Fusion Power Production from TFTR Plasmas Fueled with Deuterium and Tritium

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Peak fusion power production of 6.2 ± 0.4 MW has been achieved in TFTR plasmas heated by deuterium and tritium neutral beams at a total power of 29.5 MW. These plasmas have an inferred central fusion alpha particle density of 1.2×10^{17} m^{-3} without the appearance of either disruptive magnetohydrodynamics events or detectable changes in Alfvén wave activity. The measured loss rate of energetic alpha particles agreed with the approximately 5% losses expected from alpha particles which are born on unconfined orbits.

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Most previous experiments in magnetic fusion research have been conducted with hydrogen or deuterium plasmas, even though first generation fusion reactors are expected to operate with equal concentrations of deuterium (D) and tritium (T). One consequence of fueling with D-T is that since the $d(t,n)\alpha$ fusion reactivity is much higher than the D fusion reactivity, more fusion reactions occur and a significant population of the charged fusion products are created. Potentially, collective phenomena can arise from the 3.5 MeV alpha population influencing their confinement as well as the global plasma stability and energy balance. The Tokamak Fusion Test Reactor (TFTR) has performed initial D-T experiments and has achieved energetic alpha densities which are about 0.2% of the plasma ion density which is about 1/3–1/2 of the fraction expected in reactors. TFTR is the second tokamak to use T [1] and the first to use equal concentrations of D and T. A separate paper [2] describes the changes in plasma heating and confinement observed with T and alpha particles present, whereas this paper dis-

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cusses the energetic ion behavior, the measurements of the fusion reactions, and the search for alpha-induced instabilities.

The primary goal of these experiments was to produce a plasma with greater than 5 MW of peak D-T fusion power. With 29.5 MW of neutral beam heating, a D-T fusion power of 6.2 ± 0.4 MW was produced with a corresponding 14 MeV neutron emission rate of up to $(2.2 \times 0.2) \times 10^{18}$ sec^{-1}. For the high power D-T experiments, TFTR was operated in the supershot regime [3] with 2.0 MA plasma current, 5.0 T toroidal magnetic field, 2.52 m major radius, and 0.87 m minor radius. The D-T was fueled by operating one to eight of the twelve beam sources in pure tritium. There were seven tritium (T) discharges at 23–30 MW of total neutral beam power including one with 10% of the beam power in tritium, one with 100% tritium beam power, and five with 40%–65% of the beam power in tritium. For comparison, 42 similar D and 6 trace T plasmas were produced at the same machine conditions. These had a D-D fusion power production of about 40 kW with a corresponding 2.54 MeV neutron emission of about 3.5×10^{16} sec^{-1}.

The neutron emission rates and yields were measured with fission chambers [4], silicon surface barrier diodes [5], spatially collimated ^{4}He recoil proportional counters [6] and ZnS scintillators [7], and a variety of elemental activation foils [8]. The activation foils, ^{4}He counters, and silicon diodes can discriminate between 14 MeV D-T and 2.5 MeV D-D neutrons. The other detectors cannot discriminate between D-D and D-T neutrons, but are more sensitive to the latter. An absolute calibration of the fission chambers, proportional counters, and scintillators was performed using an *in situ* 14 MeV neutron generator [9]. The estimated absolute accuracy of each calibration is about $\pm 10\%$ to $\pm 25\%$ while the statistical deviation of all available calibration data is $\pm 7\%$. The quoted fusion power is the weighted mean of the calibrated signals with the $\pm 7\%$ standard deviation.

The measured D-D neutron emission from D plasmas was 10%–15% greater than that calculated from the measured density and temperature profiles and a calculated beam deposition profile (by the steady-state code SNAP [10] and the time dependent code TRANSP [11]). In D-T plasmas, the measured D-T neutron emission is up to 10% less than the calculated value [Figs. 1 and 2(a)]. These discrepancies are comparable to the expected uncertainty in the codes ($\pm 15\%$) and the magnitude of the individual neutron measurement uncertainty, which is based upon separate calibrations for 2.5 and 14 MeV neutrons. The D-D neutron emission from D plasmas [12,13] and the D-T neutron emission (for D-T plasmas with approximately equal D and T beam heating) increased strongly with the total plasma energy content. The measured neutron source strength normalized to the plasma energy content (Fig. 3) displays a broad maximum near equal injected powers of D and T while the 100% T beam shot had about 65% of the maximum D-T

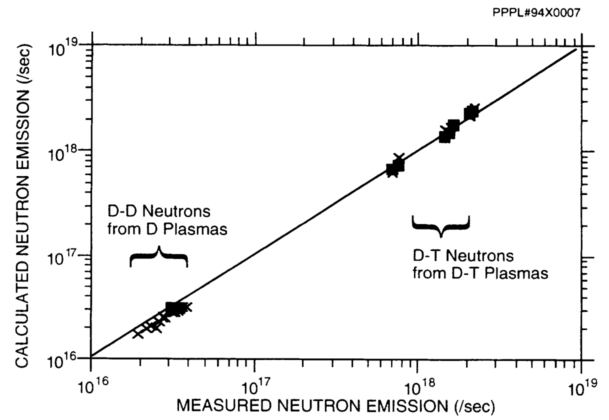

FIG. 1. The neutron emission calculated by the equilibrium code SNAP (crosses) and calculated by the time-dependent code TRANSP (solid squares) as a function of the neutron source strength measured by the TFTR fission detectors.

neutron emission. The D-T neutron rate in the 100% T beam plasma was used to assess the hydrogenic influx and transport models in SNAP and TRANSP codes and is consistent with a significant (40%) concentration of thermal D in the plasma core during pure-T injection.

The D-T neutron emission [Fig. 2(a)] reached a maximum at 3.45 s and then decreased to about 80% of the peak level by 3.68 s when a source fault caused a significant reduction in beam power. The TRANSP simulation reproduces this decrease in emission, indicating that it does not occur as a result of the anomalous loss of energetic ions but is associated with the evolution of the plasma. Similar decreases in the D-D neutron rate and, simultaneously, the plasma stored energy are often observed in deuterium supershots with high neutral beam powers. These decreases have been correlated quantitatively with the amplitudes of low mode-number ($m/n = 2/1$, 3/2, and 4/3) magnetohydrodynamics activity [14] and with secular increases in the deuterium influx from the limiters [15], both of which can occur during the heating. In the D-T discharge of Fig. 2, a growing mode with $m/n = 4/3$ was detected in the electron temperature profile starting at about 3.4 s. It is interesting to note, however, that the fractional decline in the D-T neutron rate for this plasma in the interval 3.45–3.68 s was less than that for comparable deuterium plasmas, i.e., plasmas having the same ratio of stored energy to plasma current and the same magnetic field.

The fusion alpha particles escaping from the plasma were measured with a scintillation detector [16] located near the vacuum vessel wall 90° below the midplane in the ion-gradient-B drift direction. In quiescent low-power plasmas, the relative alpha particle loss decreased by a factor of about 4 between 0.6 MA and 1.8 MA, in rough agreement with the calculated variation in the first-orbit loss to this detector (Fig. 4). The total loss of D-T alphas in the high-power D-T plasmas at 2.0 MA

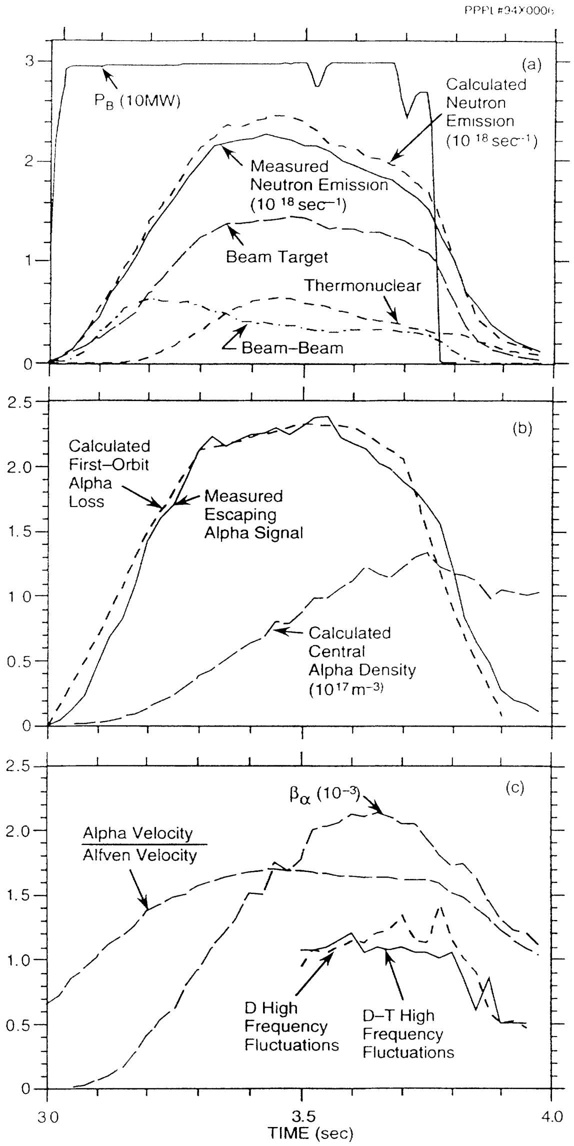

FIG. 2. Time evolution of the plasma with the highest D-T neutron emission. (a) The beam power (in units of 10 MW), the measured D-T neutron emission (in units of 10^{18} sec^{-1}) (solid line), and the TRANSP calculated value (dashed line), including the calculated contributions of beam target, beam beam, and thermonuclear reactions. (b) The measured collection rate of energetic (> 1 MeV) escaping alphas (solid line), the calculated central alpha particle denisty (in units of 10^{17} m^{-3}), and the calculated detector signal (by TRANSP) due to classical first orbit loss. (c) The TRANSP calculated central alpha pressure ($\beta_\alpha = 2\mu_0 p_\alpha / B^2$) (in units of 10^{-3}), the ratio of alpha velocity to Alfvén velocity, and the measured amplitude of the Mirnov signal at the TAE frequency range taken from several D-T and D comparison plasmas.

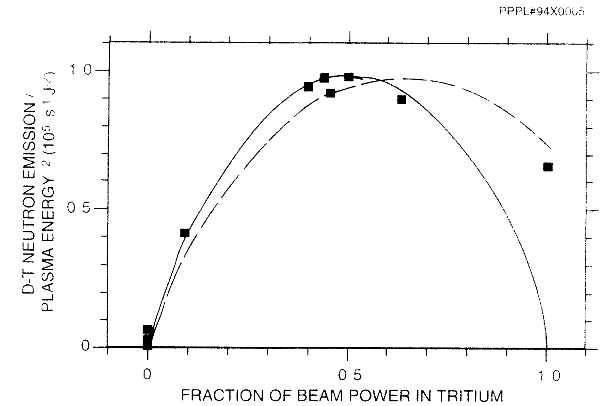

FIG. 3. D-T neutron emission at peak stored energy divided by the square of the plasma energy content plotted as a function of the fraction of the beam heating coming from T beams. The solid curve is the expected dependence if the fueling of the plasma were entirely from the beams. The dashed curve corresponds to one-half of the fueling from the beams and one-half from the walls (deuterium only). The normalization of the neutron emission to the square of the energy content was chosen on the basis of the empirical scaling of D-D neutron emission [12,13] since there have not been enough D-T data to establish its scaling.

was also roughly consistent with expectations based on the simple first-orbit loss model calibrated by the signal at 0.6 MA (where all the trapped alpha particles are lost). In particular, the alpha loss fraction did not increase significantly between the lowest and highest power D-T shots at 2.0 MA (Fig. 4) while the alpha source rate increased by more than a factor of 10. This indicates that the alpha particles were not being lost as a result of instabilities driven by the alpha particle pressure itself.

This TFTR plasma regime can be unstable to the toroidal Alfvén eigenmode (TAE) [17] in the time following the beam heating when the alpha pressure remains high [Fig. 2(c)] and the average alpha velocity reduces to the Alfvén velocity. However, the plasma fluctuation activity [18,19] in the TAE range of frequencies (250 kHz during beam heating, rising to 500 kHz after injection) were the same for D-T and D plasmas (Fig. 5). The level of broad band fluctuations measured by a microwave reflectometer [19] indicates that the upper limit of possible TAE activity is $\tilde{n}/n = 5\times10^{-5}$, compared to a total density fluctuation of about 2×10^{-2} [due mostly to the low frequencies below 40 kHz in Fig. 5(b)]. These levels are 1 to 2 orders of magnitude below the trapped-particle-driven TAE modes seen during ion cyclotron heating in TFTR or the beam driven TAE modes detected at low field and high density [20,21] by the same diagnostics in D plasmas. The behavior of the background turbulence observed during and after the beam heating is very similar in both D-T and D plasmas. There is no indication that the mode amplitude is enhanced by the presence of the alpha population during or following termination of the beam heating [Fig. 2(c)].

In conclusion, the initial D-T experiments on TFTR produced 6.2 MW of fusion power. The resulting energetic alpha population caused neither detectable anoma-

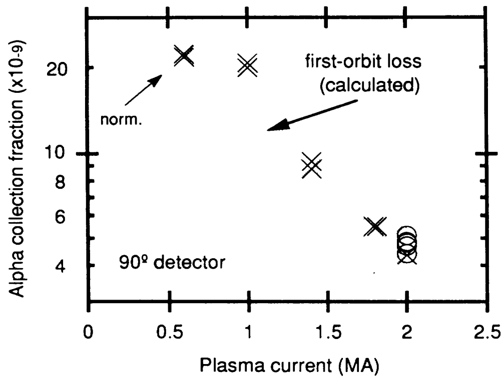

FIG. 4. The measured alpha particle loss rate to the vessel bottom per created alpha (i.e., the global neutron source strength) as a function of plasma current. The shaded region is the calculated alpha first-orbit loss for this location where the data are calibrated by the signal at 0.6 MA where all the trapped alpha particles are lost. The × points are low power, quiescent plasmas and the circles are the high power D-T plasmas.

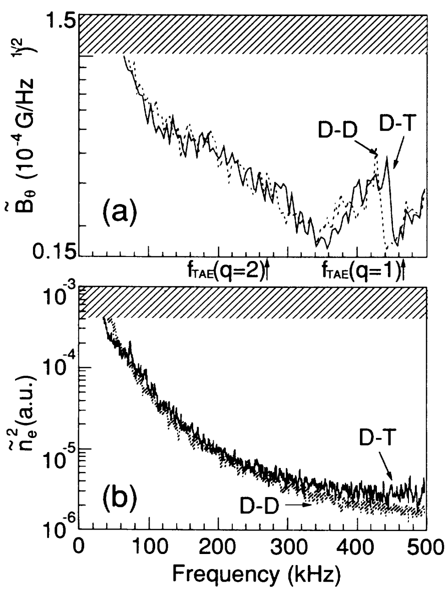

FIG. 5. High frequency fluctuation data taken immediately after the beam heating for D-T and D plasmas. The shaded region shows the approximate lower bound on the previously observed TAE mode. (a) Amplitude spectra of an outboard Mirnov coil signal showing a weak power near the expected TAE frequency. (b) Reflectometer power spectra at a major radius of 2.92 m (the plasma magnetic axis is at 2.63 m).

lous alpha particle losses nor observable instabilities. The TFTR fusion yield can be increased through increases in the T beam voltage and injected neutral beam power as well as through reductions in the hydrogen influx from the limiters, or improvement in the gross energy confinement time by lithium wall conditioning [22].

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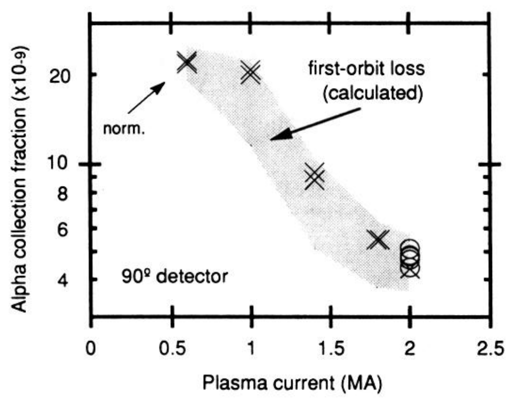

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