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PHYSICS OF HIGH PERFORMANCE DEUTERIUM-TRITIUM PLASMAS IN TFTR*

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Abstract

During the past two years, deuterium-tritium (D-T) plasmas in the Tokamak Fusion Test Reactor (TFTR) have been used to study fusion power production, isotope effects associated with tritium fueling, and alpha-particle physics in several operational regimes. The peak fusion power has been increased to 10.7 MW in the supershot mode through the use of increased plasma current and toroidal magnetic field and extensive lithium wall conditioning. The high-internal-inductance (high -l_i) regime in TFTR has been extended in plasma current and has achieved 8.7 MW of fusion power. Studies of the effects of tritium on confinement have now been carried out in ohmic, NBI- and ICRF- heated L-mode and reversed-shear plasmas. In general, there is an enhancement in confinement time in D-T plasmas which is most pronounced in supershot and high-l_i discharges, weaker in L-mode plasmas with NBI and ICRF heating and smaller still in ohmic plasmas. In reversed-shear discharges with sufficient deuterium-NBI heating power, internal transport barriers have been observed to form, leading to enhanced confinement. Large decreases in the ion heat conductivity and particle transport are inferred within the transport barrier. It appears that higher heating power is required to trigger the formation of a transport barrier with D-T NBI and the isotope effect on energy confinement is nearly absent in these enhanced reverse-shear plasmas. Many alpha-particle physics issues have been studied in the various operating regimes including confinement of the alpha particles, their redistribution by sawteeth, and their loss due to MHD instabilities with low toroidal mode numbers. In weak-shear plasmas, alpha-particle destabilization of a toroidal Alfvén eigenmode has been observed.

1. INTRODUCTION

The primary objective of TFTR has been to explore and understand the physics governing plasma confinement and stability under conditions approaching those in the core of a fusion power reactor. Since operation with deuterium-tritium (D-T) fuel began in 1993, over 841 D-T discharges producing 1.2 GJ of fusion energy have been made for systematic investigations of fusion performance, effects associated with the use of tritium, and alpha-particle physics in a variety of operating regimes. These range from L-mode to enhanced performance regimes, including supershots, the high internal inductance (high-l_i) regime, the H-mode and the new enhanced reverse shear regime. These experiments have revealed important effects associated with the use of tritium and the behavior of alpha particles.

We begin by describing the confinement and stability properties of the high-performance operational regimes used in the D-T campaigns on TFTR. This will be followed by discussions of the effects due to the tritium fuel and the physics of alpha particles.

The plasmas in these experiments were run at a major radius of 2.45 – 2.62 m, minor radius 0.80 – 0.97 m, toroidal field at the plasma center 4.0 – 6.0 Tesla, and plasma current 0.6 – 2.7 MA. The plasma boundary is defined by a large-area toroidal limiter composed of carbon-composite tiles in high heat flux regions and graphite tiles elsewhere. Deuterium and tritium neutral beams with energies up to 115 keV were injected to heat and fuel the plasma with a total injected power up to 39.5 MW. ICRF power up to 8 MW has been used. A description of TFTR and of the tritium processing systems is given in [1] and references therein.

2. FUSION POWER PRODUCTION

2.1 Regimes of operations.

The D-T experimental program in TFTR has focused on operating conditions which produce substantial fusion power, and hence can be used to study alpha-particle and other D-T related issues in reactor relevant conditions.

The first high-power D-T experiments were performed in supershot discharges [2]. Since then, the peak fusion power in TFTR has been extended to 10.7 MW in supershot discharges [3], as shown in Fig. 1. In other discharges designed to extend the duration of the fusion pulse, 6.5 MJ of fusion energy per pulse has been obtained. The most significant change responsible for the increase in peak fusion power has been increasing the toroidal magnetic field to 5.6 T and the plasma current to 2.7 MA in order to increase plasma stability [4]. To obtain supershots at this high current requires coating the inner limiter with lithium to suppress recycling. New techniques of lithium deposition *in situ* have been developed [5]. Lithium pellet conditioning of the limiter has now produced a confinement time τ_E = 0.33 s in a supershot with 17 MW of tritium neutral beam heating, resulting in a record fusion triple product $n_i \cdot T_i \cdot \tau_E^* = 8.3 \times 10^{20}\ \mathrm{m^{-3} \cdot keV \cdot s}$, where $\tau_E^* = W_{tot}/P_{heat}$. A similar plasma with D-T neutral beam heating achieved a global Q (= P_{fus}/P_{heat}) of 0.27 and a central Q of 0.6 – 0.7 with 21 MW of neutral beam heating.

As will be discussed below, the maximum stored energy and hence fusion power in supershot discharges is limited by the onset of MHD instabilities. This has motivated the development of other advanced tokamak regimes, in particular the high-l_i and reverse shear regimes, in which the current and pressure profile are modified to improve MHD stability limits[6,7].

Previously, Sabbagh *et al.* [8] reported the achievement of high values of normalized-β, β_n, and fusion power at high l_i produced by ramping down the plasma current, demonstrating the potential for increased stability. A new technique has been pioneered on TFTR [9] for generating high-l_i plasmas at high current, up to 2.3 MA, by forming a plasma at low edge-q, < 2.5, increasing the current at constant q and then rapidly expanding the cross section at essentially constant current to produce a final edge q of 4 - 4.5 at the start of high power NBI heating. With extensive limiter conditioning by lithium pellet injection, confinement has been improved in these plasmas such that P_{fus} = 8.7 MW has been attained at modest parameters (2 MA, 4.8 T).

Plasmas with reversed magnetic shear ($\partial q/\partial r < 0$) over the inner half of the minor radius have been produced in TFTR by rapidly ramping up the plasma current at maximum plasma cross-section while heating with NBI at power levels up to about 10 MW to inhibit resistive penetration of the current[10,11]. The co- and counter- tangential NBI during this "prelude" phase also provides current drive for control of the final q-profile. After forming a reversed shear plasma, the NBI heating power is generally increased to study the confinement and stability properties. In this high-power phase, spontaneous transitions to a new enhanced confinement regime, the Enhanced Reverse Shear (ERS) regime, have been observed when the NBI exceeds a power threshold, typically 18 - 20 MW for deuterium NBI in 1.6 MA plasmas. The ERS transition generally occurs after 0.2 – 0.3 s of high-power NBI. ERS plasmas exhibit a very rapid density increase in the shear-reversed region, achieving $n_e(0) = 1.2\times 10^{20}\,m^{-3}$ with $T_i(0) \approx 24$ keV, $T_e(0) \approx 8$ keV, and a pressure peaking factor, $p(0)/\langle p\rangle \approx 7$, where $\langle p\rangle$ is the volume-average pressure. In recent experiments, very steep electron temperature gradients ($\partial T_e/\partial r > 50$ keV/m) have also been observed in the region of the transport barrier in some conditions. The ERS plasmas have been brought to nearly steady-state conditions by reducing the NBI power to a low level, typically 5 – 10 MW, for up to 0.5 s in what is termed the "postlude" NBI phase.

Two interesting observations have been made concerning the threshold power for the ERS transition. The first is that injection of a lithium pellet before or coincidentally with the high-power NBI can trigger an ERS transition at lower power. This technique has been used to trigger transitions in high-current, 2.2 MA, reverse-shear discharges where the intrinsic threshold power appears to be higher. The second is that the ERS threshold power for 1.6 MA plasmas appears to be much higher for tritium NBI than deuterium. This has so far limited the range of D:T mixture accessible for studying fusion power production in ERS plasmas, because of lithium dilution of the hydrogenic species in the plasma core. The profiles of q and plasma β for supershots, high-l_i and reverse shear modes are compared in Fig. 2. Table 1 gives a summary of a set of high performance TFTR shots which include a supershot, lithium assisted supershot, high-li shot and an enhanced reversed shear plasma.

2.2 Confinement

2.2.1 Confinement in supershots and high-l_i plasmas.

The supershot regime is characterized by peaked density and pressure profiles, and confinement enhancements up to ~3 times ITER-89P scaling. To obtain supershot confinement, it is essential to maintain low edge recycling and neutral beam deposition in the plasma center. In the core of supershots, the apparent thermal diffusivity is reduced and thermal transport becomes dominated by convective losses due to the radial particle flux which remains significantly larger than neoclassical theory. [12]

The confinement characteristics of the high-l_i plasmas are quite similar to those of supershots. In particular, it is necessary to control recycling to achieve good confinement in this regime also. In the 1996 experiments, attempts to extend the fusion performance further were constrained by the power handling capability of the bumper limiter. With the level of limiter conditioning achieved in 1996, at NBI powers in excess of 30 MW and stored energies above about 6 MJ the recycling of hydrogen isotopes increased dramatically during the NBI heating pulse, causing a reversion to L-mode confinement. We have begun to explore the use of krypton or xenon puffing to form a radiating layer at boundary in order to distribute the heat load on the limiter, thereby increasing its power handling ability.

2.2.2 Confinement in reverse shear.

The confinement characteristics of reversed shear plasmas with modest heating power also resemble supershots with the same machine parameters. In ERS plasmas, however, the inferred electron particle diffusivity in the region of the steepest gradient drops by a factor of 10 - 50 to near-neoclassical levels, while the ion thermal diffusivity falls to levels well below predictions from conventional neoclassical theory [10,13]. The likely explanation for the inferred sub-neoclassical ion thermal diffusivity is the violation of the assumptions of standard neoclassical theory. Recent calculations by Lin *et al.* [14] indicate that a more comprehensive analysis of neoclassical transport which considers orbit dimensions comparable with pressure scale lengths is in better agreement with the data in the enhanced confinement regime. In addition, ion orbit squeezing, due to the large inferred radial electric fields, has recently been calculated to reduce the neoclassical ion transport.[15] Inasmuch as neoclassical transport is usually considered to be the minimum transport possible in a tokamak, these results represent a dramatic improvement in confinement and performance.

The present necessity of injecting lithium pellets at the start of high-power NBI in order to produce ERS transitions in high-current reverse-shear plasmas, coupled with the excellent particle confinement following the transition, has caused significant dilution of the hydrogenic species in 2.2MA ERS plasmas. As a result, the DD neutron rate for these plasmas is significantly depressed compared to supershots at similar parameters. Consequently, tritium NBI has not yet been used in high-current (2.2MA) ERS plasmas.

2.3 Stability

2.3.1 Stability in Supershot plasmas

The D-T fusion power in TFTR supershots is limited by pressure driven instabilities which can cause major or minor disruptions. At high plasma currents, > 2 MA, and toroidal magnetic field, >5 T, the limiting value of β_n is ~1.9. A weak inverse scaling of this limit with toroidal field is seen; $\beta_n \propto B_{tor}^{-(0.2-0.4)}$. The neoclassical tearing modes which limited operation at lower current [16] have been largely absent at higher current, and are thus not responsible for this dependence of the beta limit on the toroidal field. The stability limit in supershot plasmas appears to be set by a combination of global kink modes which may be coupled to toroidally localized ballooning modes [17,18,19]. The kink mode can locally decrease the magnetic shear and increase the local pressure gradient so that the ballooning mode becomes destabilized. While this phase can be well modeled by a 3-dimensional MHD code, MH3D, the stability of the n=1 ideal kink with q(0)<1 is still not understood.

2.3.2 Stability in High-l_i (internal inductance) plasmas

The high-l_i plasma producing 8.7 MW of fusion power disrupted at β_N = 2.35, significantly higher than in supershots at similar parameters. This limit is in good agreement with PEST modeling. The stability of these plasmas is discussed in papers by Sabbagh [20] and Manickam [21]. If the influx from the limiter can be controlled and adequate confinement maintained, it should be possible to increase the fusion performance of the 2.3MA, high-l_i plasmas substantially.

2.3.3 Stability in Reversed Shear plasmas

The investigation of reversed shear plasmas was originally motivated in part by theoretical predictions that such plasmas would have improved stability [22]. In these experiments, a new regime of improved confinement was discovered. Reversed shear plasmas at a moderate plasma current, 1.6MA, have been studied to test the theoretical modeling of stability. The core region of these plasmas does appear to be robustly stable to pressure driven modes. However, performance is still limited by pressure driven modes in the weak shear region. This is particularly a problem in the Enhanced Reverse Shear (ERS) discharges where the strong transport barrier creates a steep pressure gradient. This pressure gradient typically forms near the minimum in q, but during the evolution of the plasma the pressure gradient tends to propagate outwards while the low-shear region moves inwards as the current profile evolves on a resistive timescale. In these circumstances, pressure driven modes can develop. These are believed to be infernal modes [21], but in at least one case the infernal mode was coupled to a moderate n, toroidally localized ballooning mode, similar to what occurs in supershot disruptions [23]. Theoretical modeling of the stability with the PEST code has suggested various approaches towards extending this regime to higher currents and higher performance. The capability to control simultaneously the evolution of the q profile (through current drive) and the pressure profile (through manipulation of the transport barrier) will be necessary to develop the full potential of this regime.

2.4 Projection of D-T performance

The expected fusion reactivity enhancement in D-T plasmas over their deuterium counterparts can be estimated from the ratio of the velocity-weighted fusion cross-sections for DT and DD reactions. For fixed fuel density and temperatures the fusion power ratio, $P_{D\text{-}T}/P_{D\text{-}D}$, of purely thermal reactions reaches an idealized maximum of ~225 for T_i ~ 12 keV but the ratio falls to 150 at T_i = 30 keV. In plasmas with a significant population of non-thermal fuel ions from neutral beam injection, the beam-target reactivity enhancement also drops for T_i above 15 keV. The measured ratio of fusion power in TFTR supershots is ~115 if plasmas with the same stored energy are compared. When comparing plasmas with the same heating power, the isotope effect on confinement (Sec. 3.2) raises the DT fusion power and the fusion power ratio is ~140. Furthermore, the highest neutral beam power can be achieved with D-T operation due to the higher neutralization efficiency of tritium. As a result of this increase in power, the highest DT fusion power is actually 165 times the highest DD fusion power achieved in TFTR. However, it should be noted that to achieve this power ratio, the plasma energy increased from 5.6 MJ in the D plasma to 7.0 MJ in the D-T plasma. This emphasizes the importance of improving stability limits to achieving high fusion performance and demonstrates that the extrapolation of the highest performance D-only results, which are often stability or power handling limited, to D-T plasmas is not a simple matter of species substitution in numerical simulation codes.

3. EFFECTS DUE TO TRITIUM

3.1 Tritium transport

Tritium operation on TFTR has allowed the measurement of the local tritium density from the 14 MeV t(d,n)α neutron emissivity profile measured with collimated neutron detectors [24,25]. Tritium transport has been studied with this diagnostic technique by puffing a small amount of tritium gas into plasmas heated by deuterium NBI. Initially, tritium and helium transport were studied in low-recycling, high-performance supershots [26]. The diffusivity profiles of helium, tritium and heat were observed to be of similar magnitude and shape. This is a prominent characteristic of transport due to drift-like microinstabilities. The same helium transport coefficients successfully modeled the helium ash density in deuterium-tritium plasmas [27]. This similarity in diffusivities would allow helium ash removal in future reactors, such as ITER. Recently, helium and tritium transport measurements were performed in the steady-state “postlude” phase of ERS plasmas. The tritium profile remains hollow for a long time, > 0.15 s, and does not peak on axis. A transport barrier can be clearly observed that impedes tritium transport to the core. Helium has a similar density evolution.

3.2 Isotope effect on confinement

The first D-T experiments in TFTR showed that the overall energy confinement in D-T supershots was significantly better than in comparable D-only plasmas.[28,29] This improvement is manifested by increased central ion and electron temperatures. In order to quantify the improvement and determine its origins, experiments with different D:T ratios have been carried out. The improvement in confinement, which is found to be primarily in the ion channel [30, 31], is associated with a reduction in the calculated ion thermal diffusivity by as much as a factor two.

Studies of the isotope effect have now also been carried out in ohmic, L-mode, reversed shear, and ICRF-heated plasmas.[32] The enhancement is most pronounced in supershot and high-l_i discharges, $\tau_E \propto \langle A \rangle^{0.85}$, where $\langle A \rangle$ is the average isotope mass of the plasma. NBI and ICRF heated L-mode plasmas show similar, weaker scaling: $\tau_E \propto \langle A \rangle^{0.3-0.5}$. In ohmic plasmas, the scaling is weak, $\tau_E \propto \langle A \rangle^{0.0-0.3}$, and it is essentially absent in ERS plasmas. Figure 3 shows a comparison of the isotope scaling in these TFTR regimes. Because of wall recycling, which is predominantly deuterium, the maximum value of $\langle A \rangle$ in these studies is 2.5. These results validate the assumed $\tau_E \propto \langle A \rangle^{0.5}$ scaling in regimes closest to proposed ITER operation ($T_i \sim T_e$, broad n_e, and significant heating to the electrons). However, these results are not consistent with gyro-Bohm scaling which remains an outstanding issue.

3.3 ICRF experiments

Ion cyclotron heating at the tritium second-harmonic frequency has potential applications for ITER. This scenario has been used previously to heat D-T supershots on TFTR [33,34,35,36]. Its effectiveness for heating an ohmic D-T target plasma, containing only thermal tritium, in the L-mode regime has now been demonstrated [35]. Heating efficiency was comparable to that obtained with neutral beam injection. This result indicates that good second-harmonic tritium heating should occur during the startup phase of ITER. In L-mode plasmas with T_i and T_e approximately equal, a favorable isotope scaling $\langle A \rangle^{0.5}$ was demonstrated going from D to D-T plasmas.

Fast wave direct electron heating of the postlude phase of ERS discharges has also been demonstrated [37]. ICRF power of 2 MW increased the central electron temperature by 2 keV. ICRF heating also sustained the highly peaked density and temperature profiles characteristic of ERS, delaying the transition out of ERS mode by approximately 100 ms.

Electron heating and current drive have also been demonstrated using the mode-converted ion Bernstein wave (IBW) in a mixed-species plasma [38]. This technique has been used to drive 125 kA on axis with 2 MW, and 100 kA off axis with 4 MW of RF power in D-^{4}He-^{3}He plasmas. Mode conversion heating in a D-T plasma has been demonstrated for the first time on TFTR. However, parasitic minority-ion absorption by a dilute ^{7}Li impurity introduced by wall coatings was significant, reducing the power coupled to electrons to 20 - 30% of the input level, in agreement with modeling. This poses a potential problem in ITER and other devices which use ^{9}Be wall facing materials.

Experiments in alpha channeling have indicated coupling of the mode converted IBW to alpha particles in D-T-^{3}He plasmas. Investigations which utilize coupling of the IBW to beam injected deuterons have verified essential details of the wave propagation physics, including the first evidence that the parallel propagation of the wave reverses away from the mode conversion surface. Inferred velocity space diffusion coefficients are of the order needed to achieve cooling of alpha particles [39].

4. PHYSICS OF ALPHA PARTICLES

4.1 Classical alpha confinement and thermalization

In an ignited D-T plasma, the alpha-particle power must be transferred to the thermal plasma before it is lost to the vacuum vessel wall. Alpha-particle confinement and loss has been measured in TFTR using several unique and novel alpha-particle diagnostics developed and implemented on TFTR [40].

The energy distribution of the alpha particles confined in the plasma has been measured in TFTR [41]. Alphas in the energy range 0.5 – 3.5 MeV have been detected through conversion to neutral helium by double charge-exchange in the high-density neutral cloud surrounding an ablating lithium pellet [42]. The pellet was injected after the end of NBI, to improve its penetration, but before the alpha population had decayed. The measured spectrum is compared with the TRANSP calculation in Fig. 4 and found to be in good agreement. The alpha spectrum in the lower energy range, 0.1 – 0.6 MeV, has been detected by absolutely calibrated spectrometry of charge-exchange recombination emission [43]. The intensities of the detected signals are within a factor 2 of calculations by TRANSP, based on purely classical slowing down processes.

4.2 Effects of sawteeth

Measurements of the confined alpha distribution before and after a sawtooth crash were made with both confined alpha diagnostics, and the results are shown in Fig. 4. The alpha density on axis was reduced by as much as a factor 5 after the sawtooth crash [44]. The redistribution of the passing α-particles at the sawtooth as measured by the alpha-CHERS diagnostic with energies up to 0.6 MeV in a D-T plasma (Fig. 4a) was shown to be consistent with a relatively simple sawtooth mixing model which takes into account the reconnection of the magnetic flux which is presumed to occur at the sawtooth crash. Comparison of pellet charge exchange (PCX) measurements in the presence and absence of sawteeth in the period following the D-T heating phase indicate that the sawtooth activity transports trapped fast alphas radially outward as shown in Fig. 4b. This result cannot be explained by the conventional magnetic reconnection model for sawtooth mixing. Only the introduction of a helical electric field produced by the crash can explain the experimentally observed alpha redistribution [45].

4.3 Effects of MHD modes on the alpha particles

The first direct evidence of alpha particle loss induced by an MHD mode was due to a kinetic ballooning mode (KBM) in TFTR D-T experiments. The kinetic ballooning modes are driven by the sharp gradients in the plasma pressure profile and have localized ballooning characteristics. A significant enhancement, $\times$ 1.3 – 2, in alpha particle loss has been observed in some high-β D-T discharges. The loss enhancement correlates well with the appearance of high frequency ($f \approx 100$ - 250 kHz), high-n (≈ 6) KBM's driven by the plasma pressure gradient [46]. Particle simulation shows that the observed alpha-loss is induced by the wave-particle resonance. Similar KBM's are observed in D discharges, so the modes are not themselves driven by the alpha particles but by the pressure gradients in the plasma.

Enhancement in the loss of fusion alphas has been observed in high power D-T operation of TFTR in the presence of MHD activity. Sawteeth cause a strong, transient enhancement in the alpha loss at the time of the central crash. While the loss rate is transiently high, the net loss is small due to the short period of enhancement. Neoclassical tearing modes, as shown in Fig. 5, are also seen to enhance the alpha loss-rate. On the 60˚ alpha detector the loss may roughly double the first orbit loss. The detector signal itself is modulated at the frequency of the MHD mode, demonstrating that the loss is not toroidally symmetric; this may be important to ITER in designing plasma facing components. Stationary Magnetic Perturbations (SMP's), which are similar to locked modes, enhance the loss in a similar fashion to neoclassical tearing modes. The fusion alpha losses appear qualitatively similar to the fusion triton losses reported earlier. It is hoped to develop a quantitative understanding of these phenomena which could be applied to ITER.

4.4 Alpha driven TAE mode

The alpha-driven Toroidal Alfvén Eigenmode (TAE) had not been previously observed in supershot discharges at the highest fusion power and alpha concentration, consistent with theory. Recent theoretical calculations have shown that the predicted alpha-driven TAE threshold is sensitive to the q-profile and the plasma β. This is potentially important in advanced tokamak regimes in which the core current profile is being modified to achieve higher stability. In recent experiments with weak magnetic shear, TAE's driven by energetic alpha-particles have been observed in TFTR D-T plasmas [47]. In Fig. 6, it is shown that these modes occur 100 – 300 ms following the end of NBI in plasmas with elevated central safety factor, q(0) = 1.1 – 2.5, and reduced central magnetic shear. The fusion power threshold is ~1.5 MW for $q(0) \approx 2.4$ which corresponds to ~300 kW peak alpha power and $\beta_\alpha(0) \approx 10^{-4}$. Modes appear in the range 150 – 250 kHz with toroidal mode numbers n = 2, 3, 4, which are observed to propagate toroidally in the direction of the plasma current. From core reflectometer measurements, the dominant n = 3 mode is localized near $r/a \approx 0.3 - 0.4$, which also coincides with the region of peak $\nabla\beta_\alpha$. The central β_α for the onset of mode activity is consistent with NOVA-K linear stability calculations [48] for alpha-driven TAE's in discharges with elevated q(0), low ion temperature (10 – 15 keV) and low beam-ion damping following the termination of neutral beam injection.

5. SUMMARY

TFTR has explored a wide range of physics issues in plasmas with high concentrations of tritium. Several possible advanced confinement regimes, supershot, high-l_i, and reversed shear, have been investigated using D-T and shown to have significant potential for reactors. In general, D-T plasmas have shown improved confinement compared to similar deuterium plasmas.

The fusion performance in TFTR supershots has been extended to 10.7 MW of peak power and 6.5 MJ of fusion energy per pulse. The most significant change responsible for the increase in fusion power has been operation at increased toroidal magnetic field, up to 5.5 T, and plasma current, up to 2.7 MA and neutral beam heating power of 40MW . Conditioning of the inner wall with lithium has improved the confinement to take advantage of the increased stability at higher field.

The high-current high-l_i regime has demonstrated good energy confinement and favorable MHD stability enabling the achievement of fusion power production comparable to that achieved in supershots at similar heating powers. The proven ability to achieve high values of β_N offers the potential of still higher values of fusion power in TFTR.

The formation of an internal transport barrier in the enhanced reverse shear regime has dramatically reduced the ion heat and particle flux from the core. This is accompanied by a substantial reduction in core plasma fluctuations and a steeping of the plasma pressure gradients. Future experiments will concentrate on understanding the physics of the barrier formation and on controlling the evolution of the barrier and the current profile to maintain stability.

ICRF heating schemes of importance to ITER have been validated and a new scheme for RF current drive through mode-conversion in a mixed-species plasma has been demonstrated. ICRF heating has been shown to sustain the ERS mode without particle fueling, which is important to the development of this operational regime. The interactions of energetic ions, including fusion alphas, with ICRF waves have been investigated and support the development of the alpha-channeling concept.

Fusion alpha particles have behaved classically for quiescent MHD plasmas. Sawteeth have been shown to redistribute fusion alphas near the plasma core. In discharges with weak magnetic shear, toroidal Alfvén eigenmodes driven by fusion alpha-particles have now been observed and found to be in accord with theoretical predictions.

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TABLE 1

Summary of high performance TFTR shots

Parameter	supershot 80539A12	Li assisted 83546A15	high li 95603A02	ERS 88170A51
I_p (MA)	2.7	2.3	2.0	1.6
B_t (T)	5.6	5.5	4.8	4.6
P_{NB} (MW)	39.6 (DT)	17.4 (T-only)	35.5 (DT)	28.1 (D-only)
n_T / $(n_D+n_T)(0)$	0.47	0.58	0.42	0
$n_e(0)$ ($10^{19}/m^3$)	10.2	8.5	6.9	9.0
$n_{hyd}(0)$ ($10^{19}/m^3$)	6.7	6.6	6.0	7.0
$Z_{eff}(0)$	2.4	2.0	1.6	2.1
$T_e(0)$ (keV)	13.0	12.0	8.0	8.0
$T_i(0)$ (keV)	36	43	45	25
W (MJ)	6.9	4.9	5.7	3.9
dW / dt (MW)	0.0	3.0	8.5	3.0
τ_E (s)	0.180	0.340	0.165	0.150
$\tau_E^* = W / P_{NB}$ (s)	0.174	0.28	0.161	0.139
$\tau_{ITER89\text{-}P}$ (s)	0.095	0.119	0.074	0.073
$\tau_E / \tau_{ITER89\text{-}P}$	1.89	2.86	2.23	2.05
$n_{hyd}(0)T_i(0)\tau_E$ ($10^{20}/m^3$keVs)	4.3	9.6	4.5	2.6
$n_{hyd}(0)T_i(0)\tau_E^*$ ($10^{20}/m^3$keVs)	4.2	8.0	4.4	2.4
P_{fusn} (MW)	10.7	2.8	8.7	0
P_{fusn} / P_{NB}	0.27	0.16	0.25	0
b_{norm} (mag) (%mT/MA)	1.83	1.35	2.50	1.95
b_{norm} (TRANSP)	1.83	1.5	2.40	1.95
b_{norm}^* (TRANSP)	2.99	3.0	3.9	3.7
κ	1.1	1.1	0.975	0.978
q_{cycl}	3.07	3.61	3.57	5.0
q^*	3.22	3.79	3.47	5.0

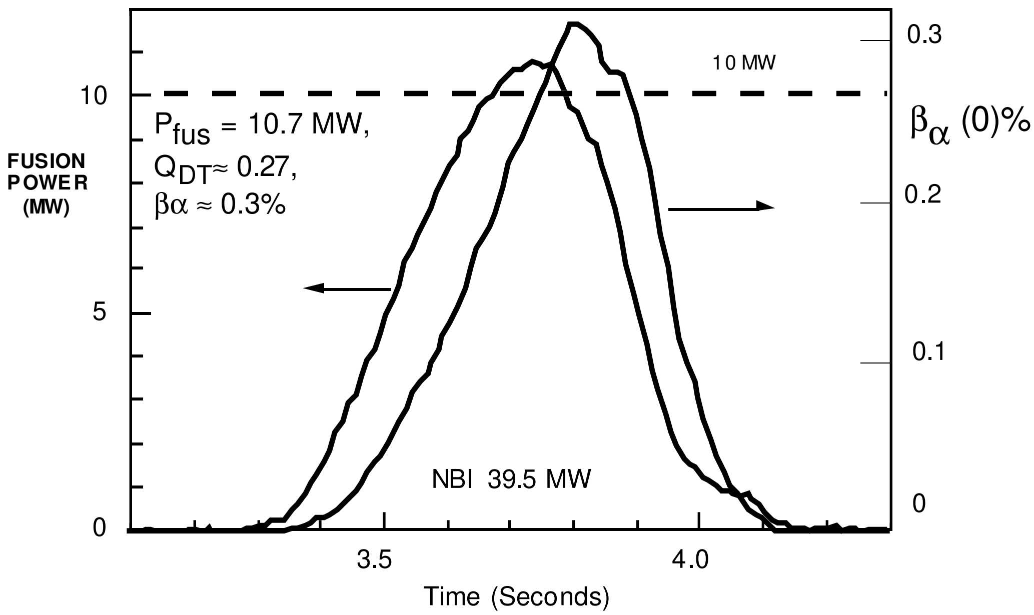

Fig. 1. Time evolution of the DT fusion power and beta alpha from a shot producing the highest instantaneous power of 10.7 MW at 39.5 MW of input power for an instantaneous Q of 0.27.

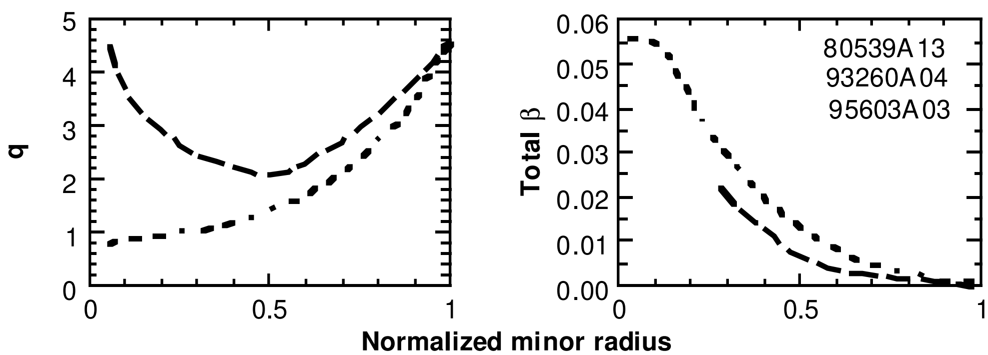

Fig. 2. Experiments in 1995-96 have explored three high-confinement regimes. The solid curves are for supershots with $\beta_{nmax} \leq 2$ which resulted in 10.7MW of fusion power. The short dashed curves are for high l_i discharges with $\beta_{nmax} \geq 2.3$ and P_{DT} = 8.7MW and the long dashed curves are for an enhanced reversed shear discharge with $\beta_{nmax} < 2.0$.

$\beta_{Nmax} \leq 2$	$\beta_{Nmax} > 2.3$	$\beta_{Nmax} \approx 2$
$P_{DT} \leq$ 10.7 MW	$P_{DT} \leq$ 8.7 MW	$P_{DT} \leq$ 5 MW

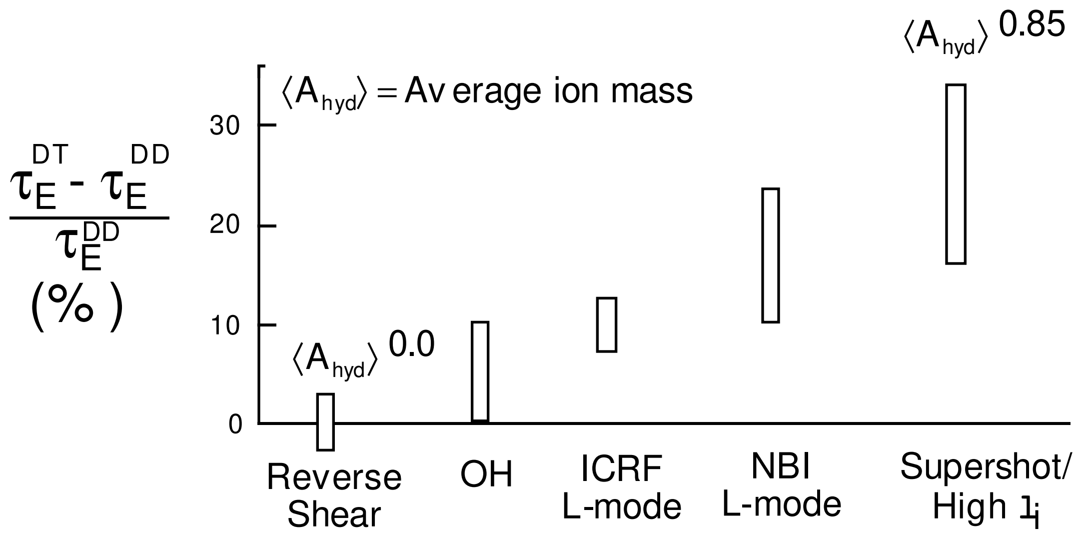

Fig.3. Comparison of the percentage increase in comparable D and D-T plasmas, for the confinement time in reverse shear, ICRF, OH L-mode, supershots and high li regimes . The results are shown for an average mass of the hydrogenic ion of 2.5.

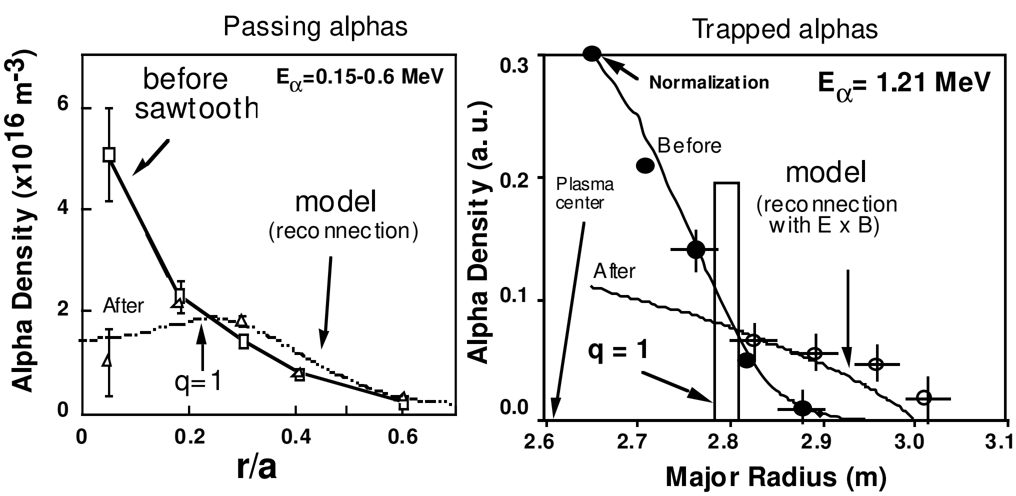

Fig. 4. Radial profiles of confined alphas near the center of TFTR as measured by a) the Alpha-CHERS system for passing particles and b) the pellet charge exchange (PCX) diagnostic. The profile just before the sawtooth crash is very peaked. The saw tooth crash significantly redistributes the alphas from inside to outside the q = 1 sawtooth inversion radius.

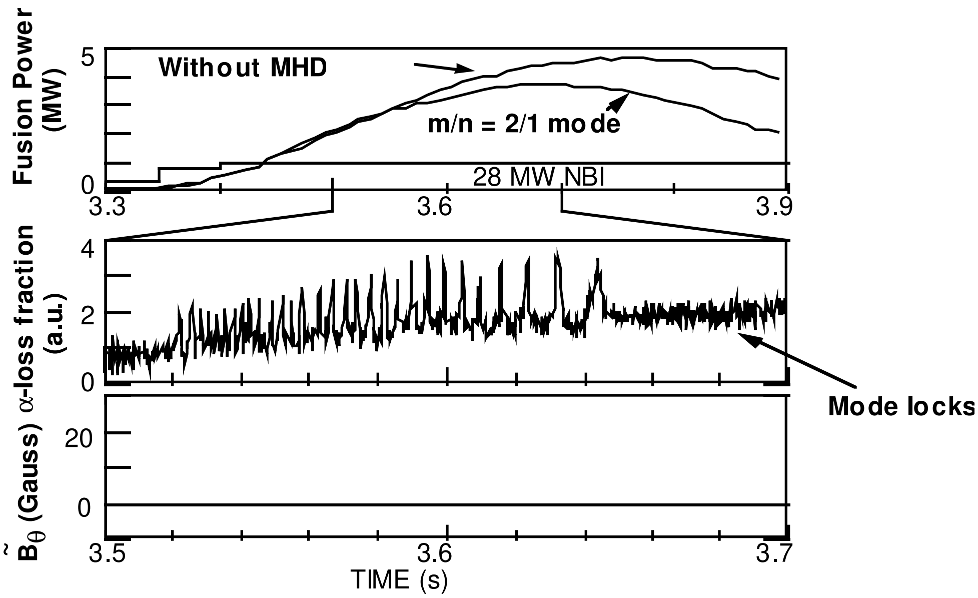

Fig. 5. With D-T operations, it is found that the alpha particle loss can be significant due to the presence of the neo-classical MHD modes.

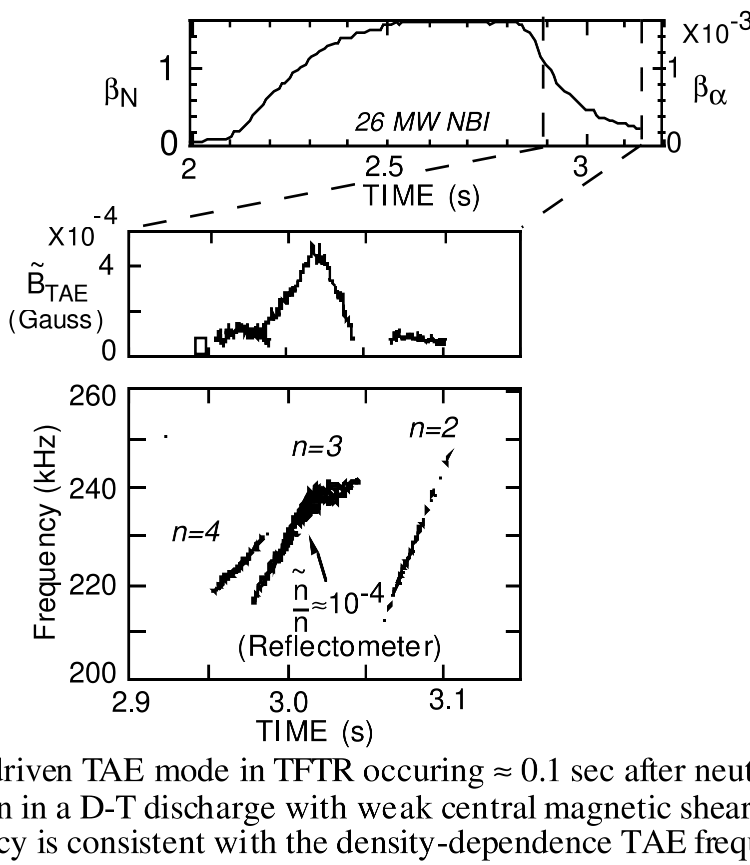

Fig.6. Alpha-driven TAE mode in TFTR occuring ≈ 0.1 sec after neutral beam injection in a D-T discharge with weak central magnetic shear. The frequency is consistent with the density-dependence TAE frequency, and mode timing is roughly consistent with theoretical prediction based on the beam ion damping.

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