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RECENT TFTR RESULTS

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RECENT TFTR RESULTS

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RECENT TFTR RESULTS

ABSTRACT

TFTR experiments have emphasized the optimization of high performance plasmas as well as studies of transport in high temperature plasmas. The recent installation of carbon composite tiles on the main bumper limiter has allowed operation with up to 32 MW of neutral beam injection without degradation of plasma performance by large bursts of carbon impurities ("carbon blooms"). Plasma parameters have been extended to $T_i(0) \sim 35$ keV, $T_e(0) \sim 12$ keV, $n_e(0) \sim 1.2 \times 10^{20} \text{ m}^{-3}$ producing D-D reaction rates of 8.8×10^{16} reactions per second. The fusion parameter $n_e(0)\tau_E T_i(0)$ in supershot plasmas is an increasing function of heating power up to an MHD stability limit, reaching values of $\sim 4.4 \times 10^{20} \text{ m}^{-3} \text{ sec keV}$. Peaked-density-profile hot-ion plasmas with the edge characteristics of the H-mode have been produced in a circular cross-section limiter configuration with $n_e(0)\tau_E T_i(0)$ values characteristic of supershots, namely up to four times those projected for standard H-modes with broad density profiles. Reduced transport is also observed in the core of high-density ICRF-heated plasmas when the density profile is peaked. At the highest performance, the central plasma pressure in TFTR reaches reactor level values of 6.5 atmospheres. In these regimes, MHD instabilities with $m/n = 1/1, 2/1, 3/2$ and $4/3$ are often observed concurrent with a degradation in performance. High β_p plasmas with $\epsilon\beta_p = 1.6$ and $\beta/(I/aB) = 4.7$ (%mT/MA) have demonstrated confinement enhancement over the low-mode confinement time with $\tau_E/\tau_L \sim 3.5$ and a bootstrap current of about 65% of the total plasma current.

The best TFTR supershots in deuterium plasmas have $Q_{DD} = 1.9 \times 10^{-3}$ corresponding to an equivalent $Q_{DT} \sim 0.31$ if the plasma and beam parameters are exactly the same in a 50/50 D-T plasma. Performance enhancements in D-T due to higher heating power, higher density, lower Z_{eff} , ion mass effect and optimum programming of the D-T mix in the beam extrapolate to D-T plasma performance near the breakeven regime, $Q_{DT}^* = 0.5 - 0.7$, that would produce 15 - 25 MW of fusion power. Lower Q (~ 0.3) plasmas at higher temperatures are expected to produce alpha-particle betas suitable for testing collective alpha instability theories.

1. INTRODUCTION

During the past two years, the TFTR program has concentrated on:

- (1) optimization of high performance plasma regimes at modest (1.6 - 2 MA) plasma currents. These regimes utilize peaked-electron-density profiles to enhance deuterium fusion power;
- (2) detailed measurements of local plasma transport and fluctuations in a variety of plasma regimes; and
- (3) preparation for D-T experiments, including the achievement of deuterium plasma parameters that extrapolate to the D-T breakeven regime, theoretical studies of alpha physics and improvements in the D-T configuration.

These activities have important consequences for optimizing the plasma regimes of BPX, ITER and a reactor of the ARIES type. The peaked-density-profile regimes enhance fusion performance ($P_{\text{fusion}}/P_{\text{loss}}$) by increasing the central density and ion temperature as well as the global energy confinement time. More fundamental understanding arising from transport studies in TFTR may yield new techniques for reproducing the favorable confinement properties of these regimes. Bootstrap and beam-driven-current studies are of major interest for ITER and ARIES operating scenarios, while the recent high β_p experiments may provide the basis for a new regime of operation near the boundary of the first regime of MHD stability.

The D-T program will provide information to BPX, ITER and ARIES on confinement of D-T plasmas, initial studies of alpha particle effects and a demonstration of significant fusion power.

2. HARDWARE CAPABILITIES

The TFTR hardware capabilities are summarized in Table I and are compared to the values specified in the 1975 Final Conceptual Design of TFTR [1]. TFTR has a circular cross-section plasma with minor radius variable from 0.4 m to 0.96 m and major radius variable from 2.1 m to 3.1 m. The toroidal field system is routinely operated at the full rating of 5.2 T and plasma currents of up to 3 MA have been achieved. The neutral beam system has injected a total power of up to 32 MW. The ICRF power systems have been operated up to their design value, with 6 MW at 47 MHz and 3 MW at 40 - 80 MHz. Two antennas, each with two current straps and carbon Faraday shields, have coupled a total of 6.3 MW to the plasma with an RF power density of 10 MWm^{-2} on one antenna. The pulse length of the auxiliary heating systems (NB and ICRF) is 2 seconds, which is ~ 10 times the typical confinement time at high temperature.

The limiter system for TFTR consists of an axisymmetric inner-wall bumper limiter and two carbon/carbon (C/C) composite poloidal arcs on the outer cross-section to protect the ICRF antennas. In 1988-1989, the bumper limiter consisted of 2000 $0.1 \text{ m} \times 0.1 \text{ m}$ POCO graphite tiles. During high power operation, small cracks or high spots on the limiter formed local hot-spots ($> 1700^\circ\text{C}$) which would evaporate significant quantities of carbon into the plasma, thereby dramatically reducing the neutron production in a high performance supershot. A typical case is illustrated in Fig. 1, where 22 MW of neutral beam power produced a "carbon bloom" at ~ 0.6 sec. It is speculated that electrons deposited their energy in a very short scrape-off layer during the disruption of a previous high energy discharge and thereby initiated cracks which propagated through the graphite tiles. In early 1990, the graphite tiles in the high heat-flux regions of the inner-wall bumper limiter were replaced with C/C fiber reinforced tiles. The new C/C limiter system has allowed operation up to 32 MW for 1 sec or 25 MW for 2 sec without carbon blooms limiting performance.

TFTR has two pellet injectors. An eight barrel D₂ pellet injector, developed and built by Oak Ridge National Laboratory, produces pellets of 3, 3.5 and 4 mm diameter at speeds of $\sim 1.5 \text{ km sec}^{-1}$. A two barrel lithium or carbon pellet injector developed, built and operated by Massachusetts Institute of Technology, uses 2 mm pellets at 0.8 km sec^{-1} for fueling and diagnostic experiments.

3. TFTR PLASMA REGIMES AND PERFORMANCE

The TFTR program has emphasized optimization and study of enhanced-confinement regimes with peaked-density-profiles such as the supershot, peaked-density-profile H-mode, and high-density pellet-injected plasmas. In addition, high β_p regimes have been produced at low plasma current.

The ratio of fusion power (P_{fusion}) to power lost from the plasma (P_{loss}) is a useful measure of fusion plasma performance. For a thermonuclear plasma with average ion temperatures in the 8 - 23 keV range, $P_{\text{fusion}}/P_{\text{loss}} = n_i(0)T_i(0)\tau_S$ where $\tau_S = W_p/P_{\text{heat}}$, W_p being the plasma energy and P_{heat} the non-fusion external heating power. This formulation gives the proper description for both steady-state and transient cases with large dW_p/dt . Additionally, it can be shown that $\tau_S = W_p/P_{\text{heat}}$ is the correct confinement time to use on the Lawson diagram with transient plasmas. TFTR was designed to enhance the fusion power output using beam-target and beam-beam reactions so that $P_{\text{fusion}}/P_{\text{loss}} = M n_i(0)T_i(0)\tau_S$ where M is the fusion reactivity multiplier due to beam-target and beam-beam reactions. It is customary to express the confinement time in terms of an enhancement factor (H) over the original L-mode expression [2] for the confinement time. Therefore:

$$P_{\text{alpha}}/P_{\text{loss}} \sim M (n_D/n_e) \gamma_n \gamma_T [T_i/(T_e + T_i)] H^2 I_p^2 (R/a)^{2.5} a^{-0.24} \quad (1)$$

where γ_n is the density profile peaking factor and γ_T is the temperature profile peaking factor. The principal goal of TFTR experiments is to increase M , γ_n , γ_T , T_i/T_e and H simultaneously to obtain high performance at modest plasma currents.

The plasma parameters achieved in TFTR are summarized in Table II. Central ion temperatures of 35 keV and particle-average ion temperatures of 12.4 keV have been attained. Similarly, central electron temperatures of 11 keV and particle average electron temperatures of 5.2 keV have been obtained in supershot plasmas with central electron densities up to $9.5 \times 10^{19} \text{ m}^{-3}$. A slight major radius compression ($C = 1.07$) has been used to increase these values to $T_e = 12 \text{ keV}$, and $n_e(0) = 1.2 \times 10^{20} \text{ m}^{-3}$. In these high density cases, the total plasma pressure is up to 6.5 atmospheres with only 10% of the pressure due to unthermalized beam ions. Pellet injection has been used to produce central electron densities of $5 \times 10^{20} \text{ m}^{-3}$ during 14 MW of neutral beam heating, while $n_e(0)\tau_E = 1.5 \times 10^{20} \text{ m}^{-3} \text{ sec}$ has been obtained in ohmically-heated plasmas. During supershots, Lawson triple products of $n_e(0)\tau_E T_i(0) = 4.4 \times 10^{20} \text{ m}^{-3} \text{ sec keV}$ are produced, exceeding the value expected in 1975 for TFTR. In 1980, the performance goal was increased to $n_e(0)\tau_E = 4 \times 10^{19} \text{ m}^{-3} \text{ sec}$ at $T_i(0) = 10 \text{ keV}$. Although these $n_e(0)\tau_E$ values have not been realized in high-temperature plasmas, TFTR has achieved the corresponding Lawson triple product at 27 keV ion temperature, which has the same QDT value.

The TEXTOR boronization technique has been employed on TFTR [3]. The benefit has been a reduction in oxygen impurities, which has greatly accelerated both startup after a major vacuum opening (one week instead of four weeks) and recovery after a major disruption. However, boronization has not reduced the carbon impurity level in supershots. The TFTR C/C limiter was conditioned for supershot experiments by running ~ 50 helium discharges at 1.4 MA which remove hydrogen and deuterium from

the limiter. This produces a pumping limiter with a low recycling coefficient, $R \sim 0.5$, and a capacity for pumping the particle input from about 50 supershots (100 Torr-liters of injected deuterium).

The impurity content of TFTR plasmas is dominated by carbon, except soon after vacuum openings or disruptions when oxygen can become significant. Metallic impurities (Fe, Ni) can become important when the plasma minor radius is increased from 0.8 m to 0.96 m and the distance from the plasma to the metal walls is reduced. High power (30 MW) supershots have $Z_{\text{eff}} = 2 - 3$ at $\langle n_e \rangle \sim 4 \times 10^{19} \text{ m}^{-3}$; this level of impurities imposes a severe limit on the performance of supershots. The quality of supershots is correlated with the carbon level prior to beam injection. The carbon content can be reduced by injecting Li pellets ~ 1 sec prior to the neutral beams [4] or intentionally generating a carbon bloom on the preceding shot by moving the plasma to a new portion of the limiter.

3.1 SUPERSHOT REGIME

In TFTR the highest performance plasmas are supershots with peaked-density profiles (Fig. 2), which have performance, $n_e(0)T_i(0)\tau_E$, enhanced by a factor of ~ 20 over a comparable L-mode plasma, or factor of ~ 5 over the standard H-mode with a broad density profile. The total enhancement is multiplicative since the peaked-density profile increased confinement ($\times 3$), central electron density and T_i simultaneously in supershot discharges. The hot-ion aspect of this regime was discovered on PLT [5] in 1978 and has been extended by TFTR at ion temperatures up to ~ 35 keV. Over the last four years, the supershot characteristics have been produced in plasmas with currents up to 2 MA and neutral beam power levels up to 32 MW.

The enhanced confinement of supershots is related to the peaking of the density profile, $n_e(0)/\langle n_e \rangle$, as shown in Fig. 3. In plasmas with constant beam power, the enhancement over L-mode rises to ~ 3 as $n_e(0)/\langle n_e \rangle$ increases to 3. The confinement enhancement has been further increased to ~ 3.5 by using very high power injection to build up the density profile and then reducing the beam power during the pulse. An important feature of the supershot regime is that the confinement time does not decrease with added heating power [6] in contrast with L-mode [2] and H-mode plasmas [7] where $\tau_E \sim P_{\text{heat}}^{-1/2}$. This feature is also evident in the local transport coefficients for supershots and L-modes [8], and suggests that the basic mechanism causing transport is substantially modified in supershots relative to L-mode plasmas (see Section 4). The absence of confinement degradation with heating power has the important consequence that $n_e(0)\tau_E T_i(0)$ increases rapidly with power at fixed plasma current in supershots (Fig. 4) until the beta limit is reached. Higher plasma currents allow the injection of higher power before this limit takes place. At the highest nT values, the central plasma pressure is near the MHD stability limit. Indeed, MHD-like internal modes with $m/n = 1/1, 2/1, 3/2$ and $4/3$ are often observed concurrently with a broadening of the density profile and confinement degradation. The MHD activity can be affected by programming the plasma current evolution, conditioning the wall and limiters and modifying the current profile using the neutral beam and bootstrap driven current. As the plasma current is increased to stabilize pressure-driven instabilities, sawteeth instabilities are more difficult to suppress and degrade performance at ~ 2 MA. ICRH has been able to stabilize sawteeth and will be used to further extend the operating regime of supershot discharges [9].

3.2 PEAKED-PROFILE LIMITER H-MODE REGIME

The enhanced central confinement of the supershot has been combined with the enhanced edge confinement of a limiter H-mode to produce a confinement regime superior to the standard flat-profile divertor H-mode. The properties of the limiter H-mode plasma are shown in Fig. 5. After 0.4 sec of beam heating, the edge H_α drops while the edge electron density and temperature increase, as is characteristic of H-modes. The plasma core retains the properties of the supershot and confinement time is enhanced 2.5 times relative to the L-mode, with density peaking of 2.3 and $T_i/T_e \sim 2$ resulting in $n_e(0)\tau_E T_i(0)$ about four times that for a "standard" H-mode. The $n_e(0)\tau_E T_i(0)$ value is not higher than that in the supershot from which the H-mode evolved, but the favorable confinement is retained despite a moderate drop in the peaking factor, which arises when the edge density increases.

3.3 HIGH-DENSITY PELLET INJECTED REGIME

Since central particle fueling by neutral beams is not feasible in near-ignition reactor plasmas, different techniques are required to produce peaked-density profiles. Peaked-profile high-density plasma experiments were done on ALCATOR C, where confinement in ohmic plasmas was found to be near the neoclassical value [10] and enhanced by a factor of ~ 2 above ohmic L-mode. Subsequent experiments on TFTR have used injection of deuterium pellets into ohmic plasmas to obtain $n_e(0) \sim 3 \times 10^{20} \text{ m}^{-3}$ and $T_i(0) \sim 1.4 \text{ keV}$ with confinement times of $\sim 0.6 \text{ sec}$ which give $n_e(0)\tau_E \sim 1.5 \times 10^{20} \text{ m}^{-3} \text{ sec}$ - about half the minimum value required for ignition. The confinement time in the TFTR plasmas was about twice the L-mode value [2]. Similar high-density plasmas heated with $\sim 2.5 \text{ MW}$ of ICRH using hydrogen minority had a central enhanced confinement region with transport coefficients reduced below those of L-mode [4], and global confinement ~ 1.5 L-mode (Fig. 6) when the density profile was peaked. The studies of this regime will be extended with the planned increase of ICRF heating from 7 MW to 12.5 MW, thereby allowing tests of confinement with higher temperature which will be more relevant to the BPX.

3.4 HIGH POLOIDAL BETA REGIME

High poloidal beta plasmas are of interest since they offer reactor concepts with the potential advantages of lower plasma current, significant bootstrap current drive and the possibility of improved confinement due to changes in the magnetic configuration. Plasmas with $\epsilon\beta_p \sim 1.6$, near the equilibrium limit, and $\beta/(I/aB) \sim 4.7$ (% mT/MA) have been produced [11] in high temperature plasmas ($T_i \sim 20 \text{ keV}$, $T_e \sim 8 \text{ keV}$) with confinement times significantly enhanced ($\tau_E/\tau_L \sim 3.5$) using a current ramp-down during the ohmic phase of the discharge to modify the current profile prior to neutral beam injection. The range of parameters produced relative to previous supershot results is shown in Fig 7. At $\epsilon\beta_p \geq 1.2$, the plasma cross-section becomes highly oblate ($\kappa \sim 0.7$) and a natural poloidal divertor forms at small major radius which is sustained for several energy confinement times. The central q value, measured using polarimetry of the emission from an injected lithium pellet [12], was found to be $q_0 = 1.6 \pm 0.5$ in 275 kA plasmas ($9 \leq q \leq 12$). Stability calculations indicate that, while these plasmas are near the $\epsilon\beta_p$ equilibrium limit, the plasmas are largely in the first stability regime with the outer part of the plasma near the predicted stability boundary for high-n ballooning modes. As

indicated in Fig. 7, the stored energy achieved in these plasmas is roughly a factor of two larger than previous supershots at a given plasma current over the full range of current studied (275 kA - 850 kA).

Previous analyses have shown that the measured surface voltage in TFTR is in agreement with the theory for beam driven and bootstrap current [13]. In the most collisionless high- β_p plasmas, transport analysis shows that the bootstrap current accounts for about 65% of the plasma current for several hundred milliseconds during the heating pulse.

4. LOCAL TRANSPORT STUDIES

Local transport coefficients χ_i , χ_e and χ_ϕ have been determined using radial power balance for the plasma regimes described in Section 3. In L-mode plasmas, it is found that $\chi_i \sim \chi_\phi \sim (2-4) \chi_e$ throughout the radial profile for different plasma parameters, and the χ -values scale inversely with I_p as would be expected from the scaling of global confinement. As the electron temperature was varied [14] by increasing the neutral beam heating power at fixed density, the transport coefficients χ_i , χ_e and D varied as T_e^x where $x = 1.5$ to 2.5 . The relative magnitudes of the various χ -values in the L-mode, especially the similarity of the momentum diffusivity χ_ϕ with the thermal diffusivities, is in general agreement with the predictions of ExB transport due to drift wave turbulence, and would seem to be at variance with transport models based on magnetic fluctuations. Microwave scattering experiments [15] indicate that fluctuations with drift wave characteristics ($\omega \sim \omega^*$, $k\rho_i \sim 1$) are present with amplitudes comparable to mixing length estimates, $\delta n/n \sim 1/(kL_n)$.

Since the global confinement in supershots does not degrade with power like L-mode confinement, it is instructive to compare the transport in the core of supershot and L-mode plasmas [16]. The ion channel is dominant for L-mode and all but the best supershots. The total χ_i (i.e., including both conduction and convection) at $r = a/3$ increases rapidly with T_i ($r = a/3$) for L-mode plasmas, but decreases rapidly with temperature in the high temperature supershot regime as shown in Fig. 8. This feature is evidently a key factor in the performance of high T_i supershots.

5. DEUTERIUM FUSION EXPERIMENTS

The present supershots produce significant D-D fusion reactions which are used as a measure of plasma performance. TFTR has an extensive neutron detection system: six detectors for flux determination, a ten channel radial profile system, one detector for fast neutron fluctuations, four detectors for D-T neutron flux measurements and a six-position foil-activation system. The D-D neutron detectors were calibrated in situ by placing a Cf^{252} neutron source or a D-D and D-T neutron generator inside the TFTR vacuum vessel at many locations to provide an accurate determination of the multiple scattering of neutrons between the plasma source and the detectors. The accuracy of these measurements is typically $\sim 15\%$. The total D-D neutron rate is shown in Fig. 9 as a function of beam heating power for a variety of plasma conditions. The upper boundary of the points varies as $P_{heat}^{1.8}$ where P_{heat} is the heating power. The maximum D-D fusion reaction rate (2 reactions per neutron) has increased to $\sim 8.8 \times 10^{16} \text{ sec}^{-1}$. The maximum $Q_{DD} = P_{fusion}/P_{heat}$ is 1.9×10^{-3} . The D-D

fusion power for the best cases is ~ 50 kW producing a yield of ~ 50 kJ per pulse with a total of ~ 50 MJ of D-D fusion energy having been produced during the lifetime of the TFTR experiments.

6. D-T OBJECTIVES

The original purpose of the TFTR D-T experiments was "The generation of reactor-like fusion power densities under conditions of approximate energy breakeven, in D-T operation", as described in the 1975 Final Conceptual Design Report. During the intervening years, the scope of the planned D-T experiments has expanded from a very brief demonstration of the use of D-T to broader studies of D-T physics issues. The present, expanded objectives are to:

- o Study confinement of D-T plasmas, especially the isotope effect in tritium plasmas, and plasma heating with neutral beams and ICRF,
- o Determine effects of alpha particles, such as single particle confinement, alpha driven instabilities, and first indications of alpha heating,
- o Demonstrate D-T technical capability, such as tritium handling, recovery of tritium inventory in tokamak in-vessel components and operation of an activated machine, and
- o Demonstrate D-T power production at fusion reactor power densities of $\sim 1 \text{ MWm}^{-3}$ at approximate breakeven.

The initial D-T experiments will study the heating and confinement scaling of a deuterium-tritium plasma. A more critical issue for the success of subsequent burning-plasma experiments is the investigation of possible instabilities driven by the finite pressure of the alpha particles, such as the fishbone, the toroidal Alfvén eigenmode (TAE) [17 - 19], high-n ballooning modes and alpha-driven sawteeth. The theoretical thresholds for these instabilities depend on β_α and $\nabla\beta_\alpha$. Some aspects of these instabilities can be simulated using neutral beam injection to produce sufficient energetic particle beta using particles with parallel velocity exceeding the Alfvén velocity. A simulation experiment to excite the TAE modes via neutral beam injection has been carried out on TFTR, using up to 14 MW of nearly balanced deuterium beams with energy 70 - 110 kV injected into plasmas with $B = 1 - 1.2$ T, $q(a) \sim 3 - 4$, $\langle n_e \rangle \sim 2.5 \times 10^{19} \text{ m}^{-3}$, and $\langle \beta \rangle \sim 1\%$. Bursts of magnetic fluctuations near the TAE frequency appeared in the Mirnov coil signal when the beam ion velocity exceeded 70% of the Alfvén velocity. A mode with $n = 3$ has been identified. Growth of this mode was accompanied by a drop in neutron emission and a burst in H_α emission, indicative of expulsion of energetic ions from the plasma core. Very recent data from beam-emission spectroscopy has shown that density fluctuations with the same frequency exist within the plasma core ($r \sim a/2$). Detailed analysis to determine the radial mode structure needs to be completed. The β_α expected for various regimes in TFTR is compared with theoretical estimates for alpha-driven instabilities in Table III and this comparison indicates that the TFTR D-T plasmas with the parameters anticipated will be able to test the theoretical predictions for the thresholds of essentially all of the major modes of instability, as well as the effect of the instabilities on the alphas and plasma.

7. PROJECTION OF D-T PLASMA PERFORMANCE

The D-T performance of TFTR has been estimated using codes which have been benchmarked against many D-D plasmas. The calculated stored plasma energy and neutron production rate for D-D supershots are consistent with the measured values to within their uncertainties. The observed dependences of the D-D neutron rate and Q_{DD} on beam power and total plasma energy are reproduced by the codes. In the D-T simulations, the measured temperature and electron density profiles were scaled uniformly to account for changes in beam power and expected confinement. The normalization of the temperature profiles is determined by matching the expected τ_E while maintaining $X_i = X_e$ at $r = a/2$ (as in the best discharges). The power balance at $r = a/2$ assumes a convective multiplier of 1.5 and includes alpha particle heating. The fusion gain is taken to be $Q_{DT} = P_{\text{fusion}}/P_{\text{heat}}$ where P_{heat} is the total auxiliary heating power. No reduction in the auxiliary heating power was made to correct for shine-through, fast-ion orbit losses or dW_p/dt .

The performance of equivalent D-T discharges was simulated by injecting equal power D^0 and T^0 beams into a 50/50 D/T plasma using the measured temperatures and electron density profiles, Z_{eff} , beam power, voltage, and species mix of a comparable D-D shot (Table IV). Equivalent Q_{DT} values up to ~ 0.31 ($\sim 185 Q_{DD}$) were obtained in this way. In this case the thermonuclear reactions contributed 42% while beam-target and beam-beam were 51% and 7% respectively. Thus, for this mode of operation, $M = 2.4$.

Significantly more fusion power and alpha production is expected if the best discharge conditions are extrapolated to anticipated D-T conditions at full beam power. In these extrapolated cases, the total neutral beam power was increased to 35 MW while the beam voltage was increased to 120 keV and it was assumed that $\tau_E \sim A_i^{0.5}$. The electron density was increased by 25%, according to present scaling with power, and Z_{eff} was reduced following the observed trend with density. For the full power case with roughly 50/50 D^0/T^0 beams into a roughly 50/50 D/T plasma, the extrapolated Q^*_{DT} is in the range 0.5 (300 Q_{DD}). Thermonuclear reactions contribute 50% of the rate, while beam-target and beam-beam are 42% and 8% respectively, as shown in Table IV. These plasmas have central β_α in the range of $\sim 0.7\%$ which is above the theoretical estimate of 0.3% for the global TAE threshold of 0.3%.

The largest Q and fusion power are obtained using the original TFTR D-T scenario which maximizes beam-target reactions by injecting 35 MW of D^0 beams into a tritium plasma. The target tritium plasma could be preheated by ICRF or ~ 10 MW of tritium neutral beams (in the latter case the D^0 beams are at 25 MW). The fusion reactions are predominantly beam-target reactions and were projected in 1975 to give Q in the breakeven regime of 0.3 to 1.0. Present projections for this mode of operation, based on the best D-D supershots, indicate that $Q^*_{DT} = 0.4 - 0.7$ could be achieved. In this case the beam-target reactions contribute 89% while thermonuclear reactions are 11% of the total rate. These will be transient cases, since the plasma composition will evolve to that of the beams, but the high- Q conditions are expected to last for times of order τ_E . The central β_α value for this case is $\sim 0.9\%$ (Table IV).

The addition of 12 MW of ICRF heating is expected to stabilize sawtooth instabilities and, through heating the electrons will increase β_{α} , thereby expanding the range of study for alpha-driven instabilities.

8. FUTURE PLANS

Experiments over the next two years will concentrate on improving the performance of supershots, especially at higher density, using ICRF and current profile control along with improved wall conditioning techniques. The ICRF heating power will be doubled to 12.5 MW and will be used for sawtooth and MHD-mode control, as well as to extend the high-density peaked-profile regime in preparation for D-T experiments to a BPX-relevant high-temperature plasma scenario. The transport studies will continue with emphasis on correlating fluctuations with transport and theoretical models. In addition, activities will increase to prepare for D-T experiments in 1993-1994.

9. SUMMARY

TFTR has developed plasma regimes with deuterium plasma parameters that exceed the TFTR goals for temperature and $n_e(0)/T_e(0)$. These deuterium plasma conditions project to D-T plasmas in the breakeven regime with fusion powers of 15 - 25 MW and alpha particle parameters suitable for testing collective alpha instability theories. The TFTR enhanced performance plasma regimes and D-T results will provide important data for the design and operation of BPX, ITER and ARIES.

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TABLE I. TFTR HARDWARE CAPABILITIES

	<u>DESIGN</u>	<u>ACHIEVED</u>
a(m)	0.45 - 0.85	0.4 - 0.96
R(m)	2.1 - 3.1	2.1 - 3.1
ELONGATION	1.0	0.6 - 1.1
B _T (T) AT 2.48 m	5.2	5.2
I _p (MA)	2.5 (3)*	3
P _{NB} (MW)	20 (26)* @ 120 keV 12 (7)* @ 60 keV	21 @ 110 keV 7 @ 55 keV 4 @ 37 keV
NEUTRAL BEAM		
PULSE LENGTH (sec)	0.5 (1.5)*	2
LIMITER	STEEL	CARBON
P _{ICRF} (MW)	0 (7)†	6.3

* INCREASED IN 1980

† INCREASED IN 1988

TABLE II. TFTR PLASMA PARAMETER RANGE

	<u>DESIGN</u>	<u>ACHIEVED</u>
$T_i(0)$ (keV)	$\sim 5 - 10$ (10)*	35
$\langle T_i \rangle$ (keV)		12.4
$T_e(0)$ (keV)	5 - 10	12
$\langle T_e \rangle$ (keV)		5.2
$n_e(0)$ (10^{20}m^{-3})	1	5#
$n_e(0) \tau_E$ ($10^{20} \text{m}^{-3} \text{sec}$)	0.1 (0.4 @ 10 keV)*	1.5 @ 1.5 keV#
$n_e(0) \tau_E T_i(0)$ ($10^{20} \text{m}^{-3} \text{sec keV}$)	1 (4)*	4.4
CENTRAL PRESSURE (ATMOSPHERE)		6.5

* INCREASED IN 1980

WITH DEUTERIUM PELLETS

**TABLE III. ESTIMATES OF THEORETICAL THRESHOLDS FOR
ALPHA COLLECTIVE EFFECTS IN TFTR SUPERSHOT PLASMAS**

<u>INSTABILITY</u>	<u>β_α (@ q = 1)</u>
FISHBONES	~ 1%
SAWTOOTH STABILIZATION	~ 0.5%
TOROIDAL ALFVEN (GLOBAL MODEL)	~ 0.3%
HIGH-n BALLOONING	~ 0.1%
TOROIDAL ALFVEN (LOCAL MODEL)	~ 0.02%

TABLE IV: PROJECTIONS OF D-T PERFORMANCE

SHOT 53848	SAME T, ETC.	50:50 DT	$D^0 \rightarrow T^+$
P_b (MW)	25.7	35	35
$\bar{n}_e$ ($10^{19}m^{-3}$)	4.8	6.0	6.0
Z_{eff}	2.25	2.0	2.
τ_E (sec)	0.15	0.18	0.19
T_{eo} (kev)	10.6	11.9	12.9
T_{io} (kev)	27.1	25.0	27.1
beam-beam (%)	7	8	0
beam-target (%)	51	50	89
Thermonuclear (%)	42	42	11
$\langle \beta_\alpha \rangle$ (corr) (%)	0.41	0.71	0.86
Q_{DT}	0.31	0.48	0.65
P_{fusion} (MW)	8.0	17.0	22.7
P_{alpha} (MW)	1.6	3.4	4.5

$P_{NB} = 22 \text{ MW}$, Graphite Limiter

$P_{NB} = 32 \text{ MW}$, C/C Composite Limiter

FIG. 1. Comparison of the total power radiated during beam injection. The graphite limiter has a "carbon bloom" at 0.6 sec, while the C/C composite limiter did not bloom when 32 MW was injected for 1 second.

FIG. 2. Density profile for a supershot with $I_p = 1.7 \text{ MA}$ and $P_{NB} = 25 \text{ MW}$.

FIG. 3. The enhancement of the energy confinement time over the prediction of L-mode scaling as a function of density profile peaking for a variety of supershots.

FIG. 4. The Lawson triple product versus beam power for supershots.

FIG. 5. Characteristics of a limiter H-mode plasma in TFTR, with $I_p = 0.8$ MA, $B_T = 4$ T, and $P_{NB} = 11$ MW (balanced). The plasma parameters were $n_e(0) \approx 4.7 \times 10^{19} m^{-3}$, $T_i(0) \approx 22$ keV and $\tau_E \approx 0.12$ sec.

FIG. 6. Confinement and transport during the density decay following pellet injection at 3.0 seconds. Hydrogen minority ICRF heating is applied at 3.05 seconds. At 3.4 seconds, $n_e(0) \approx 10^{20} m^{-3}$, $T_e \sim 2.4$ keV in a 1.4 MA deuterium plasma. χ_{eff} is average of the electron and ion thermal conductivity.

FIG. 7. Summary of $\epsilon\beta_p$ achieved in TFTR as a function of $q^* = (5a^2B_0/R_0I_p) [1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)]/2$. Plasmas became diverted when $\epsilon\beta_p > 1.25$ and an apparent equilibrium limit was found at $\epsilon\beta_p \sim 1.6$.

FIG. 8. A comparison of the total χ_i including ion conduction and convection at $r = a/3$ versus T_i ($r = a/3$) for L-mode plasmas and supershots.

FIG. 9. The D-D neutron rate for supershots with plasma currents up to 1.85 MA. The line at the upper boundary varies as $\sim P_{\text{heat}}^{1.8}$.