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High-Temperature Plasmas in the Tokamak Fusion Test Reactor

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Neutral-beam heating of Tokamak Fusion Test Reactor in the plasmas at low preinjection densities [$n_e(0) \simeq 10^{19}$ m^{-3}] was characterized by $T_e(0) = 6.5$ keV, $T_i(0) = 20$ keV, $n_e(0) = 7 \times 10^{19}$ m^{-3}, $\tau_E = 170$ msec, $\beta_\theta = 2$, and a $d(d,n)^3$He neutron emission rate of 10^{16} sec^{-1}. The ion temperature and the deuterium-fusion neutron yields were significantly higher than for previous tokamak experiments. The low initial densities were achieved by operation of the Tokamak Fusion Test Reactor with low plasma currents (≤ 1 MA) and by extensive limiter conditioning.

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One goal of the Tokamak Fusion Test Reactor (TFTR) experiment[1] is the attainment of "scientific breakeven," which occurs when the fusion power equals the power used to heat the plasma, $Q_{dt} = 1$. Recently, TFTR neutral-beam heating experiments, at low initial plasma density, have produced plasmas that project to $Q_{dt} \simeq 0.25$, or about three times better than achieved previously. This paper reports the parameters and characteristics of the TFTR plasmas in this new regime.

For the experiments reported here, the TFTR device[2] was operated with a plasma major radius of 2.45 to 2.50 m, minor radius of 0.8 to 0.83 m, plasma current of 0.6 to 1 MA, toroidal magnetic field of 4.0 to 5.2 T, and deuterium neutral-beam injection into deuterium plasmas. The neutral beams[3] supplied 0.5-sec pulses of beam power up to 15 MW at energies up to 105 keV for the full-energy component. The beams provided about equal particle flux in the full-, half-, and third-energy components.[4] Three of the beam lines were aimed cotangentially (beam current in the direction of the plasma current) and one beam line was counter tangential. Up to 5.8 MW of counter beam power has been available. These experiments were the first that applied balanced beam power to the low-density [$n_e(0) < 10^{19}$ m^{-3}] energetic ion plasmas.[5]

During the beam heating, the gross energy confinement times in the new regime (τ_E up to 170 msec) were comparable to those previously obtained with 2.2-MA beam-heated plasmas and were up to 3 times higher than predicted by L-mode scaling ($\tau_E \propto I/P_b^{1/2}$).[6] The central electron temperature (6.5 keV) is the highest obtained thus far on TFTR. The T_e profile had a broad central region (full width at half maximum of up to the minor radius) and a large outward Shafranov shift (about $\frac{1}{3}$ the minor radius). The central electron density was $\sim 7 \times 10^{19}$ m^{-3}, resulting in $n_e(0)\tau_E \sim 10^{19}$ m^{-3} sec. Both the central ion temperature ($\lesssim 20$ keV) and the total D$(d,n)^3$He fusion-neutron emission rate ($\lesssim 10^{16}$ sec^{-1}) are the highest yet produced in a tokamak.

The time evolution of a 1.0-MA, 5.2-T plasma with a particularly high central electron temperature is shown in Fig. 1. The neutral-beam power was 15 MW, of which 5.5 MW was in the counter beams. The total energy content, estimated from the diamagnetic signal and the vertical magnetic field required to maintain the equilibrium,[7] rose throughout the beam-heating pulse to about 2.2 MJ (a poloidal beta of 2.0). The increase in stored energy, dW/dt, comprised approximately 10% of the input beam power at the end of the injection period [Fig. 1(b)]. The Ohmic power was in the range of a few percent of the input beam power. The gross-energy confinement time [$W/(P_{\rm NB} + P_{\rm OH} - dW/dt)$] was 170 ± 10 msec and was approximately constant from 4.15 to 4.5 sec. The magnetic measurements can be used to indicate the pressure anisotropy. For this calculation, the plasma internal inductance was interpolated from the Ohmic values.[7] The anisotropy was high at the beginning of the beam injection while the density was low and the beam ions were important in the total energy content. By the end of the beam injection, the line-averaged density has nearly tripled and the pressure was nearly isotropic.

The peak electron temperature (Fig. 1) was about 5 keV during the initial Ohmic phase, dropped initially at

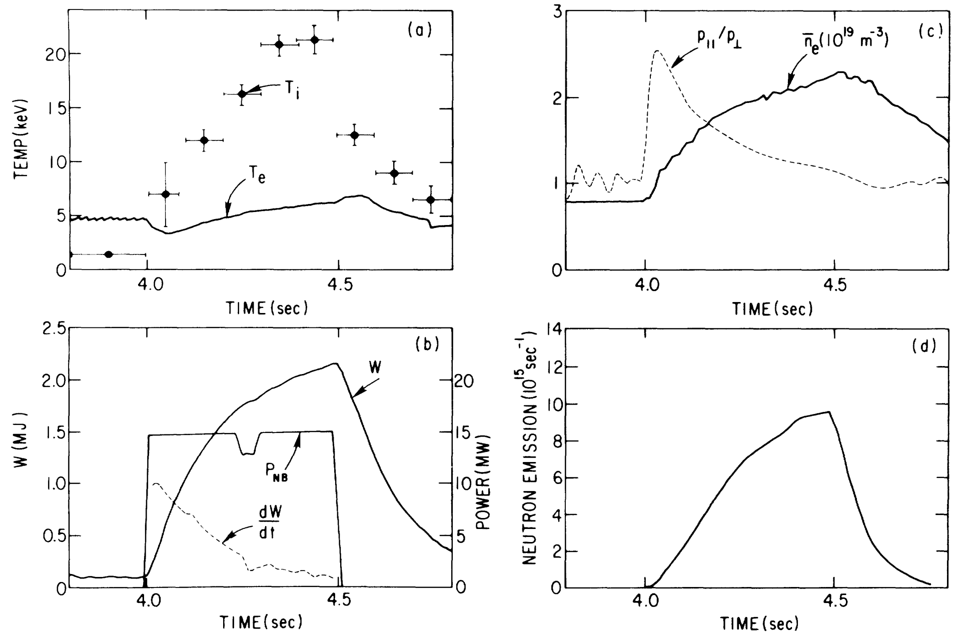

FIG. 1. Evolution of a 1.0-MA, 5.2-T TFTR plasma (No. 22984) with 15 MW of $D^0 \rightarrow D^+$ neutral-beam heating. The ratio of parallel to perpendicular pressure, $p_\parallel/p_\perp$, the total energy content, W, and the power consumed to increase the energy content, dW/dt, are derived from the diamagnetic and the vertical magnetic field signals (Ref. 7). The 50-msec reduction in beam power at 4.2 sec was a temporary fault in one of the co-beam sources.

the application of the beams, rose slowly to about 6.5 keV, and rose to about 7 keV 70 msec after the neutral beams were turned off. On Princeton Large Torus[8] the initial electron temperature drop and the thermal bloom were attributed to the heat capacity of the cold electrons deposited into the plasma by the beams. The central ion temperature was about 22 keV (Fig. 1) as determined by the Doppler broadening of the FeXXV K_α line.[9] This line was observed at a vertical chord at 2.95 m major radius. The t_i time evolution shown in Fig. 1 is affected by the shift of the plasma center into the detector line of sight. Similar ion temperatures were measured from the Doppler broadening of FeXXIV and NiXXVI lines. At present, measurements have not been made of the deuteron ion temperature. Estimates similar to those done for Princeton Large Torus indicate that the impurity ion temperature may have been about 1.5 keV higher than that of the deuterons as a result of direct beam heating of the impurity species. During beam heating, Z_{eff} was about 3 as determined by the soft x-ray emission, and the dominant impurity was carbon.[10] The $d(d,n)^3$He neutron emission rose continuously to about 9.5×10^{15} sec^{-1} peak emission level. This yield has been calculated from codes like those in Mirin and Jassby[11] to result from about 50% beam-target, 25% beam-beam, and 25% thermonuclear reactions.

The new plasma regime is characterized by substantial changes in the temperature and density profiles, and by large outward shifts (Fig. 2) caused by the high poloidal beta. The time evolution of T_e, from electron cyclotron-emission measurements, indicates that the outward shift and broad electron-temperature profile developed early in the beam-heating phase and that the broad central region had a rising temperature throughout the beam duration. The peak electron temperature was 6.5 keV for the plasma in Figs. 1 and 2, as measured by either the Thomason scattering (TVTS)[12] or electron cyclotron-emission heterodyne-radiometer[13] diagnostics and was 7.5 keV as measured by the electron cyclotron-emission Michelson interferometer.[14] The electron-density profile was strongly peaked as measured by both the TVTS system and the nine-channel infrared interferometer (MIRI). The MIRI measurement often indicated a higher density at the inside plasma edge near the inner-wall limiter, as if there were a density concentration above or below the horizontal midplane (and therefore out of the Thomas-scattering laser sight line). The difference between the central densities as determined by the two diagnostics is thought to be due to the Abel inversion of a density profile as narrow as the MIRI chordal spacing. The TVTS density is believed to be more accurate in the central region. The time evolution of the inverted interferometer data indicates that the central density was rising at about a constant rate throughout the 0.5-sec beam pulse, apparently fueled by the beam ions. More peaked density profiles were characteristic of plasmas with better confinement times in this regime.[15]

Limiter conditioning and the co-/counter-beam bal-

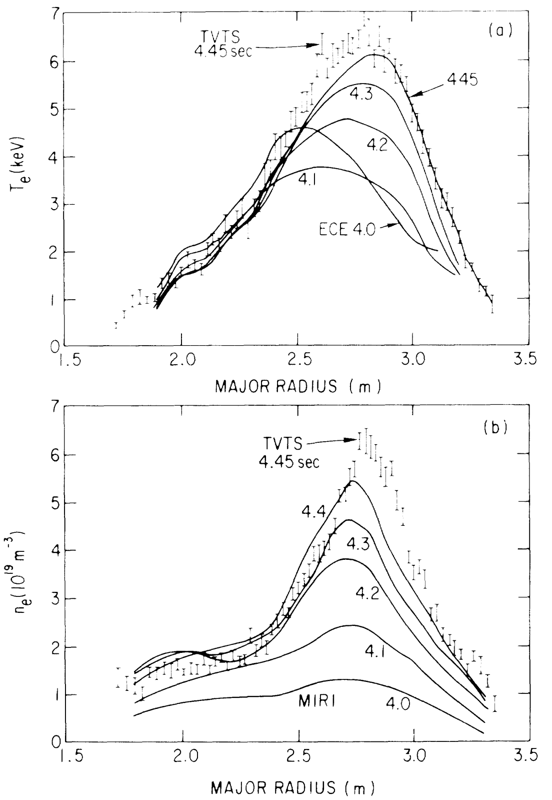

FIG. 2. Profiles for the same plasma as in Fig. 1 where the Thomson scattering measurements of $T_e(r)$ and $n_e(r)$ at 4.45 sec are presented by the error bars. (a) The curves are electron-cyclotron emission measurements of $T_e(r)$. (b) The curves are Abel-inverted interferometer measurements of $n_e(r)$.

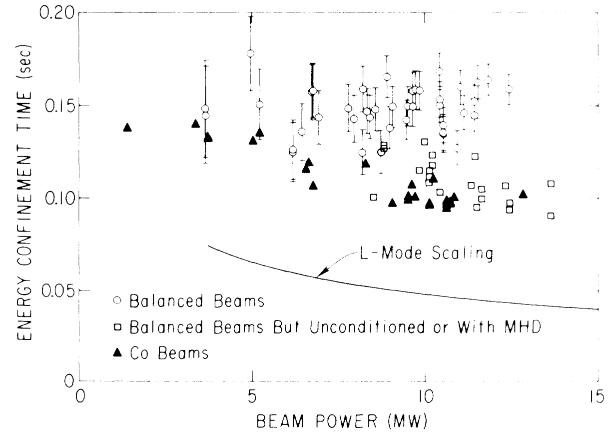

FIG. 3. Energy confinement time as a function of injected neutral-beam power for 0.8-MA, 4.8-T plasmas. The error bars represent the uncertainties in the magnetic measurements of the stored energy. The data points without error bars have similar uncertainties. The unconditioned data points were identified as plasmas obtained just prior to conditioning sequences and the data points with MHD activity were identified by the magnitude of the Mirnov oscillation.

ance are important parameters for optimization of the new plasma regime. Often, 1.4-MA helium Ohmic plasmas were run for limiter conditioning purposes prior to these TFTR experiments. The exact effect of the limiter conditioning upon the plasma behavior is difficult to determine, although deuterium spectroscopic measurements do indicate that deuterium recycling was reduced after the helium Ohmic plasmas. Operationally, the limiter conditioning meant that lower plasma densities could be obtained at a fixed plasma current. The new plasma regime was first obtained with the TFTR movable limiter which is a top-bottom pair of graphite blades at one toroidal location. At power levels of 10–12 MW, the heating of the movable limiter was high, and so the TFTR inner-wall limiter (toroidally symmetric graphite inner wall) was conditioned[16] and the new regime was also obtained with it. Apparently, the specific limiter configuration and location of particle recycling were not of prime importance for obtaining better plasmas.

There was some variability in the plasma behavior (e.g., 50% variation in the energy confinement times occurred) which correlated with the influence of the limiter conditioning, the co-/counter-beam balance, and/or the amount of MHD activity, where low levels correlated with better confinement. Large MHD fluctuations have been observed in plasmas where the confinement degraded in time through the beam heating. The fluctuations had coherent low-m-number modes ($\frac{3}{2}$ or $\frac{2}{1}$) with frequencies (10–60 kHz) consistent with the measured toroidal rotation velocities.[17] Plasmas with the largest confinement times did not have coherent MHD modes or sawtooth MHD oscillations during the beam heating. For example, the plasma in Fig. 1 had 20-msec period sawtooth activity before the beam heating, which disappeared entirely for the 0.5-sec beam duration and reappeared about 0.25 sec after the beams were turned off.

The correlation of the gross energy confinement time with limiter conditioning, the MHD activity, and the co-/counter-beam injection balance can be seen in Fig. 3, where the best confinement times were achieved with more nearly balanced injection. Apparently a continuous range of confinement times occurred, in contrast to the discrete change in confinement that characterized the asymmetric divertor experiment H-mode transition.[18] The best confinement times for nearly balanced injection were independent of beam power, whereas the best confinement times for only coinjection exhibited a degradation with beam power similar to that predicted by L-mode scaling while still exceeding the L mode by a factor of 2. The scaling of the confinement with plasma current has not yet been established although no strong variation exists between 0.8 and 1 MA. The operational range was limited at low plasma current (at high beam power) by disruptions and at high current by reduced confinement.[19,20]

In summary, a new plasma regime has been observed in TFTR low-density beam-heated plasmas. It occurred with nearly balanced beam injection, at low plasma currents, after conditioning plasmas had removed deuterium from the limiter. These plasmas had high temperatures and high deuterium-fusion yields. Assuming that the same plasma-target densities could be achieved with tritium as were achieved with deuterium, the beam-target $d(t,n)\alpha$ fusion power would be 3 to 4 MW (a fusion multiplication $Q_{dt} \sim 0.25$). The present results extrapolate to $Q_{dt} \gtrsim 0.5$ for the case of the forthcoming 120-kV beams. Further improvement is possible if the plasma impurity content can be significantly reduced.

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[1]D. J. Grove and D. M. Meade, Nucl. Fusion **25**, 1167 (1985).

[2]K. M. Young *et al.*, Plasma Phys. Controlled Fusion **26**, 11 (1984).

[3]M. D. Williams, in Proceedings of the Eleventh Symposium on Fusion Engineering, Austin, Texas, 1985 (to be published).

[4]R. A. Langley *et al.*, J. Vac. Sci. Technol. A **4**, 1087 (1986).

[5]M. Murakami *et al.*, Plasma Phys. Controlled Fusion **28**, 17 (1986).

[6]R. J. Goldston, Plasma Phys. Controlled Fusion **26**, 87 (1984).

[7]M. G. Bell *et al.*, Plasma Phys. Controlled Fusion **28**, 1329 (1986).

[8]H. P. Eubank *et al.*, *in Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nucleon Fusion Research, Innsbruck, Austria, 1978* (IAEA, Vienna, 1979), Vol. I, p. 167.

[9]M. Bitter *et al.*, Rev. Sci. Instrum. **57**, 2145 (1986).

[10]K. W. Hill *et al.*, in Proceedings of the Eleventh International Conference on Plasma Physics and Controlled Fusion Research, Kyoto, Japan, 1986 (to be published), paper No. IAEA-CN-47/A-IV-2.

[11]A. A. Mirin and D. L. Jassby, IEEE Trans. Plasma Sci. **8**, 503 (1980).

[12]D. W. Johnson *et al.*, Rev. Sci. Instrum. **56**, 1015 (1986).

[13]G. Taylor *et al.*, Rev. Sci. Instrum. **55**, 1739 (1984).

[14]F. J. Stauffer *et al.*, Rev. Sci. Instrum. **56**, 925 (1985).

[15]H. P. Furth, Plasma Phys. **28**, 1305 (1986).

[16]H. F. Dylla *et al.*, to be published.

[17]K. McGuire *et al.*, in Ref. 10, paper No. IAEA-CN-47/A-VIII-4.

[18]F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).

[19]R. J. Goldston *et al.*, in Ref. 10, paper No. IAEA-CN-47/A-II-1.

[20]R. J. Hawryluk *et al.*, in Ref. 10, paper No. IAEA-CN-47/A-I-3.