Fusion Heating in a Deuterium-Tritium Tokamak Plasma

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Evidence for fusion heating in the core of a deuterium-tritium (D-T) tokamak plasma is reported for the first time. Electron temperature profile data were analyzed for differences between D-T, D, and T plasmas in the Tokamak Fusion Test Reactor. Data from D and D-T plasmas with similar plasma parameters were averaged to minimize isotopic effects. The electron temperature in D-T plasmas was systematically higher than in D or T plasmas. The temperature difference between D-T and D plasmas with similar confinement times is consistent with alpha-particle heating of electrons.

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In deuterium-tritium (D-T) nuclear fusion, 20% of the energy production is in the form of 3.5 MeV alpha particles. These fusion-generated alpha particles provide central heating which can bring a D-T plasma to thermonuclear ignition if the alpha-particle heating exceeds the radiative and conductive losses. In a D-T fusion plasma, the alpha particles slow down predominantly on electrons, since their energy is typically 2 orders of magnitude higher than the temperature of the D-T fuel ions. Recent D-T experiments on the Tokamak Fusion Test Reactor (TFTR) have achieved fusion powers ($P_{\rm fus}$) of up to 10 MW [1] and central alpha-particle densities up to 0.3% of the total plasma ion density, approximately the fraction expected in a reactor, and central fusion power densities approaching reactor levels. Direct measurements of confined alpha particles on TFTR have confirmed that fusion-generated alpha particles slow down classically [2,3] and are well confined [4]. Alpha-particle heating of electrons in TFTR D-T discharges accounts for about 5% of the global power flow to electrons, but in the plasma core ($r/a \leq 0.25$) the fraction has reached 15%. This paper reports the first evidence for heating of electrons by fusion-generated alpha particles in a D-T tokamak plasma.

A systematic study to look for statistically significant differences in the electron temperature profile [$T_e(R)$] was performed for all the TFTR D-T neutral-beam-heated plasmas, and for comparable deuterium (D) and tritium (T) discharges. The electron temperature in the D-T plasmas was found to be systematically higher than in the D or T plasmas. For high performance discharges with similar beam heating powers and plasma operating parameters, modeling indicates that approximately half of the 2 keV central electron temperature [$T_e(0)$] difference between D-T and D plasmas is due to alpha-particle heating [5]. However, attempts to observe clear evidence for alpha-particle heating by comparing the $T_e(0)$ rise in D and D-T plasmas are challenged by several factors. First, there is a reduction in beam heating to electrons in going from D to T neutral beam injection at the same neutral beam injection power ($P_{\rm nbi}$), and there are uncertainties in calculating the neutral beam deposition. Second, the apparent dependence of the energy confinement on the mix of hydrogenic isotopes in the plasma [6–10] contributes to the rise in $T_e(0)$ in going from D to D-T. Finally, inherent performance variations due to magnetohydrodynamic (MHD) instabilities and limiter conditioning result in $T_e(0)$ changes which compete with the rise in $T_e(0)$ due to alpha-particle heating.

An earlier empirical study of $T_e(0)$ scaling for 380 D plasmas from the 1990 TFTR campaign [11] has shown that for D neutral-beam-heated discharges

$$T_e(0) = (0.32 \pm 0.02) B_T^{1.5} \tau_E^{0.5} W_b^{0.45} C_{\rm NB}^{0.2}\,, \qquad (1)$$

where B_T is the axial toroidal magnetic field (in tesla), τ_E is the global confinement time (in seconds), W_b is the neutral beam injection voltage (in kV), and $C_{\rm NB}$ is the neutral beam directionality with respect to the plasma current ($C_{\rm NB} = 1$ when all the beam power is codirected). No significant dependence on $P_{\rm nbi}$ was obtained in this study, which is probably a result of restricting the beam power to be large ($P_{\rm nbi} > 15$ MW). All the nonsawtoothing discharges from the 1993–5 TFTR D-T campaign were examined, and the condition with the most D-T plasmas that kept the parameters in Eq. (1) constant was identified. The resulting database included 2.52 ± 0.01 m major radius plasmas, with $P_{\rm nbi} = 15$–34 MW, $C_{\rm NB} = 0$–0.4, $B_T = 4.85$–5 T, and $W_b = 98$–107 kV. By constraining the database in B_T, W_b, and $C_{\rm NB}$, it was possible to express changes in $T_e(0)$ due to variations in MHD and wall conditioning through the τ_E dependence in the empirical scaling. With the above constraints, TFTR operation during the D-T campaign included 22 D-T plasmas with ~60% of the beam injection in T and $P_{\rm fus}$ up to 7.5 MW, four T plasmas with $P_{\rm fus} \sim 2$ MW (due to recycling of D from the carbon limiter [12]), and 67 D discharges. Plasma parameters were evaluated 0.7 s into the neutral-beam-heating pulse, a time late enough for the alpha-particle population to build up, but early enough to avoid the turn-off of beam heating or plasma performance degradation due to increased wall influx or MHD. There were no sawteeth or carbon blooms in the time from the

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start of neutral beam heating to 0.7 s into the neutral beam heating pulse. $T_e(R)$ evolution data were obtained from electron cyclotron emission (ECE) spectrometry [13,14]; $T_e(R)$ from Thomson scattering measurements were not included since it was unavailable for many of the plasmas in the database. In summary, we have examined the electron temperature data from all the TFTR plasmas during the D-T campaign and constrained the data set in a manner which optimizes the ability to see effects due to alpha heating.

Figure 1 shows $T_e(0)$ plotted versus τ_E for the constrained database described above. The empirical scaling for $T_e(0)$ obtained from the 1990 TFTR D plasmas is shown by the shaded region, the width of this region indicates the standard deviation in the scaling. Most of the D and T discharges (open circles and triangles) lie on or slightly above the 1990 empirical scaling. It should be noted that the 1990 empirical scaling was derived from plasmas with a major radius of 2.45 m, somewhat smaller than the discharges in the present study. The D-T plasmas with $P_{\text{fus}} < 6$ MW (solid circles) on average deviate further from the 1990 scaling, and the D-T plasmas with $P_{\text{fus}} > 6$ MW (shade filled circles) show the greatest deviation from the empirical scaling. Since D-T plasmas with the highest P_{fus} attain a much higher $T_e(0)$ than D plasmas with similar energy confinement times, we conclude that heating by alpha particles is the most likely explanation for the rise in $T_e(0)$.

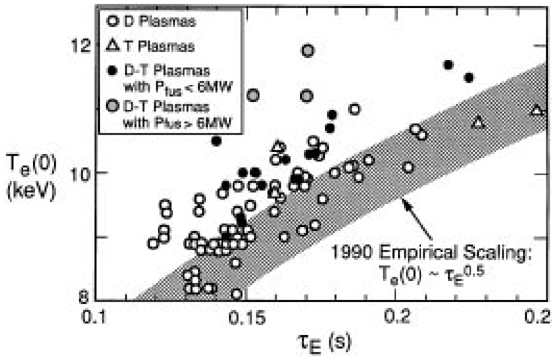

FIG. 1. Central electron temperature 0.7 s after the start of neutral beam injection versus the global plasma confinement time for D, D-T, and T plasmas with major radii of 2.52 ± 0.01 m, $B_T = 4.85-5$ T, $P_{\text{nbi}} = 15-34$ MW, $C_{\text{NB}} = 0-0.4$, and $W_b = 98-107$ kV. The empirical scaling for $T_e(0)$ obtained from the 1990 TFTR D plasmas with major radii of 2.45 m is shown by the shaded region; the width of the shaded region indicates the standard deviation in the scaling.

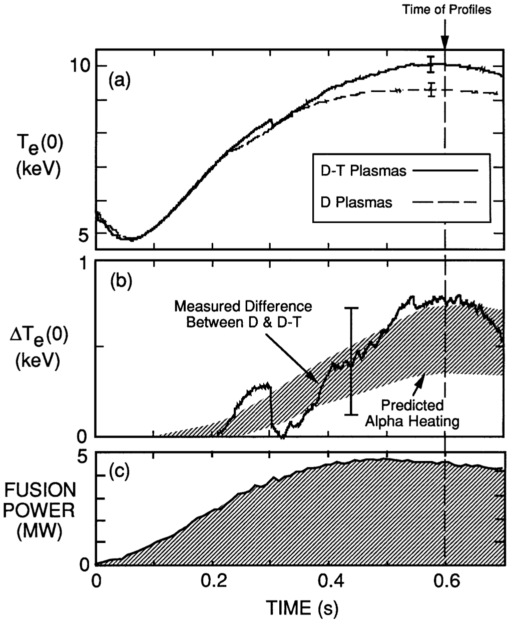

FIG. 2. (a) $T_e(0)$ versus the time after the start of neutral beam heating for six D-T plasmas with $\langle\tau_E\rangle = 0.155$ s and $\langle P_{\text{nbi}}\rangle = 24.2$ MW (solid line), and 17 D plasmas with $\langle\tau_E\rangle = 0.15$ s and $\langle P_{\text{nbi}}\rangle = 24.7$ MW (dashed line). (b) The $T_e(0)$ difference between the D-T and D plasmas in (a) compared to the $T_e(0)$ rise due to alpha heating determined by turning alpha heating on or off in the TRANSP code (shaded region). TRANSP used a thermal diffusivity from either one of the D or one of the D-T discharges, the resultant uncertainty in the predicted alpha heating is indicated by the width of the shaded region. (c) The average measured fusion power versus time for the D-T plasmas in (a).

The constrained database contains a relatively large number of D and D-T plasmas with similar τ_E, and of these there are subsets of D and D-T discharges which also have similar values of P_{nbi}. Figure 2(a) shows the time evolution of $T_e(0)$ relative to the start of neutral beam heating for ensembles of D and D-T neutral-beam-heated discharges which were closely matched in P_{nbi} and τ_E. On average the D-T discharges have a higher $T_e(0)$ that the D discharges, the error bars represent the standard deviation of the measurements included in each data set. Figure 2(b) shows that the difference in $T_e(0)$ between the D and D-T plasmas increases to approximately 700 eV 0.6 s after the start of neutral beam injection. Although there were no sawteeth up to 0.7 s into the beam heating pulse on any of the discharges contributing to Fig. 2, there were nevertheless other smaller MHD events. The largest MHD even was an abrupt collapse in $T_e(0)$ which occurred 0.3 s after the start of beam heating during one of the six D-T discharges; this is evident even on the averaged $T_e(0)$ data in Fig. 2. The average P_{fus} for the D-T discharges rises to about 4.5 MW at 0.6 s [Fig. 2(c)]. The measured $T_e(0)$ difference between the D-T and D plasmas was compared to the predicted temperature rise due to alpha-particle heating calculated by the TRANSP time dependent analysis code, assuming classical alpha-particle orbit losses [shaded region in Fig. 2(b)]. The electron temperature rise due to alpha heating was determined by turning alpha heating on or off in the TRANSP code and by using a thermal diffusivity from either one of the D or one of the D-T discharges from the ensemble of plasmas used for Fig. 2. This accounts for the range of uncertainty in the predicted temperature rise due to alpha heating indicated by the shaded region in Fig. 2(b). The measured time evolution and magnitude of the rise of the core electron temperature in the D-T plasmas compared to the D plasmas agree to within better than 50% with the prediction for alpha-particle heating, assuming classically confined alpha particles.

Figure 3(a) shows an overlay of the average $T_e(R)$ profiles for the D and D-T plasmas in Fig. 2 at a time 0.6 s after the start of neutral beam heating. The temperature difference is localized to a region within approximately 0.3 m of the magnetic axis [Fig. 3(b)]. The magnitude and localization of the temperature rise is consistent with that predicted for alpha-particle heating of electrons by the TRANSP analysis code [shaded region in Fig. 3(b)]. In addition, the localization of the electron temperature rise in the D-T plasmas relative to the D plasmas is consistent with the source profile of fusion-generated neutrons measured by a multichannel neutron collimator [15] [Fig. 3(c)]. The profile shape of the alpha-particle density and heating are computed to be close to the alpha source profile (and D-T reaction rate). Thus the electron temperature difference is located primarily in the central region where the alpha particles are born and expected to provide heating.

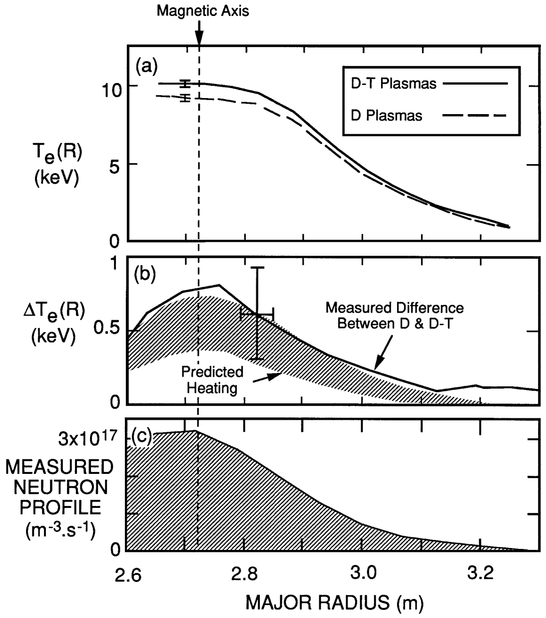

FIG. 3. (a) Electron temperature profiles versus major radius 0.6 s after the start of neutral beam injection for six D-T plasmas with $\langle\tau_E\rangle = 0.155$ s, $\langle P_{\rm fus}\rangle = 4.5$ MW, and $\langle P_{\rm nbi}\rangle = 24.2$ MW (solid line) and 17 D plasmas with $\langle\tau_E\rangle = 0.15$ s and $\langle P_{\rm nbi}\rangle = 24.7$ MW (dashed line). (b) Electron temperature difference between the D-T and D plasmas in (a) versus major radius compared to the predicted temperature increase due to alpha heating from the time dependent kinetic code, TRANSP (shaded region). (c) Measured neutron emission source profile measured by a multichannel neutron collimator for the D-T plasmas in (a).

As discussed above, to minimize changes in $T_e(0)$ due to variations in plasma MHD and wall conditioning, the value of $T_e(0)$ in the database can be normalized to the empirical dependence on τ_E derived from the 1990 D plasmas. In Fig. 4, $T_e(0)/\tau_E^{0.5}$ is plotted against the fraction of neutral beam power injected in tritium, both the data and the averaged data are indicated, the error bars represent the standard deviation of each data set. Deviations from the $\tau_E^{0.5}$ scaling are greatest for the plasmas with $P_{\rm fus} > 6$ MW, and there appears to be no dependence on the D-T isotopic mix. Since on average the T plasmas do not deviate significantly from the $\tau_E^{0.5}$ scaling, this suggests the isotope effect on τ_E causes $T_e(0)$ to rise as $\tau_E^{0.5}$.

Figure 5 shows the deviation from the $\tau_E^{0.5}$ empirical scaling and the calculated fraction of power flow to electrons within the plasma core ($r/a < 0.25$) plotted versus $P_{\rm fus}$. The electron power flow was calculated by the time independent equilibrium code SNAP [16] which was modified to include alpha heating. Because the alpha-particle slowing down time is relatively long compared to the beam heating time, the alpha heating to electrons was averaged from the start of neutral beam heating to 0.7 s into the neutral beam injection pulse. The power flow to core electrons is dominated by beam heating and thermal ion-electron coupling, but for the discharges with the highest $P_{\rm fus}$ in the database alpha heating accounts for approximately 15% of the core electron power flow. Ohmic heating accounts for less than 2% of the power flow within $r/a = 0.25$ in these plasmas. The deviation of $T_e(0)$ from the $\tau_E^{0.5}$ empirical scaling is greatest for plasmas which have the largest calculated fraction

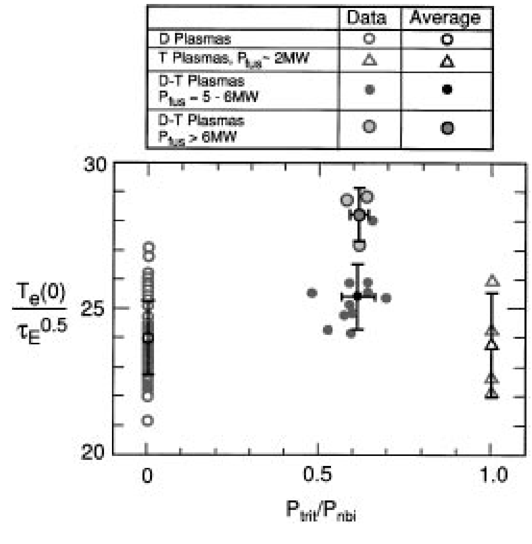

FIG. 4. $T_e(0)$ normalized to the empirical scaling obtained for the 1990 TFTR D plasmas versus the fraction of beam power in tritium.

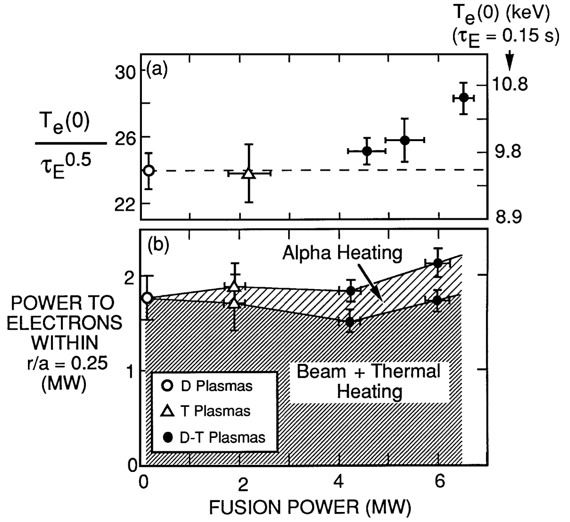

FIG. 5. (a) $T_e(0)$ normalized to the empirical scaling obtained for the 1990 TFTR D plasmas and (b) the calculated power flow to electrons versus the fusion power. Ohmic heating accounts for less than 2% of the power flow to electrons within $r/a = 0.25$.

of core electron heating coming from alpha particles slowing down.

Several complications exist in the present study. First, because the database spans nearly two years of TFTR operation, τ_E varies significantly due to changes in the carbon limiter conditioning and MHD behavior. We have attempted to minimize these effects by normalizing $T_e(0)$ to the empirical τ_E scaling. Therefore one issue is that the $T_e(0)$ variations in the TFTR D plasmas are not explicitly understood and it is difficult to know if they have been adequately addressed. Second, although Thomson scattering $T_e(R)$ data were available at one time point for most of the plasmas in the database, the data acquisition time was often taken either too early in the neutral beam heating phase, before a substantial alpha particle population could build up, or after a major MHD event such as a sawtooth, or after the neutral beam heating pulse. Further, Thomson scattering data were generally not taken at the same time in the neutral beam heating pulse, making it difficult to compare similar plasmas in D, D-T, and T. Unfortunately, there has been a long standing, unresolved, disagreement between ECE and Thomson scattering measurements of $T_e(R)$ on TFTR [17], such that Thomson scattering measurements would probably yield a much smaller $T_e(0)$ difference between D-T and D plasmas than is measured by ECE. The second issue is, then, that Thomson scattering measurements (although unavailable) would probably have yielded a different magnitude of alpha heating. Finally, in the existing database the increase in $T_e(0)$ due to alpha heating is comparable to that due to changes in τ_E as a result of the isotope effect. Thus a third issue is the competition between alpha heating and the isotope effect. Many of these issues could be resolved by future TFTR experiments which could aim to have greater control of the limiter conditioning and MHD, a slightly higher fusion power (say, 8 MW) and more tritium plasmas. Such experiments are difficult, at the limit of the TFTR device capability, and are unlikely to be performed in the immediate future.

In conclusion, the $T_e(0)$ rise in D-T compared to D and T plasmas has the following characteristics. The time evolution and localization of the $T_e(0)$ rise are consistent with the calculated $T_e(0)$ rise due to alpha heating assuming classically confined alpha particles. $T_e(0)$ increases with P_{fus} and does not appear to depend on the D-T isotopic mix. While there are several unresolved issues, these observations are consistent with the heating of electrons by fusion-generated alpha particles.

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