OVERVIEW OF RECENT TFTR RESULTS*

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Abstract

OVERVIEW OF RECENT TFTR RESULTS.

A summary of TFTR experiments during the last two years is presented. These experiments have prepared regimes for D–T experiments in 1993 and for next-step advanced tokamak reactors. Injection of lithium pellets has been found to reduce limiter carbon recycling, which extended supershot performance. Peaking of the current profile has been used to produce enhanced stability plasmas with β_N up to ~ 5, and enhanced confinement with τ_E up to ~ $3.7\tau_E^{ITER\text{-}P}$. Long-pulse studies of current profile relaxation in high-β_P plasmas show that active current profile control is required to maintain stability. Toroidal Alfvén eigenmodes have been studied using neutral beam injection and found to be in reasonable agreement with present theoretical predictions. Measurements in L-mode plasmas indicate that the density fluctuation spectrum peaks at $k_\theta \rho_i$ ~ 0.14 and that the spectrum is anisotropic. Analysis of controlled gyro-radius scans indicates that local transport has a Bohm-like scaling.

1. Introduction

In the last two years, a wide range of experiments have been undertaken in TFTR both to optimize the projected performance and utility of the plasmas during the planned D-T experiments, and to understand plasma transport and stability in order to improve the tokamak concept for the next generation of reactors. These experiments have utilized both the neutral beam injection (NBI) and ion cyclotron heating (ICRF) systems at power levels up to 33 MW and 8 MW, respectively, in separate discharges and up to 27 MW and 5 MW, respectively, simultaneously. The plasmas have spanned a range of operating modes, some of which, in addition to their potential for supporting the studies of alpha-particle physics, are of relevance to the future development of advanced tokamaks. Figure 1 shows the regimes discussed in this paper: L-mode, supershot, and high-β_P, in terms of their normalized-β, $\beta_N = \beta_T a B_T / I_p$ and the simultaneous enhancement of the energy confinement time over L-mode scaling.

In addition, considerable time and resources from the TFTR program have been devoted to preparation for the D-T experiments planned for 1993/4. This has included installing diagnostics for measuring the D-T α-particles, preparing the tritium handling systems, and meeting rigorous safety and environmental-impact standards.

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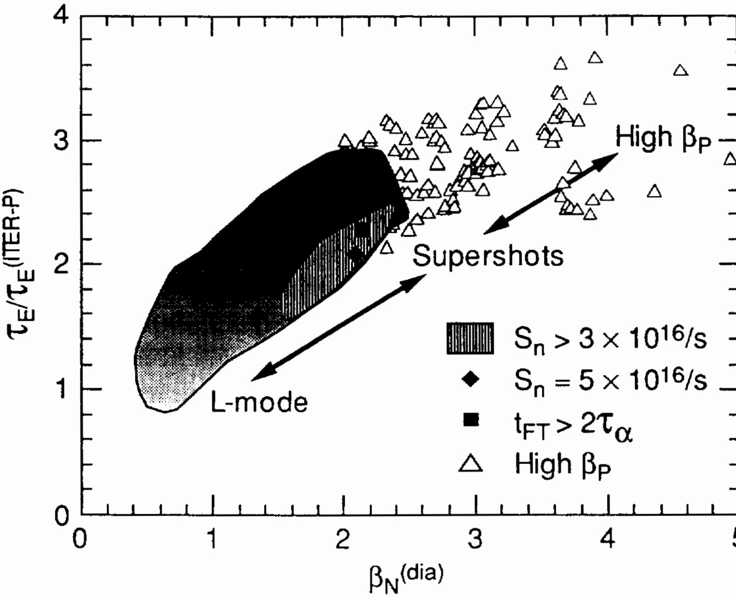

FIG. 1. TFTR regimes of operation, shown in terms of confinement enhancement over ITER-P L-mode scaling, versus $\beta_N \equiv \beta/(I_P/aB_T)$, showing L-mode, supershot, and high-β_P regions of operation.

2. Present Status of TFTR and its Plasmas

"Supershots" [1,2] continue to be the most promising regime for studying the physics of fusion alpha-particles in TFTR D-T plasmas. Supershots are produced by high-power neutral beam injection into plasmas with low edge recycling. In these conditions, the strong central heating and fueling by the neutral beams results in very high central temperatures ($T_e(0) \leq 12$ keV, $T_i(0) \leq 35$ keV), high central density ($n_e(0) \leq 10^{20}$ m^{-3}), a highly peaked density profile, and consequently a high rate of fusion reactions. Both the thermal and total energy confinement times are enhanced in this regime over the predictions of L-mode scalings, with the strongest improvement occurring in ion thermal transport [3]. In this regime, the bootstrap current can be as large as 2/3 of the total plasma current and is peaked near the plasma center as a result of the peaked density profile. Such a bootstrap current profile is of relevance to reactor designs which depend on long pulse stable operation with high bootstrap fraction. Although, in TFTR, the supershot regime projects to the highest D-T fusion power yield [4] and alpha-particle parameters,

$n_\alpha(0)$ and $\beta_\alpha(0)$, limitations on its performance have been encountered, due to limiter recycling and MHD stability at high plasma pressure. Experiments in TFTR have been developed to overcome these limits and to test specific explanations for the reduction of transport which occurs in the regime.

The power threshold for carbon blooms [5] has increased to the point where blooms are rarely observed with NB heating up to 32 MW for 1 sec. Limiter surface temperature measurements indicate a peak power flux of 5 MW m^{-2} to the limiter in these cases, with an average power flux of 0.4 MW m^{-2}. An additional six sectors of carbon-fiber-composite (CFC) tiles have been installed on the outboard side of the plasma, which has raised the power handling capability for full-sized RF-heated plasmas to more than 30MW. Measurements of the surface alignment of the bumper limiter and the heat loads to the limiter during disruptions are discussed in more detail by Janos *et al* [6].

Injection of a lithium pellet into the ohmic phase of a supershot, about 1 sec before the start of the NBI heating, suppressed the limiter carbon recycling. Previously, such a reduction was found to correlate with improved supershot performance [7]. The Li pellet injection consistently improved the fusion rate during the heating by 10 – 15 % compared to neighboring shots without a lithium pellet [8]. The beneficial effect of the lithium pellet in one shot decayed over the next 3 – 4 discharges run without pellets. A similar beneficial effect was observed in a limited test with boron pellets. Injection of lithium pellets into standard helium conditioning discharges brought about a more rapid reduction of the carbon influx and plasma density. Lithium pellet conditioning was used in the TFTR discharge producing the highest instantaneous D-D fusion rate, 10^{17} reactions/sec with an injected power of 33 MW ($I_P = 1.9$ MA, $B_T = 5.1$ T, $R = 2.45$ m, $a = 0.8$ m, $n_e(0) = 9.0 \times 10^{19}$ m^{-3}, $T_e(0) = 12$ keV, and $T_i(0) = 26$ keV). A reaction rate of 6×10^{16} sec^{-1} has also been maintained for 0.6 sec, twice the energy loss time for a fusion α-particle, in a supershot with 25 MW NBI.

Other regimes of importance for the D-T experiments and future reactors continue to be investigated. The high-β_P regime, which has improved stability at high plasma pressure, is discussed in the next section. The possibility of enhancing supershot performance with ICRF through central electron heating and possible stabilization of deleterious MHD modes is being pursued, and is discussed by Wilson *et al* [9]. In addition, the use of deuterium pellet fueling in combination with ICRF to reheat the densified core will be tested in the present run. A three-barrel pellet injector (injection speed ~ 1.5 km/sec) with an additional high-speed barrel (~ 2.5 km/sec) for deep fueling has been developed by Oak Ridge National Laboratory and installed for these experiments.

3. Stability Studies

MHD-instabilities with low mode-number, typically $m/n = 3/2$ and $2/1$, often occur coincident with a decay of supershot performance at or below $\beta_N \sim 2.2$. The proportion of plasmas which collapse increases as this β_N limit is approached, making stable operation near the limit unreliable. In addition $m/n = 1/1$ modes are often observed for $I_P > 1$ MA, but do not appear to affect performance. Enhanced losses of D-D fusion products (protons and tritons), detected during MHD activity by a poloidal array of escaping-fast-ion detectors, are discussed by Zweben *et al* [10]. In some cases, the fusion product losses are modulated in synchronism with the externally measured magnetic perturbations from the instabilities. In TFTR, as much as $\sim$ 30% of the D-D fusion products have been ejected by MHD activity. This type of MHD activity should be avoided during the coming D-T collective α-particle experiments, since it would seriously deplete the confined α population. Scaling similar MHD activity [10] to ITER indicates that MHD-induced losses of 1 - 3% of the α population could be expected, which may locally enhance power loading on the first-wall.

The MHD stability boundary has been significantly increased [11] by using a rapid decrease in I_P before neutral-beam injection to peak the current profile. This technique has produced high β_P plasmas with $\beta_N \sim 5$, simultaneous highly enhanced confinement $\tau_E \sim 3.7\,\tau_E^{ITER-P}$, and high reactivity [12]. In experiments studying the resistive relaxation of the peaked current profile using 4-seconds of neutral-beam heating, the current profile broadened and the plasma either collapsed or disrupted. Initial multi-point Motional Stark Effect (MSE) [13] measurements show $q(0)$ rising strongly in these plasmas. This is in agreement with TRANSP analysis based upon resistive diffusion which shows current profile broadening due to the broad bootstrap current profile driven by the broad density profile in these plasmas. These experiments show the importance of active current profile control for stable operation in future long-pulse tokamak experiments.

The multi-point MSE measurements of the q profile are generally in good agreement with measurements of the $q = 1$ location from the sawtooth inversion radius and with neoclassical calculations of poloidal-flux diffusion by TRANSP[14], including beam and bootstrap currents. During steady state sawtoothing discharges, the central value of q is measured as $0.6 - 0.7$ (see Fig. 2) as observed in other experiments [15,16]. The change of $q(0)$ at the sawtooth crash is $0.05 - 0.1$, which is less than predicted for a full reconnection of the current. Also shown in Fig. 2 are changes in the central q due to the beam-driven current, resulting in $q(0) > 1$ and sawtooth stabilization with co-only injection. The balanced injection supershot shown also does not

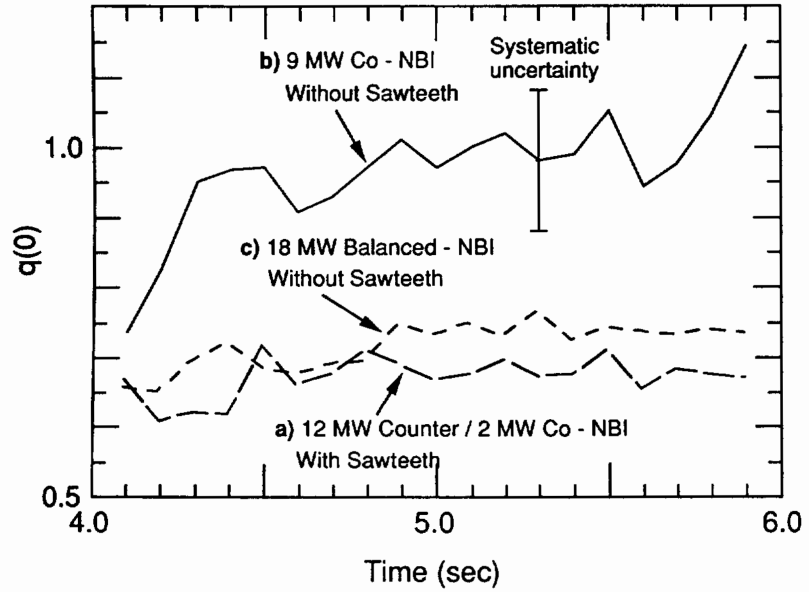

FIG. 2. MSE measurement of q(0) for plasmas with (a) I_P = 1.2 MA, P_B = 12 MW, P_{co}/P_B = 0.2, which is sawtoothing; (b) I_P = 1.2 MA, P_B = 9 MW co-injection only, which does not sawtooth during NBI; and (c) I_P = 1.3 MA, P_B = 18 MW balanced injection, which does not sawtooth during NBI.

exhibit sawteeth, but the measured $q(0)$ is ~ 0.7 indicating that a different stabilization mechanism is present.

In a number of high β_N supershot and I_P ramp-down plasmas, medium-n ballooning modes have been observed. In these plasmas, the pressure profile is calculated to be near the first stability boundary [17]. These instabilities appear just prior to the collapse of the plasma stored energy. Their toroidal mode-number n is in the range of 4 to 10, with similar poloidal mode numbers, much higher than the usual kink or tearing modes. The mode amplitude strongly peaks on the low-field side, and has a fast growth time of 10 - 20 μsec in agreement with the calculated ballooning mode growth rate for these plasmas. Stability calculations using the PEST code indicate that these plasmas are unstable to infernal-type ballooning modes [18] at the low central shear calculated by TRANSP. The mode is observed on a high time-resolution (2 μsec) ECE grating polychromator and vertical and horizontal x-ray cameras. Reconstruction of the mode indicates that it is a poloidally and toroidally localized mode packet covering approximately 40% of the flux surface. When the packet is observed at large major radius, its amplitude is 3 - 4 times larger than when it is at small major radius.

In addition to studying the stability of available plasma regimes, there has been an active effort to investigate instabilities predicted to occur with substantial α-particle populations during the TFTR D-T phase and in future reactors. Toroidal Alfvén eigenmodes (TAE) are predicted to be easily excited by super-Alfvénic ion populations. These modes were first excited and identified in TFTR [19] and DIII-D [20] two years ago using neutral beam injection into plasmas at low magnetic field. In the past two years careful mode identification was carried out by measuring the poloidal spectra with beam emission spectroscopy (BES) [21], the fast-ions ejected by the mode have been measured, and the studies have been extended to higher magnetic fields and plasma parameters.

The experimental TAE structure for a $I_P = 420$ kA, $B_T = 1.2$ T, $\overline{n}_e = 2.1 \times 10^{19}$ m^{-3} plasma is depicted in Fig. 3. The experimental spectra are in reasonable agreement with poloidal spectra calculated by the NOVA-K code [22] based on another discharge with the same nominal parameters. The simulated spectra follow the relationship $m + 1/2 \sim nq(r)$, i.e., for a given n, the dominant value of m is determined by the local value of q. Stability calculations have been performed for $n \leq 3$ and predict that $n = 2$ is the most unstable. The Mirnov coil array observes $n = 2$ as the dominant mode in this plasma.

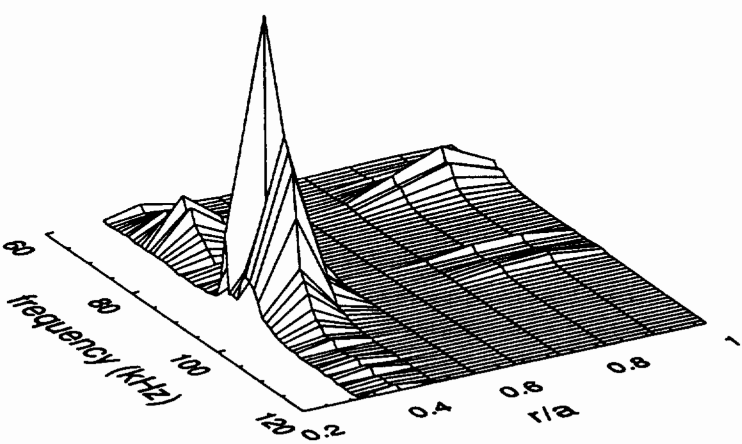

FIG. 3. BES measurement of the TAE frequency spectrum (normalized by the density gradient) as a function of radial position for a neutral beam heated plasma with $B_T = 1.2$ *T,* $I_P = 420$ *kA,* $\overline{n}_e = 2.1 \times 10^{19}$ m^{-3}*. At 72 kHz, the mode has* n = 2 *with* m = 4 *dominant at* r/a ~ 0.4*, and* m = 7 – 8 *dominant at* r/a ~ 0.9*. At 95 kHz,* m = 8 *is dominant.*

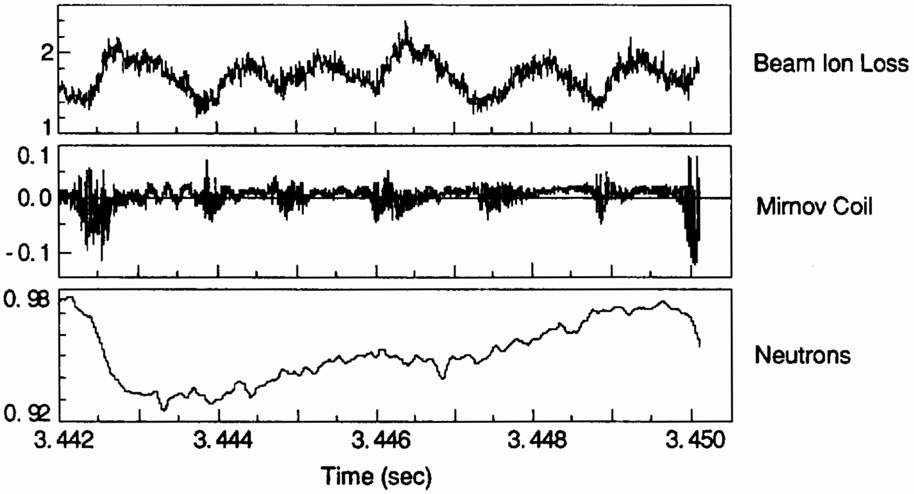

FIG. 4. Beam-ion ejection during TAE activity, as indicated by direct measurement by energy and pitch resolving lost-ion edge detectors and transient decrease in neutron emission. External magnetic measurements of the TAE activity are also shown. The edge lost-ion detector measurements indicate that full energy neutral beam ions are lost at their injection pitch-angle.

TAE activity appears in bursts whose repetition rate increases with beam power. Direct measurements of beam ion loss during TAE activity were made with the edge fast-ion detectors. Losses of full-energy ions were observed [23] that were synchronous with the TAE bursts and drops in D-D neutron emission, as shown in Fig. 4. The fast ion loss rate approximately doubles during the TAE activity. The energy and pitch angle of the loss ions do not change significantly when TAE is excited. In a typical TAE burst, approximately 6-8% of energetic ions are ejected from the plasma, accounting for about one-half of the neutral beam heating power. The instability effectively clamps the beam-β near the instability threshold [24]. The loss mechanism is expected to be closely related to that operative in low frequency MHD activity [10].

In these low field neutral-beam heated experiments, the electron temperature is low ($T_e \sim 1.5$ keV) and electron collisional damping is calculated to be dominant. The theoretical instability threshold, including electron and ion Landau damping, electron collisional damping and finite orbit-width effects [25], is a factor of two above the empirical value; this is within the experimental and theoretical uncertainty. Continuum damping can also be important depending on the density and the safety factor profiles and the mode number. By rapidly increasing I_P during neutral beam heating, which should reduce the continuum damping, TAE have been excited in plasmas with $B_T = 1.5\ T$

and $I_P = 630$ kA. Similar plasmas without the rapid I_P increase were stable to TAE. Quantitative analysis of the expected change in the TAE threshold is underway. TAE activity has also been excited at $B_T = 1.5$ T using pellet injection to raise the central plasma density to $n_e(0) \sim 6 \times 10^{19}$ m^{-3}.

ICRF minority ion tails with average energy > 500 keV are produced in TFTR. These fast ions are trapped particles and are predicted to excite TAE via a drift resonance with the mode [26]. This has been recently observed at $B_T = 3.4$ T with hydrogen minority heating, and is presented in the paper by Wilson *et al* [9].

The theoretical calculations of the TAE threshold indicate that α-particle driven TAE should be stable during the standard TFTR supershot D-T plasmas [27]. However, α-driven TAE should be observed as the density falls after neutral-beam injection terminates, and in high-T_e low density hot-ion plasmas.

4. Transport Studies

TFTR transport experiments over the past two years have concentrated on investigating the local parametric dependence of anomalous transport, and on measuring the structure of the turbulence that is suspected of causing it. The goal of this effort is to improve our ability to project plasma performance to future reactors, and to learn how to manipulate transport to improve the tokamak concept.

The new beam-emission spectroscopy (BES) diagnostic provides measurements of long wavelength ($k_\perp < 2$ cm^{-1}) density fluctuations with a spatial resolution of ~ 2 cm [28,29]. These measurements indicate that the relative density fluctuation level in the interior of L-mode plasmas is inversely correlated with the global τ_E. Large amplitude edge fluctuations (in the outermost ~ 5 cm) are also observed, but do not vary with confinement time [30]. The measured poloidal and radial correlation function, S, indicate that the fluctuation spectrum is anisotropic, with $S(k_\theta)$ peaking near $k_\theta = 1$ cm^{-1} and $S(k_r)$ peaking at zero [31,32]. Microwave scattering measures $S(k_\perp) \propto k_\perp^{-3}$ for $2 < k_\perp < 10$ cm^{-1}. Together, these measurements indicate that the fluctuation power is dominated by modes with $k_\theta \rho_i \sim 0.14$. Reflectometry in low density ohmic plasmas measured a radial coherence length of ~ 2 cm, also indicating the dominance of long wavelength fluctuations. A simple random-walk estimate of the local diffusivity based upon the BES measurements of the correlation length and the correlation time is in rough agreement with power balance calculations of the thermal diffusivity in L-mode plasmas.

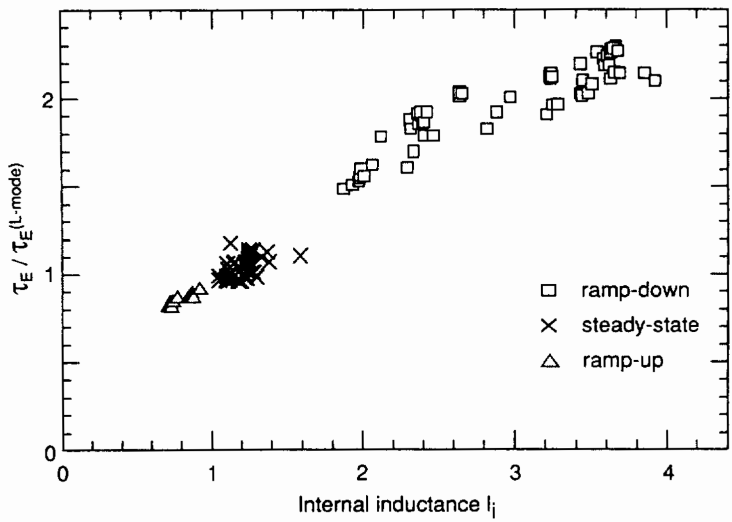

FIG. 5. Ratio of the measured τ_E (from the diamagnetic loop) to the L-mode scaling prediction versus ℓ_i for I_p = 1 MA and 2 MA plasmas with $\bar{n}_e$ = (3.4 – 8.1) × 10^{19} m^{-3} and P_B = 6 – 13 MW, (×) in steady state, (□) following a rapid decrease in I_p, and (△) following a rapid increase in I_p.

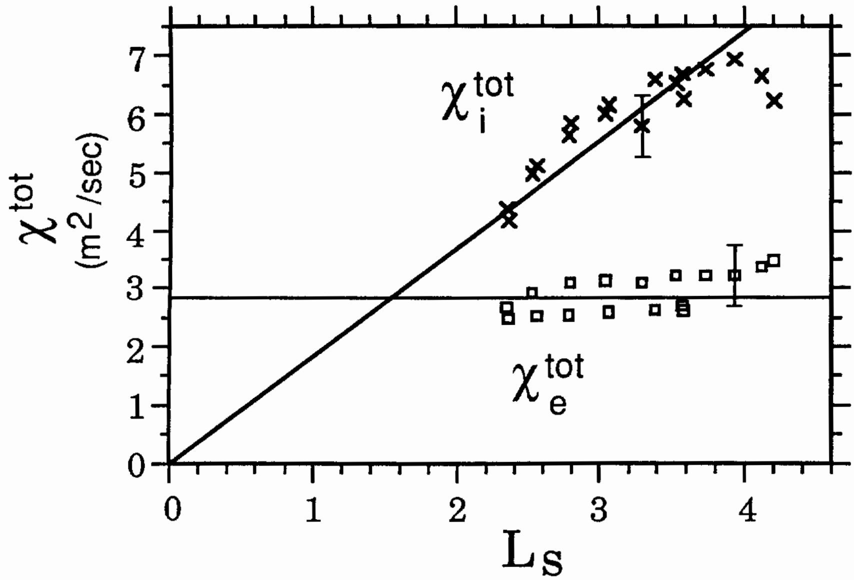

FIG. 6. Local dependence of χ_i^{tot} and χ_e^{tot} on L_s in an L-mode plasma, with $\bar{n}_e$ = 3.5 × 10^{19} m^{-3}, P_{inj} = 12 MW, at r/a = 0.75. I_p is decreased from 2 to 1 MA at 2 MA/sec during neutral beam heating to produce the shear variation. The error bars represent the uncertainty in the relative variation of χ_i^{tot} and χ_e^{tot} during the variation of L_s.

A series of experiments has been performed scanning a single non-dimensional plasma parameter in neutral-beam heated L-mode plasmas, while attempting to hold all others fixed [33,34]. The aim is to determine the fundamental parametric dependence of the thermal transport to allow more accurate projection to future reactors. Two separate scans of normalized gyroradius $\rho_* = \rho_s/a$ have been performed, at high and low density, while keeping β, collisionality ν_*, q_a, and the density and temperature profile shapes constant. In these plasmas, the global energy confinement was consistent with ITER-P L-mode scaling. In both scans, the local thermal transport was found to be consistent with a Bohm-like scaling, $\chi_B \propto \rho_s$, instead of a gyro-reduced Bohm scaling $\chi_{gB} \propto \rho_* \rho_s$. Gyro-reduced Bohm scaling is predicted by theories of fine-scale turbulence. Bohm scaling implies that the turbulence scale length varies as plasma size, implying that long wavelength fluctuations are important, as observed in the fluctuation measurements. When projecting present plasma performance to ITER, the values of ρ_* are expected to drop by a factor of $3-5$. This implies that gyro-reduced Bohm extrapolations of τ_E will be $3-5$ times higher than Bohm-like extrapolations. These experiments indicate that the Bohm-like extrapolations should be used.

The previous studies of the effects of the current profile on energy confinement [35] using dynamic I_P-ramping during neutral-beam heating, have been extended to higher confinement enhancement ($\tau_E \sim 2.3$ times L-mode scaling) and higher current profile peaking (ℓ_i up to 4) by faster ramping of I_P (Fig. 5). The fastest I_P-ramp rate used was -3.3 MA/sec. The global confinement during the relaxation of the current profile is found to be roughly described as a linear dependence of τ_E on the internal inductance ℓ_i: with $\tau_E/\tau_E^{L-mode} \sim 0.4 + \ell_i/2$. However, while I_P is changing during these experiments, ℓ_i can be forced to even higher values without an additional increase in confinement. Thus, ℓ_i does not appear to be the fundamental parameter characterizing the effect of the current profile on transport.

The local electron transport and density fluctuations (from microwave scattering and beam-emission spectroscopy, BES) are observed to be insensitive to the local q, $j_\parallel$, magnetic shear, or related quantities, for $0.5 < r/a < 0.9$. In plasmas with $\bar{n}_e \sim 3.5 \times 10^{19}$ m^{-3}, the ion and electron transport channels are not tightly coupled. In these cases, during I_P-ramp-down experiments (I_P decreasing) the ion temperature *increases* and then decays, with the peak T_i achieved somewhat after the end of the ramp. The increase in T_i is larger for faster ramp-rates, and is $\sim 25\%$ for the fastest cases. Power balance analysis of the local ion thermal transport indicates that χ_i^{tot} decreases with increased shear, with a rough parametric dependence of $\chi_i^{tot} \propto L_s$ as shown in Fig. 6, where χ_i^{tot} is defined without subtracting a convective term. As shown, no such dependence is observed in the electron transport. These observations have been found to be inconsistent in detail with many transport models which have a strong dependence on q, including resistive ballooning [36], critical temperature gradient models [37], and neoclassical-like models [38]. The dependence of χ_i^{tot} on L_s is as predicted in many theories of ion-temperature-gradient modes [39,40] but not as predicted for trapped ion modes. However, the different q and shear scaling of the ion and electron transport is in strong contrast to past observations in steady state of similar magnitudes and profile shapes for χ_i and χ_e. This difference in the scaling of the ion and electron transport indicates that somewhat different mechanisms may be operating in the two channels.

The BES measurements show that the amplitude of the large density fluctuations at the edge (outer 5 cm) of the plasma changes as $1/I_P$ during the ramp. However, this edge behaviour is not correlated with the changes in the plasma transport or fluctuations in the plasma interior. As previously observed, these fluctuations apparently do not influence the interior plasma transport.

5. Summary

In addition to preparing for the D-T experiments, TFTR has explored a number of regimes and investigated plasma stability and transport in order to improve the tokamak concept for future reactors. Peaking of the current profile improves both the beta-limit and energy confinement at a given I_P, raising the possibility of reduced I_P advanced reactors. However, long-pulse operation with broad density profiles at high-β_P and high-bootstrap fraction requires active current profile control to maintain stability. Toroidal Alfvén eigenmode activity has been excited by non-thermal ion tails generated by neutral-beam injection and from ICRF minority heating. The experimental observations are in reasonable agreement with theoretical predictions. These instabilities will be studied with α-particles during the TFTR D-T experiments.

In L-mode plasmas, BES measurements indicate that the fluctuation spectrum is anisotropic, and that relatively long-wavelength turbulence dominates the spectrum. The normalized gyro-radius scans indicate that local transport in L-mode plasmas has a Bohm-like scaling over a wide range of parameters, also implying that long-wavelengths are important. This study indicates that Bohm-like, not gyro-reduced Bohm, scalings should be used when extrapolating to future experiments. During the next year, TFTR will undergo the final preparations for the D-T experiments, which will commence in 1993.

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REFERENCES

[1] STRACHAN, J. D. et al., Phys. Rev. Lett. **58** (1987) 1004.
[2] BELL, M. G. et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1988*, volume 1, p. 27, IAEA, Vienna, 1989.
[3] ZARNSTORFF, M. C. et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1988*, volume 1, p. 183, IAEA, Vienna, 1989.
[4] BUDNY, R. et al., Nucl. Fusion **32** (1992) 429.
[5] ULRICKSON, M., the Jet team, and the TFTR team, J. Nucl. Mater. **176-177** (1990) 44.
[6] JANOS, A. et al., paper A-7-15, this conference.
[7] STRACHAN, J. D., BELL, M. G., JANOS, A., et al., in *Proc. 9th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Monterey*, J. Nucl. Materials, to appear, 1992.
[8] SNIPES, J. A., TERRY, J. L., MARMAR, E. S., et al., in *Proc. 18th European Conf. on Contr. Fus. and Pl. Heating*, volume 3, p. 141, EPS, 1991.
[9] WILSON, J. R. et al., paper E-2-2, this conference.
[10] ZWEBEN, S. J. et al., paper A-6-3, this conference.
[11] NAVRATIL, G. A. et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1990*, volume 1, p. 209, IAEA, Vienna, 1991.
[12] MAUEL, M. E. et al., paper A-3-4, this conference.
[13] LEVINTON, F. M., Rev. Sci. Instrum. **61** (1990) 2914.
[14] ZARNSTORFF, M. C., MCGUIRE, K., BELL, M. G., GREK, B., JOHNSON, D., et al., Phys. Fluids B **2** (1990) 1852.
[15] OSBORNE, T. H., DEXTER, R. N., and PRAGER, S. C., Phys. Rev. Lett. **49** (1982) 734.
[16] SOLTWISCH, H., Rev. Sci. Instrum. **59** (1988) 1599.
[17] NAGAYAMA, Y. et al., Phys. Rev. Lett. **69** (1992) 2376.
[18] MANICKAM, J., POMPHREY, N., and TODD, A. M. M., Nucl. Fusion **27** (1987) 1461.
[19] WONG, K. et al., Phys. Rev. Lett. **66** (1991) 1874.
[20] HEIDBRINK, W. W. et al., Nucl. Fusion **31** (1991) 1635.

[21] DURST, R. D. et al., Phys. Fluids B **4** (1992) 3707.
[22] CHENG, C. Z., Phys. Fluids B **3** (1991) 2463.
[23] DARROW, D. E. et al., in *Proc. 19th European Conf. on Contr. Fus. and Plasma Heating*, volume 1, p. 431, EPS, 1992.
[24] WONG, K. et al., Phys. Fluids B **4** (1992) 2122.
[25] FU, G. Y. and CHANG, C. Z., Technical Report 2852, PPPL, 1992.
[26] BIGLARI, H., ZONCA, F., and CHEN, L., Phys. Fluids B **4** (1992) 2385.
[27] CHENG, C. Z. et al., paper D-2-1, this conference.
[28] FONCK, R. J., DUPERREX, P. A., and PAUL, S. F., Rev. Sci. Instrum. **61** (1990) 3487.
[29] PAUL, S. F. and FONCK, R. J., Rev. Sci. Instrum. **61** (1990) 3496.
[30] PAUL, S. F., BRETZ, N., DURST, R. D., FONCK, R. J., KIM, Y. J., et al., Phys. Fluids B **4** (1992) 2922.
[31] FONCK, R. J. et al., Proc. 19th European Physical Society Conf. on Controlled Fusion and Plasma Physics, Innsbruck, 1992, Invited Paper to appear in Plasma Phys. and Contr. Fusion.
[32] BRETZ, N. L. et al., paper A-7-17, this conference.
[33] PERKINS, F. W. et al., Phys. Fluids B **5** (1993) 477.
[34] SCOTT, S. D. et al., paper G-3-3, this conference.
[35] ZARNSTORFF, M. C. et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1990*, volume 1, p. 109, IAEA, Vienna, 1991.
[36] KWON, O. J., DIAMOND, P. H., and BIGLARI, H., Phys. Fluids B **2** (1990) 291.
[37] REBUT, P. H., WATKINS, M. L., GAMBIER, D. J., and BOUCHER, D., Phys. Fluids B **3** (1991) 2209.
[38] KOVRIZHNYKH, L., Sov. J. Plasma Phys. **14** (1988) 834.
[39] HORTON, W., CHOI, D., and TANG, W. M., Phys. Fluids **24** (1981) 1077.
[40] BIGLARI, H., DIAMOND, P. H., and ROSENBLUTH, M. N., Phys. Fluids B **1** (1989) 109.

DISCUSSION

B. COPPI: You have shown that Bohm-type scaling is more appropriate than the so-called gyro-Bohm scaling. As you pointed out, this gives a less favourable dependence on macroscopic scale distances and would yield a shorter confinement time for ITER-type machines than assumed so far. Have you verified whether diffusion coefficients that scale like T/B but would result in a more favourable dependence on macroscopic scale distances than the simple Bohm scaling are consistent with the experiments?

M.C. ZARNSTORFF: These experiments were designed to be carried out with various values of the normalized gyroradius while keeping other dimensionless parameters (such as L_n/a, L_T/a and ν_*) as constant as possible. Therefore they are only sensitive to the gyroradius. Other experiments find a very weak dependence on ν_*, and (at best) complex relationships with the gradient scale lengths.

B. COPPI: How does the performance of large scale machines compare with that of compact high field experiments?

M.C. ZARNSTORFF: The gyroradius scaling plasmas had global energy confinement consistent with L mode scalings. To the extent that compact high field experiments with auxiliary heating are consistent with such scalings, they are likely to be consistent with the Bohm-like transport scaling found here.

R.R. PARKER: Could you comment on the implications of the high ℓ_i improved confinement results for the Rebut-Lallia-Watkins transport model?

M.C. ZARNSTORFF: The Rebut-Lallia-Watkins critical ∇T_e model does not adequately describe the experimental observations, either when comparing predicted and analysed transport fluxes or when comparing predicted and measured temperatures. The predicted electron transport has too strong a dependence on the q profile. The ion temperature is overestimated by the model and has a different variation with the q profile from that observed.

A. GIBSON: You said that the energy replacement time τ_E scaling is almost independent of species mass. Do you have a similar result for a scaling of particle replacement time τ_p?

M.C. ZARNSTORFF: The measured limiter recycling H_α/D_α emission (from a poloidal array of detectors) is independent of isotopic mass for fixed n_e, I_p, P_{NBI} and plasma size. From this, we infer that the particle confinement time is even less sensitive to isotopic mass than the energy confinement time.

F. WAGNER: You correlated the improvement in χ_i in your current ramp experiments with shear. Could it also be correlated with a further peaking of the density profile?

M.C. ZARNSTORFF: In the experiments, the density and density profile were measured to be approximately constant.

P. LALLIA: You reported disagreement between experimental results on TFTR and various theoretical models as regards ion heat diffusivity. Is the same true of electron heat diffusivity?

M.C. ZARNSTORFF: In the current profile variation experiments, both the ion and electron transport disagree with the theories tested.

J.G. CORDEY: In the ρ^* scaling experiments, did you monitor any change in the scale size of the fluctuations? No change would be the final confirmation that the transport is not linked to the Larmor radius.

M.C. ZARNSTORFF: Unfortunately, the fluctuation diagnostics were not available when these experiments were performed. We hope to repeat the scans in the future to document the changes in the fluctuations.