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Confinement and Heating of a Deuterium-Tritium Plasma

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The Tokamak Fusion Test Reactor has performed initial high-power experiments with the plasma fueled with nominally equal densities of deuterium and tritium. Compared to pure deuterium plasmas, the energy stored in the electron and ions increased by $\sim 20\%$. These increases indicate improvements in confinement associated with the use of tritium and possibly heating of electrons by α particles created by the D-T fusion reactions.

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The Tokamak Fusion Test Reactor (TFTR) has performed high power deuterium-tritium (D-T) experiments with a wide range of tritium (T) to deuterium (D) beam fueling ratios. This paper presents initial results on the confinement and heating of D-T tokamak plasmas of importance to the design of D-T tokamak reactors. In the world tokamak fusion program, only two facilities, TFTR [1] and the Joint European Torus (JET) [2], have the capability to study the physics associated with the use of D-T fuel. A limited scope "Preliminary Tritium Experiment" (PTE) was performed in JET in 1991 comprising two plasma shots with a ratio of tritium to total beam fueling of 13% [2]. The fusion neutron rate and the confinement of alpha particles in TFTR D-T plasmas are discussed by Strachan *et al.* [3].

The TFTR machine configuration and the changes made in preparation for the D-T experiments are described in Ref. [1]. The experiments discussed here were conducted in the enhanced confinement "supershot" regime characterized by peak density profiles [4]. The

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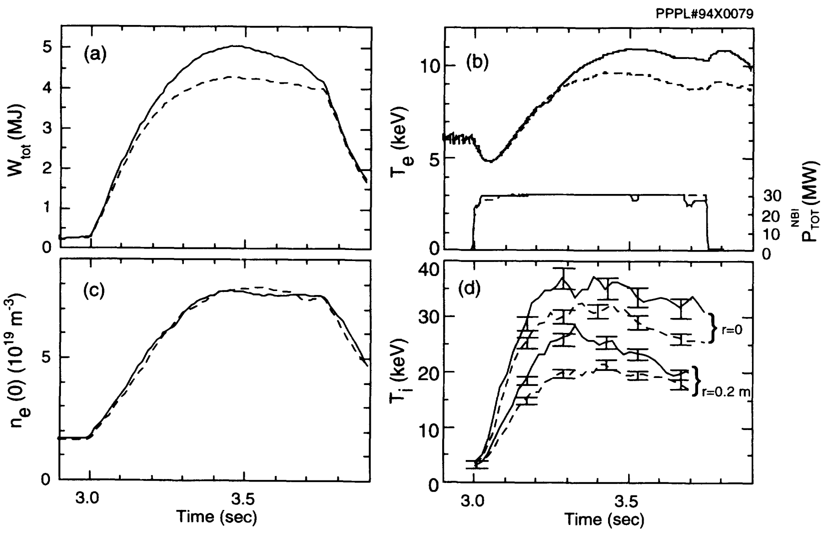

FIG. 1. (a) Magnetic measurements of the total stored energy; (b) electron cyclotron emission measurements of the central electron temperature (radially averaged ± 0.1 m) and the neutral beam power; (c) Abel inverted interferometry measurements of the central electron density; and (d) charge exchange spectroscopy measurements of the carbon ion temperature in a D-T discharge (solid curve) are compared with a D discharge (dashed curve) for the conditions given in Table I for $r=0$ and $r=0.2$ m.

toroidal field was 5.0 T, plasma current was 2.0 MA, and major radius was 2.52 m, and minor radius of the circular plasma cross section was 0.87 m. One or two lithium pellets were injected at the end of the discharge to improve the wall conditioning [5] for the subsequent discharge and reduce the likelihood of a disruption in the current ramp-down phase. D and T neutral beams with energies 90–107 keV were injected to both heat and fuel the discharge. A maximum heating power of 30 MW was delivered by twelve neutral beam sources in toroidally opposed directions yielding near-balanced injection. Twenty-seven discharges have been studied using from one to nine T neutral beam sources in order to alter the central fueling rate. No external gas fueling was applied; however, hydrogenic influx from the carbon limiter was roughly comparable to beam fueling.

A striking difference between plasmas heated exclusively with D beams and those heated with a significant amount of T beams was an increase in plasma stored energy as shown in Fig. 1(a). The increase in stored energy was clear and reproducible, corresponding to an increase in the global energy confinement time, τ_E (including the energy in nonthermal ions), from 0.15 to 0.18 s and an increase of the fusion product, $n_i(0)\tau_E T_i(0)$ from 2.6×10^{20} to 3.8×10^{20} m^{-3}s keV. In these experiments, the discharge conditions were chosen to obtain reproducible, stable, and disruption-free plasma operation. The variation in stored energy among four D discharges used to establish a baseline was less than 5%. The central electron density was very similar in D versus D-T plasmas whereas the density profile was slightly broader in a D-T plasma ($\Delta[n_e(0)/\langle n_e\rangle]\sim 8\%$).

All discharges (D and D-T) were relatively magnetohydrodynamics (MHD) quiescent before 3.4 s; however, the onset of MHD activity and a 20% relative increase of hydrogenic influx affected the subsequent evolution of the D-T discharge shown in Fig. 1. The D discharge shown in Fig. 1 had no significant coherent MHD activity, whereas the D-T discharge had a growing $m/n=4/3$ mode starting at ≈ 3.4 s. Studies in D discharges of the correlation between MHD amplitude and τ_E [6] indicate that the 4/3 activity observed in the D-T discharge could result in a decrease in the stored energy by $\sim 10\%$ at the end of the discharge. A beta collapse, such as observed in the PTE conducted at JET [2], was not observed in these D-T experiments despite the larger stored energy compared to the baseline D plasmas. Comparisons of plasma performance at 3.4 s shown in Fig. 2 and Table I correspond to conditions near maximum stored energy and prior to the onset of significant MHD activity. At this time, the plasma was close to equilibrium with $|dW/dt|P_{\rm NBI} < 0.04$.

As seen in Figs. 1 and 2, the carbon ion temperature measured by charge exchange recombination spectroscopy is 20%–25% higher in a D-T plasma than in a comparable D plasma. Classical beam-coupling calculations indicate that preferential beam coupling to carbon sustains a central carbon temperature ~ 2 keV higher than the thermal hydrogenic ion temperature in both the D and D-T plasmas at 3.4 s [7]. Thus the measured difference in carbon temperature reflects a real increase in the bulk hydrogenic temperature and the measured impurity temperature is used throughout this paper. Modeling of the effect of the energy dependence of the charge exchange reaction rate coefficient for D and T interacting with carbon [8,9] on the inferred carbon temperature indicates no systematic effect on the difference between the D and D-T plasmas. A series of dedicated experiments are being performed to examine the validity of this modeling.

The core electron temperature as measured by electron cyclotron emission (ECE) is also greater in the D-T discharge. As shown in Fig. 1, the difference in the cen-

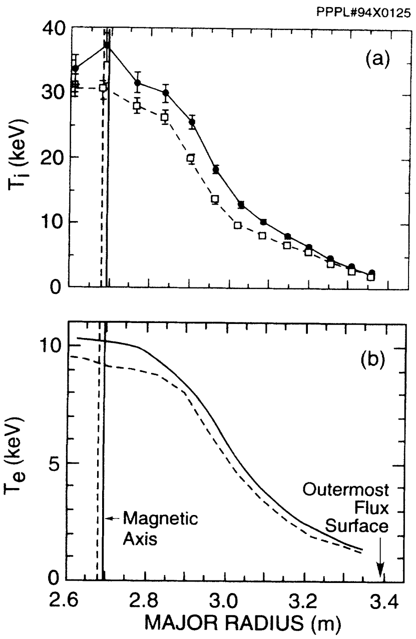

FIG. 2. (a) Charge exchange spectroscopy measurements of the carbon ion temperature profile and (b) electron cyclotron emission measurements of the electron temperature profile, and in a D-T discharge (solid curve) are compared with a D discharge (dashed curve) at 3.4 s in the discharge for the conditions given in Table I.

TABLE I. Summary of plasma parameters: The units of $n\tau T$ are 10^{20} m^{-3} s keV.

	D	D-T
P_{NBI} (MW)	29.7	29.5
P^{D}_{NBI} (MW)	29.7	10.0
P^{T}_{NBI} (MW)	0.0	19.5
$T_i(0)$ (keV)	30	37.
$T_e(0)$ (keV)	9.5	10.3
$n_e(0)$ (10^{19} m^{-3})	7.5	7.6
$\langle Z_{eff}\rangle$	2.3	2.3
$P_{\alpha e}$ (MW) (calculated)	0.0	0.86
P_{fusion} (MW)	0.044 (D-D)	6.2 (D-T)
W_e (MJ)	1.04	1.17
W_i (MJ)	1.36	1.64
W_b (MJ) (calculated)	1.98	2.21
W_α (MJ) (calculated)	0.0	0.14
W_{kin} (MJ) (calculated)	4.38	5.16
W_{mag} (MJ)	4.17	4.88
τ_E (msec)	150	180
$n_e(0)T_i(0)\tau_E$	3.4	5.0
$n_i(0)T_i(0)\tau_E$	2.6	3.8

tral electron temperature between D and D-T plasmas increases from $\sim$0.8 keV at 3.4 s to $\sim$2 keV at the end of the heating pulse. Thomson scattering measurements at 3.45 s show a smaller temperature increase of $\sim$0.5 keV than ECE ($\sim$1.1 keV). This discrepancy in central electron temperature measurement is consistently observed during high temperature supershot experiments including those with core ion cyclotron heating and has not been satisfactorily resolved [10].

Small differences in the stored energy between plasmas heated with pure D versus mixed D-T beams are anticipated due to a number of purely classical effects. These include an increased beam thermalization time for T beams, poorer radial penetration of T beams, more energy stored in the fast alpha population, and additional heating of electrons by alphas [7]. Analyses of these plasmas have been performed with the codes SNAP, to study the near-equilibrium phase, and TRANSP which follows the full time evolution of the plasma. In these interpretive codes, measurements of the ion and electron temperature, the electron density, and bremsstrahlung emission are used as inputs, together with the machine parameters. In the time-dependent calculations, the influx of hydrogenic neutrals from the limiter is assumed to be 20% hydrogen, 75%–80% deuterium and < 5% tritium consistent with spectroscopic measurements of the H_α, D_α, and T_α components of the hydrogenlike line emission in the plasma edge. The low T influx is a consequence of relatively little T operation compared with D operation and is consistent with 14 MeV neutron measurements in shots prior to and after a D-T shot. A summary of the results of the analysis at 3.4 s into the discharge is shown in Table I using ECE measurements of electron temperature. The plasma stored energy calculated from the kinetic analysis is in good agreement with the magnetic measurements. The increase in stored energy is only partially due to the effects of increased energy in the beam ions ($\Delta W_b/\Delta W_{tot}$ =29%) and the alpha particles (18%) which are calculated assuming classical fast-ion thermalization and classical radial transport. The remaining increase is in both the thermal ion (36%) and electron stored energy (17%), indicating an isotopic effect on ion energy confinement and either an isotropic effect on electron energy confinement or alpha heating of electrons.

For $r/a < 0.5$, the deduced ion thermal diffusivity is a factor $\sim$1.5 lower in the D-T plasma compared to the D plasma of Fig. 2. This suggests a strong sensitivity of ion heat conduction to isotopic composition in supershot plasmas, even though the core thermal T concentration $[n_t/(n_h+n_d+n_t)]$ is somewhat less than 50% in the D-T plasmas, due to influx of thermal D from wall recycling [3]. The isotopic effect observed in these supershots is stronger than that observed previously in H-D comparisons in *L*-mode plasmas [11] which spanned roughly the same range in isotopic composition. A weak isotopic scaling of transport is also observed in *L*-mode plasmas in JET and DIII-D, but many other tokamaks including JT60-U and ASDEX report a significant favorable isotope effect [12]. By contrast, the isotopic effect appears to be consistently observed in enhanced-confinement *H*-

mode plasmas [12]. The observed isotope effect in supershots may be related to favorable T_i/T_e scaling arising from orbit averaging of turbulence [13]. To separate isotope effects from alpha heating, comparable 1.8 MA discharges were obtained with tritium-only beam injection. After 0.4 s of natural injection, the stored energy increased from 3.18 to 3.51 to 3.82 MJ with injection of pure D, mixed D-T, and pure T beams at relatively constant powers of 22.3, 22.1, and 23 MW, respectively. The total neutron emission rate from the pure T discharges was more than 65% of the rate obtained in the D-T plasmas implying comparable core thermal T and D densities. The observation that pure T injection obtained at higher stored energy than mixed D-T injection, despite the lower fusion power, and therefore lower alpha stored energy and alpha heating, indicates that effects associated with the plasma and beam isotope dominate over alpha effects.

Within $r/a < 0.25$, the ratio of the alpha heating power, P_{ae}, to the total heating power to the electrons $P_{ae}/(P_{ae}+P_{be}+P_{ie}+P_{oh}) < 15\%$ which is comparable to $\Delta T_e(0)/T_e(0)$; however, in these experiments there are similar changes in the ion-electron equilibrium, P_{ie}, and collisional beam heating, P_{be}. The observed increase of T_e measured by ECE is roughly twice that expected from alpha heating and the changes in P_{be} and P_{ie} with fixed electron thermal diffusivity, indicating that alpha heating and other isotope effects are important. The evolution of the plasma in time has been examined for evidence of alpha heating, including slow changes on the time scale of the alpha thermalization, and rapid changes associated with pellet injection. As shown in Fig. 1, the time evolution of the temperature increase between D and D-T plasmas is different for electrons and ions. In particular, note that the electron temperature difference increases smoothly on a time characteristic of the alpha heating, which reached a maximum only after ~ 0.7 s of beam injection due to the long alpha thermalization time. By contrast, the ion temperature difference was fully developed within 400 ms.

Another indication of alpha heating is observed in the reheat of the plasma following the injection of boron and lithium pellets. Pellets were injected ~ 0.22 s after the termination of neutral beam heating in both D and D-T plasmas. Because of the differing thermalization times of beam and alpha particles, the calculated electron heating in the central region $(r/a < 0.2)$ by alpha particles is twice that by beam ions at the time of the pellet injection. The injection of the pellet increases the plasma density and drops the central electron temperature to ~ 3 keV, causing the remaining alpha particles and beam ions to rapidly thermalize by heating the electrons. The central electron densities differ in the two conditions by $< 10\%$ following pellet injection. The observed reheat of the central electron temperature following pellet injection is 85% faster in the D-T plasma than in the comparable D plasma. This agrees well with TRANSP simulations which include alpha heating and the effects of perturbed density and Ohmic heating.

In these first tokamak plasma experiments with nominally equal T and D fueling, such as will be used for future D-T reactors, significant differences in the energy confinement and heating of D and D-T plasma have been observed. These differences are due to a combination of classical beam isotope effects, isotope scaling of confinement, and possibly alpha-heating effects. In particular, there is evidence that ion energy confinement in high temperature D-T plasmas is better than in D plasmas.

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