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REVIEW OF D-T RESULTS FROM TFTR

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ABSTRACT

During the D-T campaign on TFTR, safe and successful operation has been demonstrated with tritium fuel enabling a broad range of physics studies. Transport studies have focused on the formation of internal transport barriers in the enhanced reversed shear regime. Current profile modification has been employed to study MHD stability in both reversed shear and high l_i discharges. Several important alpha physics topics have been studied including the confinement and loss of alpha particles in both quiescent and MHD active discharges and the effect of alpha-particle heating and alpha-particle destabilization of TAE modes. Plans for future experiments are being discussed.

I INTRODUCTION

The integration of tokamak fusion physics and technology is not only critical to the execution of current experiments but even more important in the design of a reactor in which cost, availability, and safety are of paramount concern. Extensive deuterium-tritium (D-T) operations on the Tokamak Fusion Test Reactor (TFTR) have provided valuable experience for the fusion community in the areas of licensing, tritium handling, operations and maintenance. Furthermore, successful and safe operation of TFTR has enabled the exploration and understanding of the underlying plasma science of the core of a reactor. The key physics issues in a reactor core which are being studied on TFTR are: understanding of the plasma transport mechanisms to improve confinement and control the pressure profile evolution; understanding and control of the mechanisms responsible for magnetohydrodynamic (MHD) stability limits and improvement of β_N^* at low ν^* and ρ^*; and understanding alpha-particle physics and control of alpha-particle interactions including alpha power channeling to ions and electrons and alpha ash removal. By improving plasma confinement and simultaneously increasing the MHD stability limits in advanced tokamak regimes, a broader range of alpha-particle physics issues can be addressed in TFTR.

II MACHINE CONFIGURATION

Since the beginning of the D-T campaign on TFTR in November 1993, the machine capability has been significantly enhanced.[1,2] The maximum toroidal field was increased from 5.2 to 6.0 T at R = 2.48 m. This entailed reconfiguring the power supplies, increasing the maximum power extracted from the motor generator sets from 950 MVA to 1200 MVA and performing a comprehensive integrated system test to operate the coils beyond their nominal design point.

The nearly circular TFTR plasma is limited by an inboard limiter composed of graphite and carbon fiber composite tiles mounted on a water-cooled inconnel backing plate. A set of outboard poloidal limiters composed of carbon fiber composite tiles is used to protect the RF launchers. The limiters can sustain heat fluxes of ~ 30 MW for 1 second. At higher power and/or longer pulse durations carbon blooms occur.

During the D-T experiments, neutral beam heating and RF heating in the ion cyclotron range of frequencies (ICRF) have been used on TFTR. The TFTR neutral beam system is composed of four beams, each with three ion sources. The ion sources can operate either in deuterium or in tritium. The maximum operating voltage is 120 kV and a maximum injected power into a D-T discharge has been increased to 40 MW, compared to a design rating of 33 MW.[3,4]

The TFTR ICRF system utilizes four antennas to launch a fast magnetosonic wave into the plasma. The operating frequency has been varied in support of different experiments. Fast wave experiments were conducted at 43 MHz utilizing ^{3}He minority heating and at 64 MHz utilizing hydrogen minority heating. Operation at 30 MHz is in support of mode conversion experiments in D-T plasmas in which the fast wave is converted into an ion Bernstein wave. In addition, mode conversion experiments have been performed at 43 MHz in deuterium-^{3}He-tritium plasmas.

III TRITIUM PROCESSING

Deuterium-tritium experiments impose additional requirements on the facility to accommodate the use of tritium and the increased machine activation from D-T reactions.

The TFTR tritium gas handling system is restricted to 50 kCi in-process tritium.[5] By restricting the tritium inventory, the accident potential is reduced to personnel working on-site as well as to the general public. The tritium gas is brought on-site in an approved shipping canister and transferred to a uranium bed, where it is stored. The uranium bed is heated to transfer the gas to the neutral beam or torus injection systems. The tritium is then injected into the torus or neutral beam ion sources, and pumped by the cryopanels in the beam boxes. The gas on the cryopanels is transferred to the Gas Holding Tank. The gas in the Gas Holding Tank is oxidized by the Torus Cleanup System and absorbed onto molecular sieve beds. These beds are shipped for reprocessing. More than 780 kCi of tritium have been processed from November 1993 to June 1996. Recently, a low-inventory cryodistillation system was developed to repurify the tritium on-site and decrease the number of off-site shipments of oxidized tritium. This system is in the process of being commissioned.[6,7]

Some of the tritium introduced into the vacuum vessel is retained on the graphite limiter and co-deposited layers on the walls. Retention of tritium in the vacuum vessel walls and components is important for two reasons. The first is associated with regulatory considerations.[8] The quantity of tritium retained must be accounted for since special controls are imposed on the handling of tritium.[9] On TFTR, the quantity of tritium permitted in the vessel is restricted to < 20 kCi to limit release to the environment in the event of a major vacuum leak and simultaneous failure of tritium containment systems. The second reason is that the interaction of the plasma with the limiter and walls results in the exchange of the hydrogenic species in the plasma with the species embedded in the limiters and walls. This can affect the concentration of tritium and deuterium in the discharge.

Since the beginning of D-T operation, a large number of high power D-T (> 786) and D discharges (>17000) were performed. Removal of tritium from the vessel was accomplished by glow discharge cleaning with deuterium and He-O_2 mixtures followed by a moist air purge of the vessel. The tritium retention was reduced from 16.4 kCi to about 8.1 kCi. It would have been possible to reduce the tritium further with additional time. The release of tritium due to exposure to air has also been studied. In a planned moist air purge experiment about 10% of the tritium was released from the vessel surfaces and subsequently processed by the cleanup system.[10] Thus, the experience on TFTR has shown that it is possible to control the quantity of tritium in the vessel within stringent regulatory requirements.

IV D-T NEUTRONICS

The production of D-T neutrons has been used to study effectiveness of shielding and machine activation. Apart from its practical importance to present operation, this is important to the design of future D-T tokamak reactors.

Due to the complexity of the tokamak structure and the surrounding hardware, including the neutral beamlines and diagnostics, accurate simulations of the effectiveness of machine shielding are difficult to perform. The approach taken on TFTR was to augment the shielding calculations with an extensive set of measurements during deuterium operation to characterize the shielding and the consequent dose both within the facility and at the site boundary.[11] The results were then compared with existing shielding calculations assuming a relatively simple model for the machine structure which was then revised to take into account the additional equipment in the Test Cell. The results of the comparison of the original neutronics modeling with the experimental measurements indicated that the calculations were conservative.[12] Prior to the D-T experiments, supplementary local shielding (especially for sensitive diagnostic equipment) was installed; however, the installation of a complex “igloo” shield around the tokamak was found to be unnecessary, resulting in significant cost savings as well as facilitating maintenance of the machine. The requirement for the design of the shielding on TFTR is that the dose at the site boundary from all sources (direct dose due to gammas and neutrons as well as from tritium and activated air) be less than 100 μSv per year. The dose from all pathways has been < 3 μSv per year.

Activation of the machine by high energy neutrons imposes operational constraints in present machines on maintenance and machine modification.[13,14] In TFTR, the level decreases rapidly with distance from the vacuum vessel enabling routine hands-on maintenance on nearly all components in the Test Cell except those very close to the vessel. From November 1993 to September 1995, 4.4×10^{20} neutrons were produced on TFTR resulting in a integrated yield of 1.2 GJ. After a week of cooldown for the short lived isotopes in the stainless steel vessel, the contact dose of the vacuum vessel decreased to 1-2 mSv/hour. Neutronics simulations of the activation of the vessel are in agreement (within a factor of 2) with the measured activation level and have provided a reliable guide for planning and design. This level of machine activation in TFTR experiments has enabled limited hands-on maintenance with considerable attention being given to reducing the duration of the task and providing local shielding.

For the long-term, one of the most challenging tasks for fusion energy development will be to develop low activation materials for a reactor. It is difficult to obtain reliable calculations of the nuclear cross-sections for reactions producing long lived half-life isotopes due to large uncertainties on fitted nuclear-model parameters. Present ex-periments have benchmarked the codes used to predict the level of activation and specific experiments have been performed to document the activation of other possibly lower activation materials for the future.[14,15]

V FUSION POWER PRODUCTION

Operation in both enhanced performance regimes (supershots, high l_i as well as enhanced reverse shear) and L-mode have been conducted to study a wide range of physics topics. The experimental program has focused on operating conditions which produce substantial fusion power, and hence can be used to study alpha and other D-T related issues in reactor relevant conditions. The following is a brief description of these enhanced performance regimes and recent results.

Strachan *et al.*[16] demonstrated that by aggressively conditioning the walls to decrease the recycling of deuterium and carbon from the limiters, enhanced confinement discharges (supershots) characterized by peaked density profiles, with $T_i > T_e$ are obtained. Recently more aggressive wall conditioning techniques employing lithium pellet injection have been used to further suppress the influx of deuterium and carbon and to extend the range of operation. By means of lithium conditioning, the plasma current in supershots has been increased to 2.7 MA, the energy confinement time to ~ 330 msec and values of $n_{HYD}(0)\tau_E T_I(0)$ of $8.8 \times 10^{20} m^{-3}$ •s• keV have been achieved where $\tau_E^* = W_{TOT}/P_{TOT}$.[17]

Enhanced confinement is important since fusion power increases with the stored energy in the plasma as shown in Fig. 1. The maximum fusion power which has been obtained is 10.7 MW in 2.7 MA discharges at $B_t = 5.5$ T.[18] The total fusion yield from a single plasma pulse has reached 6.5 MJ. The fusion power densities achieved in high performance TFTR supershots, 2.8 MW/m^3, are comparable to or greater than those expected in the International Thermonuclear Experimental Reactor (ITER). The highest value of $P_{fusion}/P_{aux} = 0.27$. The measured fusion power is in good agreement with TRANSP analyses which are based on the measured plasma profiles and beam parameters.

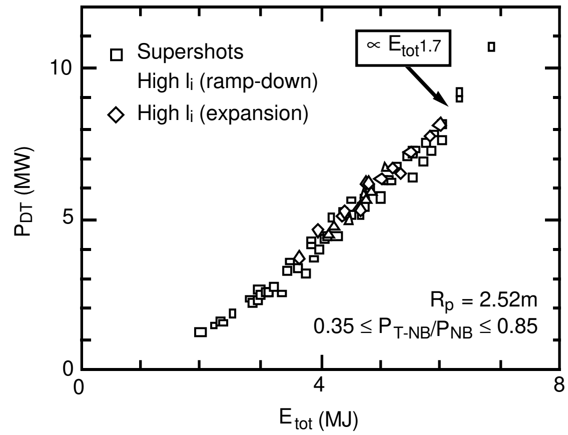

Fig. 1 Dependence of the peak D-T fusion power on total plasma energy in high-current (≥ 2.2 MA) supershots [squares], high-li (internal inductance) plasmas produced by current rampdown from 2.3 MA to 1.5 MA [triangles] and high-li plasmas at 2.3 MA produced by cross-section expansion of low-q (qa ≈ 2.5) ohmically heated discharges [diamonds]. All plasmas have the same volume and a near optimal mixture of D and T in the reactive region. The 2.3 MA high-li plasmas are calculated to have a stored energy limit against pressure-driven MHD instabilities comparable to the highest current supershots (2.7 MA) at higher toroidal field (5.5 T *cf.* 5.1 T).

In high-current, high-field supershot discharges the maximum stored plasma energy, and hence fusion power, is now limited by the onset of a rapidly growing ballooning instability.[19,20] The distortions to the plasmas caused by a large ideal mode appear to push the plasma over the ballooning mode stability boundary. A three dimensional nonlinear MHD code has successfully modeled the observed electron temperature fluctuations.[21] These simulations indicate that the high n-mode becomes even more localized and produces a strong pressure bulge that destroys the flux surface, resulting in a thermal quench. This instability limits the maximum fusion power achieved in supershots on TFTR.

Since MHD stability at present limits the maximum fusion power attainable in TFTR, current profile modification has been used to increase the operational parameter range. Two different operating regimes, high-l_i and reversed shear, have been studied.

In present high performance plasmas, the discharge duration is less than the current relaxation time. Thus by varying the time evolution of the plasma current, it is possible to change the current profile within the plasma and experimentally evaluate the effect of the current profile on confinement and stability. On TFTR, two approaches have been used to obtain high l_i discharges. By ramping down the plasma current, it is possible to transiently increase the peakedness of the current profile and increase the plasma internal inductance. Using this technique, the energy confinement and plasma stability is increased relative to a discharge with a relaxed current profile and the same plasma current. This regime of operation on TFTR is called the high-l_i (or high β_p) regime and has been studied in D-T discharges.[22] More recently another operational approach has been developed in which the plasma is formed on the outer limiter. The minor radius is restricted such that the edge q is ~ 2.5. The plasma is moved rapidly to the inner limiter and then allowed to expand to a near full aperture discharge. This is similar to the κ-expansion technique developed on DIII-D.[23] The current profile expands relatively slowly and, during this phase, the internal inductance is higher. This technique has the advantage that it is not necessary to achieve currents substantially greater than the final current to attain higher values of the internal inductance.

At present, the maximum fusion power produced in the high-l_i regime is 8.2 MW with a stored energy of 6 MJ, which is comparable to that achieved in supershots with similar neutral beam powers as shown in Fig. 1. At this time, the maximum performance is not limited by stability, but by the confinement time. Further development of limiter wall coating techniques will enable a test of the stability limits.

Theoretical studies including those in support of the design of the Tokamak Physics Experiment predicted that by creating a plasma core with reversed magnetic shear it would be possible to reduce plasma transport as well as to increase MHD stability.[24,25] The recent development of operational techniques to create this magnetic configuration coupled with new diagnostics to measure the pitch of the magnetic field lines have resulted in rapid progress and exciting new results on TFTR[26], DIII-D[27], and JT-60U.[28]

To create reversed shear, the TFTR plasma is started at full size and the current is ramped up, forcing the current to form at the edge. Since the current diffusion time is slower than the rise time of the total plasma current, the current density profile, j(r), is hollow during the ramp. A low power prelude heating phase raises the electron temperature from 2 to 5 keV, decreasing the plasma resistivity and slowing the inward diffusion of current. This is followed by the main heating phase of up to 28 MW of beam injection. With variations of beam timing and total current, a range of configurations has been produced, with q(0) in the range from 2 to 5 and q_{min} from 1.8 to 3 according to Motional Stark Effect (MSE) measurements.

The confinement characteristics of reversed shear shots with less than P_{inj}~18 MW in the main heating phase resemble supershots with the same machine parameters. However, above a power threshold of 18 - 20 MW, the core transport changes abruptly at 0.2 - 0.3 sec into the main heating phase within the region of reversed shear. Originally the effect was most clearly seen on the central density evolution which rose by more than a factor of 2 in 0.3 sec. Since the density outside the reversed shear region changed little, the density profile following the transition became very peaked, reaching values of $n_e(0)/\langle n_e \rangle$ ~ 4.2. The core electron temperature increased by 25%, and the ion temperature profile broadened. In recent experiments, very sharp electron temperature gradients (dT_e/dr > 50 keV/m) have been achieved in the region of the transport barrier as shown in Fig. 2.

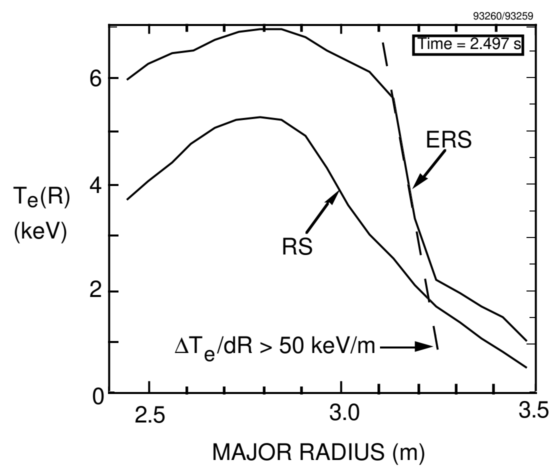

Fig. 2 The electron temperature is observed to develop sharp gradients in enhanced reverse shear discharges.

At the transition, 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.[26] Possible explanations for the inferred sub-neoclassical ion thermal diffusivity are the violation of the assumptions of standard neoclassical theory, the presence of anomalous electron-ion coupling, or a thermal pinch. Recent calculations by Lin *et al.*[29] indicate that a more comprehensive analysis of neoclassical transport which considers orbit dimensions compared with pressure scale lengths is in better agreement with the data in the enhanced confinement regime. Inasmuch as neoclassical transport is usually thought to be the minimum transport possible, these results represent a dramatic improvement in confinement and performance. The local pressure gradient in flux coordinates in enhanced reversed shear (ERS) discharges is larger, by a factor of 3-5, than that in typical supershots with monotonic q profiles, which very often have low-n MHD modes in the core. In the region of reversed shear, MHD activity is absent in ERS discharges as measured by the four channel reflectometer, suggesting that, as predicted by theory, reversed shear plasmas may indeed have greater local MHD stability. However, as the transport barrier moves into the weak or positive shear region, a rapidly growing MHD instability is observed. The maximum pressure appears to be limited in this region by the infernal mode. Comparison of the structure of the observed and calculated mode are in good agreement, and the threshold is in reasonable agreement.

Theories developed to explain the transport barrier formation in H-mode discharges[30] are being investigated to understand the formation of the transport barrier in ERS discharges.[31] The inferred shear in the radial electric field increases in the region of the transport barrier after the transitions. The growth in the shear is driven by the increasing pressure gradient in this region. A model for enhanced core confinement is being investigated whose central features are positive feedback between increased pressure gradients, the accompanying growth in electric field shear, and subsequent turbulence decorrelation and confinement improvement. A competing hypothesis suggests that gradients in the Shafranov shift of reversed shear plasmas lead to favorable drift precession of trapped electrons, and subsequent reduction of turbulence-induced flows. The ERS transition has been correlated with the suppression of turbulence by the ExB shear flow; that is when the shearing rate $\gamma_s \equiv | B_\theta/B)\, d/dr\, (E_r/B_\theta) |$ exceeds the linear growth rate of the turbulence. After the ERS transition, the fluctuation level in the core is dramatically suppressed according to reflectometer measurements.[32]

Recent experiments on TFTR have extended ERS operational regimes from 1.6 MA to 2.2 MA and the region of reversed shear from $r_{min}/a \sim 0.35$ to ~ 0.55 where r_{min} is the minor radius of the minimum value of q(r). Future experiments will extend the operating regimes to higher pressure by controlling the evolution of the current and pressure profile. Modification to the existing RF antennae are planned for installation later this year to provide such control. Mode conversion current drive from two four-strap antennae will be used to tailor the current profile and ion Bernstein waves from a direct launch antenna to control the transport barrier and hence the pressure profile.

VI ICRF HEATING AND CURRENT DRIVE

On TFTR, ICRF heating and current drive have been studied in D-T plasmas. ICRF wave physics in D-T plasmas is complicated by the possibility of multiple, spatially separated resonances and by alpha particle damping which can compete with electron absorption in the fast-wave current-drive regime. A promising scenario for heating D-T plasmas is fast wave absorption at the second harmonic of the tritium cyclotron frequency, which is degenerate with the ^{3}He fundamental. Though core damping is predicted to be acceptable, off-axis absorption near the deuterium fundamental and ion-ion hybrid layer is predicted to compete with the second harmonic tritium core damping in tokamaks with moderate aspect ratio. In TFTR supershot plasmas, with the second harmonic tritium ($2\Omega_T$) layer coincident with the Shafranov-shifted axis at 2.82 m, the $2\Omega_D/\Omega_H$ layer is out of the plasma on the low field side, but the Ω_D layer is in the plasma on the high field side at 5.66 T, or R ~2.1 m. Experiments have been performed utilizing combined ICRF heating and neutral beam injection in D-T plasmas.[33,34] Second harmonic tritium heating with ~5.5 MW (with a 2% ^{3}He minority) in a plasma with 23.5 MW of neutral beam injection (60% in T) has resulted in an increase of the ion temperature from 26 to 36 keV. The electron temperature increased from 8 to 10.5 keV due to direct electron damping and ^{3}He minority tail heating. Similar results were obtained in discharges in which no ^{3}He was added. Because of significant D (and minimal T) wall recycling, n_T/n_e was only ~25% -30% in these plasmas. Despite this relatively low T concentration as much as 70% of the RF power was absorbed by the ions. Comparisons with two independent full wave codes (PICES and TRANSP) show reasonable agreement with the observed ratio of ion to electron absorption as deduced by power modulation techniques.[35]

Majeski *et al.*[36] proposed a novel technique using the mode-converted ion Bernstein wave (IBW) excited at the ion-ion hybrid layer in a multiple ion species plasma (such as D-T) for electron heating or for localized electron currents. In more conventional ICRF heating schemes, fast magnetosonic waves launched by antennas on the low-field side of the magnetic axis propagate into the core, where absorption by minority and/or majority ions occurs as well as some mode conversion to IBW. In plasmas consisting of a majority ion species plus a low concentration minority ion species, RF power absorbed by ions near the cyclotron resonance is enhanced by the presence of a nearby ion-ion hybrid layer. Experiments on TFTR have demonstrated strong highly localized electron heating in multiple ion species plasmas with >80% of the ICRF power coupled to electrons near the mode conversion surface, achieving electron temperatures of ~ 10 keV.

Electron current drive has been demonstrated using the mode-converted ion Bernstein wave by phasing the antenna. This technique has been used to drive 130 kA of on-axis and off-axis current. The experimentally observed RF driven current[37] is in good agreement with the predicted driven current based on the Ehst-Karney parametrization. The combination of high single pass absorption and the ability to drive localized off-axis currents, makes mode conversion current drive a potentially attractive current drive technique which can be used to modify the current in the enhanced performance regimes.

VII ALPHA PARTICLE STUDIES

The behavior of alpha particles from D-T reactions is a fundamental consideration for the performance of a future D-T reactor. If a significant fraction of the alpha particles is not confined, then the $nT\tau$ requirements for ignition will increase; however, the confinement of the resultant alpha ash must be sufficiently short to avoid quenching the reaction. Also, if a small unanticipated fraction (a few percent) of the alpha particles is lost in a reactor such as ITER and the resulting heat flux is localized, damage to first-wall components could result. Thus, a detailed knowledge of alpha particle loss processes is vital to design the plasma facing components to avoid damage by energetic alpha particles.

The loss of alpha particles to the plasma facing components can be due to three generic mechanisms: first, single particle effects due to the structure of the confining magnetic fields; second, alpha particle interactions with MHD instabilities and radio frequency waves; and third, alpha particle interactions with instabilities which are driven by the presence of alpha particles. The main examples of single particle losses are first orbit losses, due to particles born on fat banana orbits which intersect the wall, ripple trapping losses, where particles are mirror trapped between toroidal field coils and drift out of the confinement region, and stochastic toroidal field ripple diffusion, where trapped particles with their banana tips in certain regions can diffuse to the wall due to stochasticity brought on by toroidal field ripple.

An extensive study of fusion product losses has been performed. The results from the detector at the bottom of the vessel (90° detector) during quiescent D-T discharges match the predictions of the first orbit loss model in magnitude, I_p dependence, and in pitch angle distribution.[38,39] Global first orbit losses in TFTR are calculated to vary from 3% of the total source rate at Ip = 2.7 MA to about 50% at Ip =0.6 MA. Further analysis of the outer midplane detectors is being performed to evaluate the contribution from stochastic ripple diffusion.

In major disruptions, losses of energetic alphas estimated to be up to 10% of the alpha population have been observed to occur in ~2 ms during the thermal quench phase while the total current is still unperturbed. Such losses, which are observed mainly on the 90°-detector and hence localized, could potentially have an impact on first-wall components in a reactor.

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.[40] The kinetic ballooning modes are driven by the sharp gradients in the plasma pressure profile. These modes are localized around the peak plasma pressure gradient and have ballooning characteristics. An enhancement of up to a factor of three in the alpha particle loss to the 90^{o} detector was correlated with a bursting kinetic ballooning mode. The resonant interaction of the waves with the alpha particles results in the increased alpha particle loss. This has been simulated using a guiding center code. Similar KBMs are observed in D discharges; so the modes are not driven by the alpha particles but by the pressure gradients in the plasma.

The distribution function of the confined alpha particles on TFTR has been measured using the pellet-charge-exchange diagnostic and charge exchange recombination spectroscopy. The pellet-charge exchange diagnostic has obtained data when lithium or boron pellets was fired into 2.5 MA D-T shots, after the neutral beams had been turned off. The measured shape of the energy spectrum of the alphas in the range from 3.5 MeV down to 0.5 MeV is in good agreement with a TRANSP calculation of the predicted spectrum.[41,42] The alpha population in the lower energy range, 0.1 - 0.6 MeV, has been detected by absolutely-calibrated spectrometry of charge-exchange recombination emission. The measured spectrum agrees with TRANSP predictions both in the absolute intensities (within experimental error of 30%) and the spectral dependence, assuming classical collisional slowing down and neoclassical confinement.[43] Measurements of the spatial profile agree with TRANSP, and constrain the value of any anomalous radial diffusion coefficient to less than 0.03 m^2/sec, in addition to the neoclassical coefficient which is estimated to be 0.01-0.05 m^2/sec.

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. 3.[44] In these sawtooth cases, no enhanced alpha loss appears on the edge scintillator probes, but the range in pitch angles which these detectors view does not include the narrow range viewed by PCX. In addition, charge-exchange-recombination-spectroscopy has been used to measure the alpha particles with energies up to 600 keV in a D-T pulse soon after the T-beams have been turned off, but with D-beams remaining on to allow the measurement. The signal from these intermediate energy alpha particles is observed to be smaller in a discharge where a sawtooth occurred prior to the observation compared to one with a sawtooth after the observation period.[45] The effect of the sawtooth on the alpha particles has been modeled and found to be in reasonable agreement with the measurements.

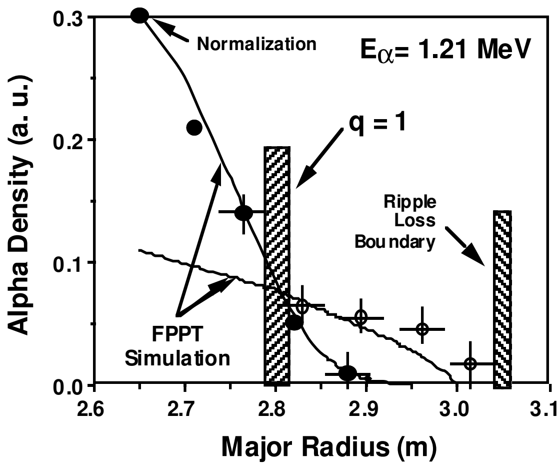

Fig. 3 Pellet charge exchange measurements of the alpha distribution before and after a sawtooth crash show a large radial redistribution of the alpha particles. The radius of the q = 1 surface is indicated as well as the ripple loss boundary. the measurements are in reasonable agreement with the Fokker-Planck-Post TRANSP (FPPT) simulation which imports the alpha distribution from TRANSP and calculates the energy distribution matching the pitch angle appropriate for PCX.

The PCX diagnostic has also been used to test the predictions of the stochastic ripple diffusion models which predict that in certain regions of the plasma the nearly perpendicular particles, which PCX measures, will be lost. As shown in Fig. 4, PCX results are consistent with the energy and q scaling of the Goldston-White-Boozer formalism for the ripple loss threshold.[46] Work is in progress to compare PCX data with the predictions of orbit following codes[47] which in turn are used to specify the toroidal field ripple requirements on ITER and other tokamak reactors.

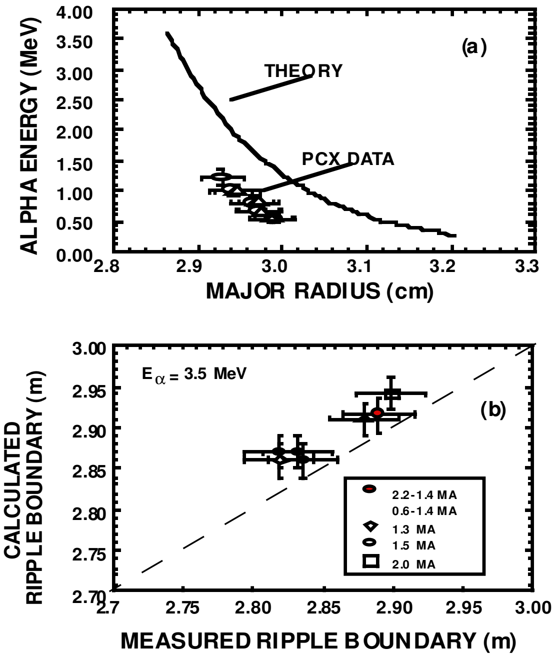

Fig. 4 The pellet charge measurements of the stochastic ripple boundary are compared with the predictions of the GWB stochastic ripple diffusion model. The data in (a) is consistent with the predicted energy dependence and in (b) with the predicted variation with q.

The production, transport, and removal of helium ash are issues that have a large impact in determining both the size and cost of a future reactor such as ITER. D-T operation provides a unique opportunity to measure alpha ash production and transport. Radial ash profiles have been made using charge-exchange recombination spectroscopy. Differences of the time history and amplitude of the thermal helium spectrum between similar D and D-T supershots allow the alpha ash profile to be deduced. These measurements have been compared to predictions from the TRANSP code, using transport coefficients from earlier gas puffing experiments in deuterium plasmas and the TRANSP calculation of alpha particle slowing-down and transport upon thermalization. The ash profiles are consistent with the TRANSP modeling, indicating that the ash readily transports from the central source region to the plasma edge. These measurements provide evidence that, in the presence of a central helium ash source, the ash transport and confinement time are roughly consistent with gas puffing measurements, and indicate that helium transport in the plasma core will not be a fundamental limiting factor for helium exhaust in a reactor with supershot-like transport.[48] Experiments are being performed to evaluate the confinement of He and impurities within the transport barrier in ERS discharges.

Previous experiments in TFTR, JET, JT-60U and DIII-D have shown that the toroidal Alfvén eigenmode (TAE) could be destabilized by the energetic ion populations created either by neutral beam injection (NBI) or ICRF heating.[49] These instabilities can be sufficiently strong to eject a large fraction of the fast particles and to damage first wall components. The initial D-T experiments in TFTR, however, showed no signs of instability in the TAE frequency range, and the alpha-particle loss rate remained a constant fraction of the alpha production rate as the alpha pressure increased, suggesting that deleterious collective alpha instabilities were not being excited. Theory has since shown that, although TFTR achieves levels of the alpha-particle driving terms nearly comparable to those of a reactor, the damping of the mode in TFTR is generally stronger than the alpha-particle drive. Experiments with ICRF have found that the RF power threshold for the TAE instability is 20% lower in D-T plasmas compared with similar D shots.[50] Analysis suggests that this is due to the fusion alpha particles.

Recent theoretical calculations have shown that the predicted alpha-driven TAE threshold is sensitive to the q-profile and the plasma β. Very preliminary results indicate the presence of a weak toroidal Alfvén eigenmode driven by alpha particles just after the high power heating phase has ended. During this phase, the beam ion density and plasma pressure is decaying more rapidly than the alpha pressure. These interesting results are being studied further to confirm the identity of this mode.

In the highest performance supershots produced so far, the alpha-particle heating of the electrons amounts to only about 1 MW out of a total of about 10 MW to the electrons, making its detection difficult. Nevertheless, the electron temperature rise in D-T shots during beam injection is greater than in D-only or T-only shots.[2,51,52] Recent analysis indicates that the change in electron temperature can be attributed to both α-heating and isotope effects.[52] However, when the database is constrained to take into account the change in electron temperature associated with confinement, the residual change has been determined to be in reasonable agreement with the predicted alpha heating. Further experiments with a higher ratio of alpha heating to beam heating power will be required to evaluate the efficiency of alpha heating.

Several techniques have been proposed to use alpha particle-wave interactions to more effectively utilize the alpha particles in a reactor.[53,54,55,56] By coupling the alpha particles to a plasma wave which then deposits its energy in the plasma it is theoretically possible to: transfer the energy of alpha particles preferentially to the ions and increase the plasma reactivity and reduce the alpha pressure; radially redistribute the alpha particles for alpha-ash control; control the alpha-heating profile which may enable pressure profile control in a tokamak; control the alpha-pressure profile which may further reduce the drive for adverse alpha particle instabilities; and transfer momentum to the electrons for current drive. While it may not be possible to achieve all of these objectives simultaneously in a reactor, this approach offers additional flexibility which may be important to the operation of an advanced tokamak reactor which requires pressure and current profile control while using as little auxiliary power as possible. Experiments on TFTR have focused on understanding the physics of energetic particle interaction with plasma waves which is a central issue for these approaches. The experiments have utilized a mode converted fast wave. In D-^{3}He plasmas, strong interaction between the mode converted wave and beam ions has resulted in strong beam ion heating. The pitch angle and energy of escaping energetic ions are in reasonable agreement with alpha particle-wave model. In addition, experiments in D-^{3}He with T gas puffs have demonstrated strong interaction with alpha particles. The recently modified 30 MHz ICRF system enables operation in D-T plasma without the complicating presence of ^{3}He. Recent experiments have demonstrated electron heating in a D-T plasma to establish the wave physics in this regime. Further experiments will aim at demonstrating extraction of energy from the particles to the wave using a modified ICRF launcher with a more directed wave spectrum. These experiments are necessary to study the physics required to establish the feasibility of alpha channeling.

VIII CONCLUSIONS

Safe and successful operation of a D-T tokamak has been demonstrated. During the 2 1/2 years of operation with D-T, the TFTR device has met and exceeded the design requirements for the device, as well as fully satisfying the stringent safety requirements of the Department of Energy. This has permitted the study of transport, MHD stability and alpha-particle physics in high performance and novel operating regimes.

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 steepening of the plasma pressure gradients. Future experiments will concentrate on understanding the physics of the barrier and on controlling the barrier by IBW.

Recent results in the high l_i regime have demonstrated good energy confinement and favorable MHD stability enabling the achievement of fusion power production comparable to that achieved in supershots at similar powers. By means of more aggressive wall conditioning techniques, it should be possible to increase the energy confinement time and challenge the MHD stability limits.

Experiments in the reversed shear regime find that ballooning modes are stable as predicted. However, as the transport barrier moves out toward the region of weak or positive shear, infernal modes are observed. Future experiments will emphasize implementing techniques to control the pressure and current profile using ion Bernstein waves to generate a transport barrier and mode conversion current drive.

New and novel operating modes have advanced our understanding of alpha-particle physics. In the supershot regime, the first indications of alpha heating have been observed. By increasing the MHD stability limits while simultaneously achieving enhanced confinement, these new operating regimes will enable extension of the study of alpha heating. Furthermore in the weak shear regime, preliminary results indicate the onset of the alpha driven Toroidal Alfvén Eigenmodes. Further experiments are planned to validate the identification of these modes.

Modification of the ICRF frequency to 30 MHz has enabled the study of alpha particle-wave interaction in a D-T plasma in order to test the underlying physics concepts associated with alpha channeling.

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