i}$. In SOC and L-mode, $\eta_I$ is well above 1, and $\eta_I$-modes should be excited. In the IOC regime and with ctr-NI, $\eta_I$ drops to 1 or below, and the $\eta_I$-modes should then become stabilized. In transport code calculations, the degraded confinement regimes of SOC and L-mode can be well described by adding an anomalous ion heat diffusivity as given by $\eta_I$-mode theory to the neoclassical term /5/. The improved regimes of IOC and ctr-NI are then consistently modelled by dropping only the anomalous term owing to $\eta_I$-modes.

Conclusions

Improvement of the energy confinement is achieved with ohmic and ctr-NI heating by reducing the gas fuelling rate. The observed peaking of the density profile results in a drop of the parameter $\eta_I = L_n/L_{T_i}$ to the stability limit of $\eta_I$-modes. The same behaviour is also obtained with pellet injection /6/. All these three regimes therefore seem to belong to the same class of plasma states with peaked density profiles. They are markedly different from the H-mode where pedestals are formed at the edge with the profiles remaining flat inside. With peaked profiles the improvement in confinement may be attributed to the suppression of $\eta_I$-modes.

References

IV. IMPURITY TRANSPORT
CURRENT PROFILE MODIFICATION AND MHD ACTIVITY FOLLOWING PELLET INJECTION IN ALCATOR C

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Abstract

Pellet fueling experiments on Alcator C focussed on the regime of improved energy and particle confinement, where it was observed that transport for the ionic species was reasonably well described by neo-classical theory [1,2]. Ion energy transport dropped and particle confinement, particularly for impurity species increased dramatically. These effects have been ascribed to the suppression of ion temperature gradient driven modes (ν_i) by the peaked density profile set up by pellet injection [3,4]. Although radiation by high Z ions was unimportant in these discharges, the accumulation of low Z impurities, principally carbon, had a profound effect on the discharge by peaking the resistivity profile and reducing the current density near the plasma center. One result of this was a modification of sawtooth activity; a lengthening of the period between sawteeth and ultimately their complete suppression. After suppression of the sawteeth, very large amplitude m = 1, n = 1 oscillations were often observed. The appearance of this mode was often correlated with saturation of impurity confinement. We speculate that this mode is a form of the m = 1 ideal mode that has been held responsible for the sawtooth crash [ref].

Impurity Accumulation

The clearest sign of the improved confinement regime in Alcator C pellet fueled discharges, is the dramatic peaking of the soft x-ray profiles. Figure 1 shows the amplitude and width of the x-ray emission profile vs time, where a single hydrogen pellet has been injected at 0.345 seconds. This behavior is due to the accumulation of both low and high Z impurities and correlates well with the improvement in ion energy and bulk particle confinement. The accumulation of carbon and molybdenum, the dominant plasma impurities, can be well modelled by neoclassical theory [1,6]. The impurity profiles are deduced from spectral analysis of soft x-ray emissions. Figure 2a. shows the evolution of the carbon profile after injection of a pellet. Analysis of these profiles during the accumulating phase of the discharge indicates that the diffusion coefficient and inward convective velocity for carbon are about 300 cm²/sec and 1000 cm/sec respectively. These observations are generally confirmed by measuring the confinement of injected impurities during the "steady state"
Soft x-ray profile width vs time after a pellet, which has been injected at .345 sec.

Soft x-ray amplitude vs time for same shot.

Results of simulation of impurity and plasma current diffusion. a. shows the evolution of the carbon density profile, b. Zeff profiles, c. current density profiles, d. q profiles.

part of the discharge (after .4 sec in figure 1). The confinement of high Z, non-intrinsic, non-recycling impurities is seen to increase by more than an order of magnitude following injection. This increase is not quantitatively consistent with the transport coefficients calculated during the transient phase and indicates some residual anomaly. Accumulation of impurities has been seen to be a general feature of pellet injection experiments [7,8,9] and for other improved confinement regimes as well [10].
MHD Behavior

Another regular feature of the improved confinement regime can also be seen in figure 1. The periodic fluctuations in the x-ray width before the pellet injection are ordinary sawtooth oscillations. After injection the sawtooth period increases, their amplitude diminishes and eventually they disappear entirely usually within 30 - 50 msec after injection. The suppression of sawteeth is essential if good confinement is to be maintained. Each sawtooth crash partially flattens the density profile and discharges in which they are not completely eliminated, will eventually revert to the normal saturated ohmic confinement mode.

With the suppression of the sawteeth often comes a different MHD phenomenon, large amplitude m = 1, n = 1 oscillations which can be seen in figure 3 and 4 [11]. These oscillations are non-rotating, suggesting the rapid and repetitive growth of an m = 1 mode.

![Figure 3](image1.png)

**FIG.3.**
Detail of m = 1, n = 1 oscillation.

![Figure 4](image2.png)

**FIG.4.**
Tomographic reconstruction of one oscillation cycle.
rather than the rotation of a steady state island. As can be seen in figure 1, the appearance of this mode was often correlated with an abrupt halt to the impurity accumulation. These data and the observations of impurity injection suggest that the mode is correlated with and may be responsible for some residual anomalous transport, perhaps through a change in the radial electric field.

Evolution of the Current Profiles

Even in the absence of significant radiation, the accumulation of low Z impurities can have a profound effect on the plasma. Figure 2 b shows the evolution of the Zeff profile that is implied by measured carbon densities. The effect on the plasma current profile can be seen by considering the equation for the evolution of the poloidal field,

$$
\frac{\partial r B_p}{\partial t} = \frac{e^2}{4\pi \sigma} \left[ -\frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial r B_p}{\partial r} \right) + \left( \frac{3}{2} \frac{1}{T} \frac{\partial T}{\partial r} - \frac{1}{Z} \frac{\partial Z}{\partial r} \right) \frac{\partial r B_p}{\partial r} \right]
$$

where we have used Spitzer conductivity $\sim T^{3/2}/Z_{eff}$. The first term is diffusive and tends to flatten the current profile. The second and third terms are convective and lead to growth or damping depending on their relative sizes. Ordinarily, the term proportional to temperature gradient will dominate and give rise to the thermal instability which drives the sawteeth. However, after injection, with impurity densities becoming strongly peaked, the third term can dominate, flatten the current profile, raise $q(0)$, and suppress the sawteeth. The results of a simulation of the field diffusion are shown in figures 2c and 2d. In this simulation, density and temperature profiles are taken from the experiment; the transport coefficients are adjusted to give impurity profile evolution which is consistent with measurements. The poloidal field diffuses classically. The current profile begins to flatten immediately, eventually becoming hollow. The $q$ profile also flattens with $q(0)$ rising from its assumed initial value of .9 to 1.0 in about .025 seconds. This is consistent with the observations of sawtooth suppression.

Connection to Theories of the Sawtooth Crash

There are several questions about these observations that we would like to answer. The model we have proposed for sawtooth suppression suggests that the $q = 1$ surface has been eliminated from the plasma. This seems at odds with the presence of the strong $m = 1, n = 1$ oscillations. Second, we would like to understand this behavior in the context of recent work which attributes the sawtooth crash to an ideal $m = 1$ "quasi-interchange" mode. This mode is driven by the pressure gradient and is unstable in the presence of very low shear [5,12]. The low shear has two effects; the mode is destabilized even at very low beta and its radial eigenmode is transformed from a rigid shift of the plasma core into a convective cell which brings a cold plasma "bubble" into the plasma center.
The reconstruction of our x-ray profiles yields a mode structure which is very similar to those seen on JET during the sawtooth crash JET [13]. The principle difference between those observations and our own are in the amplitude and radial extent of the perturbation. The interchange that is associated with the sawtooth crash is seen to extend over the entire core of the plasma, while the oscillations that we are considering here are smaller in amplitude and are limited in radial extent. Figures 5a-c show the structure of the interchange mode for several classes of q profile. The perturbation can have a non-zero derivative only near the q = 1 surface. Sawteeth have been attributed to the profiles and eigenmode of figure 5a and 5b. The first corresponds to the rigid shift of the Kadomtsev sawtooth model and the second to the model of Wesson and his co-workers. We speculate that the m = 1 mode that we have seen following pellet injection is due to the eigenmode of figure 5c. As we have seen in our modelling, the actual q profiles, as they evolve under the influence of accumulating impurities can look very much like they do in this figure. There is ample drive for the instability, as a result of the improved energy confinement the plasma $\beta_p$ can increase by a factor of 2 to 3 reaching $\beta_p \sim 1$ by the time the mode is seen.

Finally we would like to understand the repetitive nature of the oscillation. The tomographic reconstructions show it growing and decaying about once per msec. The oscillations do not cause measurable changes in temperature or density profiles nor do they seem to alter profiles in any way that would cause them to rapidly damp out. In contrast, the sawtooth crash even if due to an ideal mode must be accompanied by substantial dissipation. The crash modifies plasma profiles sufficiently to stabilize the interchange mode. This does not seem to occur in our case. The difference may lie in the non-linear behavior of the sawtooth interchange. Perhaps the smaller oscillations that we observe are almost completely reversible. Computer simulations for JET have also shown the mode to oscillate [14]. It is however often (although not universally) observed that the mode is correlated with the saturation of impurity accumulation and this suggests some small

FIG.5.
Three trial q profiles and the unstable eigenmode for each.
dissipation in the mode. Still, it cannot be ruled out that the observed MHD modes are parasitic and that an underlying and so far invisible phenomenon is responsible for the residual anomaly in impurity confinement.

Summary

The accumulation of low Z impurities is seen to accompany the improved confinement regime following pellet injection. This can, in turn, flatten the current density profile by peaking the resistivity profile. MHD activity, which is very sensitive to the q profile is altered as the sawteeth are suppressed and are replaced by non-rotating m = 1, n = 1 oscillation. Both may be manifestations of the the same ideal mode, differing primarily in amplitude and radial extent. This difference can be understood in terms of the evolution of the current profile under the influence of the accumulating impurities. The oscillations may be responsible for some residual anomalous transport which limits further accumulation of impurities.

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IMPURITY ACCUMULATION STUDIES IN PELLET-REFUELED ASDEX DISCHARGES

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Abstract

Pellet injection into ASDEX discharges allows considerable improvement of the confinement properties. Simultaneously with this improvement a strong accumulation of metallic impurities is observed, which leads to intolerable cooling of the plasma core region. We discuss the experimental phenomena and the underlying transport changes associated with the accumulation.

INTRODUCTION

Repetitive injection of pellets has been successfully applied in ASDEX to improve substantially the energy confinement in ohmically and NI-heated plasmas /1/. A characteristic feature of the high confinement phase is the pronounced peaking of the electron density profile. Similar steep profiles have also been found under the improved conditions of ohmic confinement (IOC) and counter injection heating /2/. It is therefore reasonable to assume that the underlying physical mechanism which causes the change in transport is the same in all three cases. This is to be distinguished from the H-mode, where the improvement of energy confinement is mainly a result of broadening of the density profile. In the so-called quiescent H-mode (without ELMs) with excellent energy confinement we noticed for the first time distinct coupling between energy and particle confinement /3/. Such a correlation that links the transport properties of energy, background plasma particles, impurities, and - as seen more recently - also angular momentum /2/ seems to be a rather fundamental relation: it pertains in all four regimes mentioned above.

The detrimental consequences of this coupling relation with respect to density control and impurity accumulation has already been discussed in /4/. A matter of the utmost concern is the accumulation of metals because of the large central radiation losses that are easily produced. In the case of the quiescent H-phase, concentrations of about 1% Fe could build up within ~0.1 s owing to the enhancement of the global impurity confinement in connection with relatively large Fe influxes from the boundary region /5/. The situation for the three other regimes with peaked density profiles seems even more aggravated because of strongly increased neoclassical inward fluxes as a consequence of the steep pressure gradients in the inner plasma region. For this reason the suppression of the Fe fluxes by means of carbonization is a necessary prerequisite for successful operation. Nevertheless, the residual fluxes of copper from the divertor target plates can lead to severe radiation problems. In this respect the pellet discharges with extreme peaking \( n_e(0) \approx 2.0 \) and very high axial densities \( n_e(0) = 1.4 \cdot 10^{14} \text{ cm}\(^{-3}\) \) are most delicate. In the following we give some detailed information on experimental observations made in such discharges. Furthermore, the background and results of transport simulation directed at a conclusive description of the accumulation processes are outlined.
Impurity accumulation is observed for pellet injection into pure ohmic discharges and with moderate additional NI heating ($P_{NI} < 1.3$ MW). Here we will concentrate on a well-analysed discharge where 0.5 MW co-NI ($D^0 \to D^+$) was applied. This relatively small neutral injection power was added mainly for the purpose of CXR spectroscopy of light impurities ($P_{OH} = 0.4$ MW). The resulting small rotation velocity of $v_\phi(o) < 0.5 \cdot 10^5$ m/s is believed to be insignificant with regard to accumulation.

The measured line-averaged and axial densities $\bar{n}_e$ and $n_e(o)$ as well as the central radiation $P_{rad}(o)$ and the soft X-ray emission along a central chord (SX) are shown in Fig. 1 as functions of time. The central radiation is seen to rise drastically about 100 ms after the injection of the last pellet. Simultaneously, the electron density profile starts peaking and the sawtooth activity disappears. After about 200 ms central radiation losses of 0.3 W/cm$^3$ are reached, this being already larger than the input power density of $P_{IN}(o) = P_{OH}(o) = 0.2$ W/cm$^3$. The radiation profiles as determined from bolometer and SX-array measurements strongly peak on axis for $t \geq 1.3$ s.

VUV spectra (100-320 A) taken at time intervals of 20 ms show line emission of only three elements: C, O and Cu. During the accumulation phase the spectra change only in the lower wavelength range $\lambda \leq 130$ A, where some so far unidentified strong lines (132.85 A, 110.4 A), and numerous weak ones appear. In particular, the intensity of CVI and CIV lines, which are indicative of the influx of light impurities, stay nearly constant. For the discharge considered, where the $T_e$ changes are marginal, no significant changes in the prominent line emission of CuXVIII (235 A) and CuXIX (274, 304 A) are observed either. However, these lines from Mg- and Na-like ions are also emitted relatively far out ($r/a = 0.75$) and are thus again more representative of the Cu influx than its central concentration. In the core region Cu is predicted to be in the O to Ne-like states, comprising a complex and not well-known line pattern in the range 10 - 100 A which is not accessible to survey spectroscopy in ASDEX.
For the above reasons the Cu density on axis must be determined from bolometer measurement via \( P_{\text{rad}} = n_{\text{Cu}} \cdot n_{e} L_{\text{Cu}} \), with the radiation rate coefficient \( L_{\text{Cu}}(T_{e}) \) being obtained from code calculations. In a similar way the soft X-ray emission density \( \varepsilon_{\text{SX}} \) can be treated by applying the proper Be-filter absorption function in the code calculations. From \( P_{\text{rad}}(0) = 0.3 \ W/cm^3 \), measured at \( t = 1.4 \ s \), we deduce a Cu concentration of \( 8.5 \cdot 10^{-4} \) for the core region. This Cu density is fairly consistent with calculated \( (0.10 \ W/cm^3) \) and measured \( (0.13 \ W/cm^3) \) values of \( \varepsilon_{\text{SX}} \). The contribution of \( 0.08\% \) Cu to \( Z_{\text{eff}} \) amounts to 0.3. Corrections arising from C and O bremsstrahlung are of the order of 10\% and are thus small in comparison with the uncertainty in the calculation of \( L_{\text{Cu}} \), which is certainly in the range of \( \pm 30\% \).

Information on the important question whether light impurities also accumulate is obtained from 16-channel \( Z_{\text{eff}} \) bremsstrahlung measurements /6/. Radial \( Z_{\text{eff}} \) profiles determined from these measurements are shown in Fig. 2a for the ohmic phase and in Fig. 2b for the fully developed accumulation period. The bolometrically determined profiles of \( P_{\text{rad}} \) and reduced radiation profiles \( P_{\text{rad}}/n_{e} \) are also plotted for the purpose of demonstrating the accumulation. The quantity \((Z_{\text{eff}} - 1)\), which is representative of the \((C + O)\) concentration is seen to increase only moderately from 0.4 to 0.6 at half minor radius. Even for the plasma centre the changes are not pronounced: subtracting the Cu contribution of 0.3, we notice growth from 0.6 to 1.1 for \((Z_{\text{eff}} - 1)\). The resulting concentrations during the accumulation phase amount to 2\% carbon and 0.8\% oxygen if we assume a ratio of the elements as measured in the boundary region.

**Fig. 2** Profiles of \( Z_{\text{eff}} \) determined from bremsstrahlung measurement, \( P_{\text{rad}} \) and reduced radiation density \( P_{\text{rad}}/n_{e} \) for the ohmic phase (2a) and the impurity accumulation phase (2b).

**IMPURITY TRANSPORT ANALYSIS**

As outlined in /4/, we tentatively describe the transport of impurities by adding collisional (classical + neoclassical) and anomalous fluxes. For the latter we allow only a diffusive part \( \Gamma_{\text{an}} = D_{\text{an}} \delta_{n} r/2r \) since additional anomalous inward drifts of the order of \( v_{\text{an}} = D_{\text{an}} r/2a^2 \) would yield already appreciably peaked impurity profiles under low confinement conditions, which are not observed in the experiments. On the other hand, anomalous
convective terms have to be postulated for the background plasma. These can be understood in terms of favourable phase relations between density perturbations and poloidal electric field fluctuations. However, such a phase relation can be different or absent (as is assumed here) for the impurities because of marked up-down asymmetries or other reasons.

The collisional transport is based on the formulation worked out by Hirshmann and Sigmar /7/ and is used in the specialized form presented in /8/ and /4/. The neoclassical banana-plateau fluxes taken therein apply particularly for the case that both impurities and background ions are in the plateau regime. To demonstrate that this assumption is justified, we have plotted the collisionalities for carbon-carbon (\(v_{cc}^*\)) and deuteron-deuteron (\(v_{dd}^*\)) in Fig. 3 versus radius for the discharge under discussion at \(t = 1.4\) s. The background ions are seen to be in the plateau regime in the core and boundary regions and are in the collisionless banana regime around half minor radius. In this middle zone our treatment is not strictly applicable. However, the corrections to be made are small and result primarily in a minor reduction of the temperature gradient term. Because of the scaling \(v_{zz}^* = v_{dd}^* \cdot Z^2 n_2 / n_1\) for the self-collisionality, metals (Cu) with \(Z = 20\) but with concentrations as low as \(10^{-4}\) are generally found in the plateau regime, too. These considerations apply particularly to the important BP fluxes driven by the self-viscosity of the various ions. A complete theory, which would also have to take into account the mixed viscosity terms, is still missing. A correct treatment of the multi-impurity case is therefore not possible at present. Consequently, any C-Cu interaction has been omitted in our calculations, which, in any case, are a reasonable approximation as long as the collision strength \(\alpha = Z^2 n_2 / n_1 = Z_{\text{eff}}^{-1}\) for carbon is less than unity. Finally, we show in Figs. 4a and 4b the various collisional contributions to the diffusion coefficient and drift velocity for carbon as a function of the radius.

![Fig. 3](image)

Collisionality of deuterons (\(v_{dd}^*\)) and carbon impurity ions (\(v_{zz}^*\)) as a function of radius. The banana plateau limit \(v^* = 1\) and the Pfirsch-Schluter limit \(v^* = (R_0/r)^{3/2}\) are also plotted.
To compare experiment and theory, further assumptions must be made which have a more or less sensitive influence on the results assumed:

1. Constant influxes from the boundary.
2. Reduction of $D_{an}$ takes place at time $t = t_0 = 1.2$ s when the sawteeth disappear.
3. The reduction occurs only within the inner zone $r \leq 0.75 a$.
4. Within this zone the residual anomalous diffusion coefficient is kept constant at a level of $D_{an} = 0.05 \text{ m}^2/\text{s}$, as is measured for the central diffusion coefficient of the background plasma /1/.

Whereas assumptions 1 to 3 are relatively uncritical, the residual value of $D_{an}$ must of course be chosen small enough in comparison with $D_{coll} = 0.1 \text{ m}^2/\text{s}$ to obtain sufficient impurity peaking. The influence of this parameter is demonstrated in Fig. 5 where the measured SX profile at $t = 1.4$ s is...
compared with Cu simulations. As seen from the figure, the narrowness of the measured profile postulates a reduction of $D_{an}$ from 0.8 m$^2$/s down to <0.1 m$^2$/s. The above model can also fairly describe the temporal evolution of the SX traces. In comparison with this good consistency found for Cu, the situation is less satisfying for carbon since so far no reliable CXRS measurements could be obtained. The comparison can only be made via $Z_{eff}$ as it is shown in Fig. 6 for three different times during the accumulation period. In these calculations oxygen is not distinguished from carbon. We notice that apart from the region $r > a/2$, where the measured profiles tend to increase again, the agreement between experiment and calculation is fairly good.

**Fig. 6** Comparison of measured (***), and calculated $Z_{eff}$ profiles at three different times during the accumulation phase. In the calculation only contributions from carbon are taken into account.

**DISCUSSION**

In pellet-refuelled discharges considerable improvement of the energy confinement can be achieved. The effect is correlated with a marked peaking of the plasma density. Concomitant with this improvement, a highly unfavourable accumulation of metallic impurities in the plasma centre is observed. Light impurities such as carbon and oxygen also show the tendency to accumulate, but without critical consequences for the plasma performance and with still tolerable dilution effects of less than 20%.

Our simulation calculations corroborate the basic concept according to which the accumulation process results from a reduction of the anomalous diffusive terms (assumed to be associated with turbulence), which normally compensate for the large neoclassical inward drifts of the impurities. In addition, the effect is significantly amplified by the large central pressure gradients occurring in these discharges. Applying this model, we obtain a satisfying description for copper, whereas for carbon the agreement is not as convincing. There are still several parameters undefined in such simulations, which can change the outcome to a certain extent. Thus, the residual value of the anomalous diffusion coefficient can be chosen within a range of zero to about 0.1 m$^2$/s. Furthermore, the extent of the radial zone where the reduction takes place is rather uncertain. In fact, the
accumulation would still be dangerous if this region of improved confinement is only about 1/3 of the cross-section. In this case a marginal improvement of the global energy confinement is to be paid for with grave radiation loss problems induced by accumulation in the core zone. Two ways of overcoming this shortcoming are conceivable. Firstly, a reduction of all metals to concentrations of ≤ 10^{-5} under normal confinement conditions would presumably suffice and seem to be attainable in a fully carbonized machine. Secondly, any method that allows continuation of the sawtooth activity might help as well. As discussed in /4,9/, sawteeth are found to have a cleaning effect in the central region and their disappearance is probably caused by the decreasing conductivity during the accumulation phase. This lowering of the conductivity is in turn produced by increased impurity fluxes into the central regions that tend to raise \( Z_{eff} \) and, in addition, cool the plasma. If cooling is dominant for the reduction of conductivity, HF heating in the core region should help to overcome the problems.

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IMPURITY ACCUMULATION AFTER
PELLET INJECTION IN JET

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Abstract

Centrally peaked electron density profiles lasting for several seconds are obtained by injection of one to several pellets into JET OH discharges. Subsequent ICRH and neutral beam heating result in high electron and ion temperatures on axis and narrow temperature profiles. Sawteeth are suppressed and only observed after final profile flattening. During post-pellet phases with and without additional heating, impurities accumulate on axis, as demonstrated by VUV and charge-exchange spectroscopy, as well as bolometer and soft X-ray radiation. Both light and medium-Z impurities develop profiles narrower than $n_e$ in the plasma core region. The outer plasma zones continue to be dominated by anomalous transport. Impurity behaviour is well described by model calculations based on neoclassical transport, assuming reduced anomalous diffusion in the plasma interior. During additional heating, the existence of grad $T_e$ driving forces is confirmed by the experiment. The zone with reduced transport appears to extend to half minor radius initially, and to shrink later, leading to a reduction and the eventual disappearance of $n_e$ peaking and accumulation.

1. INTRODUCTION

In magnetically confined plasmas, impurity accumulation is to be expected from the very nature of electrical forces, resulting in impurity ion profiles, $n_i(r)$, much more strongly peaked on axis than the plasma deuterons, because of their higher charge Z. Only moderately peaked $n_i$ profiles are usually observed in tokamaks, probably because of overlaid anomalous diffusion leading to a reduction of density gradients. Impurity accumulation has been observed occasionally, particularly in high energy confinement regimes like H-mode or after pellet injection/1-4/. It appears to be correlated with peaked electron density profiles and the absence of sawtooth oscillations. High Z impurity accumulation tends to lead to high radiation losses from the plasma centre and to a temperature collapse.

Pellet injection into JET plasmas has often resulted in peaked electron density profiles lasting for several seconds even if ion cyclotron heating (ICRH) or neutral beams (NB) were applied (see/5,6/ for an overview of JET pellet results). Under these circumstances, clear evidence of impurity accumulation has been obtained, which is based on the central peaking of soft X-ray (SX) and bolometer profiles, on the results of charge-exchange recombination spectroscopy (CXRS) and on the steep increase of radiation from high ionisation stages of metals as compared to a rather constant radiation from low ionisation stages at the plasma periphery.

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Because of the high electron temperatures and low metal concentrations, impurity accumulation has never led to a radiation collapse of JET plasmas, instead, accumulation signatures were observed to disappear again after a few seconds. Respective experimental results will be presented below, with particular emphasis on the similar behaviour of light and medium-Z impurities, and on the influence of sawteeth. Subsequently, neoclassical impurity transport calculations will be applied to the JET cases and compared with the experimental data.

2. EXPERIMENTAL RESULTS

In JET discharges with ohmic heating (OH), strongly peaked electron density profiles were obtained by injection of several 4 mm diam. pellets eventually penetrating to the magnetic axis of the plasma/5/. An example is given in Fig. 1, where the second pellet led to strong ne peaking lasting for several seconds, as shown by the top traces of ne(0) and ne(3/4 a) taken from Abel-inverted interferometer profiles (a = minor radius). The onset of sawteeth was delayed until after the third pellet at t = 9.5 s. The electron temperature on axis, Te(0) (from electron cyclotron emission), dropped from ~ 2.7 keV to ~ 0.7 keV and recovered only slowly to its previous value. Te profiles were fairly flat during the early phases of this recovery and peaked up later to their usual shape.

![Fig. 1: Plasma parameters and spectroscopic signals after pellet injection into JET OH plasmas.](image)

During the slow decay of the ne profile after the second pellet, a strongly peaked nickel ion density profile developed, as demonstrated in Fig.1 by the line intensities of Ni XI, Ni XXIV and Ni XXVI. Ni XI is always at the plasma periphery, while Ni XXIV is representative of the plasma centre below ~ 1.4 keV and Ni XXVI below ~ 2.5 keV. From a comparison of line ratios at 8 s and at 5 s, where Te(0) is very similar, it is obvious that the Ni XXVI radiation has increased relatively to Ni XI by much more than the respective electron densities, i.e. ~ factor 20. The emission lines of O VIII and O VII in Fig.1 also suggest a peaking of the oxygen density profile, but this is no conclusive evidence, since O VIII will not be very deep in the plasma interior. The light impurity behaviour
can rather be derived from SX profiles, because, as demonstrated by pulse-height analysis and other spectroscopic results, metal contributions to the SX radiation are very small, and it essentially reflects carbon and oxygen bremsstrahlung (energy cut-off = 2 keV). In the pulse of Fig.1, the SX profiles shrunk to a narrow 40 cm full half width within = 1 s after the second pellet, and the radiation on axis increased to = 10 times the pre-pellet value of 0.9 kW/m³. These profiles are considerably narrower than n_e in the core region. After maximum emission at about 8 s, the SX intensity decreased (see Fig.3), while the narrow profile was still maintained until = 9 s, when the profile rapidly flattened accompanied by strong MHD activity but no sawteeth. During the accumulation phase, the bolometer profiles developed a narrow peaked core resembling the SX emission, but with = 45 kW/m³ maximum radiation in addition to the usual edge shells (= 15 kW/m³). It is worth noting that these edge shells, as well as spectroscopic carbon and oxygen signals, show that the influx of carbon and oxygen was essentially constant during the whole period.

ICRH was applied to a pulse similar to that in Fig.1. It was ramped up to = 3 MW within 1.5 s, starting at the time of the second pellet injection, and led to T_e(0) = 4 keV. In that case, the initial impurity behaviour was very similar to the one just described except that the rate of rise of all signals was steeper by a factor 2. However, after about 1.5 s the n_e profile reverted to its normal, flat shape and, simultaneously, impurity accumulation disappeared. About 100 ms later the usual large-amplitude sawteeth were observed on the electron temperature.

4 mm pellets were also injected during the ohmic current ramp phase of JET pulses, and the plasmas were subsequently heated by ICRH or a combination of NB and ICRH. In these cases, electron density profiles were very peaked initially, but decayed at a much faster rate than in OH

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**Fig. 2:** Plasma parameters and impurity radiation during additional heating of pellets.

**Fig. 3:** Measured and calculated impurity radiation as a function of time for the pulse in Fig. 1.
plasmas, as shown by the $n_e$ traces in Fig.2. Electron temperatures on axis increased from a few 100 eV to over 10 keV with ion temperatures following closely, and both $T_e$ and $T_i$ profiles became very peaked on axis/5/. This phase often ended abruptly in a crash of $T_e(0)$ and $n_e(0)$ caused by strong $m=3$, $n=2$ MHD activity /5/. Due to the large $T_e$ excursions, it is more difficult here to analyse the metal impurity behaviour from spectral line emission. Fig.2 shows time traces of Ni XXVII, close to the plasma centre (excitation energy 7.8 keV), as well as Ni XXV and Ni XVIII line radiation, the latter being representative for the outer plasma regions at the high temperatures. By correcting for the temperature dependence and, in particular, by investigating the temperature crash, it is concluded that the radial ion density profile must be strongly peaked also in this case.

Information on the light impurity behaviour can again be obtained from SX radiation, line integrals of which are also plotted in Fig.2. The intensity of the Ni K-α line shows that metals contribute less than 10% to the integral SX emission (due to narrower profiles they actually contribute = 20% on axis). SX profiles again became very narrow within about 0.5 s and their peak emission increased by = factor 40 to about 20 kW/m², only partly due to the higher $T_e(0)$. An example of these profiles will be shown later in Fig.4. The SX profiles remained peaked and their intensity was rather constant for = 1 s up to the crash in $T_e$ and $n_e$. Bolometer profiles showed values of radiated power on axis similar to the SX emission and, in addition, edge shells of comparable magnitude. CXRS measurements of the carbon density, $n_c$, showed a peaked $n_c$ profile during the post-pellet phase similar in width to the SX profiles, but on a pedestal roughly half the centre value. The carbon concentration on axis was = 5%. At the crash, $n_c$ flattened and the centre value reduced by = factor 2.

During the later phases of pulses with additional heating, both $n_e$ and impurity profiles were commonly observed to peak up again to some extent, a behaviour, which can be seen in Fig.2 at $t = 6.5$ s, but which was often more pronounced. This second period of modified transport terminated with some MHD activity and was usually followed by the onset of sawteeth.

3. CODE SIMULATIONS

The observed time traces of impurity radiation and the SX profiles have been modelled using the impurity transport code STRAHL/7/ and neo-classical transport coefficients. The calculations are based on the assumption that neoclassical transport is always present, but is usually masked by a strong anomalous diffusion coefficient $D = 1$ m²/s. It has been
verified that this does not lead to discrepancies in former JET results, particularly during so-called monster sawteeth/8/, where strong grad $T_i$ driving forces are expected (see below). It is assumed that $D$ drops to a small value in the plasma core region during the post-pellet phases with peaked $n_e$ profiles, while the outer plasma zones continue to be dominated by anomalous transport. The latter conclusion is supported by the following observations: i) continuing impurity influxes result in the usual edge radiation and no impurity build-up is observed, ii) the lower nickel ionisation stages and carbon CXRS measurements indicate flat impurity profiles outside the core region, and iii) the electron density profiles also consist of a peaked core region and a flat outer part, which can be modelled on the same transport assumption/5/. The region of reduced transport roughly extends to $a/2$, but it probably varies and shrinks as a function of time in the JET pulses considered, leading to a decrease and the eventual disappearance of peaked $n_e$ profiles and impurity accumulation. In the modelling, $D$ was reduced linearly from 1 m$^2$/s to 0.001 m$^2$/s over a 10 cm radius interval centred at half minor radius or further-in.

Neoclassical transport coefficients have been used for impurities in the Pfirsch-Schlüter (PS) or plateau regimes, and for plasma ions in the plateau or banana regimes, depending on collisionality. They are based on results by Hirshman and Sigmar/9/, and have been evaluated for the actual conditions by Fussmann et al./2/. In the PS regime, which applies to higher Z impurities near the plasma periphery, temperature screening is predicted, which, however, could not be investigated due to the anomalous plasma behaviour in this region. In the plasma interior, all impurity ions are in the plateau regime and plasma ions are in the plateau or banana regimes. In these cases ion temperature gradients are expected to lead to strong or moderate inward driving forces even in the absence of deuteron density gradients.

Two impurity species have been used in the simulations, namely, carbon as the typical light impurity (carbon/oxygen ratio = 3-1) and nickel as the main metal impurity. Metal concentrations were always low in the cases concerned ($n_{Ni}/n_e = 1 - 3.10^{-4}$), contributing little to the total SX radiation and even less to $Z_{eff}$. The friction between the two impurities has been taken into account in an iterative way by prescribing a nickel density profile for the carbon transport calculation and vice versa. The plasma deuteron density has been calculated from the measured $n_e$ profiles using quasi-neutrality. Typical neoclassical diffusion coefficients and drift velocities near the plasma centre are 0.1-0.5 m$^2$/s and 1-4 m/s for fully stripped carbon in OH and heated cases, respectively; 0.05-0.1 m$^2$/s and 1-2 m/s result for He-like nickel.

The calculations predict a rearrangement of the plasma impurity content within one to many seconds, depending on plasma parameters and size of the low diffusivity zone. The subsequent behaviour is determined by the respective impurity influxes, which have been modelled as to reproduce the observed intensities of low ionisation stages (Ni XI, Ni XVIII and C VI). Their influence is small on the relevant time scales of OH plasmas; during additional heating, impurity densities on axis are expected to be rather constant after ~1 s reflecting the constant influxes. For actual JET simulations, the time period of interest has been subdivided into typically seven intervals, during which the plasma parameters were assumed to be constant and equal to the measured profiles at the end of the respective intervals. $T_i$ profiles were assumed to be proportional to $T_e$ with slightly lower axis values.

In Fig. 3, calculated results are compared with measured plasma radiation during the post-pellet phase of the JET OH pulse in Fig. 1. $D$ was assumed to be very small in the plasma core region within $r = a/2$ after pellet injection at 5.5 s, and this zone was gradually reduced to $r = a/4$...
at 9 s. Thus, the time evolution of the line-integral SX radiation is very well reproduced by carbon continuum radiation and plasma bremsstrahlung, as demonstrated in Fig.3. The calculated SX profiles also agree very well with the measurements, in particular, the intensity decrease between 8 and 9 s with roughly constant profile width confirms the model of a shrinking confinement region rather than increased diffusivity in the plasma core. A combination of $n_e/n_\Omega = 5\%$ and $n_\Omega/n_e = 2\%$ is required to explain the absolute radiation levels. The calculated time evolution of the Ni ionisation stages Ni XXIV and Ni XXVI is in fair agreement with the experimental results. Ni XXVI is in fact expected to increase more steeply and Ni XXIV to decrease earlier than observed. This could be due to an overestimate of the relevant electron temperatures or to other problems in the nickel ionisation balance. On the other hand, the simulations may predict too fast a shrinking of the nickel ion profiles reflected in these lines. The maximum intensity during accumulation is well reproduced.

Simulations of plasmas with additional heating resulted in equally good agreement of measured and calculated SX profiles and in an even better description of the nickel line intensities, now relying more on the He-like Ni XXVII. It is particularly interesting that the calculations predict accumulation to persist throughout the heated phase of those pulses, even though electron density profiles were almost flat. This is due to the theoretical grad $T_i$ drift velocity resulting from the peaked $T_i$ profiles. The observation of peaked SX profiles during the later phases of heated plasmas may therefore be considered experimental proof of these driving terms. As demonstrated in Fig.4, the SX profiles in this pulse with ICRH and NB heating are well described by neoclassical calculations including grad $T_i$ terms, while they would be predicted much wider without.

4. SUMMARY

After pellet injection into JET plasmas with and without additional heating, impurities have been observed to accumulate on axis whenever $n_e$ was peaked for a time period of 1 s or more. Both light and medium-Z impurities develop a density profile more centrally peaked than $n_e$, as expected from neoclassical theory in the absence of anomalous diffusion. Anomalous transport continues to dominate the outer plasma regions, leading to a flat pedestal outside the core region and the usual edge radiation. The region with reduced diffusivity appears to extend roughly to $r = a/2$, but it varies with plasma conditions and shrinks as a function of time, reducing the central impurity density and radiation peak. Accumulation eventually disappears completely, but some peaking-up of $n_e$ and impurity densities is observed in many pulses after additional heating. Sawteeth are only observed after the final flattening of all density profiles.

The impurity behaviour has been modelled using neoclassical transport and overlaid anomalous diffusion ($D = 1 \text{ m}^2/\text{s}$). During the post-pellet phases with accumulation, $D$ has been reduced to 0.001 m$^2$/s in the plasma core region which has been assumed to extend to $r = a/2$ initially, and to shrink eventually to $r = 0$. Results of these calculations are in good agreement with measured SX profiles and impurity line radiation. In particular, SX profiles during additional heating are well explained by the predicted inward drift due to ion temperature gradients.

ACKNOWLEDGEMENTS

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EVIDENCE FOR LIGHT IMPURITY PEAKING
AFTER PELLET INJECTION ON TEXT

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Abstract

Light impurity density profiles following hydrogen pellet fueling have
been obtained via charge exchange recombination spectroscopy on TEXT.
C⁺⁶ and O⁺⁸ peak much more strongly on axis than the electron density
following hydrogen pellet fueling, in contrast to gas puff fueled discharges.
The peaked pellet impurity profile shapes are described by neoclassical theory
while measured transport coefficients are larger than neoclassical values.

I. INTRODUCTION

Pellet fueling of tokamaks has been accompanied by an increase in particle
confinement and a peaking of the electron density profile[1]. An accumulation of
impurities in the center of the plasma was found by Petrasso, et al [2] using broad
band X-ray emissions. They found evidence for impurity peaking for both heavy
and light impurities, and the data is suggestive that the transport of both is
neoclassical. Such impurity behavior has severe implications for fusion reactors;
builtup of light impurities or helium ash could have disastrous consequences for
plasma confinement, leading to depletion of the working ions from the hot core,
high radiation levels, and subsequent disruptions. The measurements presented
here provide the first spectroscopic evidence of fully stripped, low-Z impurities
peaking on axis following pellet injection.

II. RESULTS

The experiments were carried out on the TEXT tokamak [3] which has a major
radius of 1.0 m, 0.26 m minor radius and a full poloidal TiC-coated graphite limiter.
For these studies, the operating parameters were a B₀ = 2.8 T, I₀ =250 kA , an
initial line averaged density of 3 x 10¹⁹ m⁻³ and fueling with two hydrogen pellets
[radius 1 mm] fired one ms apart at t=300 ms. Line averaged density at the time of
measurements was typically 6 x 10¹⁹ m⁻³. The electron density profile was
measured using a nine channel interferometer that could be scanned from shot to
shot. For comparison purposes, we will also present results from a sawtoothing

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gas puff fueled discharge which starts from the same initial conditions and rises to a final density of $5 \times 10^{19} \text{m}^{-3}$, near the density limit. In figure 1 we show the central soft x-ray signal for a pellet fueled discharge and the comparison gas fueled discharge. The exact nature of the soft X ray signal following the pellet injection is somewhat unpredictable; a wandering of the x-ray signal is often accompanied by minor disruptions.

![Figure 1. Central soft x-ray signals from (a) pellet fueled discharge, and (b) gas puff fueled discharge.](image)

Charge exchange recombination spectroscopy (CXRS) provides a powerful means for measuring local fully stripped low-Z impurity concentrations across the entire plasma cross section and hence their transport properties [4,5]. Uncertainties in electron density profile shape and electron temperature profile shape and amplitude introduce little error in impurity density profile measurements. There is no uncertainty of the Z of the impurity in question. Profiles were measured using a hydrogen diagnostic neutral beam injected vertically into TEXT with an injection energy in the range of 30-45 keV and an ion extraction current of 3-5 A and a vacuum ultraviolet monochromater, the Texas SIDS (Spatial Imaging Detector System) [6]. The SIDS simultaneously views 20 chords in a vertical plane, allowing for measurements of impurity concentrations over half of the plasma cross section on a single shot. The monochromater is mounted to view the entire width of the DNB (FWHM = 50 mm) with a radial spatial resolution of approximately 15 mm. Complications of multigenerational halos are minimized in this geometry. CXRS signal levels are proportional to beam density and impurity concentration $n_z$; thus, beam attenuation must be modeled to obtain $n_z(r)$. We used the attenuation code BMDEP [7], augmented by a multistep ionization process mean free path treatment [8]. This treatment takes into account ionization from excited states of neutral hydrogen.

The C$^+$ profiles were obtained by observing the 521Å $n=4-3$ line of C$^+$ following charge exchange with beam neutrals, while O$^+$ profiles were obtained by viewing the $n=6-5$ line at 1165Å of O$^+$. We ignored any mixing of high lying l levels. Emission cross sections were derived from published n, l level cross sections [9,10] and the Monte Carlo treatment of Olson [11]. Errors in the atomic physics of charge exchange directly affect inferred absolute densities of measured impurities, but have little effect on profile shapes. Typical CXRS profile measurements of C$^+$ and O$^+$ are shown in figure 2 for the gas-puff fueled and the pellet fueled case. Profiles are taken during pellet fueling by integrating the
CXRS signals from 60 to 80 ms after pellet injection. CXRS profiles for gas puff fueling were taken 60-100 ms after the puff. The pellet-fueled plasma results in impurity profiles that exhibit consistently larger impurity concentrations in the central region than the gas puff fueled case, and are characterized by strong central peaking followed by a relatively constant density plateau out to the scrapeoff layer for both C$^+6$ and O$^{+8}$. The C$^+6$ plateau is consistently higher relative to the central concentration than is the O$^{+8}$, probably due a degeneracy with the 4f-3d transition of O$^{+5}$ resulting from a charge exchange with O$^{+6}$. This does not affect the measurements on the interior portion of the profile, where O$^{+6}$ is burned out, but may contribute to measured C$^+6$ for r > 20 cm since the total abundance of oxygen is of the same order as that of carbon.

A comparison of the impurity profiles with the electron density profiles clearly demonstrates impurity peaking on axis as is shown in figure 3. The scale length of a quantity q is defined to be $L_q = q/(\partial q/\partial r)$. We can characterize the changes between impurity and electron transport using the ratio of scale lengths, $P_z = L_e/L_z$, where $L_e$ is the electron scale length, and $L_z$ is the scale length associated with the completely ionized impurity profile of charge z. For the gas puff case, average values of $P_6$ and $P_8$ are typically < 1.5 over the plasma cross section. However for the pellet case in the central region of the plasma, $P_6 \approx 2.5-3$ and $P_8 \approx 3-4$. O$^{+8}$ is consistently more peaked than C$^+6$. Outside the central core, $P_6$ and $P_8$ are nearly zero due the flatness of the C$^+6$ and O$^{+8}$ profiles. These observations lead to the conclusion that although the electron density is more peaked for the pellet case than the gas puff case, the light impurities are peaked even more strongly. They are not merely following the electrons. Additional data indicates that heavy impurities, predominantly titanium, also peak on axis, but we cannot quantify this statement with available data. Edge temperature, density, and particle flux measurements made with Langmuir probes show no significant difference between puff and pellet discharges. Thus changes in central impurity concentrations or profile behavior are not due to a change in impurity source at the
wall. However, changes in total impurity content may be a reflection of different amounts of impurities introduced in the different fueling techniques, or in changes in asymmetric edge conditions that might affect the overall impurity profile [12].

A word about beam attenuation uncertainties and their influence on the derived profiles is in order. For profiles obtained after pellet fueling, it is impossible to choose a beam attenuation cross section such that the resultant impurity profiles are less peaked than the electron density profile in the central region. Even under the assumption that there is no attenuation, the resultant impurity profiles are still steeper than the electron density profile throughout the central region.

We can compare these profiles with neoclassical theory. Measurements suggest that the impurity profiles presented here are steady state. That is, we did not observe significant changes in the profiles from 30-80 ms after the pellet injection. For the bulk of the plasma (r < 0.2 m) the source and sink of C^{+6} and O^{+8} are small. In steady state in a source free region, the flux is zero. In this region, we can express the scale length as a ratio between the diffusion coefficient and convective velocity, D/V = n_z/|\partial n_z/\partial r|. The collisionality of C^{+6} and O^{+8} in the central region on TEXT is such that the use of the asymptotic classical Pfirsch-Schluter fluxes in conjunction with the banana plateau fluxes (valid for all collisionality regimes) provides for an accurate neoclassical treatment over the entire cross section of the plasma[13]. Ion temperature profiles were measured from the center to r = 0.18 m using an active charge exchange neutral particle analyzer and measured n_e profiles. Transport due to impurity-impurity collisions is ignored, but the effects of impurity concentration as it effects the proton density gradient are included. Total measured central light impurity concentrations are on the order of 2 % of the electron density, corresponding to a proton deficit of 10-15%. The role of titanium, the most prevalent high Z impurity on TEXT, in enhancing this deficit has not been ascertained; however titanium is usually present in concentrations on the order of 0.1% during other TEXT discharges. Assuming this fractional concentration, the contribution of titanium to the proton deficit is small. Neoclassical predictions are strongly peaked on axis, as are measurements, and are shown in figure 4. The neoclassical predictions offer evidence of the observed plateau outside the central region.
Observation of the dynamics of impurity behavior is needed to measure the transport coefficients. Non periodic minor disruptions, sometimes present after pellet injection, allow for the observations of changing impurity profiles. Knowing that $\partial n_z/\partial t = -\nabla \cdot \Gamma_z$ in the source free region and measuring scale times and lengths of the impurity profiles at two times following the disruption enables $D$ and $V$ to be estimated separately. Assuming a constant $D$ and $V = V_0 r/a$, measurements give $D = (0.15 \pm 0.05) m^2/s$ and $V = (25 \pm 9) r[m] m/sec$. Measured values of $D$ and $V$ are higher than the neoclassical predictions of $D = 0.022 m^2/s$ and $V = 6 r[m] m/s$. While the measured transport coefficients are consistent with measured equilibration times, the neoclassical values imply equilibration times that are much longer than measured. This discrepancy may be due to the presence of an inward pinch after the pellet injection or disruption that is larger than the steady state neoclassical inward convection velocity.

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MEASUREMENT OF THE CURRENT DENSITY PROFILE AND MODIFICATION OF THE ELECTRON DENSITY PROFILE IN TOKAMAKS USING LOW Z IMPURITY PELLETS

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Abstract

High speed lithium pellets have been injected into Alcator C tokamak plasmas in order to measure the internal magnetic field, and thus current density profiles. In the pellet ablation cloud, intense visible line radiation from the Li$^+$ ion ($\lambda \approx 5485$ Å, $1s2s\,^3S - 1s2p\,^3P$) is polarized due to the Zeeman effect, and measurement of the polarization angle yields the direction of the total local magnetic field. A “snap shot” of the $q$ profile is obtained as the pellet penetrates from the edge into the center of the discharge, in a time of $\approx 300\,\mu s$. The spatial resolution of the measurement is about 1 cm. At a toroidal field of $B_T = 10$ Tesla, the emission in the unshifted $\pi$ component of the Zeeman triplet is more than 90% polarized, and $q$ profiles have been obtained. The pellets are perturbative ($\langle \Delta n_e \rangle / \langle n_e \rangle \approx 1$), but the total pellet penetration time is at least a factor of 1000 smaller than the classical skin time. It can thus be anticipated that the current density profile should not be perturbed significantly during the time of the measurement. The pellets also fuel the plasma, and essentially every phenomenon observed with deuterium pellet fueling of Alcator C has also been seen with lithium pellets. These include increased energy confinement time, enhancement of the global D-D fusion reaction rate, and peaking of the density profiles. The replacement of lithium by deuterium as the discharge evolves following the injection of a single lithium pellet has also been measured. A new two shot pellet injector has been built in order to continue these experiments on the TFTR tokamak at Princeton. It is capable of injecting lithium and carbon pellets, with velocities up to $1.1 \times 10^{18}$ cm/s. An improved polarimeter/spectrometer system has also been constructed and tested.

Introduction

One of the most important characteristics of a tokamak discharge, and at the same time one of the most difficult to measure, is the current density profile. Several experimental techniques have been brought to bear on this problem. These include Zeeman polarimetry utilizing lithium beams$^{1,2}$ and intrinsic impurities$^3$, Faraday rotation of FIR laser beams$^4$, Thomson scattering from cyclotron resonances$^5$, and the imaging of H$_3$ trails from ablating hydrogen pellets$^6,7$. In this paper we describe a new method, which takes advantage of the polarization of line emission due to the Zeeman effect, but rather than using an atomic beam to provide the source for the radiation, a lithium pellet has been employed instead. In the ablation cloud surrounding a pellet as it penetrates into a tokamak discharge, the atoms and ions of the pellet material radiate intensely. In general, the line radiation will be polarized, due to the Zeeman effect, and measurement of the direction of polarization yields the direction of the local magnetic field. Since the fields due to the external coils (primarily toroidal) are known, this measurement allows the deduction of the field due to currents flowing in the plasma, and therefore the $q$ profile as well. Experiments have been performed on the Alcator C tokamak$^8$, using a lithium pellet injector, to investigate this idea. Polarization measurements show that the emission from the helium-like lithium ion, near $\lambda = 5485$ Å, is almost completely split into three polarized components, and the direction of polarization, as a function of minor radius in the plasma, has been measured. This in turn has allowed for the construction of $q$ profiles for a few discharges.

A second interesting aspect of the injection of impurity pellets into tokamak discharges is the resulting perturbation to the electron density profile. The phenomena which are observed following lithium pellet injection closely resemble those which have been observed in experiments on hydrogen pellet fueling. These include peaking of density profiles, and an increase in energy confinement. In addition, it is possible to follow the evolution of the injected species spectro-
scopically, opening up new opportunities for the investigation of particle transport. Li pellets penetrate farther into a tokamak discharge, than will hydrogen pellets with the same speed and total number of electrons. Because of this, it should be possible to fuel plasmas with smaller perturbations to \( n_e \), and to test the relative effects of penetration and density perturbation on changes in transport. The penetration of impurity pellets can provide tests of theories related to pellet ablation, since the properties of these room temperature solids are so different from those of cryogenic hydrogen. In addition, impurity pellets will probably find application to other tokamak diagnostic problems, including the detection of fast \( \alpha \) particles in reacting plasmas.

The Alcator C Lithium Pellet Injector

In order to carry out the experimental investigations, a pneumatic pellet injector was designed and constructed at MIT. A cartoon of the gun design is shown in figure 1. A ribbon of isotopically natural Li is placed into the feeder track, and the feeder rod is advanced, pushing the Li into the slot in the shearing block. The ribbon, in this design, has a square cross section, 0.7 mm on a side. The length of the pellets is variable, with the maximum being 0.75 mm. The largest pellets correspond, on Alcator C, to a volume averaged electron density increase of \( 1.5 \times 10^{14} \text{ cm}^{-3} \). After the Li has been pushed into the slot, the shearing block is used to slice off the cubic pellet, and transport it to the beginning of the barrel. A fast valve is then used to expose the pellet to helium or hydrogen pusher gas, at pressures up to 30 atmospheres. The barrel is 25 cm long, and pellet velocities up to 1000 m/s are achieved. The velocity is measured by two diodes, spaced by 10 cm, which are eclipsed as the pellet passes in front of them.

![Cartoon of the Alcator C lithium pellet injector. The pellets are cubic in shape, 0.7 mm on a side. Pellet velocities up to 1000 m/s were achieved with H\(_2\) driver gas at 30 Atmospheres.](figure1)

Polarization Measurements

The setup used to measure the angle of polarization of the line radiation from the pellet ablation cloud is shown schematically in figure 2. The intensity of separate components of polarization must be measured simultaneously in order to deduce the direction of polarization. Since the emission is viewed perpendicular to the magnetic field, the \( \pi \) components are linearly polarized parallel to the field, and the \( \sigma \) components perpendicular to the field. In the Alcator C experiments, it was only possible to measure two perpendicular components on one shot. The first task is to determine that indeed there is polarized light to measure. This was accomplished by measuring the vertical and horizontal components of polarization, as functions of wavelength, on a shot by shot basis. A 0.5 m monochromator was used to select wavelength, and the output from the instrument was split, using polarizing films and a beam splitter, to direct the signals to 2 photomultipliers.
Shown in figure 3 are the results of a scan of the multiplet, near 5485 Å, from the Li\(^+\) ion. The two components of polarization which were measured are the vertical and horizontal (toroidal). The quantity plotted is the normalized difference of the two signals: +1 corresponds to light which is purely linearly polarized in the horizontal direction; −1 to light which is polarized in the vertical direction. The experimental points are shown as squares; solid squares denote the maximum polarization seen over the course of one ablation event, and the open squares show the minimum that was observed for the same pellet. The solid curve is theoretical, for He-like \(^6\)Li, with the linewidth as a free parameter. The theory has been derived by analogy with a calculation for He-like carbon\(^9\), and assumes that the various upper levels are populated statistically. The main result is that the emission in the unshifted component is almost completely polarized. These measurements were taken with a toroidal field on axis of 10 T. It then remains to measure the deviation of the polarization direction from toroidal, as a function of position in the plasma. The position is inferred from the time history of the polarization measurement, coupled with the information from an imaging camera which views the pellet ablation from below the torus (see figure 2), yielding pellet location as a function of time.

Letting the angle that the total field makes with the toroidal be \(\theta\), and defining \(\alpha\) to be the unpolarized component of the total emission at the center of the \(\pi\) feature, the relative horizontal and vertical intensities are given by

\[
I_H = \frac{\alpha}{2} + (1 - \alpha) \cos^2 \theta, \quad I_V = \frac{\alpha}{2} + (1 - \alpha) \sin^2 \theta.
\]

Since \(\theta \ll 1\) over the entire cross section (it will never be more than about 5 degrees or \(\approx 0.1\) radian), the measurements of figure 3 depend primarily on \(\alpha\). In order to determine \(\theta\), it is necessary to measure at least one more component of polarization. In the experiment, components at \(\pm 45^\circ\) from the toroidal are measured, and denoted by \(I_1\) and \(I_2\) respectively.
The intensity is most sensitive to $\theta$ at these angles, for small $\theta$. The relative intensities for these components are given by

$$I_1 = \frac{\alpha}{2} + (1 - \alpha) \cos^2\left(\frac{\pi}{4} + \theta\right), \quad I_2 = \frac{\alpha}{2} + (1 - \alpha) \cos^2\left(\frac{\pi}{4} - \theta\right).$$

For $\theta << 1$, and ignoring toroidal corrections:

$$\frac{I_1 - I_2}{I_1 + I_2} \equiv f \approx \frac{2(1 - \alpha)}{5 B_T R} \int_0^R 2\pi r' dr' j(r'),$$

or, assuming $\alpha$ is constant,

$$j(r) \approx \frac{5 B_T}{2\pi(2 - 2\alpha)} \left(\frac{f}{r + df/dr}\right) \quad \text{and} \quad q_0 \approx \frac{(2 - 2\alpha)}{R \cdot (df/dr)_{r \to 0}}.$$

In general, for low $\beta_p$ circular plasmas, such as those studied here on Alcator C, $q = r/(R \tan \theta)$, so measuring $\theta(r)$ leads directly to the $q$ profile.

One such profile is shown in figure 4. The plasma parameters in this case were: $B_T = 10$T, $\bar{n}_e = 2.5 \times 10^{14}$ cm$^{-3}$, $I_p = 550$ kA, $q_1 = 4.1$. The two solid lines correspond to the pellet's penetrating first from the outside ($R > R_0$) and then going beyond the center of the plasma ($R < R_0$). The dashed curve shows the $q$ profile which would result from $q_0 = 0.9$ and the current density proportional to $T_e^{1/2}$. The data do not go all the way into the center of the discharge, because the pellet was slightly above the midplane, and so did not sample the exact center of the plasma. One indication of the uncertainty of the measurements is given by the difference between the inner and outer curves, about $\pm 20\%$. The largest contributor to this uncertainty is the uncertainty in $\alpha$, mainly due to the fact that, since only 2 components could be measured for a given pellet, $\alpha$ is deduced from one shot, and then $\theta$ from another.

The pellet penetration time, of the order of 300$\mu$s on Alcator C, is very short compared to the classical skin time. Therefore, changes in the current density profile as the pellet penetrates into the plasma are not expected. Nevertheless, the pellet is very perturbing ($\Delta \langle n_e \rangle / \langle n_e \rangle \approx 1$) and current diffusion is by no means always classical in tokamak plasmas. It is encouraging, in this regard, that the inner and outer curves of figure 4 are in good agreement: if the pellet were perturbing the poloidal field significantly as it penetrated, this result would not obtain. Another test, which has not yet been performed, would be to inject a second pellet, very soon after the first, to see if the results are consistent.

To investigate the applicability of the technique to lower field devices, and specifically with an eye toward planned experiments at TFTR, polarization measurements were also performed at $B_T = 5$ Tesla. Since the Zeeman splitting is smaller at the lower field, and the system is farther from the high field Paschen-Bach limit, coupled with finite line broadening due primarily to the Doppler effect ($T_i \approx 10$ eV for these ions), the emission is less polarized. Nevertheless, it is sufficiently polarized ($\approx 50\%$) so that accurate measurements of $\theta$ should be possible. Since

![Figure 4](image.png)

The inferred profile of $q$, the safety factor, using the ablation signals from the pellet on both sides of the magnetic axis.

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variations in $\alpha$ become increasingly important for larger $\alpha$, simultaneous measurement of at least 3 components is necessary to achieve meaningful results. A system to do just that has been assembled, and is shown schematically in figure 5. A set of four optical fibers views the pellet ablation. Each fiber has a polarizer at the front, and these are oriented, as shown in the figure, to measure the vertical, horizontal, and $\pm 45^\circ$ components. A diffuser is placed between the polarizers and the fibers. This is necessary to smooth out differences in the relative sensitivities of the fibers as the light source (the pellet) moves within their field of view. This new polarimeter/spectrometer system, along with a two-shot pellet injector, will be used to continue these experiments at the TFTR tokamak in Princeton.

![Diagram of the new polarimeter setup.](image)

FIG. 5.
Schematic for the new polarimeter setup. The fibers carry signals from different components of linear polarisation which are selected by means of polarizers oriented as shown in the bottom of the figure.

Electron Fueling and Changes in Transport

It is of interest to compare the fueling effects of impurity pellets with those observed after injection of hydrogen (or deuterium) pellets into tokamak discharges. Figure 6 shows the time histories of a set of plasma parameters for an Alcator C deuterium discharge into which a lithium pellet was injected. Included are the plasma current, global neutron production rate, central chord soft x-ray and visible continuum brightnesses, line average density, resistive voltage, ohmic input power, and the central $T_e$ from ECE measurements. For comparison, figure 7 shows many of the same parameters for a deuterium discharge into which a hydrogen pellet was injected. In both cases, it is noteworthy that the neutron production rate increases dramatically following the reheat after the pellet is injected. In neither case did the pellet have any deuterium in it. The neutron rates increase for three reasons: the deuteron density profile is more strongly peaked after the pellet, due to particle transport changes, leading to a much larger on axis deuteron density in the hottest part of the discharge; the ion temperature increases slightly, because of better coupling to the electrons at the higher density; as lithium, (and presumably hydrogen in the second case) leaves the plasma, it is replaced by deuterium from the walls and limiter. This last point is inferred from the time history of the $Z_{eff}$ of the plasma following Li pellet injection, which is measured using the visible continuum diagnostic. $Z_{eff}$ before Li injection is about 1.4. It rises to about 2.6, and then decays back to 1.5 in about 50 ms after the injection. At this time (330 ms in figure 6) the electron density is still high, and nearly constant, while the neutron rate is still near its peak. This confirms that the Li is indeed being replaced by deuterium, while the electron and deuteron density profiles remain more peaked than those found for the gas fueled case. Comparisons of soft x-ray profiles for the two cases show that the strong peaking of the soft x-ray emission seen with hydrogen pellets is also duplicated after Li pellet injection. While explicit impurity transport studies were not performed during these Li pellet experiments, the evidence that exists points to the fact that trace impurities behave similarly in the two cases: strong peaking of the trace impurity profiles and long trace impurity particle confinement times can be expected. Further experimentation into these phenomena is warranted.
Concerning the effects of Li pellets on global energy confinement, figure 8 shows comparisons of $\tau_E$ obtained under ohmic conditions on Alcator C with 3 fueling techniques: gas puffing; hydrogenic pellet fueling; and Li pellet fueling. While the Li pellet data set is very limited, these initial results indicate that the Li pellet fueling is about the same as the best of the gas fueled shots, and the worst of the hydrogenic pellet fueled shots. In other words, Li pellets appear to fall right in between the other two cases. Clearly this is another area where further investigation is required.

Comparison of global energy confinement times for ohmically heated Alcator C discharges with gas fueling, hydrogenic pellet fueling and Li pellet fueling. The figure comes from reference 10, with the Li points added.
Conclusions

The technique of Zeeman polarimetry to measure the internal magnetic field using lithium pellets has been demonstrated. While the pellets are perturbative, it appears that the measurement technique is valid, and with some relatively straightforward modifications and refinements, precision approaching 10% for the measurement of $q$ near the axis should be achievable. The technique is viable, using Li, as long as the toroidal field is $> 4$ Tesla. Electron density profile modification can be accomplished with impurity pellets, and most of the phenomena observed with hydrogen pellet fueling have also been seen with the lithium pellets. These include peaking of the density profiles, enhancement of the neutron production, and modest improvement in the global energy confinement properties of the plasma.

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V. PELLET ABLATION
PELLET ABLATION AND TEMPERATURE PROFILE MEASUREMENTS IN TFTR*

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Abstract

Single and multiple deuterium pellets have been injected into a variety of TFTR plasmas, including ohmically heated plasmas with a wide range of initial electron temperatures, neutral beam heated plasmas at several NBI powers and high $T_e$, post NBI plasmas. Pellet penetration into these plasmas was determined by measuring the pellet speed and duration of the H$_\alpha$ light emission during pellet ablation in the plasma. These penetration measurements are compared to the predicted penetration computed using the ablation model developed by Oak Ridge National Laboratory. Provided super-thermal electrons are not present in the target plasma, reasonable agreement is found between the model and measurements of the penetration for a particular choice of the free parameter in the model. Neutral beam particles have a substantial effect on the ablation rate of pellets in low $T_e$ plasmas ($T_e < 4$ keV) while in high $T_e$ plasmas the electron driven ablation dominates. A more detailed examination of the fuel deposition profile will be presented as well as a preliminary discussion of the electron temperature profile evolution.

1. INTRODUCTION

Single and multiple deuterium pellets have been injected into a variety of TFTR plasmas, including ohmically heated plasmas with a wide range of electron temperatures, neutral beam heated plasmas at several NBI powers and high $T_e$, post NBI plasmas. Pellet penetration into these plasmas was determined by measuring the pellet speed and duration of the H$_\alpha$/D$_\alpha$ light emission during pellet ablation in the plasma. These penetration measurements are compared to the predicted penetration computed using the ablation model developed by Oak Ridge National Laboratory [1]. The plasma density profiles before and after pellet injection are used to estimate the number of particles deposited in the plasma. The plasma particle increase compared to the estimated number of atoms in the pellet yields a measure of the fueling efficiency of pellets in TFTR. The ablation cloud parameters are discussed based on polychrometer measurements of the H$_\alpha$/D$_\alpha$ line emission from the neutral cloud surrounding the pellet. The electron temperature profile evolution after pellet injection is examined for the case of multiple pellet injection into an ohmically heated plasma.

These experiments were carried out using the Deuterium Pellet Injector (DPI) developed and fabricated by the Oak Ridge National Laboratory. The DPI has eight single shot barrels.

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There are three 3 mm diameter, three 3.5 mm, and two 4.0 mm diameter barrels which fire cylindrical pellets 3.4 mm long at speeds of up to 1.5 km/s for deuterium pellets. The 4.0 mm diameter pellets contain approximately $3 \times 10^{21}$ particles resulting in a typical increase in plasma particles of $\Delta N/N \approx 3$.

The ORNL pellet ablation code was used to compare measured pellet penetration depths with a theoretical model. The measured input parameters to the model are the electron density and temperature profiles, the neutral beam heating profile, the neutral density profile, the pellet size, pellet speed and pellet composition. The free parameter in the model is the thickness of the neutral cloud surrounding the pellet. This parameter is adjusted to arrive at a reasonable agreement between measured and calculated pellet penetration depths. The output of the model which is directly comparable to experiment is the calculated ablation rate. It is assumed that the broad-band $H_\alpha/D_\alpha$ emission is proportional to the ablation rate. It is certainly true that the termination of the broad-band emission marks the maximum penetration depth of the pellet.

2. PELLET PENETRATION STUDIES

The penetration of deuterium pellets into TFTR plasmas is determined from the termination time of the $D_\alpha$ emission from the ablating pellet. This time combined with the measured pellet speed, firing time, and machine geometry yields the absolute penetration depth of the pellet into the plasma. Three cases have been investigated so far: 3.0 and 3.5 mm pellets into ohmically heated plasmas and 4.0 mm pellets into neutral beam heated plasmas. In each case, the penetration depth was calculated with the ORNL ablation model using profiles which were either measured or calculated with the SNAP [2] one-dimensional, time independent analysis code.

The results of this survey are shown in Fig. 1 for the three cases. The neutral cloud thickness was adjusted to 0.5 mm to give reasonable agreement between measured and calculated penetration depths for the 3.0 mm pellets into ohmically heated plasmas. This value was then used for all subsequent penetration calculations. The 3.0 mm pellets were chosen as the base line case for determining the neutral cloud thickness as this situation best represented the assumptions in the ORNL model used. These pellets did not penetrate deeply into the plasma and hence did not cross any low-q rational flux surfaces. An example of this shallow penetration ohmic case is shown in Fig. 2. The measured broad-band $D_\alpha$ emission is plotted along with the calculated ablation rate in arbitrary units. The termination point of both curves is in good agreement though the detailed agreement between the two curves is perhaps poorer. The discrepancy between the measured and calculated ablation in the outer region of the plasma is typical.

![Figure 1](image1.png)

Figure 1: Calculated pellet penetration from the ORNL pellet code plotted against the measured penetration for 3.0, 3.5, and 4.0 mm diameter pellets. The neutral cloud thickness was 0.5 mm to match the 3.0 mm pellet data.

![Figure 2](image2.png)

Figure 2: Comparison of measured broad-band emission and calculated ablation rate for a 3.0 mm pellet. Radius units are 10 cm.
The 3.5 mm pellets penetrated much deeper into the ohmically heated plasmas in TFTR because larger pellets penetrate deeper and with the DPI, larger pellets tend to be faster. It can be seen from Fig. 1 that the agreement between calculated and measured penetration for the 3.5 mm pellets is poor. A typical example of calculated and measured ablation is shown in Fig. 3 for these larger pellets. In contrast to the 3.0 mm pellets, there is considerable structure in the emission from the 3.5 mm pellets. Sawteeth were present in both cases during pellet injection. There is a strong decrease in emission at the plasma center and at a radius near the \( q=1 \) surface. The ORNL ablation code does not model rational \( q \) surfaces though the limited volume of the plasma center is taken into account. For these deep penetration cases where the pellet ablation decreases at rational \( q \) surfaces, good agreement between theory and experiment is not to be expected. However, the model does predict that the pellet will penetrate well into the plasma, insuring central fueling. Note that there is still a discrepancy in the outer plasma between the modelled and measured ablation rate.

The agreement between measured and calculated penetration depths for the NBI cases is also poor. The model reproduces the general features of the observed \( D_\alpha \) emission such as increased emission in the outer plasma region but overestimates the observed ablation rate. However, high energy ion ablation is important both in the model and in the experiments. Simulating the ablation without including the high energy ion ablation leads to much too deep pellet penetration. That high energy ion ablation is experimentally important is seen in Fig. 4.

Shown in Fig. 4(a) is the broad-band emission from a 3.5 mm pellet injected at 2.4 s into an ohmically heated plasma with \( T_e(0) = 3.2 \) keV. Sawteeth are present in the plasma at this time. The pellet penetrates well past the center of the plasma. In Fig. 4(b) is the emission from a 4.0 mm pellet injected at 3.0 s into the same discharge as in Fig. 4(a), but with 5 MW of neutral beam heating and \( T_e(0) = 2.0 \) keV. Sawteeth are no longer present, having been suppressed by the first pellet. Both pellets had a speed of 1.48 km/s. If high energy ion ablation
were not important, the second pellet, being larger and in a lower temperature plasma, would have penetrated much deeper than the first pellet and would probably not have been completely ablated in the plasma.

3. PELLET FUELING STUDIES

For a number of the cases shown in Fig. 1, it was possible to determine the particle content of the plasma before and after pellet injection. The fueling efficiency, defined as the increase in the particle content of the plasma divided by the number of particles in an ideal pellet, is shown in Fig. 5 for these cases plotted against measured penetration depth. It should be noted that photographs of pellets do not show the pellets to have an ideal cylindrical shape but rather to be somewhat rounded at the ends. The definition of fueling efficiency used here will overestimate the number of particles in the pellet and hence systematically underestimate the fueling efficiency.

![Figure 5: The fueling efficiency of 3.5 mm pellets into ohmically heated plasmas and 4.0 mm pellets into NBI heated plasmas.](image)

It can be seen from Fig. 5 that there is an increase in fueling efficiency with penetration depth for the 3.5 mm pellets injected into ohmically heated plasmas. This effect is real and not a result of variability of nominal pellet size. If a pellet were larger than expected it would penetrate farther into the plasma and appear to fuel more efficiently, having more particles than the average pellet. In fact, the differences in pellet penetration depth are due to differences in target electron temperature and pellet speed. Pending a better assessment of the actual number of particles in a pellet, the absolute fueling efficiency cannot be determined but it is at least 50% increasing to 75% with penetration depth.

The fueling efficiency for the 4.0 mm pellets injected into neutral beam heated plasmas appears to be worse than for the ohmic case. The beam power was approximately 10 MW for the pellets which penetrated to 0.65 m and 5 MW for the pellet which penetrated to 0.8 m. The 5 MW case is the same as shown in Fig. 4. Due to the limited amount of data, it is not possible to discern any systematic trend in the NBI fueling efficiency data other than that the efficiency is less than for ohmic heating only.

A clear example of the lower fueling efficiency in NBI heated plasmas is shown in Fig. 6 which is a plot of the increase in plasma density from pellet fueling plotted vs major radius. In this example a 3 mm pellet was injected into an ohmically heated and an NBI (\(P_{NB} = 10\) MW)

![Figure 6: The density rise from pellet fueling in an ohmically heated (solid) and NBI heated plasma (dashed). In both cases the pellets were 3.0 mm, the pellet speed was 1.05 km/s, the electron temperature was about 3.2 keV, and the plasma radius = 0.8 m.](image)

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heated plasma having approximately the same electron temperature and density. The smaller plasma density increase in the NBI case is not due to reduced pellet mass as then the pellet would not penetrate as deeply as it did. At present, there is no satisfactory explanation for the reduced fueling efficiency in NBI heated plasmas.

4. SPECTROSCOPIC MEASUREMENTS OF PELLET ABLATION

An eight channel polychromater has been used on TFTR to observe the D$_\alpha$ line emission from the luminous cloud surrounding the ablating pellet. The polychromater spans the spectral range from 630 nm to 665 nm. The measured spectra were analyzed to determine the electron density in the cloud from the Stark broadening of the D$_\alpha$ line and the electron temperature from the line-to-continuum ratio. Typically, $T_e = 1.6 \pm 0.3$ eV in the luminous cloud throughout the ablation process.

The observed spectrum has structure which yields information on the properties of the cloud. Channels near the line center have lower than expected intensity which is explained by self-absorption in the luminous cloud. Analysis indicates that the luminous cloud is a few millimeters thick.

Figure 7 shows the electron density and radiated power from the D$_\alpha$ line during the ablation of a pellet in TFTR. Figure 8 is a comparison of the broad-band emission from a three pellet sequence with the integrated D$_\alpha$ emission normalized at the peak intensity. There is good agreement between the line and broad-band emission, lending support to the use of broad-band emission as a measure of D$_\alpha$ line emission. To the extent that D$_\alpha$ line emission is proportional to the ablation rate, so is broad-band pellet emission.

5. $T_e$ PROFILE EVOLUTION

A series of pellets were injected into an ohmically heated, $I_p = 2.2$ MA, $q_{cyl} = 3$ discharge [3]. The last pellet in the series fueled the center of the plasma and suppressed sawteeth. Between 0.5 - 0.7 s after the last pellet, an intense central radiation loss develops due to brehmsstrahlung from the dense central plasma. During this time, the central radiation power density becomes a significant fraction of the ohmic input power while the electron temperature profile becomes hollow.

The density profile for $r/a \geq 0.4$, evolves from a peaked profile just after injection to a profile which is broader than the profile just before injection of the last pellet: $n_e(0.4)/n_e(0.8) = 1.72$ before injection and $n_e(0.4)/n_e(0.8) = 1.54$ at 0.7 s after injection, 10% broader. Figure 9 shows the time evolution of the density profile normalized to the
density at r/a = 0.5. The curve at 2.6 s is the target density for the last pellet in the series which was injected at 2.74 s. The profile evolves significantly during the entire period shown.

![Figure 9: Evolution of the normalized density profile from a pellet injected at 2.74 s. The pellet penetrates to the plasma center.]

After injection of the last pellet, the electron temperature for r/a ≥ 0.4 initially broadens from T_e(0.4)/T_e(0.8) = 3.07 at 2.6 s just before pellet injection to T_e(0.4)/T_e(0.8) = 2.65 at 2.9 s, 160 ms after pellet injection, a broadening of 15%. The profile shape rapidly evolves back to its pre-injection value so that 350 ms after pellet injection T_e(0.4)/T_e(0.8) is within 5% of the pre-injection value. Figure 10 shows the electron temperature profile evolution. For r/a ≥ 0.4, there is little evolution of the profile shape even though the density and radiation profiles are still evolving significantly.

![Figure 10: Normalized electron temperature profile for the same situation as in Figure 9.]

6. CONCLUSIONS

Measured pellet penetration into ohmically and NBI heated plasmas in TFTR have been compared to calculations using the ORNL pellet ablation code. In shallow pellet penetration in ohmic plasmas, the calculated pellet lifetime is in reasonable agreement with observations, though the calculated ablation appears too large in the outer region of the plasma. In deep pellet penetration in ohmic plasmas with sawteeth present, the calculated pellet lifetime is too short. A strong decrease in observed pellet ablation at the q=1 surface is not modelled. For pellet penetration into NBI heated plasmas where sawteeth were suppressed by a previous pellet, the calculated pellet lifetime is too short. High energy ion ablation is important though, both experimentally and computationally.

Pellet fueling efficiency increases with increasing pellet penetration for deep penetration in ohmically heated plasmas, reaching values of 75% or more. The data for pellet fueling in NBI heated plasmas is not conclusive, but the fueling efficiency appears to be less than for the ohmic case.

The electron temperature profile evolves to its pre-pellet shape on a ~300 ms time scale. The shape of the outer half of the profile is largely unchanged by pellet injection even though the density and radiation profiles are still evolving and the central T_e profile is hollow.

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MAGNETIC SURFACES AND STRIATIONS
DURING PELLET ABLATION

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Abstract

The striations observed on the Hα or Hβ emission signal of ablated pellets are not presently well understood. A limitation of the ablation process due to the lesser amount of energy available on resonant magnetic surfaces would be an attractive explanation. In order to evaluate the ability of the latter to produce the observed features, we developed a model which takes into account the maxwellian distribution of electrons, the proportion of trapped particles, the geometrical effects linked to the shear and the finite lifetime of the filaments. In tokamaks, it is found that our model is unable to reproduce the observed striations for smooth q profiles but that the general shape of the Hα (or Hβ) signal can be fitted by introducing small flattenings (e.g. small magnetic islands) around resonant surfaces. In low-shear stellarators, striations (rather shallow) due to rational q values can exist in the absence of magnetic islands but require the presence of a suprathermal electron tail.

1) INTRODUCTION:

Striations during pellet ablation have been observed for several years in a number of machines [1-8]. A first interpretation of these fluctuations is to relate them to resonant magnetic surfaces [2,9-11] but their poor reproducibility in macroscopically identical discharges and the observation of identical features in the low-shear stellarator W-VIIA [8] were taken as arguments against this. However, it is clear that their inclination is strongly correlated to the magnetic field since it was shown that a careful analysis of the angle between a striation and the toroidal direction led to an experimental determination of the local q value [7,12]. It is therefore tempting to investigate the possible correlation between the striations location and depth and the magnetic structure of the discharge.

2) BASIC MODEL FOR STRIATIONS:

2-a) Fundamental process:

We start from the idea that dark striations correspond to locations where ablation is lower than average, i.e. that the available electron energy is lower than at other radii. For electrons of parallel velocity, this can be understood as follows: the pellet, surrounded by its neutral cloud (of effective diameter $\Phi_p$
perpendicularly to the magnetic field) moves across the discharge with a velocity $V_p$. It interacts during a time interval $\delta t = \Phi_p / V_p$ with every toroidal shell of infinitesimal thickness. Therefore, all the electrons located at a distance smaller than $S_\| \cdot \frac{V_p}{\Phi_p}$ from the pellet (following the field line) are intercepted by the neutral cloud. If the pellet is on a resonant magnetic surface ($q = m/n$ at minor radius $r$) the field lines have a finite length:

$$L(m,n) = 2\pi \cdot (R^2 \cdot m^2 + r^2 \cdot n^2)^{0.5} \approx 2\pi \cdot R \cdot m$$

where $R$ is the major radius of the discharge. For $L(m,n) \cdot \frac{V_p}{\Phi_p}$, the energy flux on the neutral cloud vanishes after a time interval $\delta t' = L(m,n) / V_\|$, leading to a limitation of the local ablation rate in the proportion:

$$\alpha(m,n) = \frac{\delta t'}{\delta t} = \frac{L(m,n) \cdot V_p}{\Phi_p \cdot V_\|}$$

$\alpha(m,n)$ is averaged over the electron distribution function in the next Section. For a given $V_\|$, the above limitation is effective on every magnetic surface for which $\delta t' < \delta t$, i.e. $m \approx m_0$ with:

$$m_0 \approx \frac{\Phi_p \cdot V_\|}{2\pi \cdot R \cdot V_p}$$

2-b) Shape of the striations:

A first estimation of the half radial width of the zone inside which the energy flux vanishes after a time interval $\delta t'$ can be found by noticing that the influence of a resonant surface (located at radius $r'$) vanishes at the radius $[r + \delta r]$ such that the poloidal rotation difference $\delta \Theta = m \cdot \delta (2\pi/q)$ after $m$ toroidal turns reaches the angular sector sustained by the neutral cloud: $\Phi_p / r$. That is when $\delta r_0$ is such that:

$$r \cdot |\delta \Theta(\delta r_0)| = 2\pi \cdot r \cdot m \cdot \left| \frac{\delta q}{\delta r} \cdot \frac{\delta r_0}{q^2} \right| = \Phi_p$$

The shape of the striation is mainly determined by the relative sizes of the ablation cloud ($\Phi_p$) and of the zone of reduced ablation $2\delta r_0 \approx \Phi_p$, the real profile of the striation is given by the average of the local attenuation over the whole ablation cloud section:

$$\alpha(\delta r, m,n) \approx 1 - [1 - \alpha(m,n)] \cdot \Sigma$$

where $\Sigma$ is the proportion of the neutral cloud section inside which the energy flux is reduced. The total width of the striation is then $2\delta r + \Phi_p$. The smoothing due to this effect is of considerable importance in tokamaks.

2-c) Limits of the model:

For this model to be valid, the thermal diffusion must be small enough not to refill the thermal content of a flux line during its interaction with the pellet. This leads to two additional
relations, one for parallel and one for transverse diffusion:

\[ L(m,n) < T_c. \forall m < m_0 \]

\[ 2\delta r_0 + \Phi_p > \Delta r_0 = a \cdot \left( \frac{\Phi_p}{V_p \cdot T_e} \right)^{0.5} \]  \hspace{1cm} (6)

where \( T_c \) is the collision time and \( \Delta r_0 \) is the minimum striation width compatible with the mean transverse diffusion. An undervalue of which can be calculated from the confinement time \( T_e \) and minor radius \( a \). For TFR, one obtains \( \Delta r_0 \approx 0.3 \text{cm} \) (see [11]). However, it must be underlined that fast heat transport as observed during pellet injection experiments in TFR [7] is not taken into account. Our model gives therefore only an upper limit of the depth and width of the striations related to resonant magnetic surfaces.

The presence of trapped electrons should also be taken into account, but in TFR, their number is very small and they can be neglected. In the general case, due to their very low toroidal drift velocity, only a very small fraction contributes to the pellet ablation and their effect is only a diminution of the effective density.

An implicit assumption of the above calculation is that \( \Phi_p < r_p \cdot (2\pi/q) \). This condition is fulfilled for all reasonable values of \( \Phi_p \). Indeed, it was measured on TEXT that the ablation cloud diameter is about 1 cm [14] and an extensive analysis of pellet injection experiments in JET [15] showed that the measured penetrations could be modelled with \( \Phi_p = 2 \cdot (R_p + 1 \text{mm}) \), where \( R_p \) is the pellet radius. In the numerical applications presented in this paper, we use this latter expression of \( \Phi_p \) (which is the only free parameter of the model).

3) IMPLEMENTATION OF THE MODEL:

The quantity to be calculated is the material deposition profile:

\[ \Delta M(r) = 4\pi R_p^2 \cdot \frac{dR_p}{dt} \cdot \frac{\Delta r}{V_p} \cdot \eta \]  \hspace{1cm} (7)

where \( \eta \) is the pellet ice density. The ablation rate \( dR_p/dt \) is computed in [13] and can be written:

\[ dR_p = 5.71 \times 10^{-9} \cdot R_p^{-0.66} \cdot \text{Ne}^{0.33} \cdot E^{1.64} \cdot dt \]  \hspace{1cm} (8)

Using the fact that \( dR_p^3 \) is an additive function of the local electron density \( \text{Ne} \) and only depends on their velocity, one can average over the distribution function \( f(E) \) leading to:

\[ dR_p = 5.71 \times 10^{-9} \cdot R_p^{-0.66} \cdot \text{Ne}^{0.33} \cdot \int_0^\infty [f(E) \cdot E^{4.92} \cdot dt^3 \cdot dE]^{0.33} \]  \hspace{1cm} (9)

One can then introduce the effect of resonant magnetic surfaces (i.e. that the interaction time \( \delta t' \) of the electrons with the neutral cloud depends on their energy) by combining eqs. (5) and (9);
thus obtaining:

\[
\frac{dR_p}{dt} = 5.71 \times 10^{-9} R_p^{-0.66} Ne^{0.33} (\int f(E) E^{4.92} \inf(a)^3 dE)^{0.33} \quad (10)
\]

where \( \inf(a) \) is the lowest of the \( a(\delta r, m, n)'s \) over all the resonant surfaces within \( \delta r_0 + \Phi p/2 \) of the radius \( r \).

The available experimental signal is the \( H\beta \) (\( D\beta \)) emission of the ablation cloud which is assumed to be roughly proportional to \( \Delta M(r) \) \([15,16]\). However, one has to take into account the lifetime of the emission of a filament which is about 6-7\( \mu \)s \([7,12]\). This corresponds to a characteristic time \( \tau_v \approx 2.5\mu \)s for the decrease of the line emission. This effect results in a smoothing of the \( H\beta \) signal measured as a function of time which is then given by:

\[
H\beta(t=(a-r)/Vp+t_0) = C_v \int_0^t \Delta M(t-x) \exp(-x/\tau_v) dx \quad (11)
\]

where \( t_0 \) is the time at which the pellet penetrates into the discharge and \( C_v \) is a constant characterizing the probability that an atom of the neutral cloud emits a photon in the considered line (~2\% for \( H\alpha \) and 0.04\% for \( H\beta \), see \([4]\)). For simplicity, we chose to normalize \( H\beta(t) \) to 1 at its maximum value. In this paper, numerical applications are done for TFR shot \#94346, the main parameters of which are listed in the following table:

| Major radius | R: 98 cm |
| Minor radius | a: 19 cm |
| Toroidal Field | B: 4.5 T |
| Plasma current | Ip: 184 kA |
| Central density | \( Ne_0: 6 \times 10^{13} \) cm\(^{-3}\) |
| Central temperature | \( Te_0: 1.6 \) keV |
| Pellet equivalent radius | \( R_{p0}: 0.4 \) mm |
| Pellet velocity | \( Vp: 563 \) m/s |
| Pellet penetration | \( Lp: 11.1 \pm 1.5 \) cm |

4) RESULTS AND DISCUSSION:

4-a) Smooth q profile:

Figure 1 displays the computed signal \( H\beta(t) \) for a parabolic q profile drawn between \( q=4.5 \) for \( r=a=19 \) cm and \( q=1 \) for \( r=5 \) cm. The only visible striation corresponds to \( q=2 \) (one sees marginally those corresponding to \( q=3 \) and 5/2). Varying \( \Phi p \) up to 2.(\( R_p+3 \) mm) and \( \tau_v \) until values as short as 1\( \mu \)s do not change the general shape of the signal. There are two possible explanations for this absence of striations: a too small value of \( m_0 \) and/or a too low ratio \( 2\delta r_0/\Phi p \). It can be shown that, for tokamaks, the latter is essentially responsible for the smooth computed signal. This is not the case for stellarators: in these machines indeed, the q profile is flat enough for \( m_0 \) to
be much larger than $\Phi_0$ in the major part of the discharge ($m_0 2\delta r_0/\Phi_0 \approx 10$ for $r/a \approx 0.5$ from the values given in [8] for W-VIIA). The number and depth of computed striations are then limited by the value of $m_0$. In this precise case, it is possible to increase the number of striations by introducing a population of suprathermal electrons (for which $m_0$ is large due to their large $V_{th}$). One must however notice that there is no strong experimental evidence of their presence in this machine and that the computed striations remain rather shallow. Moreover, the presence of a suprathermal electron tail does not increase the number of striations in tokamaks since the latter is limited by $2\delta r_0/\Phi_0$ (which does not depend on $V_{th}$) and not by $m_0$. One must therefore conclude that, if the $q$ profile is smooth, then resonant magnetic surfaces do not explain observed striations.

4-b) Influence local $q$ flattenings.

The presence of a local $q$ flattening on a resonant surface, due for instance to a magnetic island, increases the width and depth of the corresponding striation. Indeed, the shear is small enough inside the island for the poloidal distance covered by the electrons after $m$ toroidal turns to be smaller than $\Phi_0$. In these conditions, the whole island appears as a zone of reduced ablation which results in an increase of the striation width and depth (one can find a schematic description of this effect in [17]). An example is shown on Figure 2: for the computation of this signal (thick line), we introduced local flattenings (2mm) on every resonant surface verifying $m \leq 11$ and $n \neq 1$. The former is compared on the same figure with the measured $H_\beta$ signal during shot #94346 (thin line). One can notice the good agreement of the general shapes of the two signals, but the detail of the striations is not well reproduced. A much better agreement could be
obtained by departing from the parabolic support of the q profile, but this would require the identification of the individual striations in term of m and n numbers which cannot be done unambiguously in the present state of the model.

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GENERAL REMARKS CONCERNING THE ABLATION OF A FUELLING PELLET

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Abstract

According to the general accepted view, the main shielding effect of a hydrogen (or its isotopes) pellet subjected to the impact of plasma electrons is due to the presence of a highly dense cloud around the pellet.

Assuming the stopping power process is valid for particles of any species "j" and using dimensional reasoning, the particle ablation rate of a pellet subjected to the impact of particle beam of species "j" at the energy $E_j$ and number density $n_j$ can be shown, is given by

$$\dot{N}_p = \left(\frac{n_j}{m}\right)^{1/3} \left(\frac{1}{m_j}\right)^{1/6} E_j^{1/2} f_j\left(\frac{E_j}{A_j}\right)$$

where $m$ is the molecular weight of the pellet material, $A_i$ is the energy flux attenuation cross section of the incident particle of species "j" with respect to the target particle of the "ith constituent" of the ablatant.

When most energy of the incident particle is effectively absorbed in a spherical shell around the pellet, the ablation rate $\dot{N}_p$ can be simplified to

$$\dot{N}_p = \left(\frac{n_j}{m}\right)^{1/3} r_p^{4/3} f_j[E]$$

Generalization to a multi-species ablatant does not change the scaling law of the pellet ablation rate. Finally, the ablation rate of a pellet subjected to the impact of particles of known energy distribution can be obtained by taking the proper moment of Eq. (2).

The possible existence of an effective spherical energy absorbing region of the gas-shielding model for the pellet ablation is examined by considering the ablatant as composed of our species. $H_2$, $H$, $H^+$ and $e^-$. The ablated cloud expands spherically if the local collisional mean free path of the cold ablated electrons is much less than the local electron Larmor radius. Results of the analysis showed that for magnetic field strength prevailing in most of the present tokamaks such a region exists at a distance of about $2r_p$ where approximately 80% of the incoming electron energy flux is absorbed.

One of the main concerns of pellet injection experiments in tokamaks is the particle ablation rate $\dot{N}_p$ with respect to the type of the incident particles (electrons, ions, alpha particles, etc.) and their energy distribution. Furthermore, on account of the variation of plasma temperature and density in the device, we
need to know how $N_p$ scales with the local plasma parameters and the instantaneous pellet radius as it travels in the device.

Considering the conservation of energy at the pellet surface, we have

$$\dot{N}_p = \frac{q_{jp} A_p}{H_a}$$

(1)

where $q_{jp}$ is the energy flux of the incident particles of type "$j$" received at the pellet surface with an effective area $A_p$ and $H_a$ is the heat of ablation per ablated particle. Neglecting the kinetic and thermal energy of the ablatant just leaving the pellet surface, we may take $H_a$ approximately as the sublimation energy. The remaining problem then is to find the relation between $q_{jp}$ and the ambient energy flux, $q_{io}$.

According to the commonly accepted point of view, the dominating shielding effect is due to the presence of a highly dense cloud around the pellet which acts as a stopping medium for the incident particles, $[1-8]$, $q_{jp}$ then can be related to $q_{io}$ by applying the stopping power concept, thus

$$\frac{dq_j}{ds} = \frac{\rho(s)}{m} \Lambda_j(E(s))q_j$$

(2a)

$$\frac{dE_j}{ds} = \frac{\rho(s)}{m} \frac{L_j(E)}{E_j <\cos\theta>}$$

(2b)

where

$$\Lambda_j(E) = a_j(E) + \frac{L_j(E)}{E_j <\cos\theta>}$$

(2c)

is a coordinate along the trajectory of the incident particles.

$s(E)$ is the total scattering cross section (elastic collisions) and $L(E)$ is the loss function, i.e. $L(E)/E$ is the cross section of the corresponding inelastic collisions. $<\cos\theta>$ is the average pitch angle between the particle trajectories and the the magnetic field lines. $\rho(s)$ is the local mass density of the ablatant. On account of this variation of the density of the stopping medium, the problem differs from the classical stopping power in solids. To relate $q_{jp}$ to $q_{io}$, we have to study the gasdynamics of the expanding ablated cloud. When the elastic scattering process is neglected, ($s = 0$), from Eqs. (2a) and (2b), we obtain

$$\frac{q_{jp}}{q_{io}} = \frac{E_{jp}}{E_{io}}$$

(3)

The knowledge of $q_{jp}$ thus can be inferred from that of $E_{jp}$. [4].
Considering the ablatant as a nondissipative ideal gas, the expansion and heating of the ablated cloud are described by the three conservation laws, thus

\[ \nabla \cdot (\rho u) = 0 \]

\[ \rho u \cdot \nabla u = -\nabla p \]  \hspace{1cm} (4)

\[ \nabla \cdot [\rho u (h + \frac{u^2}{2} + e)] = Q_j(r) \]

In the above, \( h \) is the specific enthalpy, \( e \) is the energy of phase change, \( Q_j(r) \) is the volumetric heat source due to the incident particles of type "j". One basic assumption of the prevailing ablation models is to take

\[ Q_j(r) = \frac{dQ_j}{ds} \]  \hspace{1cm} (5)

The gasdynamics of expansion and heating of the cloud thus is coupled to the stopping process of the incident particles. As a matter of expediency, the interaction between the gasdynamics of the expanding cloud and the stopping process of the incident particles can be decoupled when appropriate volume average of \( <Q(r)> \) is taken,[4]. However, by doing so, the details of the energy deposition of the incident particles inside the cloud (the stopping medium) is lost. Speaking explicitly, as a result of this approximation, one has no knowledge where most energy of the incident particles is deposited. Taking the dominant shielding effect as that due to the stopping power process, the ablation rate \( N_p \) can be expressed as

\[ N_p = f(m, r_p, q_j, A_j, \beta) \]  \hspace{1cm} (6a)

where \( m \) is the molecular mass of the pellet material, e.g. \( m_{\text{H}_2}, m_{\text{D}_2}\) etc., \( r_p \) is the equivalent spherical radius of a pellet which has the same volume to surface area ratio as that of a sphere. \( \beta \) is the ratio of the magnetic pressure to the gas pressure of the ablatant at some appropriate location in the ablated cloud. Since the basic concept of the stopping power process is that the degradation of the incoming particle energy is due to the presence of a highly dense, but low temperature, medium, for the shielding process to be effective, there must exists an energy absorbing region where the ablatant pressure is sufficiently high, or \( \beta > 1 \). The main effect of the magnetic field is to modify the area \( A_p \) intercepted by the pellet as appeared in Eq. (1). Eq. (6a) then reduces to

\[ N_p = f(m, r_p, q_j, A_j) \]  \hspace{1cm} (6)

Taking the dimensions of \( [q] = MT^{-3}, [m] = M \) and \( [r] = L \) as the three basic units, we obtain

\[ N_p = \left( \frac{q_j}{m} \right)^{1/2} \left( \frac{r_p^2}{A_j} \right) \]
Substituting \([q_j] = [n_j(E_j^3/m_j)^{1/2}]\) into the above expression, we obtain

\[
N_p = \left( \frac{n_j}{m_j} \right)^{1/2} \left( \frac{1}{m_j} \right)^{1/6} E_j^{1/2} \left( \frac{r_p^2}{\Lambda_j} \right)
\]

(7)

When most of the incoming particle energy is absorbed in a spherical shell around the pellet, [10], it can be shown that \(N_p \propto r_p^{4/3}\). Eq. (7) then reduces to, [11],

\[
N_p \propto \left( \frac{n_j}{m_j} \right)^{1/2} \left( \frac{1}{m_j} \right)^{1/6} r_p^{4/3} \frac{E_j^{1/2}}{\Lambda_j^{2/3}}
\]

(7a)

Recalling that for a fixed target particle, \(\Lambda_j\) is a function of the incoming particle energy \(E_j\) only, Eq. (7a) thus takes the form

\[
N_p = \left( \frac{n_j}{m_j} \right)^{1/2} \left( \frac{1}{m_j} \right)^{1/6} r_p^{4/3} [E_j]
\]

(8)

A generalization towards incident particles having an energy distribution \(g(E_j)\) can then be obtained by taking the moment of Eq. (8), [12]. Thus far, we have considered the ablatant as consisting of a single species only, e.g. a H\(_2\) or D\(_2\) gas.

When dissociation and ionization effects are present, we have to generalize \(\Lambda_j\) by \(\Lambda_j^i\), where the superscript "i" denotes the type of species present in the ablatant, e.g. H\(_2\), H, H\(^+\), e\(^-\) etc. Specifically, the stopping power equation, eq. (2b), now becomes, [9]

\[
\frac{dE_j}{ds} = \frac{1}{\langle \cos \theta \rangle} \sum_i n_i^i [\Lambda_j^i(E_j)]
\]

(9)

Similar generalization should be made regarding the energy flux attenuation, \(dq_j/ds\) of Eq. (2a).

Finally, the ablation of a pellet subjected to the impact of incident particles of various type "j" present simultaneously may be obtained by summing over the contributions of various type "j", provided their effects are simply additive and do not interfere with each other.

REFERENCES


Injection of frozen deuterium or hydrogen pellets presently are actively studied in many tokamaks among the fusion communities. Reasonable agreements between the experimentally observed pellet penetration depths and those predicted by the neutral-gas-shielding (NGS) model [1,2], or their modifications [3-8], were reported in Ohmic discharges and with RF or neutral beam heating at moderate power levels [9-14].

Whereas various versions of the models differ in their analytical treatments and in the additional shielding effects, e.g. the influence of the magnetic field [4-7], or of the ablatant composition [3,8] etc., a common feature of these models is that there exits a spherical shell of extremely dense but rather cold ablated gas enveloping the pellet. A characteristic feature of the NGS model is that as the incident electron travels through the ablated cloud, its energy drops suddenly once it approaches the sonic radius of the expanding cloud (see dashed curve of Fig.1). Computational results based on the single-species (H₂-gas) ablatant model of Parks and Turnbull [1] showed that in a wide range of plasma electron temperature \( 10^2 < T_e < 2 \times 10^4 \) eV the sonic radius, \( r_s \), occurs approximately at \( 1.6 r_p \). The energy flux \( q_s \) at \( r_s \) is about 63% of its ambient value, \( q_0 \). Whereas at an expansion radius, \( r = 5 r_p \) (or = \( 3 r_s \)), \( q/q_0 > 90\% \).

**FIG. 1.**
Variation of the ablatant state with the normalized expansion radius, \( r/r_p \), \( r_p \) is the pellet radius. Plasma state and pellet radius; \( T_e = 1.216 \) keV, \( n_e = 8.45 \times 10^{13} \) cm\(^{-3}\), \( r_p = 0.972 \) mm. The dashed curves represent the corresponding ablatant state of a single-species fluid. The normalization parameters of the 4-species and the 1-species ablatant are respectively: \( q_p, 1.21 \times 10^7 \) (4), \( 1.24 \times 10^7 \) (1) w/cm ; \( E_a, 2.0 \) (4), 2.021 (1) keV ; \( T_a, 1.04 \) (4), 2.66 (1) eV ; \( v_a, 1.17 \times 10^6 \) (4), 1.34 \times 10^6 (1) cm/s.
As long as the ablatant is weakly ionized, the corresponding electric conductivity \( \sigma \) is low; the ablated cloud will expand spherically. Such cases have been observed experimentally as in earlier Ormak experiments, (spherical pellet), where the pellet penetrations are limited to the plasma edge region [15] and as in most DANTE experiments (cylindrical pellet) where the central electron temperature is rather low (\( T_e(0) < 300 \text{ eV} \)), (see Fig. 2). In present large tokamaks with higher central plasma temperature (\( T_e(0) > 1 \text{ keV} \)), and higher pellet injection speed (\( U_p \geq 1 \text{ km/s} \)), once the pellet enters the hot core region of the device, ionization of the ablatant could become appreciable. Eventually, the ablated material must flow along the magnetic field lines to form a hose [6-7]. On the other hand, if the shielding effect is caused mainly by the stopping-power process, one should expect the existence of a highly dense ablated layer where the ablatant pressure is sufficiently high to form a spherical shell around the pellet.

![Image picture showing the nearly spherical cloud of the ablatant; exposure time 20 \( \mu \text{s} \) at an interval of 100 \( \mu \text{s} \). The picture is taken in the direction of the major radius with the Polaroid 107 film without any filter plasma state: \( T_e(0) = 200 \text{ eV}, n_e = 2.0 \times 10^{13} \text{ cm}^{-3}, B_T = 0.8 \text{ T} \). Pellet dimensions: length = dia. = 0.4 mm.](image)
The objective of the present paper is to show the existence of such a spherical region and to investigate the amount of the incident electron energy being absorbed in this region. For this purpose we have adopted an approach similar to that of Felber et al. [3] by considering the ablatant to be a mixture of four species; H$_2$, H, H$^+$ and e$^-$. Besides the basic assumptions used in the single-species ablatant model of Parks and Turnbull [1], we further assume that the ablatant is in a local thermodynamic equilibrium state. The relative concentrations of the ablatant species, consequently, are determined by the local temperature and pressure in the ablated cloud, (a detailed account of the model is given in [8]). A typical example of the ablatant state and the attenuation of the incoming electron energy, $E$, and the energy flux, $q$, in the ablated cloud, based on such a model, is shown in Fig.1. For comparison, similar variations of an ablatant of a single species H$_2$- gas are shown by the dashed curves. One notices that although the structure of the cloud depends a great deal on the composition of the ablatant, the attenuation of the energy and of the energy flux of the incoming electrons in the cloud behave essentially similar, irrespective of the ablatant composition, namely, a steep degradation occurs in a thin layer near the pellet.

To evaluate the effect of the ambient magnetic field, $B_0$, Parks has introduced an interaction number, $N_s$, at the sonic radius, $r_s$, defined as [4]

$$ N_s = \frac{\sigma_s V B_0^2}{c^2 \nu_p s} = \frac{R_{Ms}}{\beta_s} $$

(1)

where quantities with the subscript "s" corresponding to the ablatant state at the sonic radius, $r_s$. $R_{Ms}$ is the magnetic Reynolds number, $\beta_s$ is the ablation "beta". When $N_s < 1$, the ablation flow near the pellet deviates only slightly from that in the absence of the magnetic field, or a spherical region of the expanding cloud, at least, exits near the pellet. When dissociation and ionization effects are present, the governing equations of the ablated flow, in the present 4-species ablatant model, become singular at an expansion radius, $r$, within the sonic radius, $r_s$, [8]. The sonic radius varies with the ambient plasma temperature $T_0$ and density, $n_0$ and the instantaneous pellet radius, $r_p$. In the range of plasma parameters and pellet radius of practical interest, $r_s \leq 2r_p$.

$\Delta$ Sonic radius here and thereafter refers to the cloud radius where "local frozen sound speed" is reached.
Once the ablating composition is known, the evaluation of the interaction number, \( N_s \), in principle, can be done. Instead of such a tedious task, we argue that the ablating cloud should expand spherically when the local collisional mean free path, \( \lambda_{ei} \) of the cold electrons of the ablating is much less than the Larmor radius, \( \rho_e \) of the electrons corresponding to the local field, \( B_0 \) of the ambient plasma [16] (e.g. the local toroidal field in a tokamak). A critical field strength, \( B_c \) then can be defined by taking \( \lambda_{ei} = \rho_e \), thus

\[
B_c (\text{tesla}) = 1.65 \times 10^{-17} (\ln \Lambda) n_e (\text{cm}^{-3}) T_e^{-1.5} (\text{eV})
\]  

where \( n_e \) and \( T_e \) are the local density and temperature of the ablating cold electrons, \( \ln \Lambda \) is the Coulomb logarithm. Spherical expansion of the ablating cloud exists in the region where \( B_0 < B_c \). Taking \( \ln \Lambda = 5 \), using the 4-species ablating model [8], we have computed the electron density \( n_e \) and the temperature \( T_e \) of the ablating at an expansion radius of \( 2r_p \) and the corresponding critical field, \( B_c \). The results are shown in Table I for combinations of plasma state and pellet radius of current interest. In the table, \( M_s \) is the Mach number at the singular radius, \( r_s \), \( r_s \) is the sonic radius. The dissociation radius, \( r_d \) is defined where the mass concentration ratio, \( \rho_{H^+}/\rho \) attains a maximum, the ionization radius, \( r_i \), where \( \rho_{H^+}/\rho = 0.995 \).

In the last row of the table, we have also listed the result of a thermonuclear plasma, \( n_e \) and \( T_e \) of the ablating in this case are taken at the ionization radius, \( r_i \). The relatively high value of \( B_c \) is the result of the extremely high ablating electron density, \( n_e \) at the ionization radius. In this particular case, one notices that \( r_i \) is quite close to \( r_2 \), the critical radius of Parks [4].

In summary, judging from the field strength prevailing in most of the present tokamaks, and the fact that in a tokamak, a smaller pellet near the plasma core is associated with higher \( T_e, n_e \) and stronger field, \( B_0 \), whereas an initial larger pellet near the plasma edge is associated with lower \( T_e, n_e \) and the weaker field, \( B_0 \), we conclude that from the result shown in Table I an effective spherical region of \( \sim 2r_p \) does seem to exist where approximately 80% of the incident electron energy is absorbed.
REFERENCES

JET PELLET ABLATION STUDIES AND PROJECTIONS FOR CIT AND ITER*

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Abstract

Pellet penetration in JET under a wide variety of plasma conditions is analyzed and compared with the predictions of the neutral and plasma shielding (NGPS) model for pellet ablation. Specific issues addressed in the context of the NGPS model that impact pellet ablation are the effective ionization radius of the ablatant normal to the magnetic field and the role of non-Maxwellian ions and electrons in the ablation process. The model is then used to evaluate pellet penetration in CIT and ITER.

Nearly all non-ohmic heating techniques produce small populations of energetic electrons or ions. Slowing-down distributions of hydrogenic and helium ions can be used to evaluate thresholds for neutral beam injection and fusion alpha enhanced ablation respectively. Pellet ablation in neutral beam heated plasmas agrees with the fast ion treatment in the NGPS model. Classical, local thermalization of alphas from thermal reactions is shown to lead to no significant pellet ablation enhancement. Energetic distributions without a sharp energy cutoff, as produced with RF heating or runaway discharges, are far more difficult to analyze with simplifying approximations.

Projections for CIT and ITER show that active fueling of the outer half of the plasma volume is most probable for the pellet sizes and velocities considered. Penetration to the plasma center is highly unlikely at the nominal design operating conditions. Thus, it is important to understand transient particle transport under conditions of partial pellet penetration.

1. INTRODUCTION

Pellet penetration in JET is analyzed and compared with predictions of the neutral gas and plasma shielding (NGPS) model for pellet ablation [1]. The model is then used to evaluate pellet penetration in CIT [2] and ITER [3]. A simplified scaling law is derived for pellet penetration when the shielding is dominated by the cold ablatant plasma. Comparison with a similarly derived scaling law for the original neutral gas shielding (NGS) model shows that pellet size and plasma electron temperature dependences are similar, but velocity scaling is reduced or completely absent in the NGPS model. We

1 The members of the JET/USDOE Pellet Collaboration are the authors of the paper entitled 'JET multipellet injection experiments' in these proceedings.
show that projected penetration for higher-velocity pellets may be erroneous with the NGPS model. If the neutral gas shield dominates, as it probably does if the neutral gas shield is elongated along the magnetic field, pellet penetration in JET, CIT, and ITER can be significantly enhanced with higher pellet velocities.

2. THE NEUTRAL GAS AND PLASMA SHIELDING MODEL

The NGPS model for pellet ablation [1] was developed to extend the physics of the original NGS model [4,5]. The original adaptations of the NGS model treated the plasma electrons as monoenergetic; therefore, we began by considering a distribution of electron energies incident on the neutral gas cloud from the background plasma. This extension to a multiple-energy-group formalism also allowed fast ions and alphas to be included in the model. Because of the $1/E_e$ falloff of the stopping cross sections above about 1 keV, we found that electrons in the tail of the distribution contribute disproportionately to the ablation process. To stop these electrons, the neutral gas shield must be thicker than that given in the original model, which leads to enhanced ablation. Comparison with experimental results showed that the model was unduly pessimistic, so additional shielding mechanisms were sought. It was argued that, at some point in the expansion, the ablatant becomes ionized, is trapped by the magnetic field, and could provide the necessary additional shielding. This approach was similar to that of Kaufmann et al. [6], except that, instead of conduction, we considered convection of electron energy through the cold plasma shield. Attempts to derive a simple expression for the effective ionization radius normal to the magnetic field failed, so the ionization radius was left as an empirical parameter. The net result of treating the full electron distribution and the extra shielding was a slight increase in the ablation rate over the original NGS model. These results are discussed more fully in the next section.

Agreement between JET pellet penetration data and the NGPS model may be fortuitous. The additional shielding required to match experimental results may also be provided by an elongated neutral gas shield as described by Kuteev et al. in analysis of T-10 pellet injection data [7]. They also found that electrons with energies of 6–8 keV are primarily responsible for ablation when a full Maxwellian distribution is used, which leads to low projections for the penetration. It was argued that an asymmetry in the neutral gas shield arises naturally from the nonuniform illumination of the pellet because incident electrons are constrained by the magnetic field. To illustrate why either an elongated neutral gas shield or an extended cold plasma shield can lead to agreement with experimental results, we can derive scaling laws for the ablation rates and penetration depths.

A simple scaling law for pellet ablation from the NGS model is given by [8]

$$\dot{r}_p \propto \frac{n_e^{1/3} T_{e}^{5/3}}{\dot{r}_p^{2/3}}$$

where $x = r/a$ is the dimensionless plasma radius at the location of the pellet. Because time, pellet position, and pellet velocity are related by $dt = -a \, dx/v_p$, the above equation can be integrated over pellet radius ($r_{p0} \leq r_p \leq 0$) and position ($1 \geq x \geq \lambda/a$) to relate the pellet penetration depth, $\lambda$, to pellet and plasma parameters. If the plasma electron density and temperature profiles are approximated as linear [i.e., $n_e(x) = n_{e0} (1 - x)$ and $T_e(x) = T_{e0} (1 - x)$], then

$$\left(\frac{\lambda}{a}\right)_{\text{NGS}} = \left(\frac{r_{p0}^{5/3} v_p}{a T_{e0}^{5/3} n_{e0}^{1/3}}\right)^{1/3}$$

where the exponent 1/3 varies somewhat with the assumed profile shape [9].
A scaling law can be derived for pure plasma shielding for comparison. The line-integrated cold plasma density required to stop hot plasma electrons is given by [1]

$$\int n_c \, dl \propto T_e^2(x)$$

where \(n_c\) is the cold plasma shield density. The line-integrated density can also be related to the ablation rate, \(\dot{N}\), the time it takes the pellet to pass through a flux tube bound by its size, \(t_p = 2r_p/v_p\), and the cross section of the tube by

$$\int n_c \, dl = \frac{\dot{N}r_p}{\pi r_p^2 v_p} \propto \frac{r_p \dot{r}_p}{v_p}$$

where the relation \(\dot{N} \propto -r_p^2 \dot{r}_p\) has been used. Thus the ablation rate is given by

$$\dot{r}_p \propto -\frac{T_e^2(x)v_p}{r_p}$$

Converting time and integrating over pellet size and a linear temperature profile yields

$$\left(\frac{\lambda}{a}\right)_{PS} = \left(\frac{r_p^2 v_p}{a T_e^2}\right)^{1/3}$$

The scalings with pellet radius and electron temperature are similar to the NGS model, and the weak density dependence has been lost altogether. In both cases the pellet radius scaling comes from the exposed surface area of the pellet and the temperature dependence comes from the stopping cross sections, which are essentially the same for a gas or cold plasma [1]. The major difference is a lack of velocity scaling in the plasma shielding model. For a physical interpretation of this result, note that the line density in the cold plasma shield is also independent of velocity (i.e., enough mass must be left behind in each tube to stop the hot plasma electrons regardless of the pellet speed). At low enough pellet velocities, the assumption that the cold ablatant plasma and the hot electrons remain separate becomes invalid, thermal mixing occurs, and energy conduction to the pellet surface should dominate.

As Kuteev noted [7] and we concurred [1], elongation of the neutral gas shield along the magnetic field could also provide the extra shielding required to bring the NGS model into agreement with experimental results when a full electron distribution is used. Both neutral shield elongation and plasma shielding are probably present.

3. JET PELLET PENETRATION

Pellet penetration in JET is measured by arrays of soft X-ray diodes that view both horizontally and vertically. For some pellets from the ORNL injector, penetration is also determined by the duration of the signal from an \(H_\alpha\) monitor combined with the pellet velocity as determined from two light diodes. Penetration depths have been calculated for several hundred pellets under a wide variety of plasma conditions by using the NGPS model (with an ionization radius 1 mm greater than the effective spherical pellet radius), and these depths have been compared with the experimental values as shown in Fig. 1 [10,11]. Electron temperature profiles from second-harmonic ECE data and density profiles from an array of FIR chords, as well as plasma geometry from IDENTC, were used as input to the calculations. Average pellet masses were used for the 3.6- and 4.6-mm cylindrical pellets from the single-shot Garching injector [10]. A pellet-by-pellet mass correction was used in the calculations for the 2.7- and 4.0-mm cylindrical pellets from the multi-shot ORNL injector based on data from the microwave cavities [11]. No noticeable deviations occurred with either neutral beam or ICRF heating, even though
fast ion effects were ignored in the calculations—indicating that such effects are not significant in JET. The only noticeable disagreement has been for pellets injected into the current ramp phase of some discharges where runaway electrons were important. In these cases (not shown), the measured penetration was as much as 30–40 cm short of the calculated values.

The NGPS model contains both neutral gas and plasma shields. Because of the similarity in scaling with pellet radius and electron temperature, agreement with experimental penetration data would be insensitive to the relative contributions from neutral gas and plasma shielding as discussed earlier. Lengyel has recently calculated ablative cloud parameters for JET [12] by using a time-dependent model for the expansion of a cold, high-density particle cloud in a magnetically confined plasma [13]. He found that the self-consistently calculated ionization radius was in agreement with the empirical one used to model the JET data. However, the cloud radii calculated for ASDEX and NET were notably different from the radius applicable to JET, calling into question the reliability of the simple empirical constraint on ionization radius derived from the JET results. Any applications to other parameter regimes, such as those considered in the next section for CIT and ITER, must then be viewed with caution.

4. CIT AND ITER PROJECTIONS

Machine parameters for CIT and ITER—both physics (ITER-P) and technology (ITER-T) phases—are shown in Table I and compared with JET parameters typical of most of the pellet injection data to date. The nominal particle contents of both CIT and ITER are expected to be much larger than typical JET conditions—in CIT because of the high magnetic field and in ITER because of the large volume.

Table II shows a selection of pellet sizes and the fractional particle content they represent for each of the devices. The CIT and ITER pellets were chosen to represent nominal 10%, 20%, and 30% density perturbations. The JET pellets represent the selection from the multi-pellet injector. Figure 2 shows the results of pellet penetration calculations for ITER-P. A very weak dependence on velocity indicates that the model
TABLE I. MACHINE PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>JET</th>
<th>CIT</th>
<th>ITER-P</th>
<th>ITER-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$ (m)</td>
<td>2.96</td>
<td>2.10</td>
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<td>0.65</td>
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<td>$\delta$</td>
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<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>$B_T$ (T)</td>
<td>3.0</td>
<td>10.0</td>
<td>5.0</td>
<td>5.3</td>
</tr>
<tr>
<td>$I_0$ (MA)</td>
<td>3</td>
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<td>22</td>
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<tr>
<td>$V_p$ (m/s)</td>
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<td>35</td>
<td>1050</td>
<td>670</td>
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<tr>
<td>$\langle n_e \rangle \times 10^{20}$ m$^{-3}$</td>
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<td>0.4</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$N_e$ (10$^{20}$)</td>
<td>36</td>
<td>140</td>
<td>1050</td>
<td>670</td>
</tr>
</tbody>
</table>

*Typical of pellet-injected plasmas.
*Design parameters for physics phase.
*Design parameters for technology phase.
*N Nominal target density.

TABLE II. PELLET SIZES AND FRACTION OF NOMINAL TARGET PARTICLE CONTENT

<table>
<thead>
<tr>
<th>Spherical radius (mm)</th>
<th>Particle fraction (%)</th>
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</thead>
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<tr>
<td>JET</td>
<td>CIT</td>
</tr>
<tr>
<td>1.4/19</td>
<td>1.7/9</td>
</tr>
<tr>
<td>2.1/65</td>
<td>2.2/19</td>
</tr>
<tr>
<td>3.1/225</td>
<td>2.5/28</td>
</tr>
</tbody>
</table>

FIG. 2. Pellet penetration calculated with the NGPS model for the ITER-P parameters showing fractional radius penetrated as a function of (a) $r_p$, (b) $v_p$, and (c) $T_e(0)$; and (d) fractional volume penetrated as a function of $T_e(0)$. Also shown is the simplified scaling of the NS model.
is dominated by the cold plasma shield. Very similar results are obtained, both 
qualitatively and quantitatively, for CIT and ITER-T by using the pellet selection of 
Table II. It is apparent from the lack of velocity scaling in these calculations that the 
NGPS model predicts that ablation is dominated by the plasma shield Only at, the 
highest velocities does the penetration begin to improve because the pellet starts to 
outrun the plasma shield and become influenced by the neutral gas shield. The velocity 
projections for JET have also been examined with the NGPS model and show the same 
behavior.

For reference, curves showing the simple NGS scaling are also shown in Fig. 2. With 
\( v_p^{1/3} \) scaling from a nominal 1-km/s pellet, penetration projections for ITER, CIT, and 
JET are greatly improved with injection velocities of 5 km/s.

Controlled experiments with fixed pellet size and plasma conditions could be used 
to examine velocity scaling and determine the relative importance of the neutral gas 
and plasma shields. Experiments to date have concentrated on running injectors at 
near-maximum velocity, so databases normally cover a very narrow velocity range. An 
exception is the ASDEX data that cover \( v_p = 0.4-1.0 \) km/s. Velocity scaling was not 
examined as a separate parameter, but Büchel noted a correlation between penetration 
and the lumped parameter \( Z = r_p 5/3 \frac{r_p}{n_e 0} l_{\perp 0}^{5/3} \) [9].

5. CONCLUSIONS

The NGPS model for pellet ablation shows agreement with JET penetration data 
for a range of pellet sizes and plasma conditions. However, in the scaling with these 
parameters no distinction is expected between plasma or neutral gas shielding. The 
velocity range of the data is small, so the very weak velocity dependence of the NGPS 
model has not been tested; it should be tested experimentally before relying on velocity 
projections of the NGPS model. If a velocity dependence is observed in experiments, it 
would lend support to a model that relies on enhanced shielding from an oblate neutral 
gas cloud. The ionization radius normal to the magnetic field determines the relative 
importance of neutral gas shielding and plasma shielding in the NGPS model and has 
been chosen empirically. It is sensitive to asymmetries in pellet ablation produced by 
the anisotropic energy flux from the plasma and to local high beta (magnetic shielding) 
effects that cause the magnetic field lines to bend around the pellet cloud. Ionization 
closer to the pellet surface and magnetic shielding cause the ablatant to be restricted to 
a smaller-diameter flux tube and to be more effective at shielding energetic plasma 
electrons. Model development is needed for a fully self-consistent treatment of an 
asymmetric neutral gas shield, a plasma shield, and magnetic shielding.

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be published.
STATUS OF PELLET-PLASMA INTERACTION STUDIES AT GARCHING

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Abstract

Massive neutral particle sources, such as pellets injected into tokamaks, may notably affect both the local state parameters of the target plasma and the equilibrium state of the discharge at large. Indeed, since the energy influx affecting the neutral mass locally deposited is defined by the thermal or directed velocities of the energy carriers in the hot background plasma (thermal electrons, etc.), and the energy efflux from the source region is defined by the hydrodynamic (convective) velocity of the cold particles heated, the deposited mass may serve as a transient energy accumulator that depletes the energy of the rest of the energy reservoir (flux tube) affected, and may have state parameters much different from those of the background plasma. The local disturbance amplitudes caused by ablating pellets in tokamaks can be computed by means of a hydrodynamic model supplemented by the neutral-gas-plasma-shielding ablation model. The model computes, for a given local particle deposition rate, the time histories of the ablatant cloud parameters such as cloud radius, cloud length, electron density, temperature, cloud beta, etc. at a succession of magnetic flux surfaces. Computations have been performed for a number of tokamaks with different plasma parameter ranges (TFR, T-10, ASDEX, JET, NET, etc.) and the results are compared with the experimental data available (PLT, TFTR, ISX-B, TFR, and TEXT). The feedback between the local plasma parameter disturbances and the ablation rates calculated as well as the problems associated with predictive calculations are discussed.

Recently, a time-dependent MHD model was presented that allows one to compute the temporal evolution of particle clouds surrounding ablating pellets in tokamak plasmas [1]. These clouds initially consist of neutral particles that are continuously heated by the incident plasma particles. Once the particles become ionized, they interact with the applied magnetic field and are confined to magnetic flux tubes with radii proportional to the ionization radius. The ionization and confinement radii, on the other hand, are functions of a number of parameters: the total number of particles locally deposited, the energy flux affecting the cloud, and the strength of the magnetic field applied. The radius of the cloud surrounding the pellet affects the density of the confined plasma slug and hence the effectiveness of the shielding of the pellet against the incident plasma particles. Calculation of the shielding cloud evolution may be repeated at a sequence of magnetic flux surfaces in a tokamak, thus providing information on the radial distribution of the disturbance amplitudes caused by a pellet injected into a tokamak.

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I. Magnitude of disturbance amplitudes

In the majority of calculations presented here, measured electron temperature and density profiles were fed to the NGPS ablation model [2], which was coupled to the cloud expansion model [1]. Moreover, since the radius of the shielding cloud is an open parameter in the ablation model, cloud radius feedback ($R_{ci}$ feedback) was established between the cloud expansion and ablation models. Some representative results obtained for an ohmic ASDEX discharge are described in this section. For further results pertaining to discharges in TFR, T-10, ASDEX, TFTR, and TEXT, and to pellet injection scenarios in JET and NET the reader is referred to [1].

The electron temperature and electron density profiles prevailing in ASDEX discharge 24269 just before injection of the second pellet are reproduced in Fig. 1 (results based on

![Figure 1: ASDEX ohmic discharge (shot no. 24269), measured electron temperature, electron density, and $H_a$ emission profiles. The limits of the estimated pellet ablation length (penetration depth) are shown under the $H_a$ curve.](image-url)
HCN interferometry and Thompson scattering involving a YAG laser). The $H_\alpha$ emission curve shown in this figure may be used to estimate the pellet lifetime or, alternatively, for a given (constant) pellet velocity the pellet penetration depth. In the given case, a $D_2$ pellet with an effective radius of 0.75 mm (accounting for the fact that only 80% of the original pellet mass was recovered in the plasma) was injected at a velocity of 570 m/s. As can be seen, the penetration depth is between 20 and 26 cm. The measured $n_e$ and $T_e$ profiles were put into the ablation code and, by using the 10-electron energy group option provided in [2], the ablation rate was computed at a sequence of flux surfaces. The ablation rates were transferred to the cloud expansion model, and the corresponding radial distributions of various cloud characteristics were computed. Figure 2 shows the resulting distributions of the local shielding cloud radius $R_{cl}$, the length of the cloud at

![Graphs and plots](image-url)

Figure 2: Ablation cloud characteristics computed for ASDEX shot no. 24269 (see Fig. 1): quasi-equilibrium cloud radius $R_{cl}$, cloud length when full ionization is reached $Z_f$, ablation rate $\dot{N}_{ab}$, local electron density maximum $n_{e\,max}$, local beta maximum $\beta_{\max}$, and relative perturbation amplitude of the magnetic field $\Delta B/B$. 

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the moment when a bulk ionization degree of \( \approx 1 \) \( (0.995) \) is reached, the ablation rate, the local \( n_e \) spike value, \( \beta_{\text{max}} \), and the relative amplitude of the m.f. disturbance \( \Delta B/B \). In all these calculations the \( R_{cl} \) feedback to the ablation model was active. As can be seen, the local disturbances, which are of a spike nature (\( \mu s \) time scale), are rather large. The pellet penetration depth associated with the computed pellet lifetime is 24.9 cm, which is in reasonable agreement with the \( H_\alpha \) emission trace.

II. Ablation rate - shielding radius relation

Two options are available in the NGPS ablation code [2]: constant shielding cloud radius during the ablation, i.e. \( R_{cl} = \text{const} \), or a shielding cloud radius that is proportional to the pellet radius (minimum cloud radius and thus maximum shielding at the end of the pellet lifetime): \( R_{cl} = r_p + \text{const} \). In a set of JET validation calculations, reasonable agreement with measured penetration depths was obtained by assuming \( R_{cl} = 3.5 \) mm [3]. The best fit was obtained by assuming \( R_{cl} = r_p + 1 \) mm [3]. On the other hand, Gouge et al. reported that, in order to reproduce pellet penetration depths measured in different tokamaks, the (assumed) shielding cloud radius had to be varied by a factor of 10 [4].

The effect of the assumed shielding cloud radius on the ablation rate and the cloud characteristics is shown in Fig. 3. Here the ablation rate and the beta peak distributions are shown for the ASDEX discharge of Figs. 1 and 2 (shot 24269) but are now computed in three different approximations: (a) \( R_{cl} = r_p + 1 \) mm, (b) \( R_{cl} = 3.5 \) mm, (c) \( R_{cl} = R_{cl} \) (feedback). Obviously, in case “a” a much too small cloud radius has been assumed: owing to increased shielding the pellet penetrates almost up to the plasma centre. The 3.5 mm average cloud thickness assumed in case “b” seems to be a better assumption (but still somewhat optimistic). The actual cloud radius varies between \( \sim 2.5 \) mm at the plasma edge and \( \sim 4.8 \) mm in the region of intense ablation (see Fig. 2). The penetration depth limits deduced from the \( H_\alpha \) emission trace are indicated by horizontal bars under the ablation curves.

The results of calculations reported here and elsewhere [1] show that, in general, the cloud radius increases with the total number of cold particles locally deposited (i.e. with the local ablation rate). Hence the two options “a” and “b” offered in [2] and [3] for approximating the cloud radius may be supplemented by a third one:

\[
R_{cl} = \frac{c_1}{r_p + c_2},
\]

where \( c_1 \) and \( c_2 \) are “constants” to be determined by fitting calculated penetration depths to measured ones. In reality, \( c_1 \) and \( c_2 \) are functions of at least three major parameters: pellet size, applied magnetic field strength, and energy flux affecting the cloud.

III. Stopping length calculations

To afford a better understanding of the pellet heating and ablation processes stopping length calculations were performed for the dynamic expansion phase of the shielding cloud. In the given case, only thermal electrons moving along the magnetic field lines were considered. Results pertaining to ASDEX shot \# 24269 can be summarized as follows (a flux tube of \( \Delta r = a/50 \) is considered at \( r/a = 0.58 \); pellet residence time: 14 \( \mu s \)): (1) Decay lengths for electron energy (“ee” and “ea” collisions): \( 2 \times 10^{-1} \) m (ee) and \( 9 \times 10^{-4} \) m (ea), respectively, at a time instant when the bulk ionization degree \( \alpha \) is \( \sim 10^{-4} \); and \( 4 \times 10^{-4} \) m (ee) and \( 6 \times 10^{-1} \) m (ea) when \( \alpha \) approaches unity. The two decay lengths become equal at a bulk ionization degree of \( \sim 2 \% \), “ee” collisions being dominant.
Figure 3: Ablation rates and maximum beta values computed for the ASDEX discharge of Figs. 1 and 2 in three different approximations:
(a) shielding cloud radius proportional to pellet radius: \( R_{cl} = r_p + 1 \) mm;
(b) constant shielding cloud radius: \( R_{cl} = 3.5 \) mm;
(c) shielding cloud radius computed by means of the cloud expansion model (\( R_{cl} \) feedback active).

The limits of the measured pellet penetration depth are shown by horizontal (error) bars under the ablation curves.

(2) The energy flux decay length has its first maximum (~ \( 9 \times 10^{-4} \) m) when \( \alpha \approx 2 \) %, decreases to about \( 4 \times 10^{-4} \) m when full ionization is reached, and increases again, reaching about \( 10^{-3} \) m by the end of the residence time (volumetric dilution effect). The ratio of the energy flux decay length to cloud length reaches its maximum (~ 0.3) when \( \alpha \) becomes ~ 2 % and continuously decreases afterwards. At the end of the residence time, this ratio becomes ~ \( 10^{-3} \), i.e. during this time the cloud length increases faster than the energy decay length. (3) During the entire residence time of the pellet in the flux tube considered (not counting the first contact with the plasma), the pellet is heated by the cloud electrons. Their energy deposition depth in the pellet does not exceed ~ \( 2 \times 10^{-8} \) m during the first 14 \( \mu \)s of the cloud expansion time.
IV. Particle deposition with allowance for neutral cloud expansion effects

Since the initial expansion velocity of the neutral cloud may considerably exceed the flight velocity of the pellet (10^4 m/s compared with typically 10^3 m/s), the pellet particles may become ionized and confined to magnetic flux surfaces at some distance from the pellet location. Since cloud expansion transports particles in both the forward and backward directions, its effect usually cancels in the bulk of the plasma. (Notable differences may, however, remain at the edges of the deposition zone.) However, since cold neutral particles are being continuously deposited ahead of the flying pellet, the pellet moves all the time in an atmosphere notably different from the background plasma. This effect may have to be taken into account in ablation rate calculations.

V. Summary

(1) The disturbance amplitudes caused by ablating pellets are rather large: \( n_{\text{emax}} = 0(10^{24} \text{ m}^{-3}) \), \( T_e (n_{\text{gmax}}) = 0(2 \text{ to } 4 \text{ eV}) \), \( \Delta B/B = 0(0.3 \text{ to } 1) \). The additional shielding caused by the magnetic field perturbation (formation of a diamagnetic bubble) may be substantial.

(2) The magnitude of the shielding cloud radius \( R_{\text{cl}} \propto \text{const}/(\text{const} + r_p) \) notably affects the ablation rate. \( R_{\text{cl}} \) should be calculated in predictive pellet injection scenarios.

(3) The stopping length calculations indicate that "ee" collisions dominate if the bulk ionization degree of the cloud exceeds a few per cent. The pellet is exposed primarily to the electrons of the shielding cloud. Hence the state parameters of the cloud are of primary importance in ablation rate calculations.

(4) Non-local particle deposition does not substantially change the mass deposition curve. However, since the cold ablated particles precede the pellet, additional shielding results, a fact that may gain importance for reactor-grade plasmas.

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PELLET INJECTION INTO OHMICALLY AND ADDITIONALLY ELECTRON CYCLOTRON RESONANCE HEATED TOKAMAK PLASMAS

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Abstract

Frozen \( ^2 \)H and \( ^2 \)O \(_2 \) pellets were injected into ohmically and additionally electron cyclotron resonance heated (ECRH) plasmas of the FONTENAY-AUX-ROSES tokamak TFR. Without ECR heating the pellets penetrate deeply into the plasma and the ablation clouds are striated. The ablation rate is higher than predicted by the neutral shielding model. Pellet injection during ECRH leads to enhanced ablation in the outer plasma region. The position of the ECR layer has practically no influence on the penetration depth which is reduced to a few centimeters. On the photographs the ablation clouds show no particular structure when ECRH is applied. Only 2/3 of the pellet mass is found as ionized matter in the plasma, compared to the ohmic case. Radial electron density profiles have been simulated and compared with the measured ones. Broad quantitative agreement is obtained when one assumes that in the presence of ECR waves a low-density, hot electron group causes enhanced ablation in the plasma periphery and the limiter shadow.

INTRODUCTION

The injection of high-speed frozen hydrogen and hydrogen isotope pellets into magnetically confined plasmas in tokamaks and stellarators is a powerful tool to maintain or to increase the plasma density, to act on the radial density profile and to improve the plasma performances in general, see e.g. [1-10]. It is in particular important that this fuelling mechanism is maintained during additional heating of the plasma and induction-less current drive in tokamaks. A reduction of pellet penetration during high-power neutral beam heating (NBH) has been observed (DOUBLET III [4, 11], ASDEX [12, 13], HELIOTRON [14]), whereas low-power NBH has virtually no influence on penetration (HELIOTRON [14], JFT-2M [15], TFR [16]). Considerable reduction of penetration during ECRH was observed in the W VII-A stellarator [8] and TFR [17], no such reduction was found in DOUBLET III [11] although increased pellet ablation occurred during lower hybrid resonance heating [18], see also [11]. For JET plasmas, no additional ablation processes associated with the application of ion cyclotron resonance heating and NBH have been identified at the relative low-power levels which were applied [18].

Owing to this situation further refined experimental data are useful and numerical simulations are desirable in order to understand the underlying physical processes causing enhanced ablation. The present paper summarizes the TFR results.
EXPERIMENTAL SET-UP

Single undoped solid H₂ and D₂ pellets were injected into TFR plasmas (major radius $R_0 = 0.98$ m; plasma radius $a = 0.18 - 0.20$ m; radius of chamber $r_Q = 0.26$ m) using a pneumatic pellet injector. The pellets were injected radially with a velocity of $v_p = 700$ m/s (± 10 %). The pellet trajectory and the ablation cloud were photographed under an oblique angle of ~ 45° with respect to the injection plane. The H₂ (D₂) emission was measured with a fast acquisition device.

The ECR waves (ordinary mode, frequency $v_{EC} = 60$ GHz) were launched by three waveguide antennas placed at a torus port nearly opposite to the pellet injection port. The experiments were carried out at $B_0 = 2.1 - 2.4$ T, $I_p = 110 - 120$ kA. Without ECRH, the plasma parameters were $T_e(0) = 1$ keV, $<n_e> = 1.7.10^{19}$ m⁻³, ohmic power = 150 kW. With ECRH ($\Delta t = 100$ ms) and according to the number of gyrotrons (1, 2 ou 3), the plasma absorbed between ~ 150 to 450 kW when the resonance layer was situated at $r = 0$. The position of the resonance layer was changed by changing $B_0$.

Abel-inverted radial electron density profiles $n_e(r)$ were calculated from 8 chord-integrated IR laser interferograms measured in temporal distances of $\Delta t \sim 400$ µs. The radial electron temperature profiles $T_e(r)$ were measured using Thomson scattering and EC emission at twice the resonance frequency.

EXPERIMENTAL RESULTS

1. Injection into ohmically heated plasmas

Figure 1 shows $n_e(r)$ before and shortly after injection of an H₂ pellet. Also shown in the intensity $I(H_\beta)$ of H₂ emitted during the penetration of the pellet into the plasma. It is placed at the correct radial position by means of the photography. Prior to injection the plasma already shows an inward displacement relative to the center of the chamber. In the present series of experiments an average pellet penetration depth of $L_p \sim 10 - 12$ cm was measured. The pellets did not reach the $q = 1$ surface situated at appr. $r = 4.5$ cm from the plasma center.

Figure 1: Radial profiles of $n_e(r)$ before and after pellet injection and $H_\beta$ line intensity $I(H_\beta)$. Ohmically heated plasma.
For identical discharges, the radial positions of the striations were not reproducible. The time interval between two successive bright (or dark) zones gets smaller with increasing penetration depth, as if this interval depends on the ablation rate or on the pellet dimension. It was not possible to place either all bright or dark zones at values of the safety factor \( q = m/n \) for which both mode numbers \( m \) and \( n \) are reasonably small.

Figure 3 shows the measured \( T_e(r) \) profiles.

2. Injection into ECR heated plasmas

Figure 2 shows the \( n_e(r) \) profiles before and shortly (i.e. between 400 and 800 \( \mu s \)) after pellet injection and the emitted \( H_\beta \) intensity. There is no exception from the two radial \( H_\beta \) intensities shown. The ablation takes place in the outer region of the plasma and in the limiter shadow. Only 2/3 of the pellet mass is found as ionized matter, compared to injection into ohmically heated plasmas. No striations can be seen on the photographs; the visible emission extends in toroidal direction over the whole region seen by the optical device (appr. 25 cm), with a sharp luminous border in radial direction. There is no exception from this feature.

The photomultiplier signals exhibit virtually no fluctuating ablation, with the exception of only a few cases showing a very weak modulation of light emission (a few per cent) during the beginning of the ablation process.

The \( T_e(r) \) profiles for ECRH with one, two and three gyrotrons are given in Figure 3. The EC measurements are not very reliable, they may rather be considered as an indication that high-energy electrons are present.

Figure 4 gives the radial position of the emission maxima of \( H_\beta \) as a function of the radial position of the ECR layer for all exploited experiments. There is virtually no influence of the position of the resonance layer and of the number gyrotrons applied on the position of the emission maxima.

Figure 2: Radial profiles of \( n_e(r) \) before and after pellet injection and \( H_\beta \) line intensity \( I(H_\beta) \). Additionally ECR heated plasma (2 gyrotrons, \( \sim 300 \) kW absorbed HF power).
NUMERICAL SIMULATION, INTERPRETATION

1. Ohmically heated plasmas

The particle deposition profile can be reproduced (without the fluctuations) by the Parks and Turnbull formula [20] \( \text{cm}, \text{cm}^{-3}, \text{eV}, r_p = \text{pellet radius in cm} \)

\[
\frac{dr_p}{dt} = C_0 10^{-8} r_p^{-2/3} n_e T_e^{1.64} \text{ cm/s} \tag{1}
\]

with \( C_0 = 1.72 \) for \( \text{H}_2 \) pellets and \( \alpha \) lying between 0.360 and 0.370. The initial pellet radius has been calculated from the deposited electron density assuming spherical pellets. The original value [20] of \( \alpha = 1/3 \) gives too a deep penetration.

2. ECR Heated plasmas

Applying Eq. (1) to the ECR heated plasmas with the \( n_e(r) \) and \( T_e(r) \) profiles measured just before injection (see e.g. Figs. 2 and 3) does not permit describing the \( \text{H}_8 \) intensity and the \( n_e(r) \) profiles after injection, since the ablation rate is too weak between \( r = 26 \) and 20 cm (limiter shadow) and in the plasma periphery. To increase the ablation rate we have assumed that ECRH favours the existence of a "hot" electron...
group which extends to the walls. The pellet is then simultaneously submitted to the bulk plasma electrons (measured profiles $n_e(r)$ = $n_e(1)(r)$, $T_e(r)$ = $T_e(1)(r)$) and a second electron group of low density $n_e(2)$ and high temperature $T_e(2)$. The choice of $n_e(2)$, $T_e(2)$ is arbitrary; but once $n_e(2)$ is fixed, the choice of $T_e(2)$ is very limited because of the $T_e 1.64$ dependence in Eq. (1). In the following we chose $n_e(2)$ = $1.5 \times 10^{16}$ m$^{-3}$. Both groups ablate simultaneously according to Eq. (1).

We will assume that the $H_2$ pellet enters the chamber at time $t_0 = 0$. The pellet mass is the same as for ohmically heated plasmas. The ablation is terminated at $t = t_0'$. From the number of atoms deposited per unit path length, $dN_a/dr$, follows the $n_e(r)$ profile at $t_0'$ assuming rapid ionization and redistribution of matter on the magnetic surfaces and no appreciable radial diffusion during this short time interval. Figure 5 shows $n_e(r)$ profiles calculated in this way for three $T_e(2)$ values.

The $n_e(r)$ profile at $t_0'$ is then taken as initial profile in the transport code MAKOKOT [21]. $n_e$ has been constrained to fall linearly from $<n_e>$ = $1.7 \times 10^{19}$ m$^{-3}$ at $t = t_0'$, $t_0'$ = $1.3 \times 10^{19}$ m$^{-3}$ at $t = t_0' + 0.5$ ms, in agreement with the measurement at $t = t_0' + (0.4 - 0.8)$ ms. The evolution of the $n_e(r)$ profiles has been calculated for different anomalous radial convection velocities $v_A$.

Figure 6 shows the temporal evolution of $n_e(r)$ for the initial profile with $T_e(2)$ = 1.4 keV in Fig. 5 and putting $v_A$ = 40 m/s. Broad agreement between the measured profile at $t = t_0' + (0.4 - 0.8)$ ms and the calculated one at $t = t_0' + 0.5$ ms is obtained. Also the position of the $H_B$ intensity peak is well reproduced with these values for $n_e(2)$ and $T_e(2)$.
Figure 6: Temporal evolution of electron density profiles \(n_e(r)\). Comparison of calculated with measured profiles.

Other values of \(n_e(2), T_e(2)\) will lead to the same results. Physical arguments support the values assumed in the present simulations rather than electron energies in the 10 keV to 30 keV range. The important fact is that only the assumption of two electron groups brings the simulation in agreement with the experiments.

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VI. PELLET INJECTORS
PNEUMATIC PELLET INJECTOR RESEARCH AT ORNL*

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Abstract

Advanced pneumatic-injector-based pellet fueling systems are under development at Oak Ridge National Laboratory (ORNL) for fueling magnetically confined plasmas. The general approach is that of producing and accelerating frozen hydrogen isotope pellets at speeds in the range from 1 to 2 km/s and higher. Recently, ORNL provided pneumatic-based pellet fueling systems for the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET), and a new simplified eight-shot injector has been developed for use on the Princeton Beta Experiment (PBX) and the Advanced Toroidal Facility (ATF). These long-pulse devices operate reliably at up to 1.5 km/s with pellet sizes ranging between 1 and 6 mm. In addition to these activities, ORNL is pursuing advanced technologies such as the electrothermal gun and the two-stage light-gas gun to achieve pellet velocities significantly in excess of 2 km/s and is carrying out a tritium proof-of-principle (TPOP) experiment in which the fabrication and acceleration of tritium pellets to 1.4 km/s were recently demonstrated.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) has been developing pellet injectors for several years [1-15]. These devices produce frozen hydrogen isotope pellets and then accelerate them to speeds in the range of 1 to 2 km/s by either pneumatic (light-gas gun) or mechanical (centrifugal force) techniques. The designs developed include single-shot guns [2, 4, 7, 11, 15], multiple-shot (four- and eight-pellet) guns [3, 8, 12], machine-gun (single- and multiple-barrel) types [5, 6, 9, 10], and centrifugal accelerators [14]. These injectors have been used to inject hydrogen and deuterium pellets into plasmas on numerous tokamak experiments [16-21]. Recently, ORNL provided pellet fueling systems for the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET). The TFTR eight-shot pneumatic injector is described in Ref. [8]. The three-barrel repeating pneumatic injector [9, 10], which is briefly described here, is the central ingredient in the collaboration between the U.S. Department of Energy (DOE) and the European Atomic Energy Community (EURATOM) on plasma fueling. This injector, installed on JET in 1987, has been used in experiments during the last year. A new version of the centrifuge pellet injector for the Tore Supra tokamak is nearing completion. It will be featured in a collaboration with the Commissariat à l'Énergie Atomique (CEA). In the ORNL-CEA collaboration, long-pulse, reactor-relevant tokamak discharges with simultaneous plasma fueling and exhaust capabilities will be studied. Here we describe the pneumatic injector research activities at ORNL. The status of the centrifuge injector and a unique ultrahigh-velocity concept based on an electron beam-driven thruster are described in a companion paper by C. A. Foster et al. [22].

2. CONVENTIONAL PNEUMATIC PELLET INJECTORS

2.1. Three-barrel repeating pneumatic injector for JET

For plasma fueling applications on JET, a pellet injector based on the prototype repeating pneumatic design [5, 6] was developed. The original repeating pneumatic injector used in the initial pellet fueling experiments on TFTR [20] is described in Ref. [23]. In this gun-like device, a cryogenic extruder supplies a continuous stream of deuterium ice to the gun section where

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individual pellets are repetitively formed, chambered, and accelerated. The new device (Fig. 1) [9, 10] consists of three independent machine-gun-like mechanisms in a common vacuum enclosure and features three nominal pellet sizes (2.7-, 4.0-, and 6.0-mm-diam) and repetitive operation (5, 2.5, and 1 Hz, respectively) for quasi-steady-state conditions (>10 s). The pulse length is limited only by the capacity of the solid hydrogen extruder. Pellet speeds are typically 1.2 to 1.5 km/s with deuterium pellets. An example of recent pellet injector performance on JET is shown in Fig. 2, where the line-averaged plasma density is plotted as a function of time for 3-MA discharges with 6 MW of ICRF heating and fueling sequences consisting of 4-mm pellets injected at 1 Hz and 2.7-mm pellets injected at 4 Hz.

FIG. 1. Three-barrel repeating pneumatic pellet injector for JET.

FIG. 2. Density evolution in 3-MA, 6-MW ICRF-heated JET discharges.
2.2. Simplified eight-shot pneumatic pellet injector

A simplified eight-shot pneumatic pellet injector [12] developed at ORNL is the basis for plasma fueling systems for the Princeton Beta Experiment (PBX) and the Advanced Toroidal Facility (ATF). This injector is based on the so-called "pipe-gun" concept, in which deuterium and hydrogen pellets are formed by direct condensation in a one-piece, stainless steel gun barrel, a segment of which is held below the hydrogen triple-point temperature by contact with a liquid-helium-cooled block. Pellet length is controlled both by regulating the gas fill pressure and by establishing temperature gradients along the barrel tube with auxiliary heating collars. This injector (Fig. 3) features eight independent gun barrel assemblies (Fig. 4) mounted around the perimeter of a single cold block, each coupled to an ORNL-designed fast propellant valve [13].

FIG. 3. Schematic of PBX eight-shot pipe-gun injector.

FIG. 4. Gun barrel assembly details for the PBX eight-shot pipe-gun injector.
The injector can inject up to eight pellets of sizes ranging from 1 to 3 mm in diameter in arbitrarily programmable firing sequences at speeds up to $\approx 1.3 \text{ km/s}$. Each gun is equipped with breech-side and muzzle-side deuterium fill valves. The entire pellet mass range from 1 to 30 torr-L is accessible merely by varying the fill conditions and the choice of pellet sizes.

### 3. HIGH-VELOCITY PNEUMATIC PELLET INJECTOR RESEARCH

#### 3.1. Hydrogen electrothermal accelerator

A prototype accelerator \[24\], consisting of a vortex-stabilized arc discharge plasma generator coupled to the breech tube of a "pipe-gun" pneumatic pellet injector, has been developed and operated. The arc chamber is designed for arc initiation at pressures of 1 to 4 bar. Electrical power is supplied to the arc from a capacitor bank supply and from an LC-line pulse transformer supply, which can produce 1-ms pulses at 5-kA currents into 0.1-$\Omega$ loads. The arc is triggered as hydrogen gas is admitted into the arc chamber; the Ohmic dissipation increases the rate of rise of the gun breech pressure from 30 bar/ms to $> 100$ bar/ms. Muzzle velocities increase from 1.3 to 2.0 km/s for 10-mg hydrogen pellets; these increases represent a 5 to 10% conversion of electrically dissipated energy to projectile kinetic energy. The electrothermal gun performance agrees with an ideal gas gun code calculation that assumes a propellant gas temperature of 2000 K. This suggests that substantial propellant heating has resulted in the desired increase in propellant sound speed.

#### 3.2. Two-stage light-gas gun

ORNL is developing a two-stage light-gas gun \[25\] to accelerate pellets to high speeds. Two other research groups \[26, 27\] are also developing this technique. In the initial configuration of the two-stage device (Fig. 5), a 2.2-L volume (pressure $\leq 55$ bar) provides the gas to accelerate a 25.4-mm-diam piston in a 1-m-long pump tube; a burst disk or a fast valve initiates the acceleration process in the first stage. As the piston travels the length of the pump tube, the downstream gas (initially at $< 1$ bar) is compressed adiabatically. The typical pressure pulse shown in Fig. 6 was obtained with a peak piston speed near 400 m/s. Temperatures above 7000 K are inferred from an isentropic compression calculation. The increased sound speed resulting from the high temperature provides an effective way to overcome the basic limitation of the single-stage light-gas gun. In preliminary tests that used helium as the driver in both stages, 35-mg plastic pellets were accelerated to speeds as high as 4.5 km/s in a 1-m-long gun barrel. As soon as the gun design and operating parameters are optimized, projectiles composed of hydrogen ice with masses in the range of 5 to 20 mg ($\rho \approx 0.087, 0.20$, and 0.32 g/cm$^3$ for frozen hydrogen isotopes) will be accelerated. The hardware is being designed to accommodate repetitive operation as a natural extension of the repeating pneumatic injector technology already developed at ORNL.

![Schematic of ORNL two-stage light-gas gun](image-url)
A Lagrangian two-stage ballistics code was obtained from the Arnold Engineering Development Center and modified to model both single- and two-stage gas guns. The code can model either real (variable specific heat) or ideal gases and includes parasitic losses such as piston friction, heat transfer, and smooth-wall or constant-friction factor viscous losses.

When the code was used in the single-stage pneumatic mode to model single-stage injector data, the best agreement was obtained with the ideal gas equation of state and smooth-wall gas friction. With the two-stage version of the code, gas friction is the dominant nonideal effect; heat transfer and piston friction accounting for only 10% of the energy loss due to smooth-wall gas friction. The results of initial modeling of the two-stage experiments using both 25.4-mm-diam and 51-mm-diam pump tubes agree with the measured data within 10 to 15%. This agreement was obtained with a model using ideal helium gas, Reynold's analogy heat transfer losses, piston friction, and gas friction based on actual surface roughness measurements of the 4-mm-diam barrel. The code is particularly useful in predicting the effect of parameter changes on gun performance.

4. TRITIUM PELLET INJECTOR EXPERIMENT

The properties of tritium, especially its radioactive decay, are quite different from those of the other hydrogen isotopes. Decay heating, the production of $^3$He and its effect on the physical properties of solid tritium, the need for tritium-compatible materials of construction, and use of double containment to prevent tritium release are all problems unique to tritium.

A fully instrumented and automated pipe-gun-based injector has been developed for the tritium proof-of-principle (TPOP) experiment (Fig. 7) [11, 15]. The objective of the TPOP is to demonstrate the feasibility of forming and accelerating 4-mm $T_2$ and DT pellets to speeds of...
The pipe gun is ideal for tritium service because there are no moving parts inside the gun and no excess tritium is required in the pellet production process. A schematic of the TPOP cryostat is shown in Fig. 8. A cryogenic separator inside the vacuum housing removes $^3\text{He}$ from tritium to prevent blocking of the cryopumping action by the noncondensible gas. In tests at ORNL, the device accelerated unity-aspect-ratio 4-mm $\text{D}_2$ pellets (47 torr-L) to 1.85 km/s. It has since been installed and operated with tritium in the Tritium Systems Test Assembly at Los Alamos National Laboratory. Although this experiment is still in its preliminary stages, we have already shown that $\text{T}_2$ and equilibrium DT ($\text{T}_2 = \text{D}_2 = 25\%$, DT = 50\%) pellets can be formed and accelerated to 1.4 km/s. Figure 9 is a photograph of a $\text{T}_2$ pellet at the muzzle of the gun; Fig. 10 shows velocities for both deuterium and tritium pellets as a function of propellant gas pressure. The tritium velocities are lower because of the higher mass density of tritium ice.

![FIG. 8. TPOP cryostat details.](image)

![FIG. 9. Photograph of tritium pellet.](image)
The presence of $^3$He in the T$_2$ fuel has proven to be the largest obstacle to the production of pellets of good consistency. The condensation process in the pipe gun is generally inhibited at $^3$He concentrations above 0.05%. Also, a higher fill pressure (60 torr versus 20 torr) is required to form T$_2$ pellets of the same size as the D$_2$ pellets for the same cryostat temperature (10 K). This may result from internal decay heating (1 W/cm$^3$) or from a lower-than-expected thermal conductivity of the T$_2$ ice.

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THE JET MULTI-PELLET INJECTOR
AND ITS FUTURE UPGRADES

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Abstract

The present multi-pellet injector operating on JET is equipped with three repetitive pneumatic guns for three different pellet sizes capable of pellet speeds to 1.5 kms$^{-1}$. It has now been operated for more than one year according to its specification, satisfactorily and successfully, and only minor improvements have been made during that time. The best plasma performance in its application has so far been achieved with pellet deposition near the magnetic axis now possible only with relatively cold plasmas [1]. For a given plasma the pellet speed is the only free parameter with regard to the penetration depth, since the pellet size determines the number of particles delivered to the plasma. In order to enable the central deposition also at higher plasma temperatures JET plans to employ an advanced gun system following the principles of hot pneumatics by adiabatic compression in two-stage guns capable of launching initially single, and in a later version multiple, pellets with velocities towards the 5 to 10 kms$^{-1}$ range. We will describe here the present injector - concentrating on the launcher-machine interface and its upgrading - the development programme directed to make a single-pellet high-speed launcher possible and the planning of the implementation of this prototype launcher, as well as briefly outline the preparations for a future multi-pellet launcher system following from the prototype.

1. THE JET MULTI-PELLET INJECTOR

The presently installed injector has been jointly built by JET and the Oak Ridge National Laboratory (ORNL) under a collaborative agreement between the Joint European Torus and the United States Department of Energy which also covers the joint experimental programme for two operational periods from 1987 until 1990. A three-barrel repetitive (up to 5 s$^{-1}$) pneumatic pellet launcher for nominal pellet sizes of 2.7, 4 and 6mm (length and diameter) - built by ORNL - is attached to a JET launcher-machine interface (Pellet Interface) which provides all services to the launcher and its immediate control system and, in particular, provides the differential pumping to match the pneumatic gun to the vacuum pressure and flow requirements of the plasma boundary. The launcher, forming its pellets by punching them with the barrel breech out of an extruded ice ribbon, is capable of accelerating pellets of hydrogen or deuterium, in numbers more than sufficient for JET (up to 32 per tokamak pulse and barrel), with speeds up to 1.5 kms$^{-1}$; more details can be found in [2]. With its internal gas feed system the three guns can simultaneously operate only with pellets of one sort of fuel and with a common driver gas pressure; no provision could be made to make the launcher compatible with the requirements of tritium operation and remote handling for the active phase of JET.
The Pellet Interface was from the start conceived to match the ORNL Launcher to the JET machine as well as to allow - with a minimum of upgrading - any future launcher and, in particular, two-stage guns to be installed. The current project plan foresees that a simple single-pellet high-speed gun of this type will be employed to assess its merits already in 1989, overlapping with the scheduled operation of the ORNL Launcher. The main components of the Pellet Interface are: vacuum interface comprising also the structural elements for mechanical support; liquid helium (LHe) supply and LHe intermediate storage for launchers; primary fuel and propellant gas supply; specific in-flight pellet diagnostics and signal acquisition; injector control and data acquisition interfacing to the launcher controls but expandable in their own rights for future launchers; interactive unit (PLPS) to protect the machine from undesirable pellet shots during a plasma pulse. The Pellet Interface is described in some detail in [3] and in the following only those details are highlighted which are of particular interest for the future upgrading.

1.1 THE PELLET INTERFACE - DISCUSSION OF COMPONENTS

Fig. 1 shows a schematic of the pellet injector in plan view featuring the ORNL Launcher with its three barrels arranged in a plane 1.9° above the midplane of JET aiming onto a common focal point in the machine horizontal port within a horizontal cone of 4° full angle; underneath the ORNL lines mirrored by the midplane there is room for another three lines, the outer two suitable for the prototype. Pellets are launched (from right to left) and travel in free flight (i.e. without guide tubes) with a ± 0.5° divergence allowance through differential vacuum and specific pellet diagnostics (microwave interferometer to measure pellet mass and speed, pellet photography and off-line target for aiming) into the plasma.

The differential pumping is facilitated by a cryo-condensation pump of ca $8 \times 10^6 \text{ m}^{-1}$ pumping speed for hydrogen in the 3.5 m long, 7 m high and 1.5 to 2.5 m wide pellet injector box (PIB) of 50 m$^3$ volume separated from the torus vacuum (reaching into the duct) by flow restrainer tubes of nominally 60 l/s$^{-1}$ conductance. Under worst conditions the 3 bar* l per pellet of the
ORNL 6 mm gun driver gas surge is pumped away with a time constant of ca 7 milliseconds, delivering a theoretical maximum of less than $2 \times 10^{-2}$ mbar$^\text{a}$ of hydrogen to the plasma (corresponding to $1.5 \times 10^{-7}$ mbar torus filling pressure); since this surge is not being delivered in an instant the actual fraction into the torus is estimated to be considerably less and has indeed never been detected by any plasma diagnostic, even when more than one restrainer tube was open to the torus. For a two-stage gun estimates of the corresponding driver gas surges (2nd stage only) go as high as $30$ bar$^\text{a}$. However, it is believed that the pellet divergence of such guns can be held to about $\pm 0.1^\circ$, decreasing the diameter of the flow restrainer tubes accordingly; optionally a fast muzzle valve can be installed (anyway of possible advantage to solve the piston survival problem in the two-stage gun) and/or a diaphragm, partitioning a small fraction of the cryopump, can be inserted to introduce an additional differential pump stage. The low ultimate base vacuum of the cryopump and its high pumping speed ensure that successive pellets (say more than 50 milliseconds apart) will always see less than the $10^{-2}$ mbar of foreland pressure believed to be not harmful to pellets in supersonic flight.

The capacity of the cryopump, which is to be regenerated before the safety limit against an hydrogen explosion in the presence of an arbitrary amount of air in the PIB is reached, is currently set at 1000 bar$^\text{a}$. This was sufficient in the past experiments for two experimenting days on average, despite the fact that the PIB was also pumping the complete fuel extrudate of the ORNL Launcher (usually 70% of the accumulated gas). The PIB, initially designed as a pure vacuum vessel for the JET neutral beam injectors, is now being converted into a pressure vessel for 3.5 bar abs. permitting then safely a capacity of 2500 bar$^\text{a}$ (the cryopump itself is estimated to pump up to 5000 bar$^\text{a}$ and is proven to have a capacity of more than 3000 bar$^\text{a}$). On the basis of 100 bar$^\text{a}$ per tokamak pulse on average, i.e. three large pellet shots at highest speed, and negligible amounts of
gas from the pellet formation (thought to be facilitated by cryo-condensation) this will then allow operation for at least a full day, and regeneration of the cryopump can easily be performed overnight (ca 6 hours for a complete cycle). Under the above assumptions the differential pumping system will be adequate for the prototype launcher already now, and for an advanced repetitive launcher system in the near future.

Concerning the in-flight diagnostics, the microwave interferometer and the pellet photography are compatible with high pellet speeds as well as with the active phase requirements (in the latter case electronic components like microwave diodes and CCDs have still to be transferred to the JET basement in a known manner). The target for ultrasonic detection of pellet impact in off-line aiming, however, will not function for pellet speeds exceeding the sound velocities of any solid material (and this may be the case already for the prototype). We are pursuing the idea of an in-flight, on-line target where the pellet traverses orthogonal light curtains of spectrally dispersed light: the missing colour is the measure for the pellet trajectory cross point; for off-line testing a dump target with limited life-time will have to be provided. The description of the latter idea as well as that of the present diagnostics can be found in [4].

1.2 HIGH-SPEED GUN - MECHANICAL LAY-OUT

Fig. 3 shows an artist's view and Fig. 4 a schematic of the injector lay-out modified for the acceptance of two-stage guns whereby the mechanical requirements for the prototype and the advanced gun system turn out to be very similar; the main features being their lengths (for reasons of limited torus hall space the maximum length which can be made available for barrel and pump tube combined is in the order of 10 m and that may well be needed) and the impact of the piston with energies of >100 kJ which is reflected in a millisecond or so, leading to impact forces in the order of several hundred tons. The prototype as well as later guns will be mounted on a large steel beam the rear end of which is suspended from the torus hall wall by a massive structure deeply anchored into the concrete. The beam inclusive of its launchers can be tilted into a vertical position in the manner of a drawbridge to make way for the movements of large equipment.
around the machine; the trunnion bearings are also to take a large fraction of the piston reversal momentum. Currently the beam is under detailed design and the wall suspension is out for manufacture and will be mounted in about 2 months time.

2. DEVELOPMENT PROGRAMME

JET established closely monitored development contracts with major European laboratories to investigate the principles for building a high-speed gun, adopting the principle of "hot" pneumatics in the belief that none of the more exotic principles of pellet acceleration (like electromagnetic or rocket propulsion) can be made to work within the limited lifetime of the project. The basic philosophy of JET's approach has been outlined in [5].

Ernst-Mach-Institut (EMI), Freiburg FRG, developed in conjunction with JET the first small version of the two-stage gun with encouraging results (1985 to 1987): Using a 1.5 m long barrel of 6 mm I.D., a 1 m long cylinder (often referred to as pump tube) of 3.5 cm I.D. and a light piston of ca 0.1 kg driven by ca 200 bar into ca 5 bar of hydrogen, plastic pellets of 50 mg could be accelerated up to 4.6 kms⁻¹; using a pellet formation cryostat developed by CENG this experimental set-up produced a maximum pellet speed of unsupported 6 mm pellets of 2.7 kms⁻¹, limited by erosion effects, and of sabot supported 5 mm pellets of 3.8 kms⁻¹ [6].

Centre d'Etudes Nucléaires de Grenoble (CENG) of the CEA, F, complemented the endeavour by developing suitable cryogenics for the pellet formation cryo-condensation and established a data base for the formation of pellets as well as their mechanical behaviour during the acceleration (since 1985). A new 300 bar fast-valve was developed and 6 mm deuterium pellets were accelerated to 2.1 kms⁻¹ with conventional pneumatics [7,8]. Recently a repetitive (within minutes) cryostat was developed and successfully tested which allows to cryo-condense pellets into sabots in a position outside the barrel, to compact them if needed and to finally load them into the gun breech; a second cryostat of this type was delivered to JET.

An alternative approach was followed by Riso National Laboratory, DK, who undertook to investigate an electrical arc gun (1984 to 1988): The initially promising results were finally not competitive, the major difficulties being low electrical arc efficiency, ineffective arc fuelling and impurities.
2.1 PROTOTYPE DEVELOPMENT STATUS

In 1987 JET took the decision to prepare a prototype high-speed gun for a proof-of-principle experiment; this gun should be capable, in its lifetime, of delivering a few pellets to the plasma but preferably should be ready for one shot into each tokamak pulse with a minimum of maintenance (say once a week). JET has built a testbed to integrate the above mentioned resulting elements with the aim - after some intermediate steps - to build and test a gun ready to be transferred into the torus hall where implementation preparation would proceed in parallel.

The principle difficulties lie mainly in three areas:

1) The mechanical weakness of the ice (0.5 MPa) of unsupported pellets limits the possible acceleration to $5 \times 10^6$ ms$^{-2}$ (and makes them vulnerable to shocks from bursting discs or similar fast valves) and the maximum attainable speed to less than 3 km$^{-1}$ due to a velocity dependent erosion effect [6]. The technique of supporting the pellets by sabots (cartridges) has so far proven the remedy to both limitations.

2) The penalty for this measure are larger masses (factors of 6 to 30) to be accelerated requiring proportionally higher driver energies and the requirement to safely remove the sabot so that only the ice enters the plasma. Employing pump tubes of 6 and 8 cm I.D. and by 3 m long, the previous speeds have been attained with the greater mass. First attempts of sabot removal have been successful, separating the pellet from the sabot by gas pressure, either by now deliberately using erosion effect (slotted sabot), or by using the driving pressure to pressurize the rear part of a split sabot [9]; another option is the application of eddy current heating on a thin metal film inside the sabot. The resulting pressure exerts a transverse momentum to the sabot sections causing them to part. Sabot stripping is achieved in the PIB using a cone a few meters downstream from the muzzle.

3) Even for a modest repetition requirement the pump tube piston has to survive the impact at the barrel nozzle and and the tailoring of the cushion of gas not immediately leaving through the barrel is of high importance. In our guns teflon and metal pistons with teflon piston rings were already reusable for some 20 times. Cleaner solutions employing metal to metal and to ceramic low-friction partners are currently under investigation.

At present preparations are in hand for probably the final round of intermediate experiments before finalizing the design of the version to be installed on the torus after extensive testing on the testbed. The main issues are the areas listed above, as well as the soundness of conception and proof of reliability of the CENG cryostat for two-stage gun operation. We are optimistic that the prototype can operate on JET in 1989.

2.2 ADVANCED LAUNCHER PREPARATIONS

Meanwhile CENG in conjunction with CEN Saclay are concentrating their efforts to design and test a truly "repetitive" gun for several pellets per tokomak pulse approaching 1 Hz. The present phase is devoted to working out the principles and establishing the design elements. The main issues here are high-speed movements within the cryostat for re-arming the breech and the fast handling of the pump tube first and second stage gas loads. The final design, however, has to take into account the tritium and remote handling requirements, even if tritium pellets were not being employed. The latter option is still being considered. At the end of this contractual phase in the middle of 1989 the CEA hopes, in close collaboration with JET, to present a conceptual design for the advanced launcher and shows some interest in taking responsibility for its procurement provided the prototype can prove its value.
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A MULTISHOT PELLET INJECTOR DESIGN

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Abstract

A multibarrel pellet injector to inject a number of H₂ or D₂ pellets in succession is under development x). It is planned for use at RFX in Padova and FTU in Frascati. The design is based on the use of pipe guns, where the pellet is formed by condensation from the gas phase inside the gun barrel, and thereafter blown out with a pulse of high pressure H₂ driver gas by means of a fast valve. Up to 8 pipe guns are built together in parallel; they are loaded simultaneously and thereafter fired successively. The pellets are transferred to the experiment through a guide tube system while the driver gas is removed by differential pumping.

x) Patents applied for.

1. INTRODUCTION

Multishot pellet injectors, i.e. injectors that allow successive injection of a number of pellets within the duration of the plasma, have now been in use for 5-6 years and are in demand for a number of experiments.

At Risø National Laboratory we are designing multishot pellet injectors for two new large experiments in Italy1), the reversed field pinch RFX in Padova and the upgraded tokamak FTU in Frascati. Both H₂ and D₂ pellets should be available with sizes between 10^{20} and 10^{21} atoms/pellet and velocities of up to 1200 m/s or more; there should be around 25 successive pellets with around 10 ms time interval for the RFX experiment and 8 successive pellets with 100-200 ms time interval for FTU.

The multishot injector design consists of a number of independent pipe guns built together in parallel to form a multishot unit. For practical reasons the number of guns in a unit is limited to 8 and we thus need 3 units to get 24 pellet for RFX. The design involves a number of new constructions and a prototype is built first.

In the first section we discuss the need for injectors. In the second section we describe the pipe gun used. In the third we discuss the assembly and operation of a multishot unit and thereafter the transfer of pellets to the experiment. In the final section we present results obtained with a 3 shot-unit.

2. THE DEMAND FOR PELLETS

The use of pellets in tokamaks is well documented and shall not be discussed here.

Pellet injection in reversed field pinches have been made at ZT-40 in Los Alamos and at Eta Beta II in Padova2).

Deuterium pellets with mass above 10^{20} atoms/pellet and velocities around 100 m/s were injected in Eta Beta II. With these slow pellets the plasma density was
kept above $10^{20}$ per m$^3$ during the entire pulse duration of 2 ms. Apparently the velocity was slow enough for the pellet to be well inside the plasma for most of the time and the mass was large enough to provide an ablation rate sufficient to balance the particle loss, figure 1. During the discharge the values of $\beta$ were sustained at about $\beta_{0e} \geq 6\%$ and low resistance anomaly factors were observed.

It is thus considered important to have pellet injection from the first operation for RFX. The expected data for RFX are: peak electron temperature 1-2 keV, particle confinement time around 10 ms and a pulse length around 250 ms. At present the specifications for the new injector are: mass of $5 \times 10^{20}$ atoms/pellet, velocity around 800 m/s and repetition rate of 5-10 ms.

3. THE PIPE GUN

The pipe gun used is the latest version of the simplified pipe gun described earlier$^{3}$. The pipe gun should be simple in construction and the consumption of driver gas should be small. The amount entering one of the above mentioned experiments should not exceed 5% of the amount of gas in the pellets injected. It should also be very reliable in function, since all pellets should be good and with same velocities and sizes when a multishot gun is fired. A schematic drawing is shown in figure 2.

The freezing cell is a part of the barrel held at a temperature of 6-8 K through thermal coupling to a liquid helium cryostat while two outer segments are held at somewhat higher temperatures, say 40 K, to give strong temperature gradients outside the freezing cell. When pellet gas, H$_2$ or D$_2$, is let into the barrel through the muzzle, it will condense to form a pellet in the freezing cell. The pellet will extend outside the freezing cell to end where the temperatures are so that the vapour pressure corresponds to the feeding pressure. D$_2$ has a lower vapour pressure than H$_2$, and D$_2$ pellets will therefore have the longer length.

The pellet may hereafter be blown out from the barrel with a burst of high-pressure H$_2$ driver gas from a fast valve. There are two reservoirs for high-pressure driver gas in our fast valve and reservoir 2 is isolated from the high pressure gas supply with a safety valve (not shown). The valve is opened when a 500-V pulse of short duration is applied to the magnet coil so that the plunger is thrown backwards. Reservoir 1 is hereby partially emptied and the valve will be closed quickly by the pressure difference that appears between the two reservoirs.
For a magnet current of 0.8 ms duration and a driver gas pressure of 50 bar the consumption of driver gas is only around 75 bar cm³.

The pressure pulse should be transported to the pellet with little distortion. That is obtained partly by keeping a short distance between the valve aperture and the pellet position, and partly by shaping the connecting tube so that frictional losses are minimised.

With this gun design we have made and accelerated pellets of both H₂ and D₂ in a barrel of 2.1 mm inside diameter. For pellets of 3.5-4 mm length we obtained velocities up to 1300 m/s for deuterium and 1500 m/s for hydrogen using driver gas pressures up to 56 bar. The scatter in velocity for a group of pellets with the same driver gas pressure is normally less than 2%. The distance between the valve aperture and the pellet position was 70 mm, and the length of the gun barrel was 270 mm measured from the pellet position.

The operation of the pipe gun is controlled with a PLC and is divided in successive steps with activation of a number of electromagnetic valves and electric heaters.

The steps are:

Preparation and formation of pellet.
Storage until firing asked for.
Firing.
Recovery, i.e. evacuation of barrel, cooling of barrel.

The preparation for firing, i.e. formation and storage will last at least 50 seconds while 80 seconds are needed for recovery after firing. Both H₂ and D₂ pellets are made at around 8.5 K. The H₂ pellets are held at the same temperature until firing, while the D₂ are held at around 10 K until firing.

4. THE MULTISHOT INJECTOR

In a multishot injector unit, up to 8 pipe guns are built together as shown in figure 3. The guns are placed on a flange around a flow cryostat. The barrels are curved and become parallel when leaving the vacuum chamber so that the pellet trajectories will be parallel and close together. The barrels are cooled by thermal couplings to the flow cryostat and the cold parts are surrounded by a radiation shield. A gate valve is placed in front of the barrels and the guns are loaded simultaneously through the gate valve and the muzzles as for the 1-shot gun in figure 2. The guns may hereafter be fired by successive activation of the fast valves.

Figure 2. Schematic drawing of a pipe gun with fast valve.
The heating of a barrel by the driver gas will result in a heating of unfired barrels because of the thermal interaction between barrels, and this heating of an unfired barrel may affect the later firing. In a given set-up the heat input to barrel number \( n \) will roughly be proportional to \( n^2 \) and to the time interval between shots. The flow cryostat and thermal couplings to it should thus be made in such a manner that there is little mutual interaction, especially when large time intervals are wanted.

The operation follow the same scheme as that of a 1-shot gun, the only difference being that \( n \) heaters and \( n \) safety valves should be activated simultaneously, and that \( n \) fast valves should be activated successively with constant or varying time intervals.

The pellet size can be varied only slightly for a given multishot unit and one should thus have multishot units for each pellet size required.

One way to dispose of most of the driver gas is to remove it by differential pumping just outside the gun barrels. Figure 4 shows how a multishot unit is built together with a chamber of 400 l volume. The pellets are fired across a 100-mm tube leading down to the volume and thereafter continue into a guide tube system. In figure 5 is shown how the guide tube system may connect the...
The circumscribed circle for the barrels is 13 mm. The pellets can then be transported to the experiment through a rectilinear guide tube system starting with 14-15 mm inside diameter. The guide tube system will probably have to pass through a differential pumping system at the entrance port to the experiment, and it may also be necessary to let the guide tube system continue after the entrance port since the distance between the port and plasma edge will be quite large, 1 m or more.

The guide tube must be interrupted and increased in diameter when passing the optical detectors, the differential pumping system, the gate valve etc.

5. THE 3-SHOT UNIT

A number of technical problems are foreseen and should be solved before an 8-shot unit operates satisfactorily. For simplicity we have started with a unit with only 3 pipe guns before building a prototype of an 8-shot unit.

In a first test of a 3-shot unit we obtained 1350 m/s for H₂ pellets with 55 bar driver gas pressure. The individual velocities for the barrels deviated less than 20%, while the pellet sizes deviated only 7%. It was later seen that it was possible to make adjustments so that velocities agreed within 7%. The firing delay, i.e. the time between a trigger pulse and the appearance of a pellet at the first optical detector was between 1.9 and 2.1 ms for each barrel. For each individual barrel velocities and firing delays scattered below ±2% from shot to shot.

With a distance of 5 m from a pipe gun to the plasma edge, the flight time will be 3.5 to 5 ms with a scatter of a few per cent. It may therefore be possible to go down to time intervals of 1 ms between pellets.
The time constant for thermal interaction between barrels was increased by inserting pieces of Pb in the thermal connections between center segments and the cryostat. Pb has a heat capacity much higher than that of Cu at low temperature. With this improvement no thermal interaction between barrels was seen for time intervals between shots up to 1000 ms.

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DEVELOPMENT OF A SIX-PELLET INJECTOR FOR HELIOTRON E

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Abstract

A pneumatic six-pellet injector has been developed for plasma fueling applications for HELIOTRON E. The cryogenic mechanism consists of two cryogenic housings cooled by liquid helium and a pellet production disk with six holes and the shaft assembly. Frozen hydrogen pellets are formed in the disk holes. The disk is rotated from the pellet production zone to the shooting position. The pellets are propelled by high pressure hydrogen or helium gas (at pressures of up to 100 bars) from 0.52 m gun barrels. Pellet velocity and firing intervals are variable for each shot. Pellet size can be changed by replacing the pellet production disk and the gun barrels. One example of a combination of six pellet holes is three groups of two pellets, each group having a diameter of 1.2 mm, 1.5 mm or 2.0 mm and all pellets having a thickness of 1 mm. Pellet velocity ranges from 400 m/s to 1400 m/s. The time interval between each pellet firing can be changed from 0 ms to more than 100 ms. More than 90% of the pellet shots are successful in operation. One cycle presently lasts 10 minutes. Recently, a six-pellet injector has been installed on HELIOTRON E.

1. INTRODUCTION

At present, one of the most promising methods of plasma refueling in plasma fusion devices is frozen pellet injection. This method is suitable for optimizing plasma density distribution by allowing free choice of pellet size and velocity. Therefore, pellet injection has been adopted for many plasma fueling
FIG 1  SCHEMATIC OF 6-SHOT PNEUMATIC PELLET INJECTOR
applications. Most recently, a pneumatic six-pellet injector has been developed by Kobe Steel, Ltd. in collaboration with Kyoto University, and installed on HELIOTRON E for advanced pellet injection experiments. In this paper, we will present the configuration of the injector and its installation on HELIOTRON E. Preliminary injector operation tests on the injector are also described.

2. THE INJECTOR CONFIGURATION
The injector is illustrated in Fig.1. The cryogenic mechanism, which freezes hydrogen gas into pellets, is housed in a high vacuum vessel, and thermally insulated by an enclosure cooled by flowing liquid nitrogen. The cryogenic mechanism, as shown in Fig.2, consists of the main cryogenic housing, shaft assembly, gun barrel housing and pellet production disk.

The main cryogenic housing is made of OFHC copper, and cooled by liquid helium flowing through a pipe inserted spirally. Six stainless steel nozzle blocks are inserted in the housing, and each of the blocks has two passages for gaseous hydrogen and pressurized propellant gas. Each block is separated from the housing by 1 mm, and brazed only at one end. The purposes of this design are:
1) to prevent the neighboring pellets from melting due to the heat of the propellant gas, and
2) to prevent the hydrogen gas from over-cooling, because pellets frozen too soon would block the passage.

The shaft assembly is fixed to the main cryogenic housing. Two ceramic ball bearings, mounted on the outer shaft, allow smooth rotation and axial movement of the pellet production disk, and axial movement of the gun barrel housing. The axial movement is driven by pressurized helium gas introduced into a double bellows.
The gun barrel housing is also made of OFHC copper, and cooled by liquid helium. It is equipped with six sets of stainless steel gun barrels and OFHC copper seal plugs.

The pellet production disk is sandwiched and cooled between the main cryogenic housing and the gun barrel housing during pellet forming and firing. The disk is made of stainless steel and, as illustrated in Fig.3, is divided into six leaves with a pellet forming chamber sealed by two specially designed packings mounted in the grooves on both housings. The production disk is rotated by two weights of 8 kg each, which are linked to the disk rotation arms, and aligned with the precise position by a mechanical disk stopper.

3. INJECTOR OPERATION

Hydrogen gas, for forming the pellets, is supplied at a pressure of 0.7-1.1 bars, and cooled by liquid nitrogen during transfer to the pellet production disk. The pressure of the propellant hydrogen gas can be independently adjusted for the firing of each of the six pellets. Liquid helium for cooling the cryogenic mechanism is supplied at 1.5-1.7 bars, and transferred through a 3.0 m long line with an inner diameter of 3.0 mm. Helium gas for driving the double bellows is supplied at 20 bars, and cooled by liquid nitrogen during transfer to the double bellows. Helium and nitrogen gas consumed in the injector are vented through a hot water tank.

The first step of operation is the pre-cooling of the cryogenic section with liquid nitrogen. Then, it is cooled down to 6-8 K with liquid helium. The time required to cool down the cryogenic section, which weighs about 40 kg, is 1-1.5 hours for the nitrogen phase and 3-4 hours for the liquid helium phase. Forming and firing of the hydrogen pellets are performed according to the sequence illustrated in Fig.4.
4. INSTALLATION OF THE INJECTOR ON HELIOTRON E

The pellets fired from the injector travel 5.2 m from the gun muzzle to the center of the plasma target through the guide line system, as shown in Fig. 5. The purpose of this system is to help prevent propellant gas from flowing into the torus vacuum vessel, and to guide the pellets to the target plasma in the torus.

These functions can be understood by examining the schematic diagram of the system illustrated in Fig. 6. Six guide tubes are furnished for each gun barrel, and each tube is divided into four sections.

Each guide tube of the first section is bent at an angle of 1.1 degrees to the center of the plasma target, and is equipped with a fast valve whose closing time
ranges from 15 to 30 ms. To measure pellet velocity and to take pictures of the pellets in flight, two diagnostic stations are installed after the gun muzzles and after the fourth stage guide tubes.

5. INJECTOR PERFORMANCE

The performance of the injector is summarized in Table 1. Sure shot probability was obtained by examining the results of firing 120 pellets. The results of each were confirmed by penetration holes and large hollows on the aluminum foil located after the fourth stage guide tubes. An example of our experimental velocity data is presented in Fig. 7. Maximum pellet velocity is measured at 1400 m/s. The minimum cycle time needed to repeat the next six shots is, at present, 10 minutes. A decrease in pellet velocity while travelling through the guide line system was observed at 50-70 m/s.

<table>
<thead>
<tr>
<th>Guide tube size</th>
<th>Tube 1</th>
<th>Tube 2</th>
<th>Tube 3</th>
<th>Tube 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>4</td>
<td>10</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>730</td>
<td>514</td>
<td>763</td>
<td>1266</td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>15</td>
<td>20</td>
<td>24</td>
<td>27</td>
</tr>
</tbody>
</table>

**Table 1. Injector Performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sure shot probability</td>
<td>91%</td>
</tr>
<tr>
<td>Pellet velocity</td>
<td>1400 m/s MAX</td>
</tr>
<tr>
<td>Angular dispersion</td>
<td>less than 1 degree (half angle)</td>
</tr>
<tr>
<td>Propellant gas consumption</td>
<td>0.4 MJ / shot</td>
</tr>
<tr>
<td>Gas contamination in the torus</td>
<td>2.4x10⁻³ Torr-l /6 shots</td>
</tr>
<tr>
<td>Cooling consumption</td>
<td></td>
</tr>
<tr>
<td>Liquid helium</td>
<td>15 l/h</td>
</tr>
<tr>
<td>Liquid nitrogen</td>
<td>8 l/h</td>
</tr>
<tr>
<td>Cooling time</td>
<td>less than 6 h</td>
</tr>
<tr>
<td>Warming time</td>
<td>less than 20 h</td>
</tr>
<tr>
<td>Cycle time</td>
<td>10 minutes MIN</td>
</tr>
</tbody>
</table>

**Fig. 6 Schematic of guide line system and diagnostic station**

**Fig. 7 Pellet velocity data for No. 3 nozzle (shadowgraph of pellet in flight is also shown)**
6. CONCLUSIONS
The injector has successfully satisfied the original specifications required for use on HELIOTRON E. It operates at speeds ranging from 400 m/s to 1400 m/s.

REFERENCES
Abstract

A two-stage, fuseless, plasma-arc-driven electromagnetic railgun system suitable for hydrogen pellet acceleration has been developed and successfully tested. The first stage is a combination of a hydrogen pellet generator and a gas gun, which is responsible for injecting a medium-velocity hydrogen pellet into the second-stage railgun through a coupling piece. As the pellet enters the railgun, a specially designed arc-initiation scheme electrically breaks down the propellant gas which has followed the pellet from the gas gun into the railgun, thus forming a conducting plasma-arc armature immediately behind the pellet. This arc formation event coincides with the triggering of the main railgun current and allows the plasma-arc armature to subsequently propel the hydrogen pellet to a high velocity. Using this two-stage acceleration scheme with a 1-m-long railgun barrel, solid hydrogen pellet velocities in excess of 2.2 km/s have been achieved for a pellet 3.2 mm in diameter and 4 mm in length. The objectives of this paper are two-fold: first, a critical review of the achievements thus far on the railgun hydrogen-pellet injector and second, a description of the most recent technological developments and their implications for future work, in particular, the prospect of employing a railgun pellet injector for future large devices.

I. GENERAL DESCRIPTION

A schematic of the two-stage railgun system including the first-stage hydrogen pellet generator, the second-stage railgun, a coupling piece in between, the arc-initiation circuitry, the pulse-shaping network for the main rail current and the principal diagnostics is shown in Fig. 1. The hydrogen pellet generator serves a dual function: it fabricates a solid hydrogen pellet and injects it into the railgun through a coupling piece. The coupling piece helps form
Figure 1. Schematic of the University of Illinois two-stage, fuseless, plasma-arc-driven railgun system with a pressure-relieving coupling piece.
an uninterrupted pellet pathway from the gas gun to the railgun, but, more importantly, it serves as a pressure-relieving mechanism for the high-pressure propellant gas so that it does not follow the pellet into the railgun. By adjusting the number of perforations in the coupling piece, the amount of gas that can leak into the vacuum chamber that houses the coupling piece can be controlled. As a result, the pressure profile inside the railgun bore can be controlled so as to suppress spurious arcing during the railgun operation. The diagnostics are to measure the pellet velocities at the railgun breech and muzzle, to monitor the temporal behavior of the plasma-arc armature (and therefore the pellet in front of it) inside the railgun, to determine the pellet integrity and momentum, and to detect the currents through a few important circuits.

II. ARC-INITIATION SCHEME

The arc-initiation scheme that is responsible for creating a plasma-arc armature immediately behind the pellet is effected by a one-stage pulse-shaping network, one end of which is a sharp tungsten needle mounted just inside the railgun at the breech. The pulse shaping network is capable of delivering 220 A at 5 kV for a FWHM pulse width of 8 μs, and produces a very localized, high-charge-density plasma right behind the pellet. The idea is to create a lower-resistance path behind the pellet than the region in front of it so that when voltage is applied to the rails, the plasma-arc armature will form in the low-resistance region behind the pellet. All this is necessary because, in general, the gas pressure behind the pellet is higher and thus farther from the Paschen minimum than the pressure in front of the pellet and, as a result, an electrical breakdown is more favored in front of the pellet, not behind it.

The scheme described above that ensures formation of a plasma-arc armature behind the pellet works very well at low voltages. However, as the voltage is increased (which is necessary to achieve higher current) above a certain threshold voltage, it eventually stops working since the effectiveness of the arc-initiation scheme continuously weakens as voltage increases, whereas the tendency for natural breakdown in the region ahead of the pellet increases. For the 3.2-mm-diameter railgun this threshold voltage turned out to be approximately 2 kV when the propellant gas pressure at the gas gun was 600 psi. To resolve this problem, and thereby to enable high-current operation of the railgun, a perforated coupling piece housed in a separate vacuum chamber was used to reduce the gas pressure behind the pellet so that natural breakdown is equally favorable everywhere inside the railgun prior to turning on the arc-initiation scheme. The size and number of the perforations were chosen to reduce the gas pressure behind the pellet to a desired level. Using the perforated coupling piece the railgun system could be operated, without incurring spurious arcing, at voltages and currents as high as 10 kV and 23.5 kA, respectively —— an operating condition that will probably allow one to determine the critical railgun current over which the solid hydrogen pellet may fracture due to its limited yield strength.

III. HYDROGEN PELLET ACCELERATION RESULTS AND PROJECTIONS FOR LONGER-RAILGUN SYSTEMS

Using the two-stage railgun system illustrated by Fig. 1, pellet acceleration studies have been performed on solid hydrogen pellets, 3.2 mm in diameter and 4 to 6 mm in length. Output pellet velocities in excess of 2.2 km/s were achieved using an effective railgun length of 1 m, at a helium propellant gas pressure of 800 psi and railgun currents as high as 18.8 kA. The highest acceleration recorded was 2.92 x 10^6 m/s^2. Presented in Fig. 2 is a set of hydrogen pellet acceleration data corresponding to a single experimental sequence in which the railgun current was raised from 9.4 to 18.8 kA while the current pulse length, and therefore the pellet acceleration time, was held at 438 μs. The vertical and horizontal axes, respectively, represent the pellet velocity increment and the railgun current. The scatter in the data is mainly due to the variations in the pellet size and in the initial distance between the pellet and the plasma-arc armature, which could not be controlled accurately. According to this plot it appears that there is a parabolic relationship between the velocity increase and the rail current.
Figure 2. Increase in solid hydrogen pellet velocity plotted against railgun current. The solid hydrogen pellets were 3.2 mm in diameter and 4 to 6 mm in length and the pellet acceleration time on the railgun was 438 \mu s. The scatter in the data was due to the variations in the pellet size and in the initial distance between the pellet and the plasma-arc armature.

Table I. Predicted final velocities of a solid hydrogen pellet, 3.2 mm in diameter and 6 mm in length, accelerated by a 3.2-mm-diameter two-stage railgun of various lengths.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Length</th>
<th>2.0 M</th>
<th>3.0 M</th>
<th>4.0 M</th>
<th>5.0 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{i0}) (m/s)</td>
<td></td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>(I) (kA)</td>
<td></td>
<td>18.8</td>
<td>18.8</td>
<td>18.8</td>
<td>18.8</td>
</tr>
<tr>
<td>(a) (m/s(^2))</td>
<td></td>
<td>(2.00 \times 10^6) (a) ((2.92 \times 10^6))</td>
<td>(2.00 \times 10^6) (b) ((2.92 \times 10^6))</td>
<td>(2.00 \times 10^6) (b) ((2.92 \times 10^6))</td>
<td>(2.00 \times 10^6) (b) ((2.92 \times 10^6))</td>
</tr>
<tr>
<td>(v_{ou}) (km/s)</td>
<td></td>
<td>3.00</td>
<td>3.61</td>
<td>4.12</td>
<td>4.58</td>
</tr>
<tr>
<td>(t) (ms)</td>
<td></td>
<td>1.000</td>
<td>1.305</td>
<td>1.560</td>
<td>1.790</td>
</tr>
<tr>
<td>(t_p) (ms)</td>
<td></td>
<td>1.000</td>
<td>1.305</td>
<td>1.600</td>
<td>1.800</td>
</tr>
<tr>
<td>(C_1) (\mu F)</td>
<td></td>
<td>500 x 3</td>
<td>500 x 5</td>
<td>1000 x 5</td>
<td>1000 x 5</td>
</tr>
<tr>
<td>(Z_0) (\Omega)</td>
<td></td>
<td>0.173</td>
<td>0.237</td>
<td>0.146</td>
<td>0.164</td>
</tr>
<tr>
<td>(I/V) (A/V)</td>
<td></td>
<td>2.35</td>
<td>2.11</td>
<td>3.43</td>
<td>3.05</td>
</tr>
<tr>
<td>(V) (kV)</td>
<td></td>
<td>8.00</td>
<td>8.91</td>
<td>5.47</td>
<td>6.16</td>
</tr>
</tbody>
</table>

\(t\): pellet acceleration time
\(t_p\): current pulse length

Note: Using a longer gas gun barrel and hydrogen gas as the propellant, higher input velocities (thus higher output velocities) should be possible.

(a) Average acceleration
(b) Best acceleration to date
Based on these experimental results one can make predictions on the performance of a railgun with a longer gun barrel under the similar operating conditions. The predictions are listed in Table I for railguns of different lengths. The empirical acceleration values used for the calculation are the average and highest-to-date (parenthesized) values, respectively. From Table I, it is seen that a hydrogen pellet velocity on the order of 4 km/s will be possible using a 3-m-long railgun.

Since with the railgun one has the advantage of being able to exert a uniform acceleration force to a pellet, it should be possible to achieve very high hydrogen pellet velocities without resorting to a sabot to protect the pellet. Another advantage of a railgun injector is its unique capability to serve as a booster-accelerator. Since plasma-arc-armature velocities higher than 14 km/s are routinely possible, it should be a boon to attach a railgun to an existing pellet injector to further increase the output velocity. We are currently in the process of utilizing and exploring such advantages of a railgun to their fullest extent.

ACKNOWLEDGMENTS

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REFERENCES


THE ORNL/TORE SUPRA PELLET INJECTOR AND THE E-BEAM ROCKET PELLET ACCELERATOR*

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Abstract

A pellet injector capable of firing up to 80 pellets of frozen deuterium at a speed of 1.2 km/s is being prepared for experiments on the Tore Supra superconducting tokamak as part of a U.S. Department of Energy and French CEA collaboration. The pellets are accelerated in a 1.5 m graphite composite rotor which turns at 8,000 rpm. Deuterium ice is made by freezing gas onto a liquid-helium cooled rotating disk. Pellets are punched from the rim of the disk and injected into the centrifuge. By varying the position of the punch with respect to the rim, pellets can be produced in a range of sizes from 1.5 mm to 3 mm. A computer system based on Multibus-1 hardware with software developed by CEA is used to control the operation of the injector.

CENTRIFUGE INJECTOR FOR TORE SUPRA

For the application on the Tore Supra tokamak, a centrifuge-type injector design was chosen; the design is based on an earlier mechanical device [1] that provided the first-time quasi-steady-state fueling on Doublet-III tokamak in 1984 [2]. The centrifuge injector is a mechanical device that uses centrifugal forces to accelerate pellets constrained to move in a track on a high-speed rotating arbor. Two inherent advantages of this technique are steady-state capability and high pellet feed rates. Thus, it can provide a flexible fuel source for long-pulse tokamaks. The performance goals for the new injector include (1) the capability of delivering 10—30 hydrogen or deuterium pellets per second for a 30-s pulse, (2) variable pellet size (1-10 torr-L/pellet), (3) pellet speeds in the range of 0.8-1.2 km/s, and (4) pellet dispersion at the plasma surface within ±30 mm. The injector system is primarily divided into three subsystems: (1) the vacuum containment "spin tank," (2) the pellet fabrication system or "Zamboni machine," and (3) the high-speed mechanical accelerator.

Vacuum containment is provided by a 2-m-diam dome-shaped spin tank, which houses the accelerator and supports the pellet fabrication system. The Zamboni machine replaces the conventional extruder assembly as the pellet fabrication mechanism. This device freezes a rim of solid hydrogen ice on a rotating disk, which is cooled with liquid helium. On command, a quantity of pellets of variable sizes can be punched. The voids formed on the rim after punching a pellet sequence are replenished as the liquid-helium-cooled disk rotates and gas fills through the injection calipers. The accelerator is a 1.5-m-diam, snowshoe-shaped graphite composite hoop that is coupled to a high-strength aluminum hub and is driven with an induction motor. A recessed area in the aluminum hub accepts the pellets from the Zamboni and guides them into a V-shaped groove in the composite hoop, where centrifugal forces accelerate the pellets to twice the peripheral speed of the rotor (tested at up to 127 Hz). The pellets will be shot through a guide tube injection line to the plasma. After satisfactory operation of the injector is established at ORNL, it will be delivered to Tore Supra for installation and checkout.

A method is proposed to accelerate solid deuterium-tritium fuel pellets to high velocity for the purpose of fueling toroidal magnetic confinement fusion reactors. An electron beam [3] will be employed to ablate a portion of the fuel pellet, thereby accelerating the remaining pellet. The use of pellets to fuel tokamaks has a relatively long history [4]. Two techniques are now used on experimental machines: the pneumatic gun and the centrifuge. The present capabilities of these devices are 2 km/s and 0.8 km/s, respectively. Both methods are being refined, and they have a potential useful speed of approximately 4 km/s. The present goal of the pellet fueling program is to be able to continuously fuel a burning fusion reactor. This will require a fueling rate of approximately 3–10 pellets/s, a pellet diameter of 3–6 mm, and speed that should be as high as practical given the constraints of economics. As the pellet speed is raised, the penetration into the plasma increases. Present models indicate that pellet penetration scales as the cube root of the pellet velocity. With pellet speeds in the range of 1–2 km/s the fuel deposition will occur in the outer half of a burning core reactor plasma. As an alternative to gas fueling, with which the fuel would be deposited in the outermost edge of a reactor, pellet fueling at 1–2 km/s has great potential advantages. Many phenomena such as charge-exchange recycling, impurity influx, neutral beam power deposition, and fuel throughput may be strongly affected by fueling the plasma inside the scrape-off region. Some positive aspects of pellet fueling, however, may require deeper penetration. Penetration to or near the plasma center [2, 5] has provided the best confinement results, producing highly peaked density profiles and fusion reaction rates a factor of 4 to 10 times greater than gas-fueled discharges at equivalent power levels. However, extending the penetration by a factor of 2 in a reactor environment will require increases in pellet speed of a factor of 10 or an increase in kinetic energy of a factor of 100. Clearly, the complexity of any such pellet fueling device would be substantially greater than that of injectors operating at 2 km/s, but if the performance of the reactor is improved such an effort could easily be justified.

Several aspects of any technique of achieving an ultrahigh-velocity pellet injector are common and are essentially determined by the energy levels required and the inherently weak properties of solidified deuterium and tritium. For example, a 6-mm-diam deuterium pellet at a speed of 20 km/s has a kinetic energy of 5.6 k J. Accelerating it over a path length of 20 m in 2 ms would require a pulsed power of 2.8 MW. Assuming an efficiency of 20%, a power of 14 MW would be required. An average power of 280 kW could accelerate 10 pellets per second.

In order to attain these very high velocities, it is clear that the acceleration path of the pellet must be extended. Solid hydrogen and its isotopes are very weak solids and are, therefore, easily shattered. Both the pneumatic and centrifuge techniques are now near the limit of pellet integrity. Therefore, the acceleration path of any ultrahigh-speed technique should be a minimum of 1 m and should be scalable to 10–100 m. A 20-m path at 20 km/s would allow a 2-ms acceleration time. Assuming a constant acceleration force over a 20-m path, a 6-mm pellet would have an acceleration pressure of 10 MPa (100 atm), which is the pressure now being applied to accelerate pellets to 1–2 km/s in the pneumatic guns and the centrifuge.

Many techniques have been proposed to accelerate pellets to higher velocity including electrostatics, rail guns, laser-rocket, etc. We are proposing a method of utilizing an intense electron beam to accelerate pellets by the rocket effect. There are several advantages of both a practical nature and the basic physics understanding of the electron-beam/solid-hydrogen interactions which make this an interesting concept. The equation for the velocity of a rocket is

\[ v_r = v_e \ln \frac{m_M}{M} \]

where the velocity of the rocket \( v_r \) is proportional to the velocity of the exhaust \( v_e \) gas times the log of the mass ratio. The key to this method will be the ability to raise the exhaust velocity. Since solid hydrogen has a vapor pressure of 1 atm at 20k the exhaust velocity is only 250 m/s. The ablation rate to the pellet is locked by the required acceleration time, so raising the exhaust temperature by increasing the surface temperature is not feasible. However, our understanding of pellet ablation in tokamak experiments is that while the surface temperature is pinned to cryogenic values, the ablation cloud, which screens the pellet from the incident plasma electrons,
is rapidly heated by the intense electron power flux. This heating occurs in a region within one pellet radius from the surface of the pellet. Electron-beam rocket effects are probably the cause of the distinct curves in the trajectories of pellets injected into tokamak and RFP plasmas.

The neutral shielding ablation model can be used to determine the acceleration of the e-beam rocket. At the surface of the pellet the power flux from the e-beam is balanced by the evaporation rate of the pellet.

\[
I \left[ E_\infty - \int_0^r n(r)L(E)dx \right] = n r_p^2 \rho v_b H_v
\]

where \( r_p \) is the rocket radius, \( v_b \) is the propellant burn velocity, \( H_v \) is the heat of vaporization, \( \rho \) is the solid density of the pellet, \( L(E) \) is the electron loss function for electrons in molecular hydrogen, \( n(r) \) is the density of the ablation cloud, \( I \) is the electron current, and \( E \) is the electron beam voltage.

For high power fluxes, the pellet ablates at a rate such that the screening term dominates, reducing the power flux to the surface. This is the reason that the heat of vaporization does not appear in the neutral shielding models.

The density required to produce an opaque cloud is derived. By definition of \( L(E) \),

\[
dE = nL(E)dx
\]

for electron energies above 1 keV \( L(E) \) can be approximated by

\[
L(E) = \alpha/E
\]

where \( \alpha = 2 \times 10^{-16} \text{ V}^2 \text{ m}^2 \).

Assuming a spherical expansion at constant velocity, the electron loss to the surface of the pellet is

\[
E^2/2 = n_0 a r_p
\]

where \( n_0 \) is the density at the pellet surface.

Given the ablation density and the sonic velocity, the burn velocity of the solid pellet is determined by conservation of mass flux,

\[
n_o v_s = n_s v_b
\]

where \( n_s \) is the solid density. The burn velocity is then

\[
v_b = \frac{\nu_s E^2 m}{2a \rho r_p}
\]

where \( m \) is the mass of molecular hydrogen

For \( E = 2 \times 10^3 \text{ V}, r = 2 \times 10^{-3} \text{ m}, v_s = 300 \text{ m/s}, \rho = 70 \text{ kg/m}^3, m = 3.3 \times 10^{-27} \text{ kg}, \)

\[
v_b = 7 \text{ m/s}
\]

The burn rate is determined by the pellet size and electron energy; the electron current is then chosen to provide the power flux required to raise the temperature of the exhaust gas. If a fraction \( f \) of the incident power is converted into directed exhaust velocity, then

\[
f I E = 1/2 \pi r^2 v_b \rho v_e^2
\]
Substituting for \( v_b \),

\[
v_e = \left( \frac{4fa}{\pi r v_m E} \right)^{1/2}
\]

For \( I = 20 \) A, and \( f = 0.5 \),

\[
v_e = 8 \times 10^3 \text{ m/s}
\]

The accelerating pressure

\[
P = v_e p v_b
\]

\[
= \left( \frac{fu_m E^3}{a n r^3} \right)^{1/2}
\]

For these parameters,

\[
P = 4 \times 10^6 \text{ Pa}
\]

The velocity of a hydrogen rocket of length \( L \) is

\[
v = v_e \ln \frac{L}{L - v_b t}
\]

For an initial length of 12 mm, the accelerating distance and speeds are as follows:

<table>
<thead>
<tr>
<th>Time ((\times 10^{-3} \text{ s}))</th>
<th>Position ((\text{meters}))</th>
<th>Speed ((\times 10^3 \text{ m/s}))</th>
<th>Final projectile length ((\times 10^{-3} \text{ m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>12.0</td>
</tr>
<tr>
<td>0.13</td>
<td>0.04</td>
<td>0.62</td>
<td>11.1</td>
</tr>
<tr>
<td>0.511</td>
<td>0.68</td>
<td>2.85</td>
<td>8.4</td>
</tr>
<tr>
<td>0.88</td>
<td>2.31</td>
<td>5.95</td>
<td>5.7</td>
</tr>
<tr>
<td>1.26</td>
<td>5.43</td>
<td>11.10</td>
<td>3.0</td>
</tr>
</tbody>
</table>
The apparatus being constructed to test the feasibility of accelerating pellets with an intense electron beam is shown in Fig. 1. The long pellet/propellant sticks of solid hydrogen are produced in a pipe gun and launched into the accelerator at a speed of 60 m/s using a mechanical piston/plunger. Pellets of hydrogen and deuterium 4 mm in diameter by 12 mm long have been produced and launched down a guide rail. The pellet is transported into the accelerator through a guide tube. A ramp/funnel guide tube section loads the pellet from an off-axis trajectory into the accelerator rails. The pellet is constrained to travel down a set of three graphite guide rails, 0.6 m long. The acceleration column is in the center of a 1 T axial field that compresses and contains the intense electron beam. The electron beam is formed in the throat of the solenoid at a field of 833 G. The electron gun is a diode with a radiatively heated lanthanum hexaboride single-crystal cathode. Three 6-mm crystals are cemented in a close-packed mosaic 1.2 cm in diameter. The 12 to 1 compression ratio of the coil magnetic field compresses the beam to 3.5 mm. Beams of up to 25 A and 20 keV have been extracted, and a beam of 14 keV, and 11 A has been compressed and transported through the solenoid, burning a 3.5-mm hole through a piece of graphite paper located in the middle of the solenoid. Preparations are now being made to start pellet acceleration tests.

REFERENCES

VII. CONCLUSIONS
INJECTOR DEVELOPMENT — SUMMARY AND REVIEW

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Abstract

The paper reviews the results presented at the meeting on injector development.

Since the main goal of this meeting was to review and discuss the method of pellet injection and its effects on plasma confinement there has only been a short session of six papers on the development of pellet injectors at this workshop and therefore the subject was not covered quite comprehensively. The presentations also contained many elements of what I would call “status of work report” which I will not go into in the following because they elaborate on applications of well-known and already proven technology. I will undertake to summarise and review only those developments which have shown some advances since the last two reviews at similar workshops [1,2] and are of interest for the application of pellet injection to plasmas of increasing fusion relevance; but I will also include the situation in the field from the view of the speaker (terms of references as given by the workshop organisers). I want to apologize in case anything fulfilling these criteria has slipped my attention.

1. SUMMARY OF PAPERS (concerning advanced elements)

S. Milora high-lighted three development areas in his report on pellet injector activities at ORNL: Electrothermal gun, two-stage light gas gun, and tritium pellet production. This was complemented in a second paper by C. Foster, also from ORNL, on centrifuge and e-beam rocket accelerators: - Post-acceleration of initially pneumatically driven pellets with hot gas from a vortex-stabilised arc leading to a velocity increase from 1.3 to about 2 km/s with an electrical efficiency of 5 - 10 % on the pellet kinetic energy had already been reported earlier [2] and this seems still to be the status. - In initial two-stage gun experiments 0.035 g plastic pellets were accelerated to 4.5 km/s in a 1 m long barrel matching similar results at Milano and at JET; the gun is said to soon be equipped with a pipe gun cryostat to accelerate deuterium pellets. - With the “Tritium-Proof-Of-Principle” (TPOP) experiment ORNL has succeeded in forming 4 mm tritium (T) and DT mixture (50/50 %) pellets and in accelerating them to 1.4 km/s at the Los Alamos NL’s Tritium Systems Test Assembly (TSTA). This is an important demonstration silencing earlier doubts that the formation of these pellets due to the radioactive properties of T will be prevented. The threshold concentration of 3He beyond which ice with acceptable mechanical properties could not be formed was assessed to be 0.05 % and is smaller than expected. - Although centrifuge-type injectors have successfully been applied for quite some time the injector built by ORNL to be employed on the TORE Supra tokamak has several features interesting for the next generation of experiments and beyond: it is to deliver pellets of variable size (up to ca 2.5 mm cylindrical diameter/length equivalent, but particularly shaped due to the formation/punching geometry) with repetition rates of up to 30 pellets/second for a 30 s pulse at a speed in the range of .8 to 1.2 km/s. These specification have been announced earlier but the
device was now said to be in its final commissioning stage at ORNL; the pellet fabrication system is working and the 1.5 m diameter rotor with the accelerating hoop has been spun up to 127 s\(^{-3}\). The e-beam rocket pellet accelerator is one of the few devices which in principle would permit to achieve pellet velocities in excess of 10 kms\(^{-1}\). First principles were discussed in [1] (the principles are extensively discussed in this paper) and experimental proposals and preparations for a first test in [2]. The e-beam gun - a gyratrontechnology spin-off - has delivered an e-beam through the guiding magnet, the pellet formation was tested, and preparations are now being made to start pellet acceleration.

K. Kim of University of Illinois gave a report on the progress of the electromagnetic railgun development, another scheme principally capable of accelerating pellets to more than 10 kms\(^{-1}\). In this approach pneumatically pre-accelerated bare hydrogen pellets are post-accelerated by an arc gas armature along a 1 m long rail system to slightly more than 2.2 kms\(^{-1}\). A number of technical and procedural improvements have been made since the last workshop [2]. However, one of the most important problems seems not being resolved. The achieved accelerations are with 2-3*10\(^6\) ms\(^{-2}\) significantly less than is to be expected from the electro-magnetic pressure and even if these were acceptable (but makes it much harder to achieve a speed of more than 10 kms\(^{-1}\)) the question remains: On which principles should the scaling-up of the present device be based?

The report on the JET injector and its preparation for implementing a single-shot light-gas two-stage gun as a prototype to probe the benefits on plasma performance of pellets at speeds around 4 kms\(^{-1}\) was given by P. Kupschus. Since [2] work has concentrated on technical issues of the two-stage gun - in order to make it manageable for immediate employment on JET - rather than on achieving higher pellet speeds. JET in collaboration with the Ernst-Mach-Institut and CEN Grenoble have previously reported a velocity dependent erosion effect which lets bare deuterium pellets suffer from in interaction with the barrel wall limiting reasonably achievable speed to around 3 kms\(^{-1}\). For higher speeds therefore pellets have to be accelerated in sabots which have to be removed before the pellet can be delivered to the plasma and which require larger guns to account for the higher total mass to be accelerated. A testbed with two of such guns has been built at JET and advances in two of the major technical problem areas have been made: The lateral drift of split sabot halves caused by internal gas pressure form the pellet or the residual driving pressure behind the pellet when it leaves the barrel seems now sufficient to warrant their reliable removal, and the piston lifetime could be increased to more than 40 shots without maintenance so far (marginally already sufficient to ensure ca 1 week of tokamak operation on JET). From the collaboration with CEN Grenoble, JET has now received and is commissioning a pellet forming cryostat which permits in principle remote loading and filling of sabots with ice and charging the breech once for every tokamak pulse. JET plans to install on the torus by late 89 a gun of this type; for its adaption a considerable effort is being undertaken as given in the paper. In parallel, in a collaborative effort CEN Grenoble attempts to expand the prototype into a truly repetitive high-speed gun with rates approaching 1 s\(^{-1}\), speeds in excess of 5 kms\(^{-1}\) and together we have to work out the principles to make this gun tritium and remote handling compatible.

Just for completeness I want to mention the two remaining papers on pneumatic injectors at Riso NL for employment at Italian laboratories by H. Sorensen, and at Kobe Steel Ltd for HELIOTRON E by M. Kanno; these as well as omitted elements of the ORNL and JET reports are considered to be within the state-of-the art technology. I should also mention here that we missed reports of the CNR-CNFM/Polytechnico di Milano/ENEA Frascati (cf [1]) collaboration on two-stage gun development and the activities at Leningrad
on similar and arc heated guns; I would assume that for application on JT 60 similar Japanese activities will emerge soon.

2. REVIEW of STATUS

2.1 General Remarks

Let me now list the different injector types from which we are or hopefully will be able to choose and list their advantages and disadvantages as they appear to me at this moment in time, set against a rather vague background of requirements from the present day experiments onward to reactor scale devices. I like to distinguish in the following between the injector as a system and the launcher/gun as the accelerator.

Generally as it stands, the pellet size seems to be the parameter which can most easily be adapted to any demand: The pellet diameter is unlikely to ever exceed 10 mm and 6 mm are already experimentally available (JET). With regard to the fuel, i.e. hydrogen isotopes or mixtures thereof, there seems now with the successful TPOP experiment (ORNL) no principle obstacle in a rather free choice. The repetition frequency and the total number of pellets for an experimental cycle (e.g. tokamak pulse) are either sufficient or the technology is at hand in principle to cover any likely extension of these parameters (though for some of the advanced gun schemes the technical effort might actually be quite demanding).

However, present injector pellet velocities of up to 2 kms⁻¹ will not let us reach the center of high temperature plasmas of much larger than 5 keV even not with the largest pellets (cf summary paper by W. Houlberg); and even if those would be accepted without disruptive termination of the plasma they may not be desirable because of the large sudden increase in plasma density and the mixing cooling effect linked to this (e.g. to bring the particle contents in a 6 mm D₂ pellet to 5 keV on average ca 22 MJ are required). The scientific community is today still divided whether fuelling just beyond the recycling layer or central deposition are the methods to solve the problems of ash and impurity removal and to generate the particle sources within the plasma for the generation of profile effects. In order to meet the task of getting suitably sized pellets sufficiently deep into the plasma the only free parameter (i.e. without direct effect on the plasma) to solve the problem is the pellet velocity; increasing this in view of the uncertain, but in any case expectedly weak scaling of penetration depth with speed is a somewhat risky (because of the unknown outcome) and demanding task involving considerable technical effort. The justification for it to be carried out stems from the need for this tool to the plasma for which other solutions are not (yet?) available; accordingly a major part in the development is devoted to the subject of high speed.

2.2 Conventional Pellet Launchers

2.2.1 Centrifuge

Devices have been proven to work in experiments (ASDEX, D III) with pellet speeds in the .6 to .8 kms⁻¹ range; rotors have spun up close to expected design limits (equivalent pellet speeds of 1.5 kms⁻¹); but pellet sizes were so far limited to 2 mm (ca 2.5 mm in preparation) and speeds of .8 kms⁻¹ have not been exceeded in routine operation. Development is needed with regard to the feeding of pellets into the rotor, their acceleration guiding without loss of their mechanical integrity and the dynamical/mechanical stability of the rotor (the latter two items are more difficult to achieve for even larger pellets). But the ability to vary pellet sizes during a plasma pulse and to arbitrarily (modulo revolutions of the rotor) fire pellets are being implemented. Advantages: very high repetition rate (like 30 s⁻¹); total number of pellets per experimental pulse very large and quasi-continuous mode can be imagined; simple vacuum
interface to the experiment; high variability in terms of programmable pellet sequence (pellets > 2.5 mm possible?); feed-back pellet request by plasma control can be imagined (dead time @ reciprocal rotor frequency; typically 10⁻² s). Disadvantages: large aiming divergence (can be compensated for in this speed range by guide tubes), and relatively low speed.

2.2.2 Pneumatic single-stage launcher

Here, the gun equation limits the maximum speed roughly to 1.5 times the sound velocity of the driver gas; hence, for hydrogen the speed limit is slightly exceeding 2 kms⁻¹. Pellet sizes of .5 to 6 mm have been employed, but the small sizes have not been tested to the highest speeds. So far, the ORNL built JET launcher is probably the most flexible device combining three highly repetitive guns for differing sizes to deliver sufficient numbers of pellets (provided by cutting out of a continuously extruded ice ribbon) in a randomly programmed fashion within the limits of repetition rate (cf also the RPI injector previously used on TFTR). Advantages: high repetition rate (up to 5 s⁻¹); high total number of pellets - quasi-continuous operation; plasma feedback can be imagined (dead time for single pellet ca 5*10⁻³ s, for repetitive pellets ca .2 s); relatively high speed; as with all of the following launcher schemes employing guided pellets, aiming is very good (± .4°) and expected to even improve with higher velocities. Disadvantages: vacuum interface with large gas handling capability (e.g. 6 mm pellet may be driven by 2-3 bar of hydrogen) needed for differential pumping (which can be met with cryogenic pumping, though for a price); pellet variability limited - different pellet sizes during an experimental pulse require multi-barrel approach.

2.3 High-velocity Launchers

2.3.1 Two-stage Light-gas Gun

This is actually a pneumatic launcher in which the pellet driving gas (2nd stage) is heated to several 1000° K by adiabatic compression of a piston being accelerated itself by gas pressure (1st stage); The heated driver gas features a higher sound velocity (=VT), permitting perhaps pellet speeds up to 10 kms⁻¹, and the functional dependence of the driving pressure with time can also be partially tailored (pressure ramping up to several 1000 bar) to compensate for the decline of the actual driving pressure at the pellet because the gas is expanding (transformation of internal energy into energy of motion). The driving pressure at the pellet should ideally be constant and at the limit set by the mechanical properties of the pellet. For bare deuterium pellets this leads to maximum tolerable accelerations of 5-10*10⁶ ms⁻², an order of magnitude lower than those applied in the military applications of the last 25 years or so in which close to 10 kms⁻¹ have been reached for far heavier loads, however on a much shorter time frame. On the according longer time frame JET found already below 5 kms⁻¹ indications of the influence of heat transfer to the barrel when comparing carbon and stainless steel barrel material. Also JET/EMI/CENG encountered the above mentioned erosion effect which is believed by them to be a boundary layer phenomenon effecting the performance of all guided pellet schemes above 3 kms⁻¹. As a consequence sabot techniques have to be employed. So far, only testbed work can be reported (as is true for the remainder of the concepts) though an application is now planned on JET. The JET/EMI/CENG collaboration, CNR-CNPM/Milano/Frascati and ORNL have accelerated in trials 3 to 6 mm plastic pellets to 4.5 - 5 kms⁻¹ with relevant parameters for the acceleration of bare deuterium pellets; the first two groups have actually fired bare pellets with 2.7 and 2.9 kms⁻¹ of maximum speed with already degraded pellet integrity and JET has brought 5 mm sabot-supported deuterium pellets to 3.8 kms⁻¹ with good integrity. Using the sabot technique the erosion problem is virtually
eliminated and it is expected that the maximum acceleration tolerated by the deuterium ice can again be increased. As mentioned, sabot removal techniques and the piston lifetime issues have successfully been tackled but the compatibility of the hot high-pressure surge with the requirements of the pellet forming cryogenic breech environment (though no problem for a single-shot launcher) have still to be solved for a repetitive version, together with the piston cycle timing (the piston can only be expected in the starting position for a new shot when its energy of the order of 100 kJ gained in the previous shot has safely been dissipated). Despite of considerable effort still needed to turn it into an experimental viable and reliable device the two-stage gun is certainly the first contender to be picked if and when higher velocities are desirable and/or necessary. Advantages: higher speed compared to conventional pneumatics. Disadvantages: Even higher gas loads to be expected (up to 30 barl which still can be managed by cryopumping); due to the longer firing cycle (likely to require close to 1 s) and the trigger delay (piston needs some .05 s to compress gas) a reduced variability will also result from this; shock and vibration problems, particularly when carried into the pellet cryostat.

2.3.2 Electrothermal (Arc) Gun

This uses the same principle as the two-stage gun, namely hot pneumatics, but the generation of the hot gas is to be facilitated by an electrical arc. The hope was that such a gun would be less bulky, free from impact problems and that the desired pressure surge could be more easily programmed in time by electrical rather than mechanical means. The scale of the problem can be appreciated when considering that a good deal of the piston energy of the above gun, say 50 kJ, have to be converted in the pellet acceleration time of typically $10^{-3}$ s, leading to a peak power requirement in the order of 50 MW or even higher; this power is now to be fed in electrical form to a gas in a volume of only a few cm$^{-3}$ (with no dead volume allowance) which then is to flow out through a few mm diameter barrel while assuming near sonic velocity. Arc physics and technology are here outside of known experience and the attempts made so far have - despite of some advances - not been able to convincingly overcome the problems of lacking of electrical coupling efficiency on the whole and with regard to the desired shape in time of the produced pressure surges, of electrode erosion and impurity production and of insufficient gas feed into the arc chamber (arc fuelling). As far as I understand the ORNL effort has now ceased; and JET terminated their contract with Riso NL because for those reasons the arc concept did not look competitive on the timescale of the experiments on JET.

2.3.3 Rail Gun

This is an electromagnetic accelerator in which the field build-up between the rails behind a sliding connector bar (arc armature) provides the pressure to drive the pellet in front of the bar (provided the bar does not overtake the pellet). For constant current $I$ the force $F = 0.5L' I^2$ ($L'$ = inductance per unit length) should be constant which is very desirable for a constant acceleration as required for mechanically weak pellets. So far, at the U. of Illinois' work the expected acceleration was apparently not reached and I suspect that the gun is actually some kind of electrothermal gun with as yet unknown potential. If a rail gun can be made to work then two major advantages were obvious: there is no basic upper limitation in velocity for our purpose (barrel length would simply scale with the square of the speed) except the one imposed by pellet-barrel interaction (as found on bare pellets by JET and certainly to be expected with sabots - hopefully at very much higher speeds); in constant current mode with approximately constant voltage the power supply would be much simpler. However, the fact that this type of gun needs a pre-accelerator to
avoid arc spot problems and therefore requires a complex interface with critical arc triggering and well-matched acceleration take-over will require a high technical development effort. Of possible advantage could be that the gas load is likely to be small, but I suspect that sabot acceleration has to be used as well and it is far too early to speculate on the suitable removal technique.

2.3.4 E-Beam Rocket Accelerator

The idea is to couple the power of an electron beam into the surface subjected to gas (or indirect magnetic) pressure in the preceding schemes - like in a solid fuel rocket - and ideas have been tossed around to facilitate the same with either ion beams or lasers. It is hoped that the ORNL experiments will answer principal questions of power coupling in the correct pellet ablation zone and of electron beam generation and guidance in the presence of high gas loads from the rocket exhaust (by measuring suitably acceleration and "burn" rate of the pellet of which the largest fraction has to be "sacrificed"). Like in the rail gun case no inherent maximum limit in speed should exist but again it looks like sabots will be needed to maintain integrity of the pay-load and the erosion effect might also lead to trouble with the rocket fuel part; there might also be a control problem to keep the power input in line with the decreasing pellet mass. Again it is to early to go further into systems implications at this stage; but potentially the gas load to the plasma can be lower by perhaps a factor of 10 than that of the two-stage gun at the same speed.

4. CONCLUSIONS

So, in my view, the main effort of next-phase development is needed in the field of two-stage guns (particularly to make them reliable, long lasting and repetitive, inclusive of an adequate repetitive cryogenic breech part which I did not have the time to cover) to assess the benefits of higher speeds; in addition the systematic consolidation and refinement of technology, available in principle, is the other major task to arrive at injectors with satisfactory specifications to serve the experiments, in particular the ones of the next generation. It seems that some progress has been made but with regard to the high-speed feature it is slow and the number of professionals and the means they have available seems rather marginal to hope for a fast arrival of a universal tool to answer the fuelling questions posed by the fusion experiments of today and those of the next generation.

REFERENCES

1) International Pellet Fueling Workshop, La Jolla Ca, Oct 30 - Nov 3, 1985, proceedings ed. by ORNL, Conf.-8510266
2) Pellet Fueling Workshop, at the 34th National Vacuum Symposium of the American Vacuum Society, Anaheim Ca, Nov 6, 1987
   For full name and address of laboratories, detailed author list and respective references the contributed papers should be consulted.
   A comprehensive review of pellet injection technology and application has recently been given by S. Milora (35th National Vacuum Symposium of the American Vacuum Society, Atlanta Ga, Oct 3-7, 1988), to be published.
Abstract

The results presented at the meeting on ablation phenomena is given and which includes pellet heating and ablation modeling, ablatant cloud expansion, pellet shielding, penetration depth and velocity scaling, pellet wake structure. The survey is based mainly on the comparison of the existing theoretical models with various experimental observations.

INTRODUCTION

A broad survey of pellet ablation is given, based primarily on information presented at this meeting. The implications of various experimental observations for ablation theory are derived from qualitative arguments of the physics involved. The major elements of a more complete ablation theory are then outlined in terms of these observations. This is followed by a few suggestions on improving the connections between theory and experimental results through examination of ablation data. Although this is a rather aggressive undertaking for such a brief (and undoubtedly incomplete) assessment, some of the discussion may help us advance the understanding of pellet ablation.

Engelmann presented a summary of pellet fueling issues in future devices [1]. The issue most closely connected with pellet ablation is that of peilet penetration. Partial pellet penetration and deep penetration have different implications for technology development. Getting beyond the scrape-off layer and the poorly confined edge region is a fairly straightforward task and can be accomplished with present technology. This can be used to improve on the fueling efficiency of gas injection. Deep penetration, as seen in many experimental results, provides added control over the plasma density profile and access to improved confinement regimes. ASDEX results indicate that partial pellet penetration gives some confinement benefits [2], but JET results seem to indicate that the maximum benefits are gained with central fueling [3]. The relationship between pellet penetration and confinement is still a fairly open question, covered in the summary by Lackner [4]. We may not have any conclusive answers on the relationships between fueling profiles and confinement, however, until we better understand the basic plasma transport processes.

The means of improving pellet penetration are pellet size and pellet velocity. The pellet size is limited by physics — by how large a mass increase the plasma can tolerate. The pellet velocity is limited by technology [5]. So these two parameters must be played off against each other to reach optimal fueling conditions, but one involves physics and the other technology. To quantify the trade-offs between pellet size and velocity, a better understanding of the ablation process is needed. We would like to be able to predict pellet penetration and particle source profiles in planned experiments and to provide guidance for technology development. So the basic question we come down to is how pellet ablation and penetration scale with pellet size and velocity.

EXPERIMENTAL OBSERVATIONS AND IMPLICATIONS

Various experimental observations can be used to provide clues to the important considerations in pellet ablation physics. Many of these features are widely observed. Some have widely accepted explanations, while others have several possible interpretations. In many cases, quantified comparison between theory and experiment is not yet possible.

Curved Pellet Trajectories

One of the earliest observations was that pellets do not necessarily travel in a straight line. The explanation for this was given many years ago and is now used as the basis for electron beam acceleration of pellets [6]: asymmetric illumination of the pellet causes a rocket effect. When the incident fluxes to the pellet co and counter to the magnetic field are unbalanced, the nonuniform evaporation of the pellet surface accelerates the pellet in the direction of the imbalance of the forces. It is less of an effect in large tokamaks than small tokamaks because of a combination of larger pellet sizes and smaller perturbation of the electron distribution by the applied electric field. The effect is most notable in the ZT-40M reversed field pinch, where reorientation of the injector was required to improve control over the mass deposition [7]. The importance of the magnetic field and plasma distribution functions is implied by this observation. It emphasizes that pellet ablation models must consider nonuniform illumination and anisotropic distribution effects. Neutral shielding models take into account the restriction of the incident electron flux to the cloud by using $2\pi r_p^2$ for the exposed surface area rather than the $4\pi r_p^2$ of a sphere. Otherwise, a uniform spherical expansion of the cloud is generally assumed — appropriate for uniform illumination and expansion into a vacuum.

Reduction of $H_\alpha$ at Magnetic Axis

ISX-B experiments were the first in which pellets penetrated to magnetic axis, where a very large dip was seen in the ablation rate. The effect has been seen in many other experiments since then. The obvious explanation is that there is a geometric singularity at the magnetic axis which limits the amount of plasma energy available in the ablation process. The implication is that the magnetic geometry is very important in the ablation process — specifically, that the plasma cannot always be treated as an infinite medium. Ablation models that account for finite plasma volume are said to include self-limiting ablation effects, because as ablation proceeds the temperature of the remaining plasma is reduced and further ablation is restricted.

$H_\alpha$ Fluctuations

The explanation of the large dip in $H_\alpha$ signals at the magnetic axis has been extended to cover small fluctuations in $H_\alpha$ signals by arguing that the plasma volume connected to the pellet is restricted at rational flux surfaces. The argument has been largely qualitative because of the difficulty in including all the proper geometry and kinetics. Because of the large number of fluctuations, relatively high-order rational surfaces must be considered. Pégourié [8] has recently developed a comprehensive model of the effect of rational surfaces, including the lack of depletion of trapped electrons because of toroidal drift, and concludes that the magnitude of the dips at rational surfaces can only be explained if there is a flattening of the $q$ profile in the vicinity of each rational surface. In reality, the effect may be even more complicated. All experiments use cylindrical pellets, which tumble as they pass through the plasma. Because the illumination of the pellet is primarily on surfaces normal to the magnetic field, the pellet exposes a fluctuating cross-sectional area to the plasma. The magnitude of the usual $H_\alpha$ fluctuations is generally consistent with the different cross-sectional areas exposed to the plasma by a tumbling cylinder. Another possibility that has long been recognized is that there may be hydrodynamic instabilities in the neutral or ionized clouds. Lengyel has recently developed a time-dependent, single-cell Lagrangian model for the expansion of the cold ablatant plasma that may be used to address compressive oscillations as a possible source of the fluctuations [9]. It is likely that some combination of these effects is necessary to explain the oscillations: rational flux surfaces and tumbling introduce a time-dependent source and pellet cross-section that cause oscillations in the hydrodynamic solution, which may fail to reach a true steady state and appear largely random in magnitude. The very large dips seen in the $H_\alpha$ signals may still be associated with islands or very low order rational surfaces. Passing through an X-point or the center of a rotating island would make the magnitude of the dip vary considerably from shot to shot and appear irreproducible.
In apparent contradiction to the rational flux surface argument are the fluctuations observed in the Wendelstein VII-A stellarator, where there is very little shear. However, the high energy electrons produced by ECRF heating in that experiment make higher-order rational flux surfaces more important, if the high energy electrons are constrained to flux surfaces on the ablation timescale. The tumbling pellet argument still holds in shearless plasmas. Would a spherical pellet exhibit fluctuations? Are the fluctuations from highly elongated pellets more pronounced? Do the fluctuations generally get smaller as the mass is eroded and the pellet presumably becomes more spherical? There is probably not much promise in developing more detailed models for this; the net effect of the fluctuations is possibly some small net reduction in the ablation rate. Nonetheless, the fluctuations pose interesting physics questions about the ablation process.

**Striations**

It is generally observed that visible light from pellet ablation is extended along the magnetic field. Viewed instantaneously, the light is constrained to a long narrow tube. The pitch of the tube has been used in TFR to measure the local components of the magnetic field [10]. Time exposure normal to the pellet path and magnetic field shows very narrow striations aligned with the magnetic field that are apparently correlated with the observed fluctuations in the $H_\alpha$ signal. The ablatant must be ionized very close to the pellet surface to be so well constrained by the magnetic field, or the striations would be washed out. The visible light means that this ablatant plasma must be highly susceptible to recombination followed by immediate re-ionization — it is a cold, dense plasma. This observation is consistent with the addition of a plasma shield to the basic neutral shielding model, and the shield may be further enhanced if the initial neutral ablatant is preferentially emitted along the magnetic field, which follows from non-uniform illumination of the pellet [11, 12]. The implication of these observations, of course, is that the total shield is non-spherical, possibly in both the neutral and plasma shields.

**Lack of $H_\alpha$ Fluctuations**

After all the attention to $H_\alpha$ fluctuations it must be pointed out that there are instances in which no significant $H_\alpha$ fluctuations exist. These cases may tell us as much about the cause of the fluctuations as anything else if a reasonable physical connection can be made between the observations. Generally, it appears that the lack of $H_\alpha$ fluctuations is associated with the presence of a high-energy electron population, as in the TFR ECRF heating experiments [13], where the ablation rate is extremely high. An explanation of this observation could be that the energetic particles are less constrained to flux surfaces, are not significantly impeded by the neutral and plasma shields, and therefore provide a more uniform illumination of the pellet regardless of plasma geometry and shield details. But how do the observed fluctuations in W VII-A fit into this argument? The implication of a lack of fluctuations is that a hydrodynamic instability is not the sole cause of the fluctuations.

**Broad $H_\alpha$ Profiles**

The usual observation in ohmic plasmas is that the $H_\alpha$ signal rises more or less continuously (except for fluctuations) until near the end of the pellet life. Often under auxiliary heating conditions, however, the signal rises very rapidly as the pellet enters the plasma and remains nearly constant over much of the pellet lifetime. These atypical $H_\alpha$ signals are usually associated with enhanced ablation effects from neutral beam injection [14] or ECRF heating [13, 15]. Also connected with these enhanced ablation profiles is a lack of mass accountability. These observations can be explained by the influence of nonthermal distributions on the ablation process. The shield, which is largely sustained by the thermal electrons, is relatively weak in the plasma edge. Nonthermal electrons or ions may penetrate the shield and ablate more mass than can be ionized in a compact shield by the thermal electrons. The mass accountability could be associated with a significant neutral and charge-exchange loss of particles not otherwise observed when the shield is compact. The implication of this is that the distribution functions of plasma electrons and ions are important. The compatibility of pellet fueling with various heating schemes needs to be evaluated. It points to the possibility that fast alphas in fusion plasmas could present a
problem with enhanced ablation, but if fast alphas are reasonably constrained to their birth surfaces while thermalizing, they may not exist in sufficient quantity to enhance ablation in the outer plasma where the pellets are most vulnerable [16].

\( T_e \) Profile Response During Ablation

One final observation that seems to defy adequate explanation is that in some instances ECE signals indicate a precooling of the electrons significantly ahead of the pellet during the ablation process. This was noted in Alcator-C, TFR, and ASDEX experiments where a drop in \( T_e(0) \) appeared soon after the pellet entered the plasma but significantly before it reached the axis. In JET the precooling on axis did not appear until the pellet penetrated beyond the \( q = 1 \) surface. Neutrals from the pellet could penetrate to the plasma center on this time scale, but they would affect the ions — the electrons would see this cooling on a \( \tau_c \) time scale, which is too long to explain the observation. Another possible explanation is that a macroscopic transport process is induced by addition of the pellet mass to the plasma. It might be expected that a major loss of energy from the plasma would be involved — something that is not observed. Somehow, then, the effect is contained within the plasma, as a sawtooth or other internal disruption (i.e., not extended to the limiter or walls), but apparently affecting only the electron temperature profile and not the density profile.

ABLATION MODEL DEVELOPMENT

What do these observations mean in terms of ablation model and code development? What are the key elements that need to be included for a more complete picture of the ablation process? The elements of a complete model include starting with the basic neutral gas shielding model, because of its general success in both qualitative and quantitative agreement with observed ablation rates.

The energy distribution of electrons and fast ions incident on the pellets must also be included. Approximating thermal electrons as monoenergetic is generally not adequate for plasma temperatures above a few hundred eV [16]. Detailed treatment of the atomic physics of the cloud is required, including all neutral and ionization states, to make quantitative contact with \( H_q \) measurements and improve the hydrodynamic calculations in the cloud [17]. Non-thermal electron distributions from ECRF and LH heating schemes and from runaway electrons have been shown to be important, but quantified comparison with experimental results is very difficult because of inadequate knowledge of the distribution function. Qualitative agreement is possible [13]. Fast-ion-enhanced ablation from neutral beam injection can be evaluated quantitatively because of better knowledge of the energy distribution of these ions [14].

Both conduction and convection of energy through the shield need to be evaluated for detailed assessment of the cloud features and shielding effectiveness [17]. This generally tends to require a kinetic treatment of beginning far from the pellet with a Maxwellian distribution of electrons, moving through the outer portions of the cloud where mixing of the cold and hot electrons occurs and the total electron distribution is non-Maxwellian (the collision mean free path of the most energetic electrons is longer than the gradient scale length), and continuing into the very dense cold cloud where a cold electron fluid can be considered. This is a very complex kinetic problem that has only been solved with limiting approximations to conductive and convective flow of energy.

Asymmetry in the ablation parallel and perpendicular to the magnetic field is important. It may elongate the neutral shield in the direction of the magnetic field [11, 12]. Perhaps this implies that a cylindrical model should be considered for the neutral shield as well as for the plasma shield [9] — rather than using a spherical approximation for the neutral shield with a correction for the exposed surface area. A cylindrical model would simplify hydrodynamic calculations by removing the singularity at the critical radius and give some insight into various physical processes of both the neutral gas cloud and the plasma shield.

A possible additional shielding effect that has not received much attention is magnetic shielding. The large amount of energy that the electrons deposit in the vicinity of the pellet leads to a low-temperature, high-density plasma cloud. In higher-temperature plasmas, the kinetic pressure in this cloud may expand the magnetic field around the pellet and
reduce the incident flux by reducing the upstream cross-section of the plasma tube that maps onto the pellet and its cloud [9].

The geometric reduction of plasma near the magnetic axis is significant, but perhaps not that important in assessing details of pellet requirements; if the pellets reach the magnetic axis, the major problems of pellet penetration have already been overcome. The reduction in ablation at the axis is an interesting one from a physics standpoint, however.

Perturbations to the background plasma that occur on the ablation time scale should be addressed. Local self-limiting ablation has been modeled by considering various collision and mixing time scales of the plasma electrons [16]. Generally, in larger, hotter plasmas this tends to be less important. In smaller experiments where the plasmas are more collisional, propagation of the ablatant mass around the torus and mixing with the hot plasma may need to be considered. This appears to be particularly important in ZT-40M [7].

Another type of perturbation to the background plasma is nonlocal deposition of the pellet mass over the ablation zone. Generally, models that evaluate the ablation locally use strictly local deposition. In large, hot plasmas, where the scale of the ablation zone is very small compared to the plasma dimension, local deposition is appropriate. But what about global perturbations to the plasma, separate from deposition, as indicated by the ECE measurements showing a \( T_e \) response far ahead of the pellet?

The effect of fluctuations in the ablation process as evidenced by the H\( _\alpha \) signals may have to be included in some general way if they significantly alter net ablation rate. To be able to model this in detail may be more difficult than can be justified. As stated earlier, it is an interesting physics problem.

Many of these effects have been included in various extensions of the neutral shielding model. Most of them have not been included in any single computational model. Future development will generally concentrate on bringing the various pieces together in more comprehensive, complete models. To guide this effort and to highlight the most important features of these models, further analysis of experimental ablation data is indicated.

**ABLACTION DATA ANALYSIS**

From the physics included in basic ablation models we need to develop scaling laws for pellet ablation and penetration and suggest tests against experimental data. Are there key features of the physics of ablation that change, for example, the scaling of penetration with velocity and pellet size? Are there other relatively simple experimental tests of the basic elements of a given theory that can be proposed?

Detailed comparisons with experimental data are needed. It has been shown that many cases are needed to develop a statistical analysis because of scatter associated with the absolute measurement and penetration depths [11]. Similar uncertainties exist in the pellet mass measurements and plasma properties. We should not only compare the penetration depths with experimental results, but also try to determine whether the shapes of the deposition profiles are in agreement with experimental results.

Tests of ablation and penetration scaling should be done under controlled conditions. Only plasmas with thermal electron distributions and no notable fast ion effects from neutral beam injection or ICRF should be included in analysis of the basic electron ablation. Auxiliary heating conditions must be considered in extending the temperature range of the data, but the results should not be clouded with the effects of non-Maxwellian distributions. Fast ion effects from neutral beam injection in TFTR dramatically change the H\( _\alpha \) trace [14]; changes in the H\( _\alpha \) signal may then be used as an indication of fast ion effects. No such fast ion effects have been noted in JET ICRF or neutral-beam-heated plasmas [11]. Separate analysis of the effects of runaway electrons and ECH heating is needed. Also, cases with large anomalies due to plasma singularities, e.g., pellets that penetrate too near the magnetic axis, need to be analyzed separately. Most simple scaling arguments break down close to the magnetic axis because geometric effects and lack of approximate linear rise of the temperature profiles.

Cases with very large dips in the H\( _\alpha \) signal (presumably from very low order rational surfaces or islands) and cases that produce snakes (crossing the \( q = 1 \) surface) likely indicate geometric restrictions in the plasma. The JET results show a high correlation between the presence of these large dips in the H\( _\alpha \) signal and deeper pellet penetration than in similar cases with more normal signals.
Applying these constraints, we can use statistical analysis of pellet injection data to address the following relationships that arise in evaluating ablation models. The diagnostics required are generally available: a wide-angle Hα monitor, a time-of-flight determination of $v_p$, a relative mass measurement of individual pellets with a microwave cavity, penetration depth determined from time of flight or soft X-rays, and plasma electron temperature and density profiles.

$H_\alpha$ and $\dot{N}$

One question of long standing is how are $H_\alpha$ and the pellet erosion rate $\dot{N}$ related? We assume that they are linearly related at all temperatures and plasma densities so that the shape of the $H_\alpha$ trace indicates the fueling profile and can be compared with calculated ablation rates. The total integral of the $H_\alpha$ signal plotted versus pellet mass for various pellet sizes, velocities, and experimental conditions should exhibit a linear relationship with small scatter.

Penetration and $r_p$

How does penetration depth scale with pellet size? A wide selection of pellet sizes is available on the JET injector. The ASDEX centrifuge can generate various pellet sizes. Natural variation in pellet sizes also occurs. Individual mass measurement of each pellet is required. A velocity window could be selected to remove any velocity variations. Controlled plasma conditions are needed to remove temperature and density effects.

Penetration and $v_p$

How does penetration depth scale with pellet velocity? This question arises in assessing the differences in scaling between a neutral shield and a plasma shield. A scan of lower pellet velocities with present injectors under controlled plasma target conditions should be possible. Velocity and mass measurements are needed for each pellet. The mass measurement removes any clouding of the results by a correlation between pellet size and velocity. The plasma has to be under fairly controlled target conditions so that plasma temperature and density effects can be removed. Another alternative is to probe the plasma with higher velocity test pellets. This high-velocity pellet program is planned, but more immediate experiments can be done at lower velocity.

Penetration and $B$

Another question that has not been addressed is how penetration depth scales with the magnetic field. The idea here is to see if magnetic shielding is playing a role. Controlled experiments with the magnetic field as an independent parameter while everything else is constant are not done very easily, but perhaps something could be tried to see if any interesting information is gained. Temperature, velocity and size effects need to be eliminated. Statistical analysis could be a means of systematically eliminating the other effects in the same way that global confinement is analyzed.

$\dot{N}$ and $r_p$

How does the local ablation rate vary with the pellet size? Klaus Büchl has made some observations on ASDEX that show the initial rise of the $H_\alpha$ signal to be independent of pellet size in identical plasma discharges. Is this a general phenomenon? If so, it may indicate that the ablation is restricted by a mass erosion rate — that $\dot{N}$ is independent of $r_p$ — a result contrary to our present ablation models that show $\dot{N} \propto r_p$. (This presumes a linear relationship between $H_\alpha$ and the ablation rate.) Another possibility is that a finite time is required to establish quasi-equilibrium in the pellet cloud and that our hydrodynamic equilibrium models are not applicable in the plasma edge. Individual mass and velocity measurements on pellets of different sizes under controlled plasma conditions are required. A detailed comparison of the initial rise of the $H_\alpha$ traces should be sufficient to answer this question, once the above constraints are met.
SUMMARY

Much physical insight into the rich detail of pellet ablation physics has been gained over the past decade. Understanding the complexity of the large local perturbations introduced by pellets requires insight into a wide variety of plasma physics issues. Progress has been made in the development of computational models that include much of the observed detail. More guidance from analysis is needed, however, to gather the most important pieces of the puzzle together and solidify the projections of pellet needs for future large, hot plasmas.

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TRANSPORT MODIFICATION THROUGH PELLET INJECTION

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Abstract

Highlights from the theoretical papers presented at the IAEA Technical Committee Meeting on Pellet injection and Toroidal Confinement on transport modification in discharges with pellets are summarized: Energy transport by electrons and ions and particle transport are discussed with emphasis on experimentally observed features produced by injecting pellets into the large tokamaks.

1. Introduction

Improvement in the energy confinement time has been demonstrated in recent years under different sets of conditions having as a common feature strongly peaked density profiles. Means of achieving this were pellet injection (Greenwald et al., 1984), NBI injection in the counter-direction (Gehre et al., 1988), but also particular scenarios for density build-up by conventional means: supershots (Hawryluk et al., 1987) and the IOC regime (Söldner et al., 1988a). The confinement improvement mechanism seems to be qualitatively different from that in the H-regime (Wagner et al., 1982), leaving hope for possible further improvement by superposing the two effects.

The following discussion is limited to the modifications in energy and electron particle transport. Obviously, impurity and poloidal field (toroidal current density) transport are also affected, and all four types of transport will in general interact with each other, as schematically shown in Fig. 1.

![Fig.1: Schematic view of interrelation of different transport processes.](image)
Here thick arrows indicate influences which (in our opinion) are always of a dominating order, whereas connections shown by thin lines are large and determining only under particular circumstances. The latter is the case with, for example, the effects of impurities, which will have a strong influence on temperature (through radiation) and current density profiles (through $Z_{\text{eff}}$) only when present in sufficient amount.

Some of the above classifications are open to discussion: theoretical models of rigorous profile consistency would, for example, always make current density profiles - through MHD - a determining factor for the temperature profiles. For some time observations also indicated a strong correlation of peaked density profiles with sawtooth suppression: situations have been identified in the meantime which break this correlation (notably in the IOC regime) but sawteeth may still play an important role in forbidding or allowing access to peaked profiles under marginal conditions. In general, however, a situation like that in Fig. 1 would justify a perturbation approach in which the influence of temperature and hydrogen ion density profiles on impurity and poloidal magnetic field transport are assumed to be of lower order than the reverse effects.

Energy and electron particle transport, on the other hand, seem to mutually influence each other already to lowest order. We can affect both the energy confinement by changes in the particle refuelling (e.g. through pellet injection - Greenwald et al., 1984) and the particle confinement through energy input (viz. acceleration in the post-pellet density decay on JET following application of ICRH - Schmidt et al., 1988). It is therefore expected that a combined treatment of the two transport processes will ultimately be necessary, particularly in order to understand the transition between the two regimes of energy and particle confinement time ($\tau_E$ and $\tau_P$, respectively) at given values of the line-averaged density ($\langle n \rangle$) and heating power ($P_{\text{tot}}$) through minor changes in the externally controllable parameters (Söldner et al., 1988a). A separate discussion of particle and energy transport, like in the following, is nevertheless justified since (1) we do have a plausible theoretical explanation for a causal link in one direction, and (2) pellet injection provides a reproducible means of imposing a large change in density profiles on a time scale more than two orders of magnitude shorter than $\tau_P$ (so that, at least in principle, we can impose starting density profiles independently of any transport).

The question also arises whether driving forces and transport processes additional to those indicated in Fig. 1 have to be considered simultaneously to understand the phenomena accompanying and causing density profile peaking. That this must indeed be the case is shown by comparison between co- and counter-injection experiments on ASDEX (Gehre et al., 1988), the differences between which cannot be accounted for simply by the variation in particle and energy deposition profiles. The origin of the effect is suspected to lie in the different sign of the radial electric field arising from the displacement of the fast ion orbits with respect to the flux surface on which the ions were born and from the different rates of ion-orbit losses. No detailed modelling studies of this effect have yet been carried out for tokamaks, although theories of anomalous transport do exist, which predict an influence of radial electric fields (Callen, 1977, Shaing, 1988).
2. Electron Density Profiles and Particle Transport

In papers presented at this meeting the particle transport is analyzed by interpretative and simulation codes for discharge conditions leading to density profile peaking. The electron particle flux $\Gamma_p$ can be formally described by an ansatz

$$\Gamma_p = -D_p \cdot \left( \frac{\partial n_e}{\partial r} \right) + v_r \cdot n_e$$

where the drift term $v_r \cdot n_e$ may stand for either the neoclassical Ware pinch or an anomalous inward drift. In the stationary case and over a source-free region encompassing the magnetic axis $\Gamma_p$ is identically zero, and the $n_e$-profiles depend only on the ratio of $v_r/D$, but not on the separate magnitudes of the two terms. To establish the necessity of an anomalous contribution to $v_r$, these studies therefore concentrated on transient phases. Even without detailed analysis two qualitatively different paths to peaked density profiles seem to emerge, which are exemplified by the pellet injection results of TFTR and JET on the one hand and those of ASDEX or Alcator C on the other. Schematic representations of the different profile time developments are given in Figs. 2 and 3.

![Fig. 2a](image1.png)  ![Fig. 2b](image2.png)

Fig. 2: Schematic view of two types of time development of density profiles after injection of a pellet in a large device.

In the two large machines, either the attainment of peaked profiles requires penetration of the pellet to the plasma centre (2a) or they are obtained only during the general decay of the profiles (2b). In both cases (2a and 2b) there is never any substantial net inward flow of electrons up a density gradient.

On ASDEX, on the other hand, pellets generally penetrate only to about half the minor plasma radius. After termination of a string of pellets, the central density continues to rise in a form requiring substantial net plasma flow up a density gradient (Fig. 3a). This is even more pronounced in the transition between purely gas-puff-refuelled discharges of the SOC and IOC types, where a reduction in the gas-puff rate triggers an increase in the central plasma density and a transition to more peaked $n_e$-profiles (Fig. 3b). Peaking of density profiles has also been
observed on ASDEX following the injection of very slow pellets (300m/s - Kaufmann et al., 1988a). These pellets with shallow penetration thus seem to constitute a link between the two situations depicted in Figs. 3a and 3b.

![Fig. 3a and Fig. 3b](image)

**Fig. 3**: Schematic view of time developments of density in ASDEX leading to peaked profiles: 3a...after non-central pellet deposition, 3b...transition from SOC to IOC regime.

In accordance with these different observations, it was not necessary in the modelling efforts for TFTR and JET (Baylor et al., 1988), (Houlberg et al., 1988) to enhance the value of \( v_r \) beyond that predicted by neoclassical theory. On ASDEX, on the other hand, an enhancement of \( v_r \) by a factor of the order 3 over \( v_{\text{Ware}} \) (Mertens, 1988) in the central plasma region seems necessary to explain the plasma inward flow during the peaking phase. A large enhancement of \( v_r \) over \( v_{\text{Ware}} \), but restricted primarily to the outer plasma regions, had already been established in a number of devices, including JET (Gondhalekar et al., 1985), in density build-up experiments with gas fuelling, which did not lead to strong profile peaking. It is obvious that the conclusiveness of the evidence for and against an enhanced pinch velocity in the plasma interior will have to be re-examined. It is quite possible, however, that both modelling conclusions are right, reflecting a basic difference between medium and large-size devices.

All analyses for JET (Baylor et al., 1988, Houlberg et al., 1988), TFTR (Hulse et al., 1988) and ASDEX (Mertens, 1988) do agree, however, in the conclusion that two regimes of electron particle transport exist in the central plasma region. They also concur that the reduced post-pellet decay rate of the density in the favourable cases on JET (such as the ohmically heated cases and the ICR heated cases exemplified by shot nr. #16211) and the density peaking on ASDEX following pellet injection or the transition to the IOC regime are a consequence of a reduction in \( D_p \) rather than an increase of \( v_r \). For the case of the transition from SOC to IOC even direct evidence for this conclusion is given by the results of gas oscillation experiments (Söldner et al., 1988b). The reduction of \( D_p \) and the extent of strong density peaking are found, however, to be strictly limited (Fig. 4 shows the radial profile of \( D_p \) used in the JET simulations of Baylor et al., 1988 and Houlberg et al., 1988) to a region over which a reduction in heat and impurity particle diffusivities is also observed.
One possible conclusion would thus be that in the interior regions of the plasma two regimes of transport exist, of which the one is distinguished by reduced values of all diffusivities. For unchanged inward drift velocities this regime would necessarily exhibit peaked electron density profiles, accompanied by peaking of the impurity densities and improved energy confinement over the affected region. The physical mechanism for this sudden reduction in the anomalous diffusivities would remain unexplained, although we do know some empirical recipes how to trigger it.

A less symmetric point of view is suggested by the theory of so-called $\tau_1$-modes, which should be excited if the value of $\tau_1 = (d \log T(r) / d \log n(r))$ exceeds a certain threshold value in the range of 1 to 2. According to the current view, the quenching of these modes following peaking of the density profile would account for an improvement in energy confinement. No consistent explanation has yet been given, however, for the spontaneous peaking of the density profiles in regions not reached by refuelling (the situations in Figs. 3a, b). In the interior, weakly collisional regions, $\tau_1$-mode turbulence would give rise to an outward drift of electrons (Lee and Diamond, 1986). The persistence of steep density gradients in regions where they have been directly produced by pellet deposition could thus be explained by the following scenario: the usual flat density profiles are due to a competition between the $\tau_1$-mode driven outward drift and an additional inward drift due to a different mechanism. The former would then be quenched by the steepening of $n_e(r)$ due to the particles deposited by the pellet. However no modelling calculations have been reported so far substantiating this suggestion, which anyway could seemingly not explain situations where peaking proceeds to the inside of the deposition zone.

![Fig.4: Radial profile of electron particle diffusivity used in JET simulation calculations (Baylor et al., 1988), (Houlberg et al., 1988) to describe slow density decay after pellet injection.](image-url)
A further consequence of pellet injection possibly linked to the particle transport in the plasma interior is the observed increase in the operational limit for the line- or volume-averaged electron density ($\bar{n}_e$ and $\langle n_e \rangle$, respectively). The most straightforward explanation for this would be that the density limit usually observed is in fact a limit to the density in the near boundary zone, which obviously would then correspond to higher values of $\bar{n}_e$ and $\langle n_e \rangle$ in the peaked-density cases. Although this suggestion has so far hardly been contested, it has, on the other hand, not yet been substantiated by quantitative analyses either.

3. Energy Transport

Under a variety of conditions it has been observed that the global energy confinement $\tau_E$ increases following pellet injection and/or peaking of the electron density profiles. This was first explicitly shown on Alcator C (Greenwald et al., 1984), where pellet injection led to higher values of $\tau_E (\bar{n}_e)$ in the regime of usually saturated ohmic confinement. It seems plausible, however, that previous discrepancies between the results for $\tau_E(\bar{n}_e)$ of conventional gas-fuelled discharges on FT (Alladio et al., 1982) and Alcator C (Fairfax et al., 1980) in the corresponding density regime were already due to systematic, but uncontrollable differences in the density profiles of the two machines (DeMarco et al., 1986). The existence of two such regimes in gas-fuelled discharges (labelled SOC and IOC for saturated and improved ohmic confinement, respectively) together with a reproducible prescription for initiating the transition between them was demonstrated on ASDEX (Söldner et al., 1988a). Improvement in the energy confinement at given heating power $P_{\text{tot}}$ under conditions leading to peaked density profiles (preceding IOC-phase or pellet injection or counter-nbi) has also been observed with neutral beam injection in the L-regime (Fussmann et al., 1988, Gruber et al., 1988). On JET, a regime was found in which application of centrally deposited ICRH following pellet injection and density peaking led to no deterioration in heat diffusivity and through the change in the deposition and density profiles - even to an enhancement of global confinement compared with the ohmic phase (Schmidt et al., 1988). First reports have also been given of $\tau_E$ enhancement through pellet injection into H-regime discharges (Kasai et al., 1988). Finally, although not discussed at this conference, also the supershot-regime discovered on TFTR is distinguished by peaked density profiles.

3.1. Ion Energy Transport

The analyses presented for ASDEX and JET concur in that they both find a reduction of ion heat conductivity over the region of peaked density profiles. TRANSP analyses for ASDEX under these conditions (Gruber et al., 1988) showed conclusively that $\chi_i$ has to be quite close to the neoclassical value in the interior plasma regions, because otherwise either practically no energy flux would remain to be transported by the electrons or the measured ion and electron temperature profiles could not be explained within the error bars. Whist code simulations (Houlberg et al., 1988) of the JET case #16211 employed $\chi_i = \chi_{i,\text{an}} + \chi_{i,\text{neo}}$, with $\chi_{i,\text{an}}$ =
$\chi_{e,\text{an}} = 13 \frac{D_p}{4}$ and the $D_p$-profile shown in Fig.4. This still implies an enhancement of $\chi_i$ over the neoclassical value, but nevertheless a very strong reduction over the region of strongly peaked densities. At odds with the findings of Gruber et al. (1988) is the fact that the same values for $\chi_{i,\text{an}}(r)$, $\chi_{e,\text{an}}(r)$ and $D_p(r)$ - including the dip in the region $r/a < 0.4$ - could be used and also gave a good fit to results for the ohmic phase before injection of the last pellet, although the authors made no statement about the sensitivity of the results to this point. The observed improvement in energy confinement following ICRH could thus be explained purely by the changes in the power deposition profile $h(r)$ and the density profile, as can be understood from the formula

$$\tau_E = \frac{3}{4} \int_0^a \frac{1}{\chi} \left( \int_0^r h(p) \rho \, dp / \int_0^a h(p) \rho \, dp \right) r \, dr$$

which can be obtained through partial integration from the definition of $\tau_E$ and the heat flux equation and which is valid in the above form for $T_e = T_i$ (and $\eta_i = \eta_e = \eta_i$) and $\chi = \chi_e = \chi_i$.

This reduction of $\chi_i$ over the peaked density region, first found on Alcator C, is strongly indicative of a role being played by $\eta_i$-modes. Even some more detailed and quantitative features of the theory of $\eta_i$-mode driven turbulence have been verified in experiments. In particular, measurements of the density fluctuation spectrum on TEXT (Brower et al., 1988) showed the predicted existence of waves travelling in the ion diamagnetic direction for flat density profiles, which disappeared following pellet injection and peaking of $n_e(r)$. Results of this experiment with gas-puff and pellet-fuelled discharges were also in good agreement with simulation calculations combining $\eta_i$-mode-driven ion heat conductivity with an $\chi_e$-model of drift and trapped particle modes constrained to satisfy a profile consistency condition (Tang et al., 1986). It was also found on ASDEX (Gruber et al., 1988) that the magnitude of $\chi_i$ deduced by TRANSP analysis for ohmic or L-regime conditions and flat density profiles agrees well with the quantitative predictions of the $\chi_i$-model of Lee and Diamond. One obvious difference in the findings of JET (strong temperature profile peaking in the peaked density region and persistence of $\chi_i > \chi_{i,\text{neoc}}$) and ASDEX (nearly invariant temperature profiles, but a reduction of $\chi_i$ to its neoclassical value) can probably be well explained by the relative magnitudes of $\chi_{i,\text{neoc}}$, the different heating power distributions and the scales of the machines. Following peaking of $n_e$ and quenching of the $\eta_i$-mode the temperature profiles would tend to steepen in both machines: for the power fluxes on ASDEX one soon hits, however, the neoclassical $\chi_i$, which has also increased owing to the rise in density. On JET, on the other hand, this limit is farther away and the $T_i$-profile can steepen till it ultimately again arrives at the threshold $\eta_i = \eta_i,\text{crit}$, albeit now at much larger values of $\nabla T_i$ and $\nabla T_i/T_i$.

There still exist a number of further, as yet qualitative points of agreement with $\eta_i$-mode theory. For example, the H-mode is distinguished by rather flat $n_e$-profiles in the interior, and indeed the confinement improvement found in this region is restricted to the electron channel,
with $\chi_I$ being enhanced over the neoclassical value by approximately the same factor as in the standard L-regime.

One critical point in the comparison with theory concerns the predicted isotope dependence of the energy transport. Transport due to $\eta_I$-modes, like that due to other drift-mode-related turbulence or to neoclassical effects, is supposed to increase with isotope mass, in contrast to the general observation for the global $\tau_E$ (Murmann et al., 1988), which increases when changing from H to D. At present it is not clear, however, whether the latter observation also holds separately for the ion channel. As $\eta_I$-driven transport has a threshold behaviour, the explicit isotope dependence appearing in the $\chi_I$ expression could in fact also be rather easily masked by small, systematic differences in the density profiles, as in fact seem to exist (Gehre et al., 1986).

3.2. Electron Energy Transport

It is obviously of great interest whether the electron energy confinement also improves in the presence of peaked density profiles, and whether this improvement can also be accounted for by theoretical models. Analysis of the ohmically heated pellet injection or IOC discharges on ASDEX indeed shows a significant reduction of $\chi_E$, which, however, can - within present error bars - probably be simply described as a consequence of the increase in density, and a manifestation of the general $1/n_e$ behaviour of $\chi_E$ found in ohmic discharges (Gruber et al., 1988).

An improvement of $\chi_E$ in the peaked density regions is also found, however, in discharges with additional heating, such as the ICR-heated shot #16211 on JET analyzed by Houlberg et al. (1988) and the counter-injection experiments on ASDEX (Gruber et al., 1988), in a regime in which electron energy confinement is usually claimed to be density-independent. This improvement runs counter to the predicted behaviour of drift and trapped-particle mode driven electron heat transport (see compendium by Ross et al. (1987)), which should be enhanced by steeper density gradients. In the trapped electron regime, relevant to situations with additional heating, $\eta_I$-modes should, however, also make a contribution to $\chi_E$, which - apart from the common threshold behaviour - scales differently from $\chi_I$, but can become large under appropriate conditions (Lee and Diamond, 1986). A comparison with these predictions would of course be of great importance to our theoretical understanding.

An alternative - non-local - approach to the question of energy transport is given by the so-called profile consistency concept (Coppi, 1980, Lackner, 1987), according to which the shape of the $T_e(r)$-profile is determined by macroscopic constraints. The absolute magnitude of $T_e$ is then further assumed to be either fixed by the volume-averaged entropy production due to other, local, transport-inducing instabilities (drift and trapped-particle modes in the case of Tang et al. (1986)), or by conventional, purely local transport in a limited region close to the plasma boundary (Furth, 1986). Evidently, such a concept is compatible with the observations.
on ASDEX (Kaufmann et al., 1988b), where $T_e$-profiles, in the absence of centrally dominating radiative losses, indeed show very small variations with changes in other discharge conditions except $q_a$. The significant changes in $\frac{d \log T_e}{d r}$ observed with pellet injection and ICRH in the 16211-like discharges on JET, on the other hand, rather suggest a strongly nonlinear dependence of the heat flux on $\nabla T_e$ leading to a stiffening of the $T_e$-profiles. As a by-product, such a nonlinear, but local heat conductivity law would also lead to enhancement of the value of $\chi_e$ as determined from heat pulse propagation studies over that given by the stationary energy balance. Temperature profiles, following adiabatic cooling by pellet deposition, would also be restored on a faster time scale, although a quantitative comparison of this feature with the observed re-arrangement of $T_e(r)$ on a time scale of a few ms in ASDEX (Kaufmann et al., 1988b) is missing. (Still faster profile arrangements, as reported from TFR by Drawin and Geraud (1988), are probably a different phenomenon altogether, having little connection with usual transport phenomena). Global energy confinement scalings of the off-set linear type are equivalent to local transport laws with a sharp increase of $\chi_e$ for $\nabla T_e > \nabla T_{e,\text{crit}}$. As such laws lead to $\frac{d \log q}{d \log |\nabla T_e|} \gg 1$, they yield profile resilience with respect to heat deposition profiles and an enhancement of $\chi_e$ during non-stationary phases. In their present form, (like the Rebut-Lallia law in the form given in Rebut et al., 1988), they cannot yet explain, however, the favourable consequences of an increase in $|\frac{d \log n}{d r}|$.

4. Summary and Conclusions

The confinement improvement accompanying density profile peaking gives an important boost to our confidence that the $\tau_E$ enhancement factors of magnitude < 2 above ordinary L-mode behaviour needed for most ignition device or reactor proposals can indeed be realized. Such experiments - similarly to H-mode shots without ELMs - have generally been hampered by a secular growth of impurity effects ascribed to a parallel improvement in their confinement. Results of IOC regime shots - where persistent sawtooth activity avoided lethal growth of the impurity levels, in spite of a large increase in energy confinement - suggest, however, the possibility of finding a remedy for such situations as well. A balanced strategy would thus be to try to maximize the $\chi_e$ and $\chi_i$ reduction by density profile peaking (like we attempt also, and hope ultimately to do even in parallel, by H-mode operation) but to require a rather large reserve when utilizing these results in reactor designs. This “safety factor” in confinement will then be available to allow for the deterioration in the $\chi$’s expected to accompany measures to control impurity effects, to be developed in the meantime. It is to be expected, that the outcome of such a strategy will still be a net improvement of the ignition probability in relation to conventional L-mode operation.

At the same time, transport modifications accompanying density profile changes offer important clues for our general understanding of confinement. The papers presented and the discussions at
this conference suggest, in particular, a number of short-term goals for further experimental studies, analyses of the results and further development of theories:

- More detailed assessment of the electron heat conductivity changes following $n_e$-peaking: Are the changes in the ohmic regime also quantitatively consistent with continuous $X_e \sim 1/n_e$ behaviour? How large are the required changes in $X_e$ in the cases with additional heating and how do they compare with the T$_1$- mode predictions?

- Existence of an enhanced inward drift in the central plasma regions: What are the uncertainties in the analyses coming to the differing conclusions? Or are there indeed two different regimes, corresponding at the same time to success or failure of peripheral pellet refuelling?

- Isotope dependence of $X_i$: Can we make definitive statements about it on the basis of the experimental data, and can we discriminate between an explicit dependence of $X_i$ on H,D and a possible merely implicit one brought about by differing $n_e$-profiles.

- T$_1$- mode theory and electron particle and impurity transport: Can we build a quantitative model of density peaking based on the different predictions of T$_1$-mode theory for particle transport in the collisional and collisionless regimes (boundary and central zones)? What are the predictions of T$_1$-mode theory for impurity transport?

- Effects of co- versus counter-injection: What is the detailed physical mechanism causing electron density peaking in counter-injection discharges?

- Dynamics of spontaneous transitions: What form of dependences of $D$ or $v_r$ on $dT/dr$ and of $X_i, X_e$ on $dn/dr$ do we need to get two stationary solutions (at given $n_e$), corresponding to the SOC and IOC regimes? Can the transitions be explained by existing T$_1$-mode theory, or do they require some additional mechanisms, or a completely new theory?

Ultimately, however, of greatest practical importance, but also a key element for our theoretical understanding of confinement is the compatibility of peaked density profiles with the H-regime and the possibility of superposing their associated confinement improvements.

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Abstract

Improvements in the energy confinement properties of tokamaks have been achieved by means of central fueling with solid hydrogen pellets. Evidence from laser scattering experiments indicates that the reduced anomalous transport may be due to the suppression of $\eta_i$ driven modes. These changes in energy transport, which appear to be primarily in the ion channel, are accompanied by changes in majority species and impurity transport. In particular, for discharges showing enhanced confinement, electron density profiles remain peaked for long periods following the injection of even a single pellet, and impurity accumulation on axis is observed. Other enhanced confinement modes also show similar changes in particle and impurity transport; similarities with, and differences from, the pellet induced changes are discussed.

Introduction

This paper summarizes the results presented at this conference concerning impurity transport following the injection of fueling pellets into tokamak plasma discharges. The primary result is the strong correlation between increased impurity confinement and regimes of improved energy confinement. Results from Alcator C[1,2], TEXT[3], ASDEX[4], TFTR[5] and JET[6] all show similar phenomena: in cases where energy transport through the ion channel is suppressed and electron density profiles peak, impurity species are found to accumulate on axis, showing very strongly peaked profiles. Similar effects were also reported from the Heliotron-E, current free stellarator device[7]. A number of improved confinement regimes have been discovered in tokamaks. In addition to the pellet fueling cases, these include H-mode[8], Improved Ohmic
Confinement[9], counter neutral beam injection[10], and supermode[11]. While there are important differences among these different regimes, certain features are common; in particular, with the possible exception of the supermode, the improvement in energy confinement is due to a reduction of transport in the ion channel which is positively correlated with increased impurity particle confinement times. In many cases, the resulting central radiation limits the improvement which can be achieved, and in extreme cases, a complete collapse of the discharge ensues.

Post-Pellet Impurity Transport Phenomena

Results on the post-pellet impurity peaking in ohmic discharges are typified by data from Alcator C. Figure 1 shows the normalized profiles of tomographically reconstructed soft x-ray emission before and after the injection of a single pellet into a typical discharge.[1] The extreme peaking of the soft x-ray profile is due primarily to a combination of two effects: 1) the density profile has become more peaked; 2) the impurity density profiles have become much more peaked. There is essentially no change in the temperature profile, once the recovery from the initial perturbation due to the rapid density increase

Figure 1.

Normalized profiles of soft x-ray emission before and after the injection of a deuterium pellet into an Alcator C tokamak discharge.
is complete. Figure 2 shows post pellet profiles of molybdenum and carbon, inferred from differentially filtered soft x-ray arrays[1,12]. Model predictions, based on the assumption that the impurity transport is due entirely to collisional neoclassical effects, are shown for comparison. The experimental profile data are, within the uncertainties, consistent with the neoclassical predictions, at least over this central portion of the discharge where the strong peaking is seen to occur. However, the fact that the experimental profiles, particularly for the molybdenum, appear to be somewhat broader than those predicted from the modelling, may be evidence of the presence of some residual anomalous transport. Corroboration for this view comes from trace vanadium transport studies on similar discharges. Figure 3 shows results from these experiments in which trace amounts of vanadium were injected, by the laser blow-off technique, into a series of discharges.[1] Shown are the central chord line integrals of V^{+20} line brightness, comparing the pellet and gas fueled cases. Again, the dramatic change in impurity particle transport is apparent. However, the vanadium transport in the pellet case is not consistent with the predictions assuming neoclassical theory alone; a modest amount of anomalous transport is still required, although it is much reduced from that which is needed to explain the gas fueled results.

![Figure 2](image_url)

**Figure 2.**

Profiles of carbon and molybdenum inferred from x-ray data for a post pellet Alcator C discharge. The dashed curves show the results of model predictions assuming that the transport is due entirely to neo-classical effects.
Concerning this last point, the work reported from ASDEX[4] is particularly relevant. The basic results look essentially identical to those of Alcator C. For the ASDEX data, detailed modelling indicates that, at least for $r/a < 0.75$, in comparison to the gas fueled case, the anomalous diffusion coefficient decreases by about one order of magnitude for pellet fueling; it does not disappear entirely. This model explains both the soft x-ray profiles (influenced mainly by copper impurities) and the $Z_{eff}$ profiles derived from visible continuum measurements. Those comparisons can be seen graphically in figures 5 and 6 of the paper by Fussmann et al. in these proceedings[4]. Calculations for TFTR[5] and JET[6] have led to similar conclusions.

Concerning the peaking of low Z impurities in the pellet fueled, enhanced confinement mode, there has in the past been some controversy. However, where careful direct profile measurements have been made, particularly those utilizing the charge exchange recombination technique, it has been found that the low Z impurities do unambiguously peak up, usually to about the same degree as is found for the high Z impurities. Results from the TEXT tokamak[3] show clearly that both oxygen and carbon density profiles are strongly peaked in the core of the discharge.
The Role of Sawteeth

Yet another clear correlation is the one between sawtooth behaviour and the post pellet transport regime: in discharges which continue to sawtooth normally after pellet injection, there is no significant peaking of the impurity or electron density profiles, nor is there any substantial change in the ion energy transport; discharges in which the sawtooth period increases substantially, or where the sawteeth are suppressed entirely, do exhibit the characteristic changes in transport. Two competing points of view have been developed to explain this correlation. In one, it is assumed that the sawteeth themselves play the dominant role: the absence of sawteeth reduces the average central impurity transport, in turn allowing for the on-axis density and impurity build-up; the return, or continuation of sawtooothing activity reverses or prevents the accumulation. There is no question that the sawtooth crash does cause particle and impurity transport\[13\]. However, in the second model, the dominant cause and effect are assumed to be just reversed: the build-up of impurities (particularly low Z) causes an increase in the on-axis $Z_{eff}$ and therefore resistivity, which in turn prevents the $j$ profile from peaking, suppressing the sawtooth instability; when the impurity transport returns to normal, the resistivity drops, $j$ can peak and the sawtooothing resumes. This second model, as expounded in \[1\] to explain the evolution of Alcator C post pellet discharges, is corroborated by results from JET\[6\]. In at least one JET discharge, the sawtooth-free period with peaked profiles lasted for more than 1 second. As with other experiments, the impurity peaking is found only in the central region of the discharge; in the outer part, the profiles are relatively flat. Toward the end of this time, the region of impurity accumulation shrinks toward the axis. Finally, the enhanced impurity and energy confinement is completely lost, and only then does the sawtooothing reappear.

Relation to Other Enhanced Confinement Regimes and $\eta_i$ Modes

As mentioned in the introduction, several enhanced confinement regimes, in addition to that induced by pellet fueling, have been observed in tokamaks. A common thread, which ties most of these results together, is the fact that impurity particle confinement is increased along with energy confinement. An exception is the supermode from TFTR\[11\], where initial studies indicate that $Z_{eff}$ profiles remain relatively flat, and the transport of injected trace germanium is essentially unchanged in supermode, when compared to either ohmic or L-mode discharges\[14\]. The improved ohmic confinement
mode, seen on ASDEX[9], is achieved by sharply decreasing the gas puffing after the desired density is achieved; the plasma is maintained by recycling from the divertor thereafter. In these cases, all the signatures common to the pellet mode are found: peaking of the density profile; increase of trace impurity confinement time by a factor of 3; accumulation of light and heavy intrinsic impurities; and a sharp decrease in energy loss through the ion thermal transport channel. In addition, the sawtooth behaviour also changes drastically: the period increases by about a factor of 2 and the temperature modulation is reduced by about 30%. For the improvement with counter neutral beam injection, the story is again very similar[10]: particle and impurity confinement times increase, density profiles peak, and the sawtooth period increases, or sawteeth are entirely suppressed[15]. For typical cases on ASDEX, after about 0.5 seconds into the beam heating pulse, the sawteeth disappear, and $\beta$ starts to decrease, as the plasma succumbs to central impurity radiation, with the discharge finally terminating in a major disruption. The situation in H-Mode discharges is somewhat different. While impurity confinement does increase, it appears that the transport changes occur primarily at the edge of the plasma, rather than in the core. Finally, it is of note that a steady-state H-Mode, with continuous low level ELMS has been achieved on DIII-D[16]. In this case, the ELM activity provides sufficient impurity transport to avoid a catastrophic accumulation of impurities, even while the energy confinement is significantly improved.

It has been suspected for some time that it is the suppression of $\eta_i$ driven modes[17,18] which leads to the reduced transport in discharges with peaked density profiles. Direct evidence for this comes from the FIR laser scattering measurements on TEXT which were reported at this meeting[19]. In this experiment, the propagation direction of density fluctuations has been measured during gas fueled and pellet fueled discharges. For the high density, saturated confinement gas fueled cases, two clear features are seen in the scattered spectrum, one propagating in the ion diamagnetic drift direction, the other in the electron direction. However, after the injection of pellets peaks the density profile, and particle and impurity diffusion are reduced, the ion drift feature is greatly diminished. While not constituting proof that $\eta_i$ modes are in fact responsible for the particle or energy transport, these results are certainly incriminating.
Summary and Conclusions

Experiments from numerous tokamaks, and at least one stellarator, have shown improved confinement regimes brought about by central fueling with pellets. The improvement appears to be due to a reduction of anomalous energy transport through the ion channel, possibly due to a suppression of \( \eta_i \) modes. The transport changes can lead to new quasi-steady state profiles, wherein the electron density remains strongly peaked long after the injection of even a single pellet. Accompanying these changes in ion energy and majority species transport are drastic reductions in the anomalous diffusive impurity transport, leading to nearly neo-classical-like transport and strong impurity accumulation. Similar dynamics appear to be at work in other enhanced confinement modes, including Improved Ohmic Confinement, and Counter-Neutral-Beam injection. While impurity accumulation accumulation also usually occurs in H-Mode discharges as well, the main changes in transport appear to occur near the boundary of the plasma in this case, in contrast to the changes over the central 2/3 of the discharges which are seen in the other regimes.

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