CONF-831203--179

CONF-831203--179

DE85 000957

TRITIUM PELLET INJECTION SEQUENCES FOR TFTR*

W. A. Houlberg, S. L. Milora, and S. E. Attenberger
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

C. E. Singer and G. L. Schmidt
Princeton Plasma Physics Laboratory
Princeton, New Jersey 08544

Abstract: Tritium pellet injection into neutral deuterium, beam heated deuterium plasmas in the Tokamak Fusion Test Reactor (TFTR) is shown to be an attractive means of (1) minimizing tritium use per tritium discharge and over a sequence of tritium discharges; (2) greatly reducing the tritium load in the walls, limiters, getters, and cryopanels; (3) maintaining or improving instantaneous neutron production (Q); (4) reducing or eliminating deuterium-tritium (D-T) neutron production in non-optimized discharges; and (5) generally adding flexibility to the experimental sequences leading to optimal Q operation. Transport analyses of both compression and full-bore TFTR plasmas are used to support the above observations and to provide the basis for a proposed eight-pellet gas gun injector for the 1986 tritium experiments.

Introduction

The injection of frozen tritium pellets into TFTR was originally proposed in 1978 as a possible means of reducing the tritium inventory in TFTR while maintaining the goal of $Q \approx 1$ operation [1]. At that time, however, many uncertainties still existed in the viability of pellet injection because very little experimental data was available. Among the issues were penetration of the pellets into hot, neutral beam heated plasmas (with the attendant assessment of whether the velocity requirements could be met) and the plasma response to pellet injection.

Since the original discussions, an extensive data base on pellet injection in both ohmically heated [2-7] and neutral beam heated [7,8] plasmas has been accumulated. The pellet ablation process in ohmic plasmas appears to be reasonably well explained by the neutral gas shielding model in which the plasma electrons are the dominant contributors to heating the dense cloud and evaporating the pellet surface [9]. The energetic ions from neutral beam heating were shown to significantly enhance the pellet ablation rate in the first of such experiments on the Impurity Study Experiment (ISX) [7]. This has led to a modification of the neutral gas shielding model, which includes the effects of fast ions [10].

In all ohmically heated and neutral beam heated discharges, the plasma responds adiabatically to the essentially instantaneous particle source — the density increases and the temperature decreases such that the plasma energy content is unchanged, except for the energy consumed in ionizing the fuel. Direct measurements of charge-exchange neutrals in the vicinity of pellet injection on the Poloidal Divertor Experiment (PDX) [4] and the ASDEX tokamak [6] have shown that there is very little charge-exchange loss associated with pellet injection (i.e., the fuel is essentially fully ionized by the time the particles reach the boundaries of the dense cloud, so free neutral atoms or molecules are not available for charge exchange with the background plasma ions).

Very large pellets have been injected in almost all of the experiments with global density increases up to several hundred percent without deleterious effects on the plasma. In PDX the density on-axis has been raised to 3×10^{14} cm^{-3} with four pellets [8], and in Alcator-C central densities of 2×10^{15}cm^{-3} have been reached with the injection of two pellets [5]. The significance of large pellets is that greater penetration can be attained with lower pellet velocities and, in TFTR in particular, the tritium concentration can be rapidly raised to the desired level with a single pellet.

Fueling is more efficient with pellet injection, as compared to neutral gas injection, as was demonstrated most clearly in PDX-diverted plasmas with low particle recycle [3]. Even in cases where pellets have not penetrated fully to the magnetic axis, the density profile is centrally peaked when measured within a few milliseconds after pellet injection. In some cases, this can be explained by mixing due to sawtooth activity [3]. Measurements on Alcator-C [5] and ASDEX [6] have shown that the density profile fills in within a few hundred microseconds in the absence of sawtooth activity. This mixing may be due to a kinetic instability driven by the strongly inverted density profile. Because the mixing process is not deleterious to confinement, it should generally relax pellet penetration requirements in tokamaks.

An even more promising observation made on Alcator-C is the improvement in energy confinement associated with pellet injection [5]. Since the physics of the density mixing process and the improvement in energy confinement are not clearly understood, these effects are not included in the present analyses for TFTR. Both, however, would tend to improve plasma performance for the tritium pellet injection sequences relative to the tritium gas-fill sequences.

The BALDUR transport code was used to model the TFTR tritium compression sequences [11], and the WHIST transport code was used for the full-bore plasmas. The relative performance between pellet and gas-fill sequences within the framework of assumed confinement models is emphasized. Some variations in the confinement models have been investigated, with the predicted Q values being more sensitive to the confinement models than the relative performance of pellet and gas-fill sequences. More definitive calculations on expected Q values will be performed as the experimental data on confinement in TFTR is incorporated into the models. We close with a brief description of the proposed tritium pellet injector.

MASTER

Compression Sequences

The compression cases for TFTR are discussed in more detail in Ref. [11] and so will only be briefly summarized here. The precompression plasma has a minor radius of 55 cm and is located toward the outside of the chamber. The precompression density is the same for both the tritium gas-fill and pellet cases, with deuterium replacing tritium in the pellet case. As shown in Fig. 1, the 32-ms compression stage is begun after 200 ms of neutral beam heating. In the pellet injection case, a tritium pellet with an equivalent spherical radius of 1.25 mm (25 Ci or an average density increment of 4.6×10^{13} cm^{-3}) is injected just prior to compression.

---

*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

The instantaneous and time-integrated neutron production rates are shown in Fig. 1(a) and 1(b), respectively, for a case with 33.5 MW of neutral beam injection. The instantaneous neutron production rate for the pellet case is about 60% higher than the maximum value for the gas-fill case, although the integrated neutron dose is 30% lower. This implies that almost twice as many Q = 1 discharges could be run with pellet injection within the given integrated neutron dose limits for TFTR. Some of the improvement in performance with pellets may be attributed to the assumed confinement model. In these cases, the International Tokamak Reactor (INTOR) model of $\chi_e = 7 \times 10^{17}/n_e$ (cgs units) was used for the electron thermal diffusivity, which yields improved energy confinement with increasing density. The pellet case has a higher density after pellet injection and, thus, better confinement properties. When each sequence is individually optimized with respect to density with a given confinement model, the peak neutron production rates are comparable, although the integrated neutron doses remain significantly lower for the pellet cases. The difference in the integrated neutron dose comes primarily in the precompression phase, where the plasma conditions are not optimal for high Q.

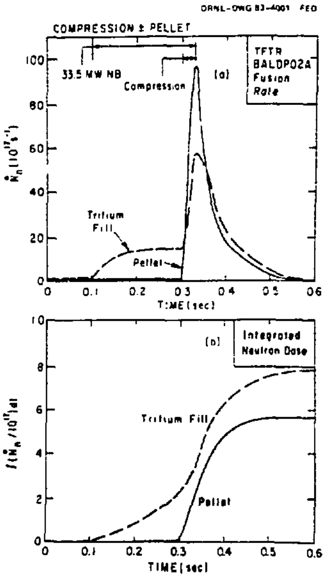

Fig. 1. Neutron production rate (a) and integrated neutron production rate (b) with 2.0-km/s pellet (solid lines) and reference tritium gas-fill simulation (dashed lines).

The difference in tritium consumption between the gas-fill and pellet injection sequences is very pronounced. As stated earlier, the pellet injection case requires only ~ 25 Ci of tritium and does not rely on high particle recycle (i.e., no prior tritium history is required in the sequence of discharges preceeding tritium pellet injection). In the gas-fill cases, high recycle means that the tritium concentration in the limiters, walls, getters, and cryopanels must be relatively high; thus, prior tritium operation is required.

Full-Bore Sequences

Full-bore cases for TFTR were then examined in more detail with an upgraded model for the effects of fast beam ions on pellet ablation [10]. These cases also include improved pellet and neutral beam penetration from the shifted magnetic surfaces at finite beta. In the reference cases for both tritium gas-fill and tritium pellet injection, the plasma is ohmically heated for 500 ms, followed by a 750-ms, 27-MW neutral beam heating phase. Parameters are examined after 500 ms of beam heating (design goal) and again after 750 ms to evaluate the benefits of extended beam operation and to determine its impact on tritium pellet requirements.

The confinement model for these simulations is given by

$$\chi_i = 3\chi_i^{NC} ,$$

$$D = 2.0 \times 10^3[1 + 9(r/a)^4] \text{ cm}^2/\text{s} ,$$

and

$$\chi_e = 3.7 \times 10^3[1 + 4(r/a)^2] \text{ cm}^2/\text{s} ,$$

where χ_e is found by conservatively scaling the "L-mode" results of PDX. The plasma minor radius is taken as 85 cm with 2.5-MA of current and a toroidal field of 4.2 T. Note that there is no density dependence in D or χ_e, unlike the "INTOR" scaling.

During the tritium gas-fill simulations, the tritium density is maintained by gas puffing and recycle at 3×10^{13} cm^{-3} which yields near-optimal fusion rates for the assumed confinement model. The deuterium input from the beams is allowed to recycle at the same rate as the tritium. The tritium makeup by gas feed, integrated over a single shot, is a function of the assumed recycle coefficient (displayed in Fig. 2). At a recycle rate of 95%, a total of about 350 Ci of tritium makeup is required, while at 90% recycle about 700 Ci is required. These results are also sensitive to the assumed particle diffusion rate near the plasma edge, but appear to be reasonably consistent with other extrapolations of particle confinement from existing experiments.

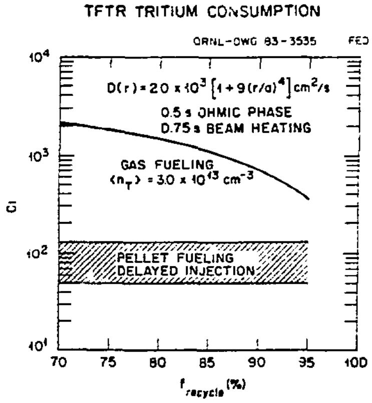

Fig. 2. Tritium fueling requirements for the reference gas-fill case and tritium pellet injection cases as a function of the tritium recycle rate. The band representing pellet injection spans a range of pellet sizes and timing.

Several different methods of pellet injection were examined, including single and multiple pellets and early and delayed injection with pellets in the range of 1.5-2.0 km/s. The range of pellet sizes, with their particle and Curie content, is shown in Table 1. An ohmic discharge with a volume-averaged deuterium density of 1.5×10^{13} cm^{-3} serves as a target plasma for the neutral beams and tritium pellets. This relatively low deuterium density is based on the observation that a minimum level of deuterium is desirable for the highest Q results. Q values comparable to those in the tritium gas-fill case are obtained with much less tritium consumption. Typical tritium consumption levels, shown by the shaded region in Fig. 2, corresponds to most combinations of one or two of the pellets listed in Table 1. These results are very insensitive to the particle recycle rate because the pellet-injected tritium has a much longer particle confinement time than the recycled tritium. Delayed injection refers to the first pellet being injected some time after the beam is turned on.

Table 1. TFTR pellet injection parameters[a]

d_p, l_p[b] (mm)	r_p[c] (mm)	N[d] cm^{-3}	Ci
2.50	1.42	7.92×10^{20}	38
2.75	1.57	1.05×10^{21}	51
3.00	1.72	1.37×10^{21}	66
3.25	1.86	1.74×10^{21}	84

[a] v_p = 1.5–2.0 km/s.

[b] d_p, l_p are the cylindrical diameter and length.

[c] r_p is the effective spherical radius.

[d] $N = 3.54 \times 10^{20} \div \langle \Delta n \rangle = 1.0 \times 10^{13}$ cm^{-3}.

Even the smallest pellets penetrated to near the magnetic axis when injected just before beam initiation. This early injection of a tritium pellet could provide an increased target density for the beams and a high initial central tritium density. During the first 100 to 200 ms of beam heating, the fast ions reduced the pellet penetration to about half way into the plasma. After this point, the thermal electrons again dominate the ablation (since the plasma temperature has risen significantly), and penetration remains about constant as the outward shift of the plasma tends to offset the reduced penetration from an increasing plasma temperature. The time scale for the inverted density profile to fill in via diffusion is typically about 100 ms.

Figures 3 and 4 illustrate the instantaneous steady-state Q values and the time-integrated D-T neutron production rates, respectively, for three typical cases. The instantaneous steady-state Q value is obtained by correcting the beam power and beam plasma fusion rate to a level in which the total plasma energy content is constant in time, since even at the end of 750 ms of beam heating the plasma energy content is still rising. Case A is the reference gas-fill case. In case B one pellet is injected at the start of the beam pulse, and a second is injected 300 ms later. Case C is identical to case B, except that the injection time of both pellets is delayed by 300 ms. The pellets in these examples are the smallest of those in Table 1 (38 Ci).

Figure 3 shows that the pellets can be staged to obtain the maximum Q near the end of the beam pulse. All three cases have comparable Q values after 500 ms of beam heating. The pellet injected after 300 ms of beam heating in cases B and C gives the main contribution to Q at the end of a 500-ms beam pulse,

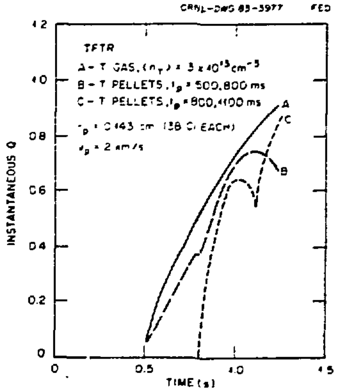

Fig. 3. Instantaneous Q value for the reference tritium gas-fill case and two pellet injection cases.

even though penetration is not complete. If the profile fills in more rapidly, as observed in other experiments, a greater benefit from delayed tritium pellet injection would be expected. The pellets can be delayed as in case C to obtain optimal Q conditions at the end of a longer beam pulse.

Figure 4 shows the total number of D-T neutrons produced during the entire shot. The pellet cases produce fewer neutrons, particularly in the delayed injection case. This is due to limiting the fusion demonstration stage of the discharge to a smaller time interval at the end of the shot. Delayed pellet injection also permits interlocks to be placed on the tritium injection system, which checks whether all beams have fired properly and whether the plasma conditions are optimal for a tritium demonstration shot.

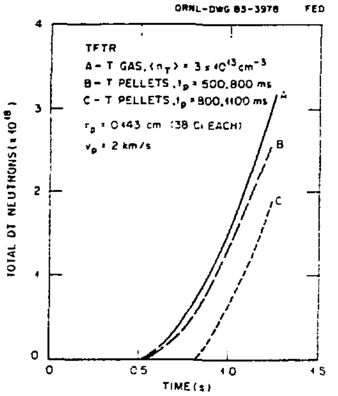

Fig. 4. Integrated neutron production rate for the reference tritium gas-fill case and two pellet injection cases.

Tritium Pellet Injector

A tritium pellet injection system has been designed which incorporates sufficient flexibility to permit a wide variety of fueling options and to mitigate against uncertainties in the particle transport in TFTR. As designed, the gun-type injector is capable of delivering a charge of up to 500 Ci (140 torr-L equivalent) in eight pellets to the plasma at a pellet speed in the 1500- to 2000-m/s range. Four different pellet sizes are available, ranging in diameter and length from 2.5 to 3.25 mm in increments of 0.25 mm, with two pellets of each size. These are summarized in Table 1. The design features low system tritium inventory (1500 Ci within the glove box secondary containment) and minimal tritium waste consistent with TFTR tritium operating and safety requirements. The vacuum system design is tritium-compatible; its primary function is to provide a high vacuum interface to the TFTR torus, to supply vacuum thermal insulation to the injector cryogenic systems, and to evacuate the roughly 2000 torr-L of hydrogen propellant from the pellet injection line following a shot.

The design of the pellet injector (Fig. 5) features eight individual gun barrel/propellant valve subassemblies located in a radial pattern around a single central magazine. The velocity performance is achieved with heated, high-pressure hydrogen propellant at a design point of 250°C and 68 bar (1000 psia).

The pellet formation and chambering steps are illustrated in Fig. 6. Solid tritium is formed from the gas feed in the low-volume extruder. The extruder loads all eight pellets simultaneously, but only those pellets needed are chambered in the guns by moving the appropriate pellet slides. The unused tritium is recovered from the injector, before a shot, by heating and pumping on the magazine and extruder/condenser subassembly.

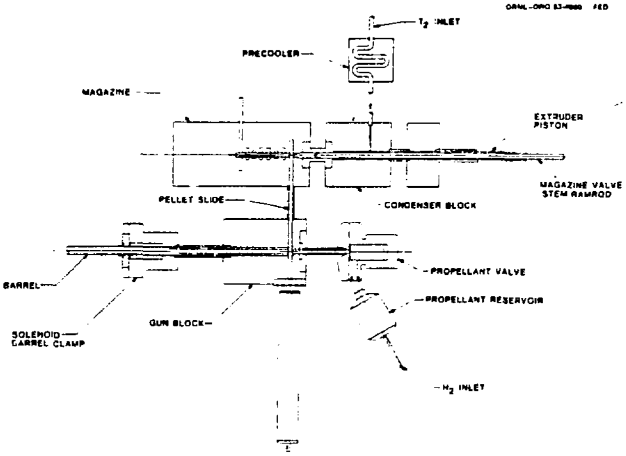

Fig. 5. Schematic of the proposed eight-pellet tritium injection system for TFTR.

Concluding Remarks

Tritium pellet injection offers several advantages over tritium gas fill, including less tritium consumption, reduced neutron activation, and the ability to tailor the tritium fueling to the length of the beam pulse through staged injection. In the sequences leading up to tritium pellet injection, pellet penetration and plasma response to pellets of different sizes and timing can be checked with deuterium pellets. This means that essentially all features of the plasma and pellet injection system can be completely optimized at the time of the first introduction of tritium. Pellet injection therefore represents the most economic use of tritium and yields the lowest total neutron production and system activation, while still maintaining or even enhancing the scientific goals of the experiment.

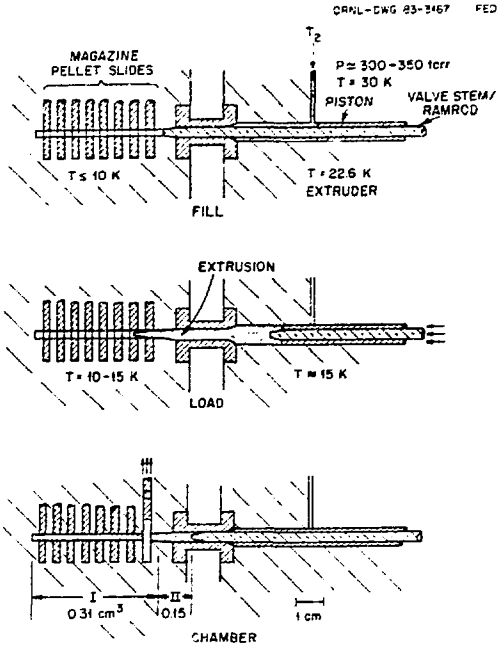

Fig. 6. Schematic of the filling, loading, and chambering stages in the proposed tritium pellet injector for TFTR.

References

1. Chairman J. F. Clarke, Final Report of the Ad Hoc Committee on TFTR Physics, U. S. Department of Energy, Office of Fusion Energy, 1979.
2. S. L. Milora, C. A. Foster, C. E. Thomas, C. E. Bush, J. B. Wilgen, E. A. Lazarus, J. L. Dunlap, P. H. Edmonds, W. A. Houlberg, H. C. Howe, D. P. Hutchinson, T. C. Jernigan, M. Murakami, G. H. Neilson, J. A. Rome, and M. J. Saltmarsh, "Results of Hydrogen Pellet Injection into ISX-B," Nucl. Fusion Vol. 20, p. 1491 1980.
3. S. L. Milora, G. L. Schmidt, W. A. Houlberg, V. Arunasalam, S. E. Attenberger, R. Fonck, C. A. Foster, B. Grek, D. Johnson, K. McGuire, and D. Mueller, "Pellet Injection into PDX Diverted Plasmas," Nucl. Fusion Vol. 22, p. 1263, 1982.
4. G. L. Schmidt, R. J. Fonck, B. Grek, D. Johnson, R. Kaita, T. McBride, K. McGuire, D. D. Meyerhofer, S. L. Milora, D. Mueller, J. Ramette, R. Reeves, and S. Sesnic, "Pellet Injection — PDX," Bull. Am. Phys. Soc., Vol. 27, p. 1049, 1982.
5. M. Greenwald, J. Parker, and Alcator Group, "Particle and Energy Transport Following Pellet Injection into Alcator-C," Bull. Am. Phys. Soc., Vol. 28, p. 1248, 1983.
6. K. Buchl, Max Planck Institute for Plasma Physics, Garching, FRG, private communication, 1983.
7. S. L. Milora, C. A. Foster, C. E. Thomas, C. E. Bush, J. B. Wilgen, E. A. Lazarus, J. L. Dunlap, P. H. Edmonds, W. A. Houlberg, H. C. Howe, D. P. Hutchinson, T. C. Jernigan, M. Murakami, G. H. Neilson, J. A. Rome, and M. J. Saltmarsh, "Results of Pellet Injection into ISX-B," Nucl. Fusion Vol. 2, p. 1491, 1980.

8. G. L. Schmidt, M. Bell, R. Fonck, R. Goldston, B. Grek, D. Johnson, R. Kaita, D. Mansfield, T. McBride, K. McGuire, S. Milora, D. Mueller, and S. Sesnic, "High Density Plasmas Produced by Pellet Injection in PDX," Bull. Am. Phys. Soc., Vol. 28, p. 1176, 1983.
9. S. L. Milora and C. A. Foster, "A Revised Neutral Gas Shielding Model for Pellet-Plasma Interactions," IEEE Trans. Plasma Sci., Vol. PS-6, p. 578, 1978.
10. S. L. Milora, New Algorithm for Computing the Ablation of Hydrogenic Pellets in Hot Plasmas, Oak Ridge National Laboratory, ORNL/TM-8616, 1983.
11. C. E. Singer, D. B. Heifetz, and D. E. Post, "Pellet-Injection in TFTR," J. Vac. Sci. Technol. Vol. A1, p. 964, 1983.