Observation of Alpha Heating in JET DT Plasmas

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An experiment at the Joint European Torus (JET) has demonstrated clear self-heating of a deuterium-tritium plasma by alpha particles produced in fusion reactions. The alpha heating was identified by scanning the plasma and neutral beam mixtures together from pure deuterium to nearly pure tritium in a 10.5 MW hot ion H mode. At an optimum mixture of $(60 \pm 20)\%$ T, the fusion gain $(= P_{\text{fusion}}/P_{\text{absorbed}})$ was 0.65 and the alpha heating showed clearly as a maximum in electron temperature. The change in temperature produced by alpha heating was $T_e(0) = 1.3 \pm 0.23$ keV in 12.2 keV. The effect of the heating could also be seen in the ion temperature and energy content. [S0031-9007(98)06446-1]

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In magnetically confined fusion (MCF) plasmas, the 20% of the DT fusion power which is carried by alpha particles is, in principle, available for plasma heating. For this power to be absorbed, the alphas must be trapped and slow down in the plasma. The Joint European Torus (JET) tokamak was designed with sufficient plasma current [1] that alpha particles, at their birth energy of 3.5 MeV, have orbital excursions away from their mean magnetic flux surfaces which are at most 10% of the plasma minor radius. Thus, in the absence of instabilities which couple to the alphas and cause them to suffer anomalous transport, classical expectations are that fusion heating should be effective in JET. For typical electron temperatures of 10 keV, or thereabouts, more than 95% of the alpha power is transferred to the electrons. Accordingly, the first indications of alpha heating will be seen in the electron temperature. Toroidal Alfven eigenmodes (TAEs) [2] are thought likely to be the most significant plasma instabilities to be excited by alpha particles in burning, tokamak plasmas. However, the alpha pressure in the JET DT experiments [3] was too small to excite TAEs so the alpha heating experiment described here is a test of the classical process of trapping and slowing down in the presence of MHD instabilities such as sawteeth or "outer modes" [4].

The TFTR team was the first to observe alpha heating in an MCF plasma [5]. The alpha power was 3% of the total heating power absorbed by the plasma, so the electron heating due to alphas was only twice the error arising from pulse to pulse variation. With a fusion power gain 3–4 times that of TFTR, JET was in a better position to observe alpha heating. The TFTR experiment established the importance of eliminating isotopic effects, due to the change from D to DT fuel, and averaging out, or eliminating, the effects of MHD instability.

In addition to any effect that there might be on the anomalous plasma thermal conductivity, the isotopic mixture of the plasma and neutral beam heating influences heating deposition profiles, electron-ion coupling, neutral penetration, and plasma rotation frequencies; the latter affecting MHD stability. Thus, if alpha heating is to be observed when it is much less than the total power input to the plasma, these isotopic effects must be eliminated. This was accomplished in this experiment by scanning the plasma mix from pure D to as nearly pure T as could be managed. Since the alpha production at the extremes of the scan should be small, a maximum must lie in between which should be visible in the plasma temperature.

A 3.8 MA/3.4 T neutral beam heated (NBI) hot ion *H* mode [6] was chosen for the alpha heating experiment. It featured a low target density ($\sim 1 \times 10^{19}$ m^{-3}) and low levels of neutral recycling in order to achieve the hot ion regime. The NBI provided a large core particle source so its DT mixture had to be varied in concert with that of the plasma. In order that this be done with constant power and little variation in the particle source, the power was constrained, by features of the JET NBI system and its operation with tritium, to 10.5 MW and the scan to 5 points. Nevertheless, in spite of this low heating power, the plasma density, energy content, and fusion yield grew continuously until terminated by a type-I edge localized mode (ELM) [7], 2.5–3 s after the start of NBI heating. The high performance phase is significantly longer than the central alpha particle slowing-down time and the plasma energy confinement time, both of which are approximately 1 s. The NBI particle source varied from 6×10^{20} atom/s in T to 8×10^{20} atom/s in D. The volume average electron density just before the ELM was approximately 4×10^{19} m^{-3} for all the pulses in the scan. TRANSP [8] predictions indicated that the fusion output would be 5–6 MW with a 50:50 DT mixture and that the alpha heating should be 30%–40% of the power input to the core electrons.

In order that the recycling composition be the same as that of the gas and NBI sources, the vacuum vessel walls and divertor target had to be loaded with the required DT mixture. This was done by loading to ~90% tritium first, using high density, tritium fueled, ion cyclotron resonance heated (ICRH) pulses. The use of ICRH increased the particle flux to the plasma-facing surfaces and kept the neutron yield to acceptably low levels. Each NBI heated pulse of the scan was preceded by a pulse of the same type with the NBI substituted by 3 MW ICRH. This had the effect of restoring low recycling conditions because of the small gas input and allowed all the settings, including the DT mixture, to be checked prior to a high yield pulse. The 3 MW ICRH was necessary to prevent locked mode disruptions at low density. In the event, the first attempt at a ~100% tritium pulse was somewhat unsatisfactory because the core concentration was only 75%, in spite of more favorable indications from edge diagnostics. The rest of the scan was completed and a 92% tritium pulse was obtained later, after a period of pure tritium fueling for other purposes.

The fusion performance of these plasmas turned out to be slightly better than anticipated. The best was pulse 42 847 which produced a maximum of 6.7 MW fusion power with 60% tritium concentration. Some traces for this pulse are shown in Fig. 1, together with those for pulse 43 011, with 92% tritium. The alpha heating power is computed in TRANSP using the computed birth profile normalized to the measured fusion rate. The trapping and slowing down of the alphas are modeled in a Monte Carlo package, similar to that for NBI. It may be seen that, although the absorbed NBI powers are nearly identical, the 92% tritium pulse has a very much lower alpha heating power. Since the pure deuterium pulses have essentially zero fusion power, the aim of obtaining a clear maximum in the fusion yield had been achieved. Notice that the neutral beam power of 43 011 is larger than 42 847 for the first 0.5 s. As a result, both energy content and temperatures grow more rapidly to begin with. Once it has built up, the effect of the alpha heating in 42 847 is apparent during the last second of the beam pulse. The ion temperature increase is due to transfers of equipartition and NBI power from the electrons rather than direct alpha heating. The spikes in the alpha heating power, at the end of the high performance phase, are due to the sudden decrease of slowing-down time as the plasma cools.

The alpha heating of the electrons can be seen clearly in the contour plot of central electron temperature, determined from electron cyclotron emission (ECE), versus time and DT mixture, which is shown in Fig. 2. The DT mixture is that required to reconcile TRANSP estimates of the peak neutron yield, using experimental temperature and density profiles, with the experimental value. The maximum electron temperature grows with increasing tritium concentration, up to a maximum at 60%, and then declines to nearly the same value as in pure deuterium. The effect of sawteeth is strongest at low T concentration, and alpha heating is best seen in the electron temperature reached just before sawtooth crashes. For this reason, pulses 42 847 and 43 011 were compared in Fig. 1.

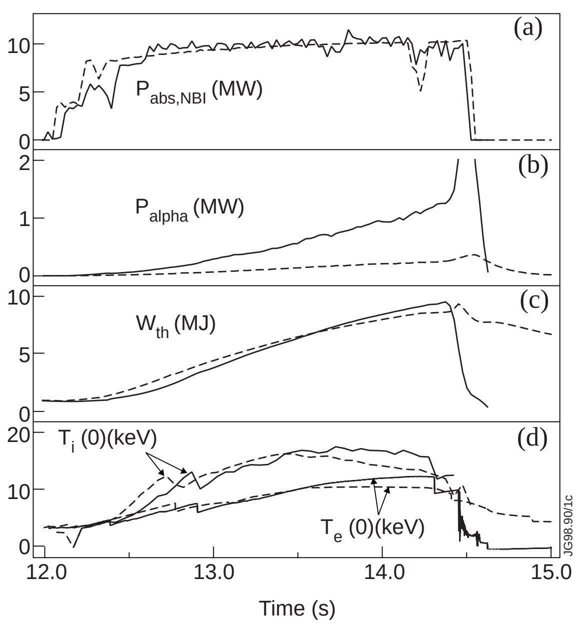

FIG. 1. Traces of (a) absorbed NBI power, (b) alpha heating power, (c) thermal plasma energy content, and (d) central ion (CXS) and electron temperatures (ECE) for pulse 42 847(solid), which had the largest fusion output of the scan, and pulse 43 011(dashed), which had the largest tritium content.

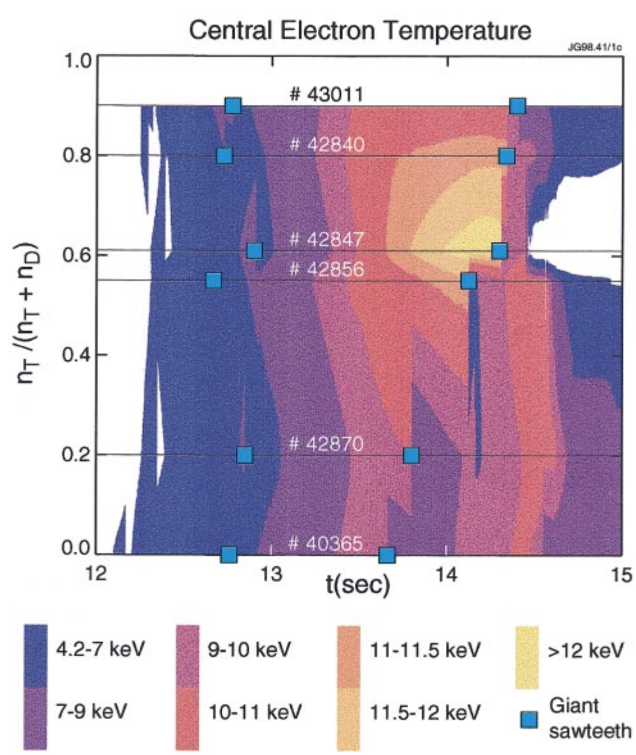

FIG. 2(color). A contour plot of central electron temperature against time (horizontal) and $n_T/(n_T + n_D)$ (vertical) for the six pulses of the alpha heating scan. Giant sawteeth are marked with squares.

The error in the value of the neutron based DT mixture is 3% at 10% or 90% T. However, the error increases to 20% at 40% or 60% T because the yield is insensitive to the mixture there. Part of this error is due to an uncertainty in Z_{eff} which will be corrected once the optical transmission of vacuum vessel windows has been measured. This is delayed because it must be performed as a remote handling task, but, on the basis of previous experience, the peak yield will move closer to 50% once it is done.

The late phase of the 20% tritium pulse and some pulses, whose data have not been included, showed a clear deterioration of the central electron temperature when edge MHD activity was present. In the following, data were selected from the peak of sawteeth when such activity was not present. It will also be noted that the data in Fig. 2 show an increase of sawtooth period with increasing tritium concentration. The reason for this is being investigated.

Using data selected as described in the last paragraph, the alpha heating can be brought out very clearly. Figure 3 shows the central electron temperature against alpha heating (or ICRH) power. There was some variation of the neutral beam power, particularly for some deuterium and the 20% tritium points, where it was as much as 1 MW. The points in Fig. 3 were selected to have no more than 5% variation from the nominal NBI plus Ohmic power (10.6 MW), achieved in pulse 43 011 so that most of the electron temperature change is that due to alpha heating. The remaining variation relative to the nominal applied power is indicated by the horizontal bars. The tick marks at the ends of the bars represent points with the alpha power corrected by the variations in NBI power and indicate how much of the temperature variation is from this source. The figure includes, for comparison, some ICRH points which had been used before the DT experiments to test the feasibility of detecting alpha heating. The effect of ICRH is very similar to that of alphas because it mainly heats the plasma electrons. The DT points are all marked with the percentage of tritium. A number of points can be made about Fig. 3: (a) The change in electron temperature is proportional to alpha power; (b) the correlation is improved if the alpha power is corrected for NBI variations; and (c) the alpha and ICRH power sources are identical in their effects.

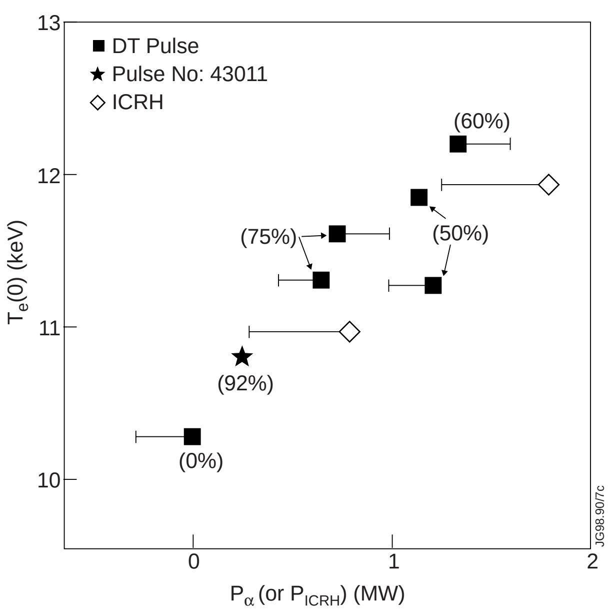

FIG. 3. Central electron temperature (ECE) versus alpha (or ICRH) power. The DT data (squares and star) and the ICRH data (open diamonds) are identified. The bars indicate the variation in NBI power compared to the 92% T pulse, 43 011. The figures in brackets are $n_{\mathrm{T}}/(n_{\mathrm{T}} + n_{\mathrm{D}})$.

A regression fit to all the data, including those with too large an NBI power variation for Fig. 3, gives $T_e(0) = (0.21 \pm 0.99) + (0.99 \pm 0.09)P_{\mathrm{heat}}$ where P_{heat} is the total power absorbed by the plasma including ICRH and alpha power. Separating the alpha power in the fit gives $T_e(0) = (0.07 \pm 1.04) + (1.0 \pm 0.1)(P_{\mathrm{heat}} - P_\alpha) + (0.99 \pm 0.13)P_\alpha$. If the electron density or $n_{\mathrm{T}}/n_{\mathrm{D}}$ is included in the regression fit, their weights are zero within errors. The lack of any significant mixture dependence indicates that there can be no isotopic effect in energy confinement. That the electron temperature shows no dependence on the electron density is consistent with the simultaneous increase in plasma energy content and density during the ELM free phase of these plasmas. The regression fit gives a change in central electron temperature of 1.3 ± 0.23 keV with 1.3 MW alpha power. The standard error for the temperature has been given, which reflects the pulse to pulse variation in the data. It should be remembered that the data are selected to be free of MHD activity and that there are systematic, calibration errors for $T_e(0)$ and P_α which are estimated to be 5% and 10%, respectively.

The power balance has been studied using TRANSP. Figure 4 shows the profiles of different contributions to the electron power balance for the pulses of Fig. 1. The rate of change of electron energy density is shown as well. The Ohmic, NBI, and equipartition power densities are little different across most of the plasma cross section. However, the central power density in pulse 42 847 is 50% higher due to alphas and this is responsible for the difference in heating rate between the two pulses. That this is roughly true across the plasma cross section, as an examination of Fig. 4 reveals, encourages the belief that the alpha heating profile is being faithfully reproduced by classical trapping and slowing down.

The regression analysis of the T_e data showed that there was no discernible isotope effect in the electron heating. This is confirmed by the dependence of the thermal energy confinement time on mixture. Figure 5 shows the diamagnetic and thermal energies together with the plasma energy confinement time versus DT mixture. The thermal energy content and energy confinement time are those obtained from the TRANSP analysis. The error bars in the energy confinement time reflect the fluctuations in value from one time slice to the next and are not statistically based. The

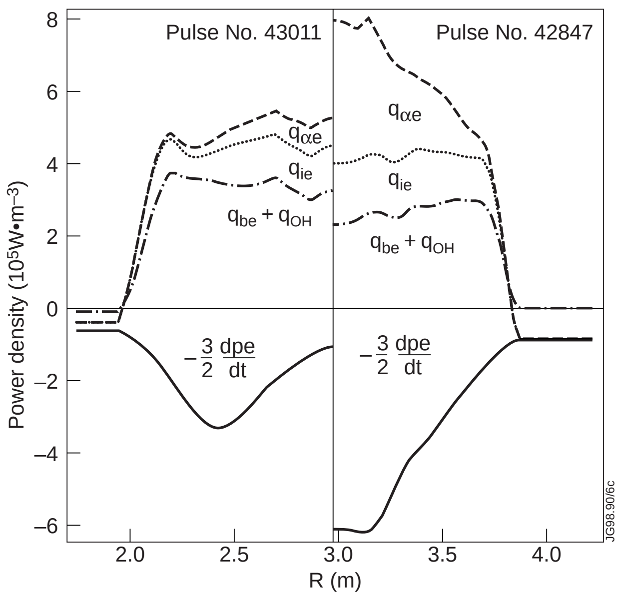

FIG. 4. Electron power density profiles for pulse 43 011, inside the magnetic axis, and pulse 42 847 outside. Beam electron plus Ohmic heating, ion-electron equipartition, and alpha heating are shown. The electron heating rate appears negated for clarity.

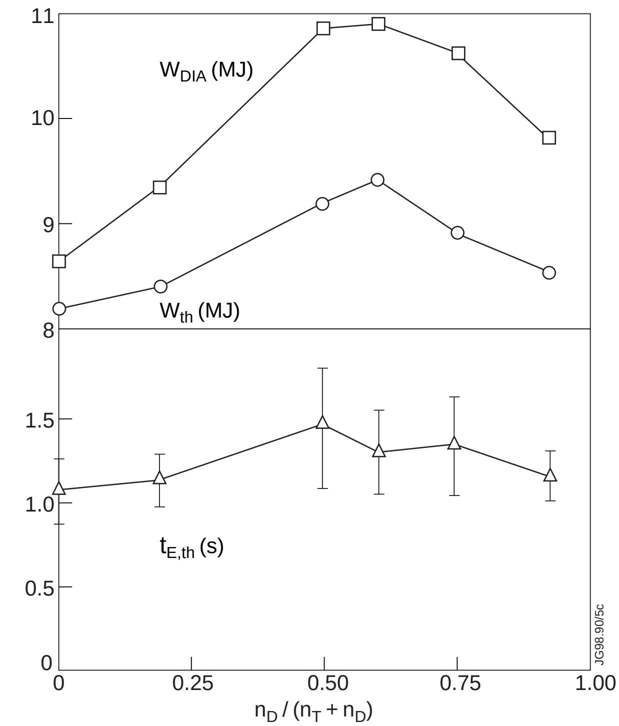

FIG. 5. (top) Diamagnetic and thermal energy contents with (bottom) the plasma energy confinement time versus DT mixture.

data points are taken when the diamagnetic energy content peaks, which is normally just before the end of the ELM free phase. The difference between the energy contents mainly reflects the energy contained in the slowing-down NBI ions; this can be as much as 2 MJ. The maximum alpha energy content is 0.25 MJ. The alpha heating is visible in the thermal energy. The figure shows that the thermal energy confinement time is the same for pure D and pure T plasmas, within errors. Thus, if there is any isotopic dependence in the plasma thermal conductivity, it is rather weak. The increase in errors for the pulses with significant alpha heating is due to the larger dW/dt term. That there is a slight increase in confinement time as well is due to the more favorable alpha particle deposition profile and to the resulting peaking of the pressure profile.

In summary, alpha particle heating has been unambiguously observed in JET DT plasmas. A scan of DT mixture was used successfully to separate the effects of alpha heating and potential isotopic dependence of energy confinement. A change in central electron temperature of 1.3 ± 0.23 keV is ascribed to 1.3 MW of alpha heating. The scan showed that the plasma energy confinement in the hot ion H mode regime has no significant isotopic dependence. With a plasma energy confinement time of 1.2 s, the alpha heating produced an increase of plasma energy content of more than 1 in 9 MJ. Alpha heating was observed, in this study, to be as effective as hydrogen minority ICRH. This is a strong indication that there are no unpleasant surprises with respect to alpha heating and that there are no anomalous effects on trapping or slowing down. Furthermore, it is highly encouraging that the peaked alpha heating profile shows up in the heating rate and the energy confinement time.

It is a pleasure to acknowledge the unstinting efforts of the rest of the JET staff, who made the DT experiment go remarkably smoothly. Particular thanks are due to the NBI operations team; their efforts to commission "mixed quadrant" operation, which allows D and T to be injected from the same NBI system, made this experiment possible.

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