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ALPHA PARTICLE STUDIES DURING JET DT EXPERIMENTS

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Abstract

The 1997 DT experiment (DTE1) at the Joint European Torus included studies of the behaviour of alpha particles in high temperature plasmas. Clear alpha particle heating was observed in a series of otherwise similar 10MW hot-ion H-modes by scanning the DT mixture from 0%T to 93%T. Maxima in central temperature and energy content were obtained which corresponded with the maximum in fusion yield. Alfvén Eigenmodes (AEs) have been detected in JET, driven by NBI or ICRH fast ions. However, in agreement with theory, no AE activity was observed in DT plasmas which could be attributed to alpha particle drive, except in the afterglow of some Optimised Shear pulses. Ion Cyclotron Emission (ICE) was detected at harmonics of the alpha particle cyclotron frequency at the outer edge of the plasma. The ICE is interpreted as being close to magnetoacoustic cyclotron instability, driven by inverted alpha distributions at the plasma edge. The high-energy neutral particle spectra showed features, which are ascribed to a mixture of alphas, neutralised by helium-like impurities, and deuterons, born from elastic collisions with alpha particles and neutralised by hydrogen-like impurities. The results of all these studies are consistent with classical alpha particle trapping and slowing-down. Future DT experiments will aim to increase alpha particle pressure, so interactions with plasma instabilities can be studied. The measurement of knock-on neutral triton spectra offers a clean way to determine confined alpha densities in these future experiments.

1. INTRODUCTION

JET was designed to be able to trap alpha particles produced by DT fusion reactions. One of the four areas of work, foreseen in the JET Design Proposal [1], was "the study of alpha particle production, confinement and the consequent plasma heating". A start was made on this work in the recent DTE1 experiments and this paper will describe the results obtained.

The behaviour of MeV range ions in JET plasmas had previously been studied using ICRH minority ions and DD or D^3He fusion products [2]. The results showed that the trapping and slowing-down of high-energy ions is classical and that they can be redistributed by mhd events, such as sawteeth. These fast ion distributions are not, however, typical of that expected of DT alpha particles, slowing-down in a burning plasma. The ICRH minority ion distributions have $v_\perp/v_\parallel \gg 1$, in contrast to the isotropic distribution of DT alphas, whilst the pressure of DD and D^3He is at least two orders of magnitude too small. These features are not of importance for classical processes but do have a profound effect on instabilities driven by fast ions. The most important of these are thought to be Alfvén instabilities, such as TAEs [3], which theoretical studies indicate could be a major cause of alpha-particle losses. Thus the DT experiments in TFTR [4] and JET presented the first opportunities to study appropriate fast ion distributions in high temperature plasmas.

The highest gain JET DT plasmas have $P_\alpha/P_{heat} \approx 0.13$, where it is possible to detect the increase in temperature and energy content due to alpha heating. The next section describes an experiment [5], designed to distinguish alpha heating from potential changes in plasma behaviour due to isotopic effects. The third section describes measurements of Alfvén instabilities in DD and DT plasmas and the results of associated stability calculations. Ion Cyclotron Emission (ICE), driven by high energy ions, has been observed in a wide range of JET plasmas [6]. The fourth section describes observations of ICE in DT plasmas and deductions that can be made from them about the alpha particle distribution function. The

[1] see Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L. Watkins)

fifth section describes NPA measurements of neutral alpha emission, arising from double charge exchange, and the observation that the low energy part of the spectrum is dominated by deuterons, knocked-on by elastic collisions with alpha particles. The sixth section discusses the implications of these studies for burning DT plasmas and future DT experiments in JET.

2. THE ALPHA HEATING EXPERIMENT

During the preparation of high performance plasmas for DTE1, a 3.8MA/3.4T hot ion H-mode was obtained with 10MW NBI which had an ELM-free period in excess of 2.5s and sawtooth periods of more than 1s. These timescales should be compared with those of the energy confinement time and the central alpha particle slowing-down time; both of which were about 1s. Simulations showed that more than 5MW fusion power would be produced in a 50:50 DT mixture so that significant electron heating by alpha particles should occur. An experimental test was carried out using ICRH as a substitute for alpha heating. This showed that the 1-2keV increase in $T_e(0)$ would be detectable against the variations due to sawteeth and that the ELM free period was long enough for the alphas to stack up. A previous measurement of alpha heating on TFTR [7] had indicated the need to separate alpha heating from isotopic effects on plasma confinement and heating. Having obtained a hot ion H-mode at 10MW, it became technically possible to perform a 5 point scan from pure T injection to pure D injection. By matching the plasma mixture to that of the NBI, a scan could be performed in which the alpha heating would stand out as a maximum on top of variations due to isotopic effects.

In order to obtain plasma DT mixtures, which matched those of the beams, it was necessary to load the plasma facing surfaces with the correct mixture, using high density tokamak plasmas. This procedure resulted in a scan from pure D to 93%T, where 1.5MW fusion power was obtained. The optimum mixture, of 50-60%, produced a fusion power of 6.7MW. Thus the intended maximum in alpha heating power, with mixture, had been achieved.

The pulse with the maximum fusion yield (pulse 42847) is compared with that with the maximum tritium content (pulse 43011) in figure 1. The sawtooth period is comparable for all the tritium rich pulses and rather longer than the deuterium reference pulses because of an increase in fast ion pressure around the q=1 surface, associated with tritium NBI [8]. For clarity, therefore, a deuterium pulse has not been included in figure 1. The figure shows the clear increase in central temperatures and thermal energy content due to the alpha heating. Not only is the energy content larger in pulse 42847 but there is an 800kW difference in heating rate. This is comparable to the computed difference in alpha heating powers. Profile analysis shows that alpha heating increases the central power density to the electrons

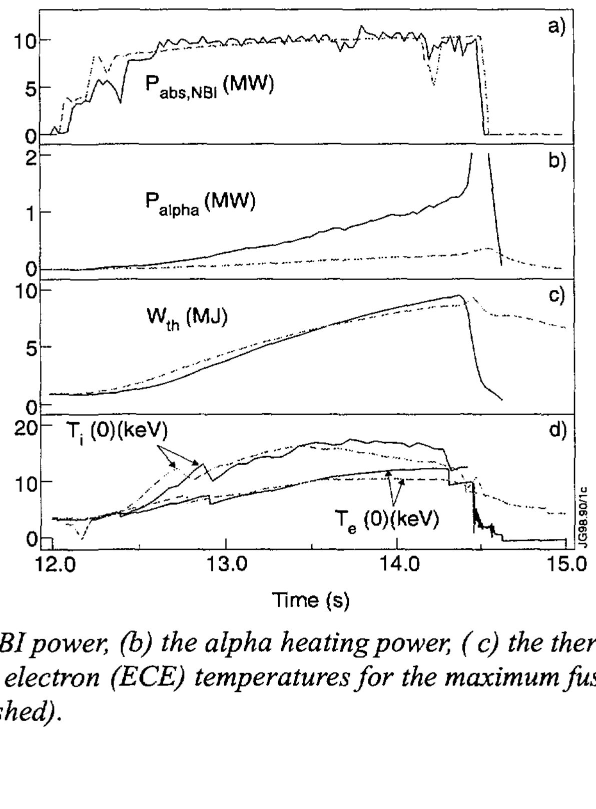

Fig.1. (a) The absorbed NBI power, (b) the alpha heating power, (c) the thermal plasma energy and (d) the central ion (CXS) and electron (ECE) temperatures for the maximum fusion yield pulse (solid) and the 93% tritium pulse (dashed).

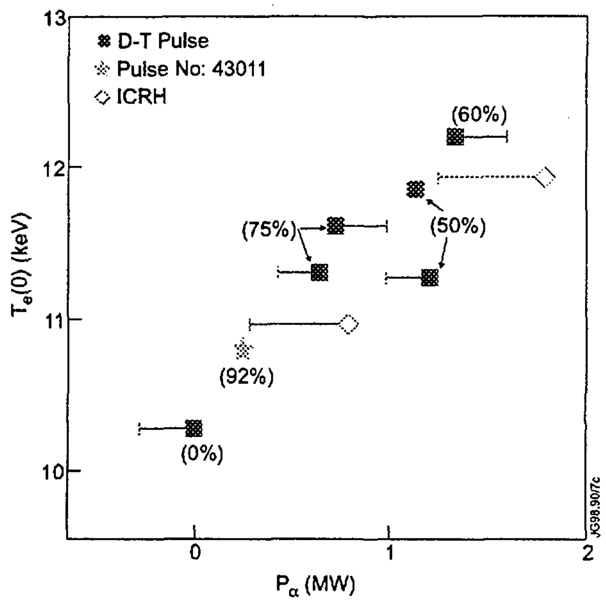

Fig.2. Central electron temperature (ECE) against alpha (or ICRH) power. The bars indicate the variations in NBI power relative to the nominal 10.6MW.

from 50kW.m^{-3} in pulse 43011 to 80kW.m^{-3} in pulse 42847; to be compared with a difference in rate of increase of energy density of 50kW.m^{-3}. These comparisons indicate that, within errors, the data are consistent with the alpha particles being trapped and slowing down classically.

Figure 2 shows the central electron temperature, at the sawtooth peak, against alpha or ICRH power for selected pulses from the dataset. Some pulses, most notably the 20%T point, showed a clear deterioration in $T_e(0)$ when edge mhd was present. These points were excluded from figure 2, together with those which show a deviation of more than 5% from the nominal applied power of 10.6MW. The figure shows a clear correlation between $T_e(0)$ and alpha power. The tick marks at the ends of the horizontal bars indicate the residual variation in applied power, relative to that in pulse 43011, and indicate how much of the temperature change is from this source. Data from the ICRH test pulses has been included for comparison since, like alpha power, ICRH mainly couples to the electrons and is concentrated near the plasma centre. It is encouraging that the effects of alpha heating and ICRH are so similar.

A regression fit using the entire dataset, of $T_e(0)$ to the applied power and the alpha power, shows that the change in $T_e(0)$ due to 1.3MW of alpha power is 1.3±0.23keV. The standard error for the fit has been given, which reflects pulse to pulse variation in the data, and it should be remembered that there are systematic, calibration errors of 5% for $T_e(0)$ and 10% for the alpha power. If the electron density or isotopic mix are included as regression variables, their coefficients are zero, within errors. Curiously, the coefficients for the applied power, which is predominantly NBI, and the alpha heating power are identical, even though NBI predominantly heats the ions in the core. This has not been explained, although it might be speculated that this is an indication that the central and edge electron temperatures are strongly coupled.

The effect of the alpha heating also shows up across the mixture scan as clear maxima in the ion temperature and thermal energy content. The latter shows an increase of slightly more than 1MJ in 9MJ. The thermal energy confinement time is constant across the scan, within errors, at 1.2s. There are some signs that the points with maximum alpha power have slightly better confinement which might be ascribed to the peaked alpha source. However, this is a 20% effect on points which have 20% errors. More importantly, the energy confinement time of the pure D and nearly pure T pulses is the same and so does not show any isotopic effect.

Unambiguous identification of the alpha heating in other high performance DT hot ion H-modes is not as easy as in this dedicated scan. The extra NBI power that was available with tritium was exploited as much as possible and one of the NBI systems was not operated with tritium. Thus corresponding pure deuterium or tritium pulses do not exist. However, record plasma energy contents and electron temperatures for this type of pulse show clear signs of the alpha heating. It is notable that the transport analysis of similar DD and DT pulses yield the same core electron thermal diffusivity when the alpha heating source is included but very different values when it is not [9].

3. ALFVEN INSTABILITIES IN DD AND DT PLASMAS

The excitation threshold for TAEs, driven by ICRH-accelerated energetic protons, is $P_{ICRH} \approx 4MW$ in JET high performance H-mode discharges (with the central safety factor $q \sim 1$, magnetic fields ranging from 3 to 3.6T and plasma currents up to 3.4 MA) [10]. This threshold is consistent with theoretical modelling [11], in which the minimum proton energy required for the AE instability was estimated to be in the range from 500 keV to 1 MeV. ICRH-driven AEs were used during the recent JET campaign to obtain diagnostic information about the ICRH-accelerated fast ion population [12,13].

The ICRH-driven AE instability threshold, in Optimised Shear (OS) discharges with high central q and low initial plasma density, can be as low as $P_{ICRH} \approx 1MW$. This is consistent with a lower energy ion tail required for the AE instability and with the significantly increased efficiency of AE interaction with energetic ions, $\gamma / \omega \propto q^2$. Figure 3 shows a spectrogram of magnetic fluctuations measured using a magnetic pick-up coil in an OS pulse 40399. TAEs and Ellipticity induced AEs (EAEs), driven by ICRH minority ions, can be seen.

Resonance conditions with NBI ions of energies up to E_b = 150keV can only be obtained in low toroidal field plasmas $B_T < 1T$. Excitation of Alfvén Eigenmodes was seen during the injection of tritium beams, E_b = 160keV, into a tritium target at a toroidal magnetic field 0.9T (pulse 43014) and the injection of deuterium beams, E_b = 140keV, into a deuterium plasma at a toroidal magnetic field of 0.8T (pulses 43846, 43847). No evidence for the excitation of Alfvén Eigenmodes was seen in low magnetic field, B_T = 1T, hydrogen plasma heated by the hydrogen beams with energy E_b = 110keV. The threshold NBI power was found to be P_{NBI} = 8-10MW, corresponding to a beam density of $n_b = 5x10^{18} m^{-3}$. Simulations using the CASTOR-K model showed very strong drive, $\gamma / \omega > 1\%$, provided for the AE by the neutral beam ions in tritium and deuterium cases. In contrast, the simulations showed that no significant drive could be provided by the 110 keV hydrogen beams for similar experimental conditions. Details of this work are being prepared for publication elsewhere.

In the high performance hot ion H-mode experiments on JET with fusion powers up to 16.1 MW and central $\beta_\alpha(0) \approx 0.7\%$ (pulse 42976), no observable AE activity was found on the external magnetic measurements. The absence of the alpha particle driven AEs is in agreement with the CASTOR-K stability calculations [14]. Due to a combination of the mode structure and finite orbit effects, the most

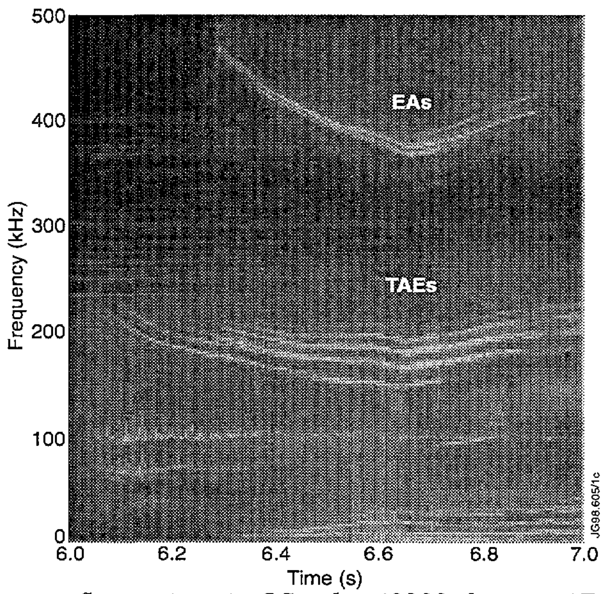

Fig.3. Spectrogram of magnetic fluctuations in OS pulse 40399 showing AEs excited by ICRH minority ions at frequencies around 200kHz (TAEs) and 400kHz (EAEs). The signals at 100kHz and below are due to mhd instability.

unstable modes in JET in the presence of DT alphas are Kinetic TAEs with toroidal mode numbers ranging from $n = 5$ to 8. The analysis shows that although alpha particles have a strong destabilising effect, the experimental $\langle\beta_\alpha\rangle \leq 10^{-3}$ is approximately a factor 2 too low to overcome the damping associated with NBI ions and mode globalisation.

In OS plasmas, AEs are found to be always unstable during the high performance phase due to the presence of a high energy minority ion tail generated by the high power ICRH used in the regime. The most favourable condition for the observation of alpha particles excitation of AEs is created by a sudden switch off of the auxiliary heating [7]. AE activity is observed around 500ms into the afterglow phase. Stability calculations performed by the CASTOR-K model shows that, a few hundreds of milliseconds into the afterglow phase, the drive from slowing-down alpha particles can overcome the AE's several damping mechanisms. The presence of a slowing-down tail of ICRH generated ions provides an additional drive, which can be comparable to the alpha particle drive. However, quantification of the ICRH drive contribution is difficult without a reliable estimate of the mean minority ion velocity.

4. ION CYCLOTRON EMISSION FROM DT PLASMAS

The collective effect most easily excited by DT alpha particles is spectrally structured, suprathermal Ion Cyclotron Emission (ICE) [15]. Indeed, the observation of ICE, driven by the fusion products of DD reactions, predates the use of tritium in JET [6]. Such emission has provided useful information on the behaviour of fast ions, particularly DT alphas, and further studies of ICE in present experiments should facilitate predictions of alpha behaviour in Next Step machines. The difficulty of observing alpha particles in the core of tokamaks is such that ICE has received considerable theoretical interest for the diagnostic information that it might yield. There is a consensus view that the mechanism for fusion product driven ICE is based on the Magnetoacoustic Cyclotron Instability (MCI) [16]. The MCI is driven by marginally-trapped fusion products, born in the plasma centre, which generate an inverted population at the edge because the fusion rate is relatively low there.

During DTE1, ICE was detected by using one of the ICRH antennae as a receiver [17]. It had been thought that, in any discharges with ICRH, the ICE would be swamped by the fast wave source. However, this turned out not to be the case and there is clear evidence of ICE in the radiofrequency spectra of several ICRH heated DT plasmas. In pulse 42697, for example, which had ICRH, T^0 and D^0 NBI, emission was detected at the second, third, fourth and fifth harmonics of the edge alpha particle or deuteron cyclotron frequency. T^0 and D^0 NBI were used at similar levels in this pulse; so, the absence of ICE at harmonics of the tritium cyclotron frequency is taken to mean that the ICE that is observed is due to alphas, rather than NBI deuterons. It is possible that fundamental emission was present as well but was missed because the spectrum analyser sweep crossed the fundamental frequency too early for there to have been a build-up of alphas which could cause ICE. An important feature of ICRH heated plasmas is high central electron temperatures and slowing-down times. In the case of pulse 42697, the central alpha slowing-down time was 1.8s, which was three times as long as the spectral sweep used for measurement of the ICE. Thus, at the time of measurement, the alpha particle distribution was highly peaked towards the birth energy.

A series of T^0 NBI heated plasmas (pulses 41571-41576) show ICE at the fundamental alpha particle cyclotron frequency which increases in strength with NBI and so DT fusion power. The spectra from three of the pulses are shown in figure 4. The absence of emission at harmonics of the alpha cyclotron frequency is notable. In contrast to the ICRH heated plasma, the alpha slowing-down time is, at most, 0.3s. This means that, by the time of measurement, the slowing-down distribution is more developed and less peaked towards the birth energy.

The observed ICE has been interpreted by computing the linear stability for a model alpha particle distribution, which is a narrow Gaussian distributed about the passing/trapped boundary for alphas born in the core of the plasma. The MCI dispersion relation is solved with the model alpha distribution contribution to the dielectric tensor. The instability drive is found to be very sensitive to the width of the alpha distribution. As the width of the distribution increases, the higher harmonics are stabilised first. This suggests an explanation for the observed difference between the ICRH heated pulse and the T NBI series: With its very long slowing down time, the ICRH heated plasma had an narrow alpha particle distribution

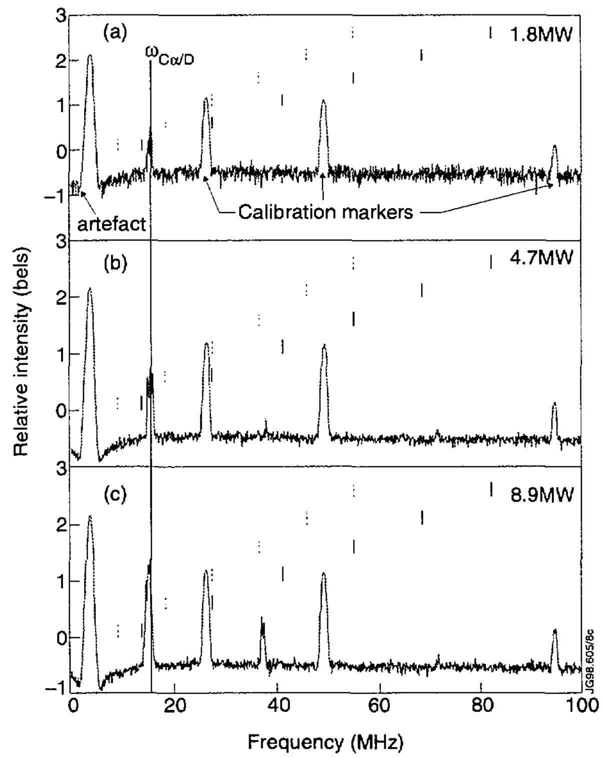

Fig.4. The ICE spectra of three T^0 NBI heated plasmas. Solid markers show $\omega_{CD/\alpha}$ and harmonics whilst dotted markers show ω_{DT} and harmonics. Calibration markers are indicated on the top spectrum. The emission at $\omega_{C\alpha}$ can be seen to increase with NBI power.

at the plasma edge and this drives MCI strongly at all harmonics of the cyclotron frequency. On the other hand, the pulses in the NBI series had a short slowing down times, so that the alpha distribution was broad and the MCI drive at cyclotron harmonics was weak. Whilst not definitive, these observations are strongly suggestive of the applicability of classical slowing-down to alphas in DT plasmas.

5. ALPHA DENSITY MEASUREMENT USING A HIGH ENERGY NPA

This section describes the first non-perturbing measurement of the distribution function of confined alphas in the energy range $0.8 \leq E(\text{MeV}) \leq 3$ and MeV energy knock-on deuterons, produced in elastic nuclear collisions between alphas and plasma ions[18]. The measurements were made using a conventional E||B neutral particle analyser. Neutralisation of alpha particles was effected by double charge-exchange interactions with helium-like intrinsic impurities, C, Be and He, analogous to the neutralisation of MeV hydrogen atoms by hydrogen-like impurities [19]. Mixing of ^{4}He and D neutral fluxes in the NPA is a consequence of the degeneracy of the NPA with respect to ^{4}He atoms of energy E and D atoms of energy E/2.

Measurements of the line-of-sight integrated energy distribution function $\overline{F}(E)$ were made in hot ion H-modes, using only D^0 and T^0 NBI with a fuel mixture $n_D/(n_D+n_T) \approx 0.5$. Figure 5 shows the atomic flux, $\Phi(E)$, measured in two time intervals; the first being the initial 0.5s of NBI and the second the subsequent 0.75s. Both of these intervals are about the same duration as the slowing-down times, 0.65s and 1s respectively, and longer than the characteristic time for the increase in the alpha particle source-rate, which is 0.25-0.4s. The alpha particle distribution function should be far from equilibrium so that $\Phi(E)$ should be depleted at low energies. However, this is far from being the case. The solid lines are model predictions, based on classical alpha slowing-down, and are far short of the data below 1.6MeV. This excess signal is ascribed to deuterons, knocked on from the thermal distribution by alphas.

When the formalism in [18] is used, it is found that the neutralisation probabilities for knock-on deuterons and alphas are related by $P_{vd} \approx 150 P_{v\alpha}$. This circumstance makes it possible that the flux of neutralised knock-on deuterons be comparable in magnitude to that of neutralised alphas, even though the density of knock-on deuterons is $\sim 10^{-2}$ of that of the alpha particles. Since the tail of knock-on

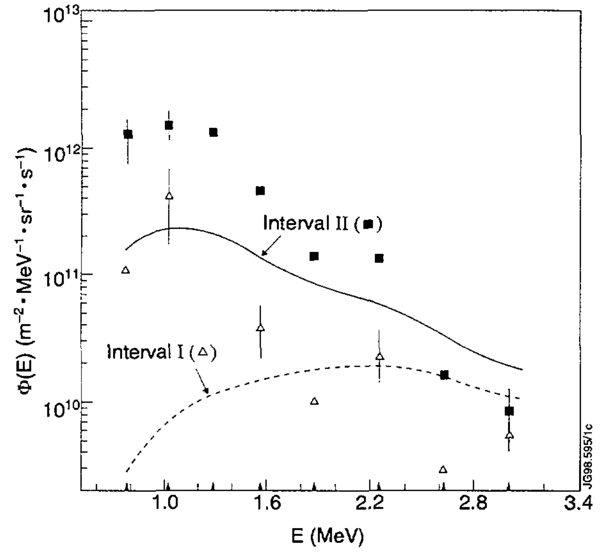

Fig.5. The normalised atomic flux at the NPA, Φ(E), integrated over intervals I and II, described in the text. The NPA was set up for measurements at 8 energies, indicated by thorns on the energy axis. Errors due to uncertainties in neutron noise and counting statistics are shown. The curves show the expected Φ(E) if alphas were the only source of atomic flux.

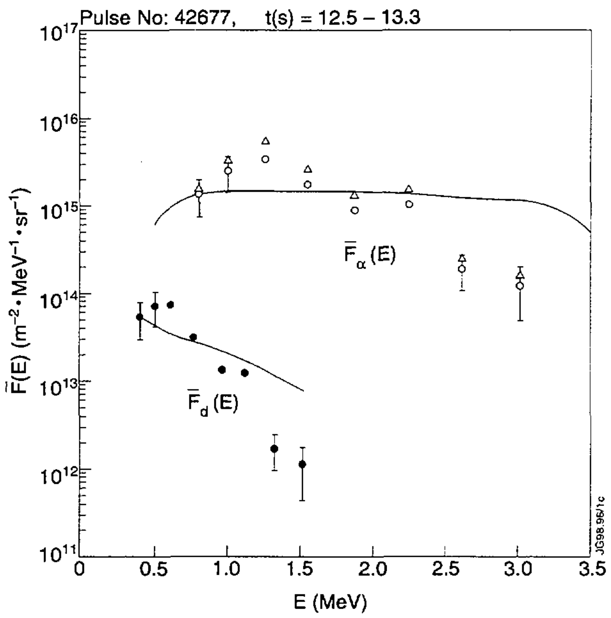

Fig.6. The measured line-of-sight integrated distribution function for alpha particles and knock-on deuterons, deduced from NPA measurements in the second time interval, described in the text. The error bars incorporate counting statistics, uncertainties in subtraction of neutron noise, uncertainties in key plasma parameters and in determining the neutralisation probabilities $P_{v\alpha}$ and P_{vD}. For comparison, calculated distributions are shown as solid lines.

deuterons has typically suffered only one substantial elastic nuclear collision, the high energy deuteron distribution function is linearly related to that of the alphas. Thus, separate line-of-sight distribution functions can be deduced from the NPA data. These are shown in figure 6 and are compared with calculated distributions. The agreement is satisfactory, apart from the two highest energy points where a depletion of the signal occurs at high power levels of the neutral beam under the neutral particle analyser. The reason for this is not understood but appears to be due to anisotropy which is not being modelled.

This observation of a knock-on deuteron tail offers an attractive possibility for measuring the alpha particle distribution function in future DT experiments: The high energy triton neutral spectrum should be unpolluted by any other neutrals and the atomic physics of hydrogenic neutral production is simpler than that of helium. Therefore, the knock-on triton spectrum should be relatively simply related to the alpha particle distribution function.

6. CONCLUSIONS

During the JET DTE1 experiment, a definitive demonstration of plasma heating by alpha particles was obtained in a dedicated series of hot ion H-modes. The level of heating is such that there cannot be significant anomalous alpha losses and the temporal development of the heating is consistent with classical slowing down, although it must be said that this does not constitute a strong test of this. This series of plasmas also showed little or no isotope dependence for energy confinement in the hot ion H-mode. All observations of TAEs in DD and DT plasmas are in accord with stability calculations. NBI ions provided strong damping during high performance DT pulses so that unambiguous alpha-driven instability was not observed. Ion Cyclotron Emission was observed and, as previously, can be related to edge magnetoacoustic cyclotron instability driven by alphas whose orbits extend from the plasma core to the edge. All ICE observations are consistent with classical alpha trapping and features of the data support classical slowing-down as well. Measurements of the neutral alpha and deuteron fluxes show a significant component of high energy deuterons, knocked-on from the thermal distribution by confined alphas. The measured spectrum is in reasonable accord with calculations, which assume classical slowing-down and measured or calculated elastic nuclear cross-sections.

A future DT experiment in JET should benefit in developments in plasma performance to enable better alpha particle studies. Of particular value would be the attainment of sufficient alpha pressure that TAE instability occurs so that the resulting alpha losses and instability saturation levels can be evaluated. It had been intended to use the saddle coils during DTE1 to excite TAEs. However, the low-n modes to which the saddle coils couple were so stable in divertor configurations that this intention was not realised. A dedicated coil with a wider n-spectrum should allow definitive tests of TAE theory, even when the modes are stable. It will be necessary to document the effects of mhd instability, such as sawteeth and ELMS, on alphas in steady-state plasmas. To this end, the measurement of core alpha density profiles through the neutral knock-on triton flux will be of great utility.

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