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TFTR DT experiments

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Abstract. The Tokamak Fusion Test Reactor (TFTR) is a large tokamak which has performed experiments with 50:50 deuterium–tritium fuelled plasmas. Since 1993, TFTR has produced about 1090 D–T plasmas using about 100 grams of tritium and producing about 1.6 GJ of D–T fusion energy. These plasmas have significant populations of 3.5 MeV alphas (the charged D–T fusion product). TFTR research has focused on alpha particle confinement, alpha driven modes, and alpha heating studies. Maximum D–T fusion power production has aided these studies, requiring simultaneously operation at high input heating power and large energy confinement time (to produce the highest temperature and density), while maintaining low impurity content. The principal limitation to the TFTR fusion power production was the disruptive stability limit. Secondary limitations were the confinement time, and limiter power handling capability.

1. Introduction

Tokamak fusion research has concentrated upon resolving the issues for power production from the d(t, n)α fusion reaction. However, most experiments have not used tritium, due to the difficulty of handling the radioactive gas and of dealing with the 14 MeV neutron activation. In 1993, TFTR became the first tokamak experiment to use 50:50 deuterium–tritium fuelling [1, 2] and in April 1997 the TFTR experiment stopped operation. This paper will summarize some significant results from the TFTR tritium campaign.

TFTR was designed in the mid-1970s during a time of rapid progress in tokamak fusion research. The very first neutron measurements on a tokamak were reported in 1972, from T-3 [3], at the level of 0.1 mW from d(d, n)3He fusion reactions. In 1994, TFTR achieved 10.7 MW of d(t, n)α fusion power, with central plasma parameters (n, Te, Ti) comparable to those required in an ignited reactor. TFTR has large enough ion temperatures and energetic beam ion energies, that the ions were near the peak of the D–T fusion cross section, so that the central D–T fusion reactivities about equalled those expected in an ignited tokamak. The difference between the TFTR plasma and an ignited plasma is the role of the alpha particles in the plasma energy balance. On TFTR, the alpha heating was just observable and contributed, at most, up to about 15% of the power to the central electrons. On the other hand, the energy balance in an ignited plasma will be dominated by the alphas since the conduction losses from the reactor will be smaller (due to the larger size and correspondingly smaller temperature gradients).

During the TFTR tritium campaign, 225 refereed publications have so far been produced from TFTR experiments. A rather complete survey of those results is being made by Hawryluk [4]. This paper summarizes only a small part of the TFTR research, namely the TFTR results on the fusion power production, the limitations to the fusion power production, and the alpha particle behaviour in the supershot regime.

2. TFTR experiment

TFTR was a circular tokamak ($R = 2.52$ m, $a = 0.87$ m, $B < 6$ T, $I < 3$ MA) which had neutral beam (<40 MW, 120 kV) and ICRF (<10 MW) auxiliary heating systems. The tritium fuelled the plasma either by gas puffing or by tritium neutral beam injection. 80% of the approximately 1090 tritium TFTR plasmas used beam fuelling while the remaining 20% had tritium gas introduced at the plasma edge—often at trace levels for particle transport purposes. Extensive tritium gas puffing combined with tritium neutral beam heating was used only in determining the isotope effect in L-mode plasmas.

During the campaign of more than 3 years, about 1 MCi of tritium (100 g) was processed while maintaining a 50 kCi site limit. During the last 3 months of TFTR operation, the tritium was processed on site, with a tritium purification system (TPS). The tritium and the 14 MeV neutrons have caused contamination and activation of the machine components. Routine maintenance, recovery from technical problems (neutral beam source replacement, small vacuum repairs, electrical bus replacement), and apparatus installation (RF antennae, lithium vapourization system and the TPS) occurred without remote handling equipment. During this time and also during the post operation shutdown, the radiation doses to PPPL workers were maintained at pre-tritium levels. The key factors, which allowed this safety record, were thorough documentation of the installed hardware and careful planning of all activities.

TFTR's last plasma was on April 4, 1997. 35% of the approximately 5 g of tritium introduced into the vessel remained after the last plasma. Some had been removed at a tritium cleaning campaign in November 1995, so that 50–60% of the tritium introduced into the vessel remained after normal operations. A 5 week tritium removal campaign [5] reduced that level to about 13 kCi (25% of all the tritium ever introduced into the vessel) which was considered to be tenaciously held. The tritium removal campaign consisted of discharge cleaning, glow discharges, vessel bakeout, and moist air purges. The most air purges were the most effective at removing tritium. The vacuum vessel and neutral beam sources remain on a continuous purge system (outgassing at a few Ci per day) while documentation of the tritium retention in vessel dust, the limiter tiles, and in the co-deposited is completed.

3. Fusion power production

One goal of the TFTR program was to obtain its maximum possible fusion power. By achieving the maximum possible alpha population, the alpha particle phenomena would be most readily observable. The physics associated with the fusion power production is the energetic ion physics studied extensively, on many devices, and summarized in the review article [6] by Heidbrink and Sadler (figure 1). On these devices, the measured d(d, n) fusion rates, typically, agree within the quoted uncertainties of calculations. These calculations describe the deposition of the beam ions inside the plasma and predict their ability to produce fusion reactions while the ions slow through Coulomb collisions. Usually, the energetic ions are assumed to have no spatial transport.

The TFTR D–T results for supershot plasmas also agree with these calculations. The TFTR D–D results, shown with the plus signs in figure 1, are from deuterium plasmas just preceding and interspersed amongst the D–T plasmas. This data represents all the plasmas where the tritium levels were sufficiently low that the D–D fusion rate could be determined. Both the D–D and D–T results are compared to the SNAP analysis code. The TFTR results, quoted by Heidbrink and Sadler, were taken in 1989 and 1990 and compared to the TRANSP and SNAP codes, which each had the same relation to experiment. However, these earlier calculations did not include depletion of the deuterium by hydrogen (from the walls) which is now known to have been about 10–15% of the hydrogenic influx observed in TFTR plasmas. Thus the experimental D–D fusion results did not change from 1990 to 1993, but the calculated values have been decreased. The experimental D–D neutrons were slightly below theory in 1990, while being slightly above in 1993 to 1997. The disagreement, in each case, was approximately the uncertainty in either the neutron measurement, or of the ensemble of measurements that make up the kinetic analysis.

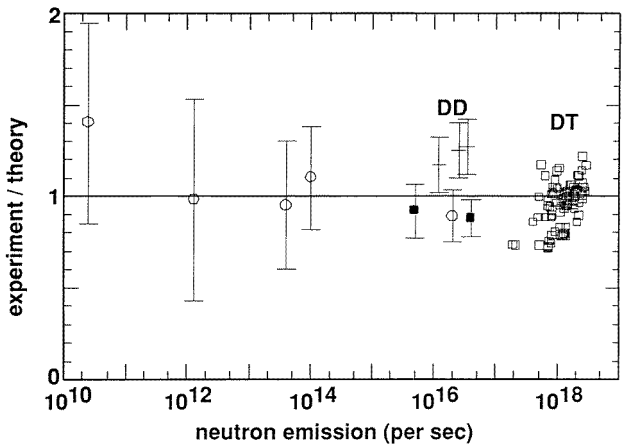

Figure 1. Ratio of the experimental neutron emission to the calculated emission. Open circles, data from the Heidbrink and Sadler review [6]; 'plus' points, TFTR D–D data (about 200 plasmas averaged, with error bars being the standard deviation of the data); open squares, 65 individual TFTR (nominally 50:50) D–T plasmas; full squares, TFTR D–D data from 1989 and 1990 [6].

An interesting aspect of figure 1 is the relation between the D–D and D–T comparisons to theory. The data were taken over the same time period, measured by the same diagnostics, and calculated by the same code. Cross section errors are probably not the reason for the different relation to the calculations. It would seem that the tritium beam ions were exhibiting some anomalous behaviour, or that there was a measurement difference between deuterium and D–T plasmas. Some diagnostics which experienced differences were the neutron calibration which was different for D–D than for D–T, the ion temperature measurements by charge exchange recombination fluorescent spectroscopy, which often used tritium beams for the light instead of deuterium beams, and the calibration of the neutral beam power, which was studied more extensively in deuterium than in tritium. The remainder of the plasma diagnostics (electron temperature from electron cyclotron emission, Z_{eff} from visible bremsstrahlung, and the density from infrared interferometry) were unlikely to be different between deuterium and D–T, although the neutron noise was higher in D–T.

The dominant empirical scaling of the D–D or D–T fusion power is with energy content (figure 2), and the calculations of the expected D–T neutron emission also scale similarly. At the same magnetic energy content, the measured electron, thermal ion and energetic ion energy contents were similar for deuterium (figure 3) and D–T plasmas (figure 4). Moreover, the relation between the total kinetic energy content and the magnetic energy content were similar. This indicates that the difference between the deuterium and D–T plasmas probably did not lie in the thermal plasma measurements, the calibration of the beam power, nor in the energetic tritium ion behaviour.

The prediction of the D–D fusion rates was underestimated (figures 1 and 5) while the prediction of the D–T fusion rates was slightly overestimated (figures 1 and 6). Most likely, the difference originated with the different D–D and D–T neutron calibrations. Although the neutron detectors and calibration techniques [7] are the same, the calibration sources are different (Cf for D–D and a 14 MeV neutron generator for D–T) so differences exist in the absolute calibration using these sources. The quoted accuracy of the neutron calibrations had a standard deviation of 10–15%, which was also the magnitude of the differences observed in figures 1, 5 and 6.

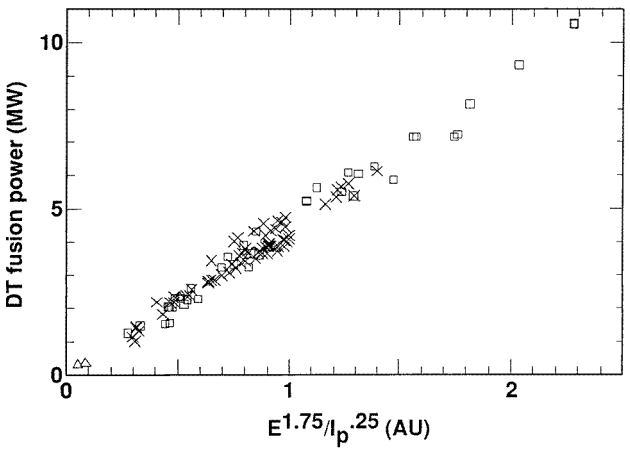

Figure 2. The empirical scaling of TFTR D–T fusion power production determined by regression analysis and limited to plasmas with a fixed size ($R = 2.52$ m). The $\times$ points, supershot plasmas without lithium conditioning; open squares, plasmas aided with lithium conditioning; triangles, L-mode plasmas. E is the total plasma energy, and I_p is the plasma current.

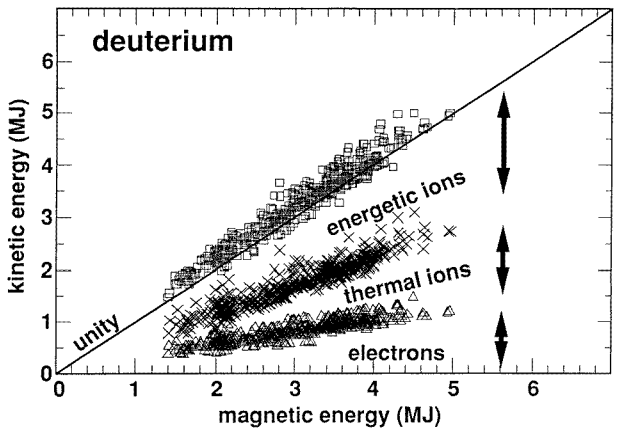

Figure 3. The SNAP calculated kinetic energy content and the energy components for 350 deuterium plasmas.

4. Performance limitations

Empirically, the fusion power production (figure 2) depended primarily upon the plasma energy content. The fusion power was maximized by maximizing the product of the input heating power and the energy confinement time (figure 7). There were three main limitations to the plasma energy content depending on where the plasma existed in (τ_E, P) space.

At low beam powers (<15 MW), the energy confinement time was the limitation. The maximum beam heated confinement time was 0.33 s. On TFTR, the confinement time was, in turn, constrained by limiter influxes. The supershot confinement time scaled with parameters that correlated to the limiter influxes. A direct regression of the confinement time, at peak energy content, to the deuterium influx indicated a good correlation in a dependence

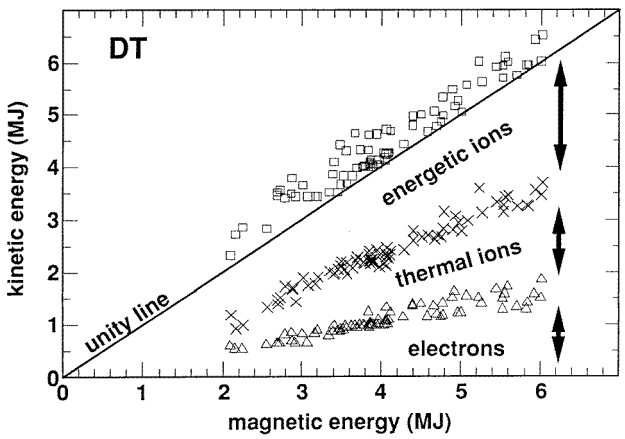

Figure 4. The SNAP calculated kinetic energy content and the energy components for 65 nominally 50:50 D–T plasmas.

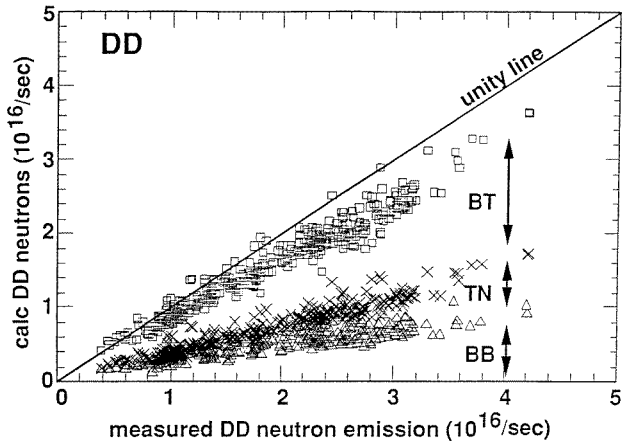

Figure 5. The D–D neutron emission and components as calculated by SNAP for the deuterium plasmas where the D–T neutron emission was low. BB are the beam–beam reactions, TN are the thermonuclear reactions, and BT are the beam target reactions.

that appears similar to a particle confinement time (figure 8) [8]. Simultaneously, good correlations, to the same data, were found with parameters such as peakedness of the beam fuelling (figure 9) [9], or the edge ion temperature. Experimentally, such correlations were difficult to separate since an increase in the limiter influx was accompanied by an increase in the edge density, which was necessarily accompanied by reductions in the beam penetration and the edge ion temperature. Whichever the underlying physical process, the confinement was increased by reduction of the deuterium influxes from the limiter. On TFTR, the control of edge influxes has been achieved by improvements to limiter conditioning (transition from L-mode to supershot) and, further, by the use of lithium conditioning [10]. The favourable role of thin layers of lithium on plasma facing components is thought to relate to the low work function of lithium. Lithium is different from all other materials in that it is more likely to come off the plasma facing component as an ion rather than a neutral. As an ion,

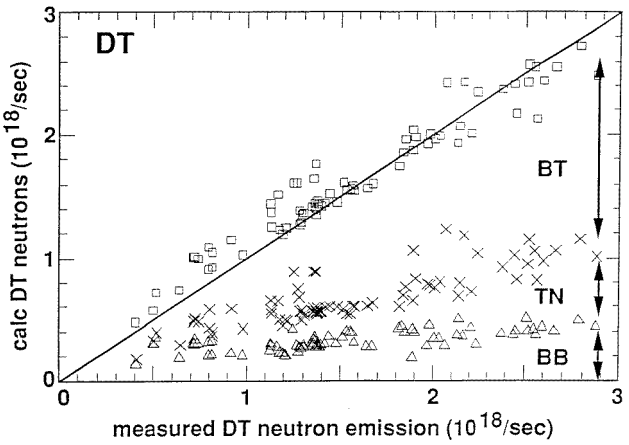

Figure 6. The D–T neutron emission and components as calculated by SNAP for the nominally 50:50 D–T plasmas.

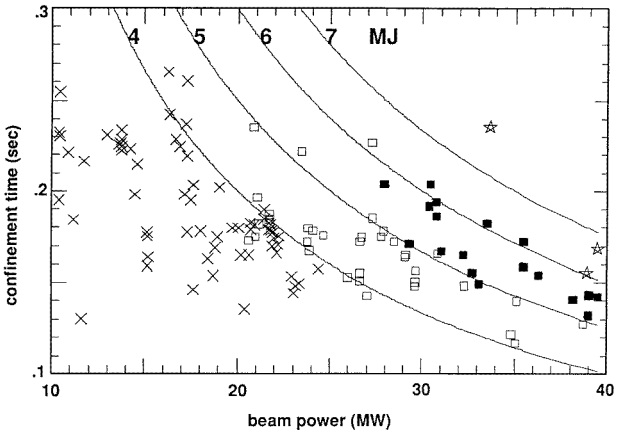

Figure 7. The measured energy confinement time plotted against the applied beam heating power for the nominally 50:50 D–T plasmas. The curves represent constant energy content. The different symbols indicate different observed D–T fusion powers (× points, <4 MW; open squares, 4–6 MW; full squares, 6–8 MW; and the stars >8 MW).

the lithium is likely to remain in the scrape-off layer and return to the walls, never reaching the plasma boundary. We speculate that lithium can thus reduce the influx from the limiter, as well as the edge density. At the time of TFTR shutdown, a new technique for lithium introduction, using laser vapourization [11], was being evaluated and did show promise. This technique allowed more control on the timing and amount of lithium introduced and was less perturbative than previous (pellet ablation) techniques.

The second limitation occurred at the highest beam powers (>30 MW) and was due to limiter power handling. In preparation for the D–T experiments, the TFTR inner wall carbon limiter had been reworked several times in order to strengthen it, and to distribute more evenly the power over the limiter surface. This engineering eliminated the severe influxes called blooms. However, presumed rough edges and thick co-deposited layers still

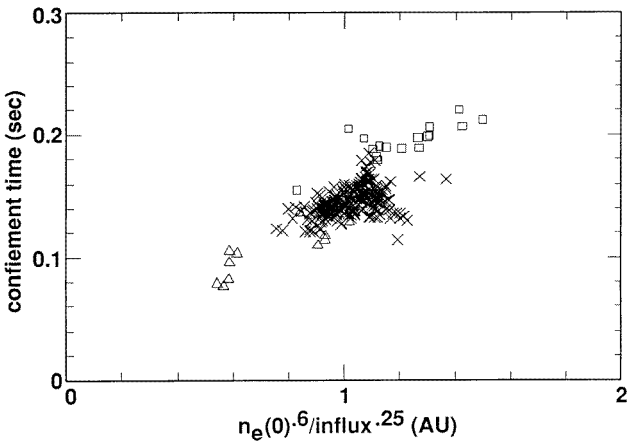

Figure 8. Correlation of the global energy confinement time (measured at peak energy content) with parameters including the deuterium influx. The exponents were obtained by regression analysis.

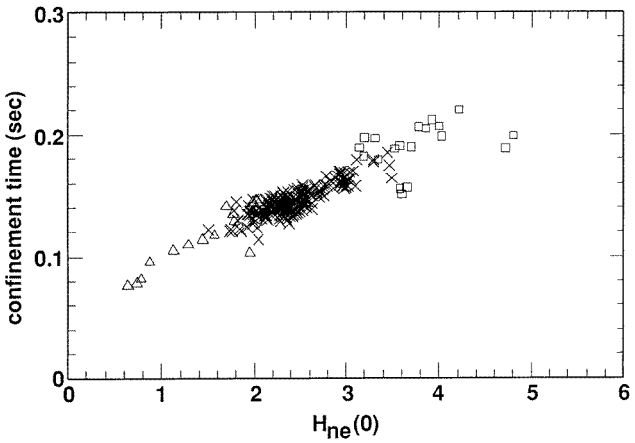

Figure 9. Energy confinement time for the data in figure 5 plotted against the peakedness of the neutral beam fuelling [8].

needed to be removed by conditioning. Empirically, the wall was conditioned for high-power operation by several techniques including repeated high-power operation. This step was difficult when the beams were operated in tritium since the tritium beams achieved about 20% more power (due to their greater neutralization efficiency) and thus the conditioning had to be performed in tritium. The limited tritium inventory was not able to accommodate the required number of plasmas to complete this step. The consequence of operation with a deconditioned limiter was an increased limiter influx and a reduction in confinement with time (termed rollover) which was correlated to the time evolution of several plasma parameters as in figures 8 and 9. Experiments performed near the end of TFTR operations showed promise at radiatively controlling [12] the limiter handling problems. At lower beam powers (<20 MW), the introduction of controlled impurities (Xe, Kr, and Ar) was successful in radiating the power without significant reduction in global energy confinement.

The third major limitation was in stability which appeared on TFTR as pressure-gradient driven, high-m ballooning modes that were 30 μs precursors to plasma-terminating disruptions. These tended to occur at the highest confinement (i.e. the heaviest conditioned by lithium) when the beam power was raised above 15 MW. These plasmas also featured the highest density peakedness and the largest pressure gradients. The net result was that the achievable normalized β was reduced as the energy confinement increased [5]. This reduction made it difficult to use the highest confinement to increase the fusion power. If the highest confinement plasmas had been stable at the highest beam power, then two to four times more DT fusion power would have been achieved.

A similar performance-related degradation in the stability limit was observed in TFTR toroidal magnetic field scans of the disruptive stability limit. The stability limit had a normalized beta of 3.2 of TFTR operation at 2 T. However, at 5 T, the limit was 1.9 and, moreover, the nature of the limit changed from a soft confinement degradation at 2 T to a hard disruption above 4 T. The underlying physics may relate to the large gyro-radii or lower electrical conductivity of the low-field experiments. Recent TFTR experiments were aimed at modifying the stability limit by modification of the plasma current profile. These experiments showed promise, including interesting confinement modifications [13].

The maximum Q that TFTR achieved was approximately 0.3. One of three possible modifications to TFTR may have achieved $Q = 1$.

(1) If the neutral beams were changed to negative-ion neutral beams, then the one-half and one-third energy components of the beam heating would be eliminated. Since the full energy component was calculated to be most useful in producing fusion reactions in TFTR, these lower energy components had primarily the negative effects of taking up some of the stability limit and of making the limiter power handling more difficult. Since about one half of the TFTR beam power was in the lower energy components, then significant improvement in Q could be obtained with negative-ion neutral beam heating.

(2) If the stability limit obtained at lower magnetic field could have been obtained at the highest toroidal magnetic field and the highest confinement times, then the increased energy content would cause, by the scaling of figure 2, $Q = 1$ to be obtained. If the toroidal magnetic field dependence actually turns out to be related to an average gyro-radius, then the higher beam voltages of the negative-ion neutral beams might have been helpful.

(3) If the toroidal magnetic field coils were changed to allow cooling to liquid nitrogen temperatures, then the TFTR power supplies could have supplied 8 T magnetic fields. A normalized beta of 1.9 at 8 T would have provided enough stability for $Q = 1$ to be achieved.

The largest fusion power TFTR achieved was in October 1994 when 10.7 MW of D–T fusion power was produced using 39.6 MW of beam heating (figure 10). In order to avoid the disruptive stability limit, the plasma was operated with less than maximum lithium conditioning, and therefore reduced confinement. The confinement rollover (observed as the reduction of fusion power in time, in figure 10) was ascribed to the limiter influx and limiter power handling difficulties. The plasma was calculated to produce central alpha densities of 2×10^{17} m^{-3}.

5. Alpha particle physics

TFTR had many features which helped the understanding of the 3.5 MeV D–T alpha particle behaviour. TFTR had a comprehensive set of alpha particle detectors [14–17], a plasma current which was varied to change the classical first orbit losses from 2 to 50%, and also achieved reactor-relevant alpha densities. Although the information has not been fully

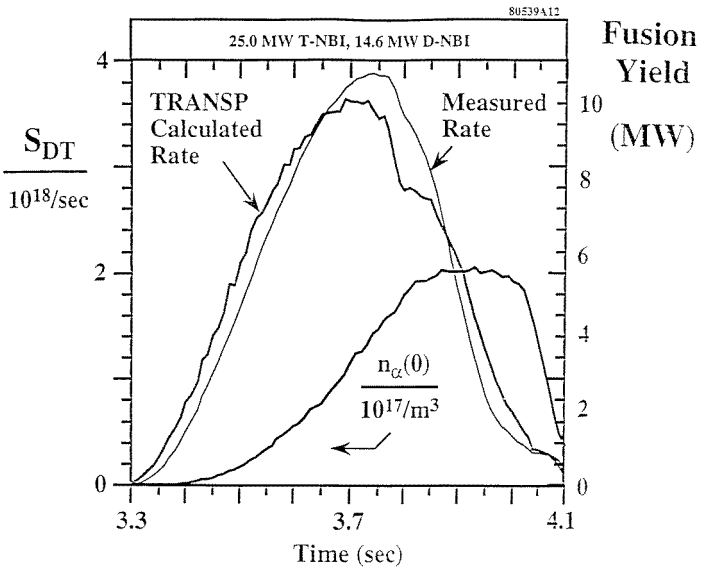

Figure 10. Time evolution of the fusion power, the TRANSP calculation of the fusion power, and the TRANSP calculation of the central alpha density for the TFTR plasmas that had the highest fusion power.

Table 1. Qualitative estimates of the MHD correlated alpha loss.

Type of MHD	Magnitude of loss
Sawtooth (at reconnection)	$\ll$1%
Kink/tearing modes ($n = 1$–2)	1–5%
Kinetic ballooning modes ($n = 6$)	1–5%
Plasma disruption (at reconnection)	$<$10%

analysed, the alpha particles generally show classical, benign behaviour and their energy is transferred to the bulk plasma. The D–T alpha confinement is good, although predictably influenced by classical first-orbit losses, toroidal field ripple losses [18] and MHD events [19] (table 1). In all observations, the alpha particles were similar to other energetic ions (neutral beam ions, ICRF tail ions, and D–D charged fusion products) that have been extensively studied in tokamak plasmas [6].

In MHD quiescent plasmas, the D–T alpha transport coefficient can be defined in a manner similar to the other energetic tokamak ions [6] (figure 11). The thermalization of the energetic ions by collision with the plasma electrons places a limit on the ability to measure energetic ion spatial transport. For energetic ions in tokamak experiments, the diffusion coefficient has usually been below the detection limit. The same observation applies for the TFTR D–T alphas. However, the limit on the alpha assessment was about three times lower than for the other ions, since the confined-alpha diagnostics have good spatial and energy resolution, and the lost alpha measurement system detected even a small flux of particles crossing the passing–trapped boundary. Once an alpha became trapped, first orbit loss moved it to the detectors outside the plasma. One limitation on the alpha measurements is that each is sensitive to only a small part of velocity space. Thus it is possible that an undetected part of the alpha population had high anomalous losses.

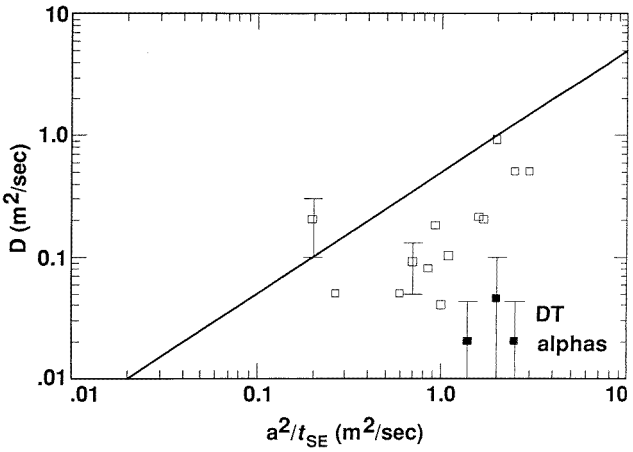

Figure 11. Experimental energetic-ion diffusion coefficient plotted against the coefficient that would be calculated if electron slowing were interpreted as spatial diffusion. Open squares, D–D fusion products, RF tail ions, and beam ions from Heidbrink and Sadler [6]; full squares, TFTR alpha particle data.

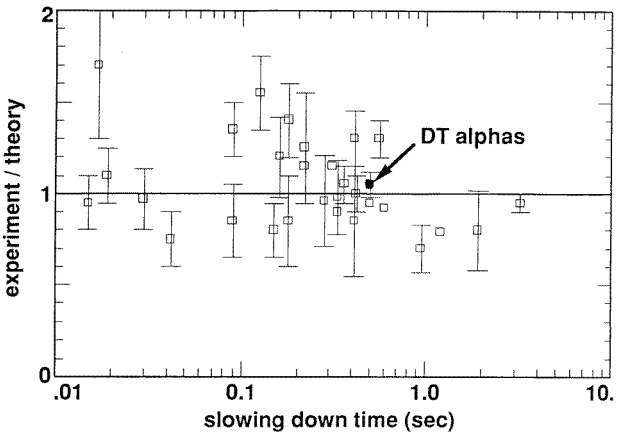

Figure 12. The relation of the observed energetic ion slowing time to that expected for Coulomb collisions. Open squares, the tokamak literature on beam and D–D fusion product ions [6]; full squares, TFTR alpha particle data.

Similarly, the thermalization rates of the D–T alphas were consistent with Coulomb collisions on the electrons (figure 12) as is typically observed for other energetic ions such as D–D fusion products and beam ions. The D–T alpha measurement was made using the confined alpha diagnostics to measure the energy distributions and time delays that occurred after the creation of short bursts of alphas [20].

Since the alphas were confined and thermalized at rates consistent with electron collisions, those electron collisions heated the thermal electrons by up to 15% of the central electron energy balance [21]. Identification of the alpha heating was accomplished by comparison of the achieved electron temperature with otherwise similar deuterium plasmas. The D–T electron temperature was higher than for the deuterium plasmas and had profiles

(spatial and temporal) consistent with those expected for alpha heating. On a shot-to-shot basis, the confinement time, and thus the electron temperature, can vary with small uncontrolled changes in the limiter influx (e.g. figure 8). These variations were normalized by defining a scaling law for the central electron temperature in terms of the global energy confinement time. The electron temperature rose modestly beyond the normal shot-to-shot variations in the confinement time when a large alpha population existed. The highest electron temperature (14 keV) ever observed in TFTR was produced in a D–T plasma with significant alpha heating.

6. Summary

TFTR has finished a tritium campaign of more than 3 years that featured over 1000 D–T plasmas. Safe machine operation and maintenance were accomplished without remote handling. D–T fusion power production of 10.7 MW was obtained and limited by plasma stability. Documentation of the stability limit indicated a dependence upon plasma performance such that cold, low magnetic field, low confinement time plasmas have a higher disruptive stability limit as described by beta normal. Development of several alpha diagnostics allowed TFTR to make an extensive set of D–T alpha particle measurements. In MHD quiescent plasmas, the D–T fusion alphas were well confined, classically slowed by collisions with electrons, and consequently heated them measurably.

Acknowledgments

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