## Title

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# Deuterium and Tritium Experiments on TFTR

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**Abstract.** Three campaigns, prior to July 1994, attempted to increase the fusion power in DT plasmas on the Tokamak Fusion Test Reactor [TFTR]. The first campaign was dedicated to obtaining >5 MW of fusion power while avoiding MHD events similar to the JET X-event. The second was aimed at producing maximum fusion power irrespective of proximity to MHD limits, and achieved 9 MW limited by a disruption. The third campaign increased the energy confinement time using lithium pellet conditioning while raising the ratio of alpha heating to beam heating.

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## 1. Introduction

TFTR commenced tritium operation in November 1993 [1,2] and produced 182 plasmas containing some amount of tritium by July 1994. A major element of this period was to determine the DT fusion power level which can be achieved in TFTR. A fusion power output of 6.2 MW was attained in December 1993 and 9.2 MW in May 1994. Subsequently, similar plasmas have been used to study tritium isotope effects [3] and expected alpha-particle driven instabilities. Analysis of those effects will be reported in other papers at this conference and in future publications. The primary purpose of this paper will be to describe the campaigns directed at raising the fusion power and the relevant issues.

The challenge of maximizing fusion power production is simultaneously addressing several important problems in tokamak research: the plasma must have good energy confinement, with high neutral beam power, and low impurity influx from the limiter and walls. Comparative experiments between DT and DD are best conducted away from stability limits to ensure that small changes in stability boundaries due to isotope and other effects do not complicate the comparison. Moreover, since the expected alpha particle heating and isotope effects are modest in magnitude, high reproducibility of plasma conditions is required to allow the isotope scaling and alpha heating to be identified separately. This was accomplished by comparing performance in pure deuterium, pure tritium and 50:50 DT plasmas. The plasma performance must be predictable since the desired plasma conditions must be obtained on the specific (and infrequent) plasmas in which tritium is used. Since a separate goal is to attain the highest fusion power regardless of reproducibility, then plasmas with the highest beam power, highest confinement, lowest impurity influx, and best stability must also be obtained in DT.

The most striking feature of the campaign to raise the fusion power has been that in the course of optimizing the energy confinement time through lithium conditioning [4], the confinement rose so much that the overall performance of TFTR is no longer confinement limited but is stability limited. That is, TFTR operating with maximum beam power and the maximum achievable confinement time encounters high $\beta$ disruptions even at maximum plasma current and toroidal magnetic field.

## 2. Experimental Campaigns

TFTR operated at R/a = 2.52m/0.87m, 5.1T toroidal magnetic field with neutral beam heating in three different campaigns to produce DT fusion power (Fig. 1). The three campaigns were:

### *2.1. December 1993 Campaign*

In December 1993, $I_p = 2.0$ MA, and $P_B = 29$ MW was used in an effort to obtain greater than 5 MW of fusion power. The machine parameters were selected to avoid a minor disruption which on TFTR would appear similar to the JET X-event [5].

Essentially, this required operating the experiment at less than full beam power (29.5 MW out of a potential 37 MW) and at less than the optimum energy confinement time. The confinement time was kept low by not using lithium pellet conditioning. The result was that 42 deuterium comparison plasmas were performed with only six having minor disruptions while none of the trace tritium, 50:50 DT, or full tritium plasmas had a minor disruption.

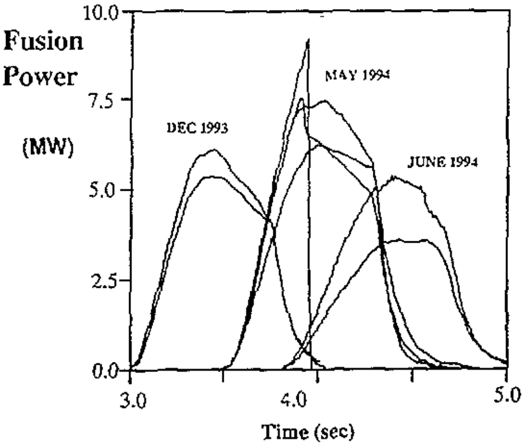

Figure 1. Time evolution of the DT fusion power produced during the three campaigns to increase the TFTR fusion power. In December 1993, the beam power was up to 29.5 MW and the duration was from 3.0 to 3.75 sec. In May 1994, the beam power was up to 32 MW and the duration was from 3.5 to 4.25 sec. In June 1994, the beam power was up to 21 MW and the duration was from 3.7 to 4.7 sec.

A consequence of this experiment was that an excellent set of DD to DT comparison plasmas was obtained in which the key parameters known to affect energy confinement and neutron emission in supershot plasmas were held constant, including the beam power, the fraction of beam power in the co-direction, the plasma current, and the degree of wall conditioning (as expressed empirically by the carbon influx at the beginning of the beam injection). The parameters obtained in this campaign (Table 1) consistently indicated that the DT plasmas have better performance than the DD plasmas. An analysis of these differences is being reported elsewhere [3]. Of considerable interest is that in TFTR, the fraction of the electron density due to alphas is about one-half that of ITER. This motivates campaigns to increase fusion power on TFTR, and thus to make the beta-alpha more relevant to an ignited plasma.

### 2.2. *May 1994 Campaign*

The second campaign occurred in May 1994 using $I_p = 2.5$ MA, $P_B$ up to 33 MW, and up to two lithium pellets (about 1 sec before neutral beam injection) to improve the plasma confinement. The plasma current was chosen as the maximum available (with a reasonable flattop time) in order to maximize the Troyon β limit and achieve the maximum energy content in the plasma. The intention was to apply the maximum neutral beam power; however, minor and major disruptions occurred with about 33 MW of beam power (11 out of 12 sources). Effectively, the plasma performance was limited by the disruptive behavior at the highest injected beam powers.

The campaign in May 1994 was remarkable for the effect that the lithium pellet conditioning had upon the energy confinement time during beam heating. The previous best TFTR confinement time at 2.5 MA had been about 0.11 sec (at the time of peak neutron emission) (Fig. 2) which was modestly above L-mode. At the beginning of the campaign, even without lithium pellet injection, the confinement time was about 0.15 sec. This increase is presently interpreted as a conditioning effect from the preceding experiment which featured intensive lithium pellet conditioning. The confinement time rose to about 0.2 sec as first one lithium pellet was added prior to beam injection, then two lithium pellets, and finally two lithium pellets as well as a 1.6 MA ohmic preconditioning plasma (with 4 Li pellets). With DT plasma operation and 1 or 2 Li pellets before the beam injection, the isotope effect brought the confinement time up to 0.24 sec or nearly three times the L-mode confinement.

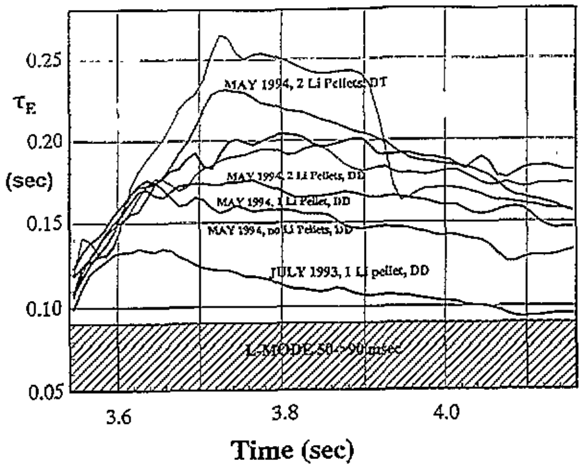

Figure 2. Time evolution of the energy confinement time for 2.5 MA beam heated TFTR plasmas. The range of L-mode energy confinement is indicated in the shaded region and depends upon the beam power. The bottom curve represents the best TFTR performance at 2.5 MA up to July 1993. The next four curves represent the effect of lithium pellet conditioning of DD plasmas as part of the May 1994 campaign. The top two curves represent the effect of lithium pellet conditioning of DT plasmas. The beam injection began at 3.5 sec in all cases.

The May 1994 sequence of DD plasmas in Fig. 2 were all taken at 19.5 MW of beam power and illustrate (Fig. 3) the pronounced effect that the lithium conditioning had upon the density profile, and particle influxes during the beam injection. At about

400 msec after the start of beam heating (3.9 sec in Fig. 3), the hydrogen influx and carbon influxes were halved while the central density was about constant (or increased by 10%); the density peakedness was increased by about 50%, and the energy confinement time increased about 30%.

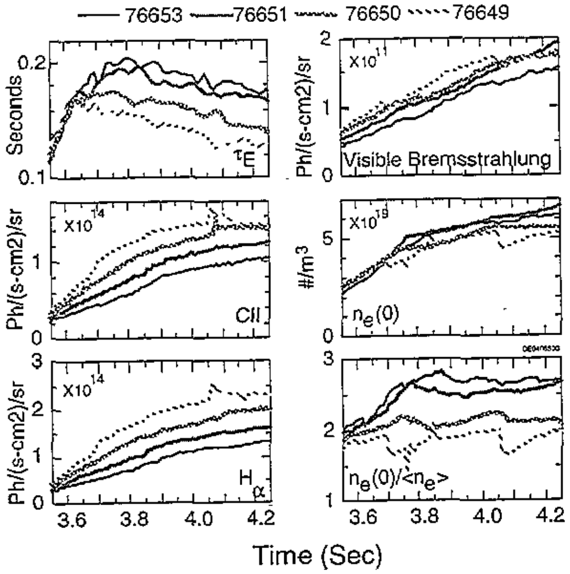

Figure 3. Time evolution of four plasmas each having 19.5 MW of beam heating. 76649 had no lithium pellets, 76650 had one Li pellet about 1 sec before beam injection, 76651 had two Li pellets about 1 sec before beam injection and 76653 had two Li pellets prior to beam injection and was preceded by a four Li pellet ohmic (pre-conditioning) shot. The data are, energy confinement time, visible bremsstrahlung emission, $H_\alpha$ light-hydrogen flux, CII light-carbon influx, central electron density, and density peakedness $n_e(o)/\langle n_e\rangle$. The beam injection began at 3.5 sec.

The general observations are consistent with previous measurements of the effects of lithium pellets [4] except that they seem more pronounced at the higher plasma current (2.5 MA) of this campaign. Higher plasma current also correlates with higher particle influxes from the walls, especially during ohmic heating. Qualitatively, the lithium conditioning seems to be effective at reducing the higher particle influx at higher plasma current. Historically, supershot performance in TFTR has deteriorated at higher plasma currents. Initially (in 1986), supershots were most effective at low plasma current (~ 1.0 MA) and, over the years, conditioning improvements meant that supershot behavior extended to higher plasma currents. The maximum current that can sustain $\tau_E > 1.8\ \tau_E^{L\text{-mode}}$ has increased from 1.0 MA in 1986 to 2.5 MA in 1994.

### 2.3. June 1994 Campaign

The third campaign took place in June 1994 using $I_p = 2.1$ MA, $P_B \sim 20$ MW and four Li pellets injected at least 1 sec before neutral beam heating. In this campaign, the plasma current was chosen as the maximum that allowed enough time for the four lithium pellets to be injected. The beam power was reduced sufficiently to avoid approaching $\beta$ limits. As a consequence, approximately the same DT fusion power was produced as in December 1993 but using about two-thirds of the beam heating power. The peak energy confinement time achieved was about 0.28 sec.

There are several significant features about the profiles (Fig. 4) produced at the highest confinement times. Compared to the July 1993 plasma (Fig. 2), there are significant reductions in $D_e$, $\chi_e$, and $\chi_i$ with associated increases in $n_e(o)$, $T_e(o)$, and $T_i(o)$. At the time of the highest confinement, the central $T_i$ actually became flat at a value of about 35 keV for $r/a < 0.25$, and the ion energy balance became convection dominated (Fig. 5). The initial impression is that the increases in $\tau_E$ due to Li pellet conditioning are accompanied by a broad, flat $T_i(r)$ as the region dominated by convective losses became broader. Similar observations have been made previously on supershot behavior [6]; however, the June 1994 plasmas seem to be a more extreme example.

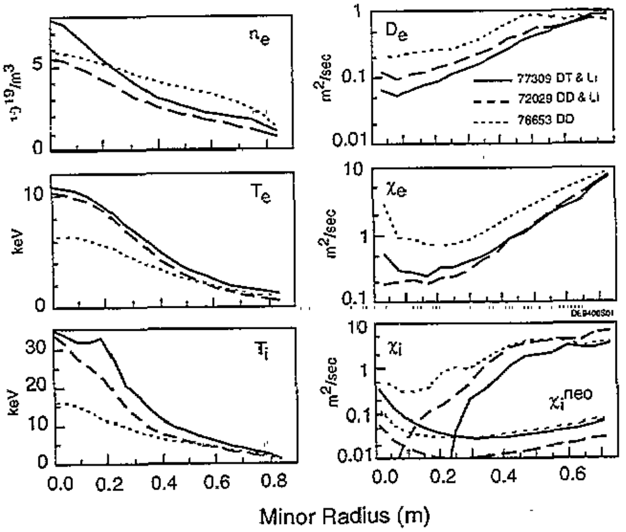

Figure 4 The $n_e(r)$, $T_e(r)$, and $T_i(r)$ profiles with the deduced $D_e(r)$, $\chi_e(r)$, and $\chi_i(r)$ profiles. The solid line is the best TFTR DT confinement time from the June 1994 campaign (2.1 MA, 20.5 MW DT), the long dashed line is the July 1993 plasma (Fig. 2) (2.5 MA, 30.5 MW, DD), the short dashed line is the top DD data point in Fig. 2 from the May 1994 campaign (2.5 MA, 19.5 MW, DD). The quoted $\chi_i$ assumes there is no convection and all the ion losses are conduction.

## 3. Fusion Power Production

The fusion power can be calculated by the TRANSP code [7] for all nominally 50:50 DT plasmas including the plasma with the highest fusion power (Fig. 6). This means that the neutron production agrees in magnitude with that expected for d(t,n)α fusion reactions produced in a plasma with the measured temperature and density profiles. For these TFTR plasmas, the beam-target reactions tend to dominate (Fig. 6) with significant thermonuclear and beam-beam reactions. These ratios are typical for TFTR supershot plasmas.

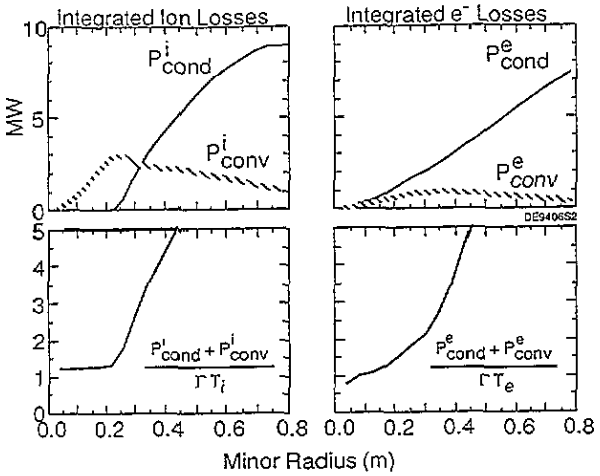

Figure 5. The radial dependence of the conduction and convection terms in the energy balance near the time of peak energy confinement time. The ratio of the total ion loss to the convective ion losses indicates that the convective multiplier is in the range of 1.2 and is probably within uncertainties of 3/2.

Empirically, the D(d,n) $^3$He fusion neutron emission, $S_{DD}$ from TFTR supershots (with neutron components similar to Fig. 6) has scaled [8] as

$$S_{DD} \propto E^2/\sqrt{I_p} \tag{1}$$

where E is the total energy content in the plasma and $I_p$ is the plasma current (Fig. 7). The DT data in which the fraction of tritium beam power lies between 30% and 70% of the total also follows a similar scaling relation with (Fig. 8)

$$S_{DT} \propto E^{1.8}/\sqrt{I_p}\,. \tag{2}$$

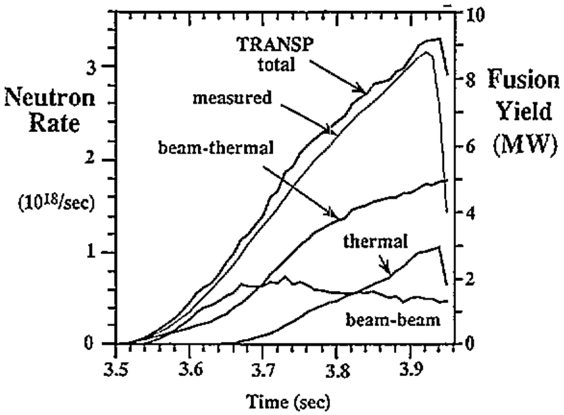

Figure 6. Time evolution of the DT fusion power from the highest yield TFTR plasma with the TRANSP calculation of the expected DT fusion power and its components.

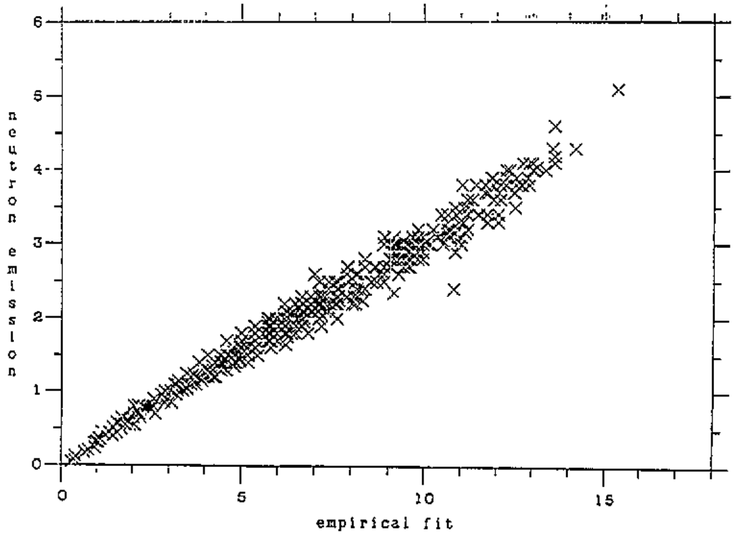

Figure 7. The DD fusion neutron rate from the 1990 TFTR data set plotted against the empirical scaling relation $E^2/\sqrt{I_p}$.

The variation in $I_p$ is only between data at 1.8 → 2.1 MA and 2.5 MA (Fig. 9). The scalings [Eq. (2)] of the DT plasmas is quite similar to the scaling of the DD [Eq. (1)] plasmas indicating that optimization of the deuterium plasmas for DD neutron emission is a valid indicator of expected DT neutron performance. Further, the strong dependence upon plasma energy content indicates that the relevant parameters for

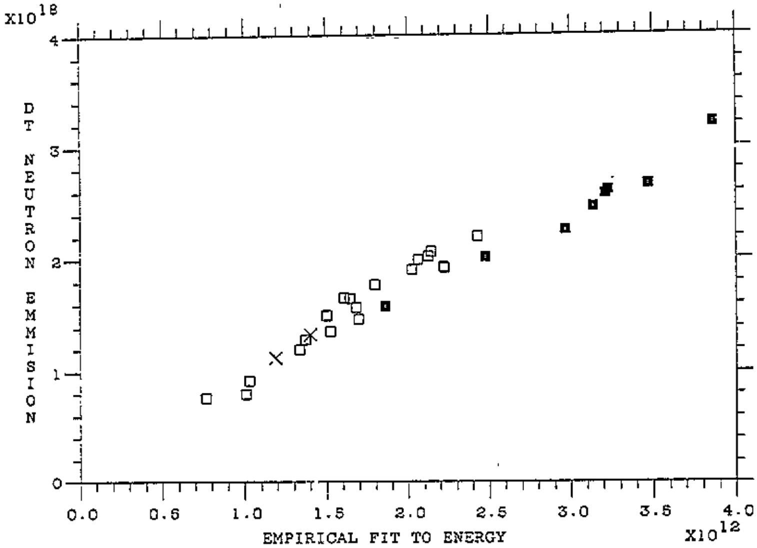

Figure 8. The DT fusion power production from the plasmas with the fraction of tritium sources between 0.3 and 0.7 plotted against the empirical scaling relation $E^{1.8}$. The X points are at 1.8 MA, the open squares are at 2.0 or 2.1 MA and the solid squares are at 2.5 MA.

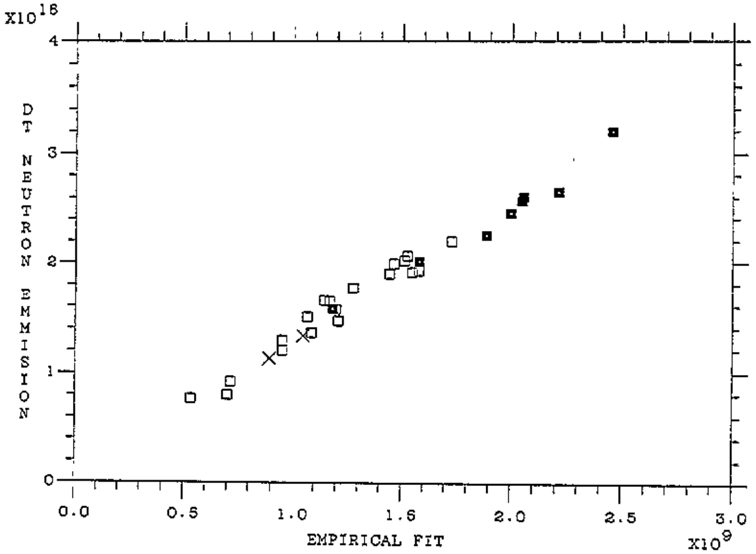

Figure 9. The DT fusion power production for the data in Fig. 8 plotted against the empirical scaling relation $E^{1.8}/\sqrt{I_p}$.

improving the DT fusion power are the product of the energy confinement time and the applied neutral beam heating power. Plotting the 1990 and 1992 DD supershot data (over 1,000 plasmas) in $\tau_E$, $P_B$ space (Fig. 10) indicates that DD data tended to evenly fill a space below 32 MW and 160 msec confinement time. The DT plasmas form bands of fusion power along contours of constant plasma energy content irrespective of whether that energy content is obtained at high applied beam power or high energy confinement time.

The DT neutron production plotted as a function of the percentage of the beam sources that are used in tritium (Fig. 11) has a broad maximum around 50%. The plasmas with tritium-beams only have 40-60% of the DT neutron emission expected from Eq. (2). The fact that they have any DT neutron emission is due to the deuterium influx from the walls where a large reservoir has been established from DD plasmas. Figure 11 indicates that there is little further benefit to operating slightly rich in tritium beyond the effect of maximizing the plasma energy content.

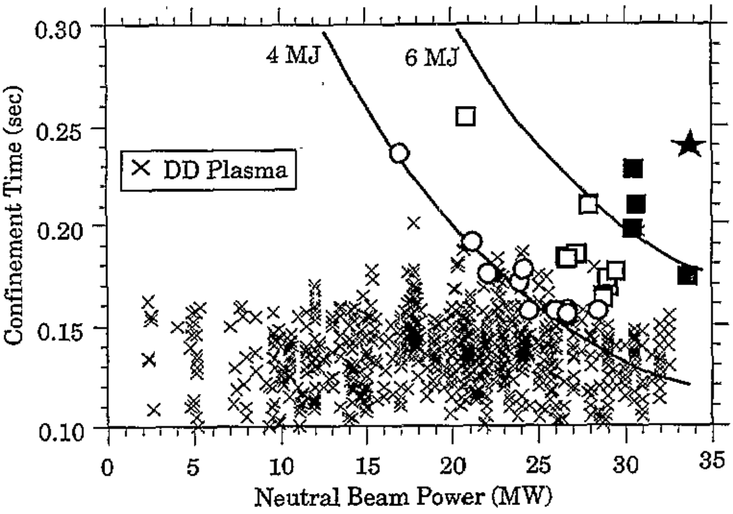

Figure 10. The energy confinement time (at time of peak neutron emission) plotted against the applied neutral beam power. The X-points are the DD data from 1990 and 1992 (over 1,000 plasmas). The remaining symbols represent DT plasmas having different fusion power 3.5 - 5.0 MW is open circles, 5.0 - 6.5 MW is open squares, 6.5 - 8.0 MW is the solid squares, and 9.2 MW is the star. The lines are constant energy content.

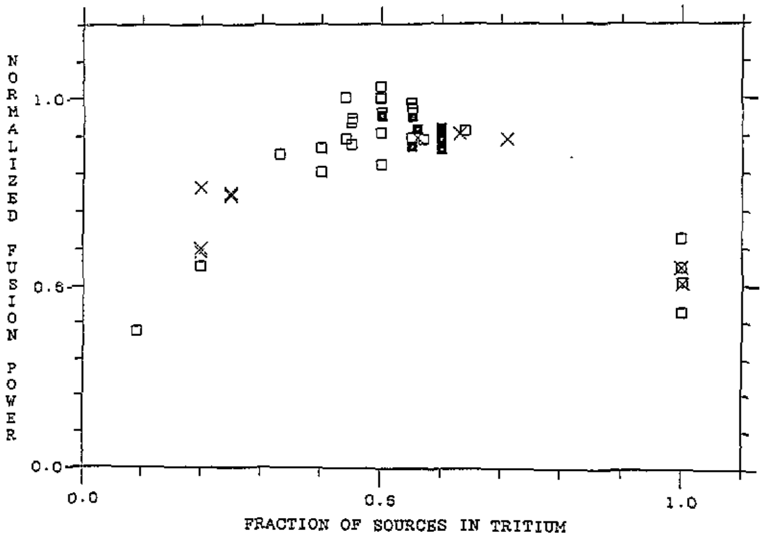

Figure 11. The DT fusion power divided by the empirical scaling law [Eq. (2)] plotted as a function of the fraction of beam power in tritium.

## 4. Summary

TFTR has achieved fusion power up to 9 MW limited by disruptive MHD activity. These results are due, in part, to the dramatic effect of lithium pellet conditioning and the tritium isotope effect upon energy confinement time. In order to further increase the peak DT fusion power and to extend the duration of high DT fusion power for alpha studies, it is proposed to increase the toroidal magnetic field from 5.2 T to 6 T. Empirically, it has been observed that the maximum DD neutron emission scales with the fourth power of the toroidal magnetic field (Fig. 12). This is possible from a scaling law like Eq. (1) where the maximum attainable energy content is determined by a Troyon-like energy limit

$$E_{Troyon} \propto IB \propto B^2 / q, \tag{3}$$

and if q is about constant, then

$$S_{DD\max} \propto B^4. \tag{4}$$

The fact that q ≅ constant may be a consequence of the high central pressures in TFTR supershots suggesting that the q = 1 surface is important, or that the q on axis is important (i.e., central current density). The empirical data in Fig. 12 indicates that a

potential 1.7 times increase of the DT fusion power may occur by raising the toroidal magnetic field from 5.2 T to 6 T.

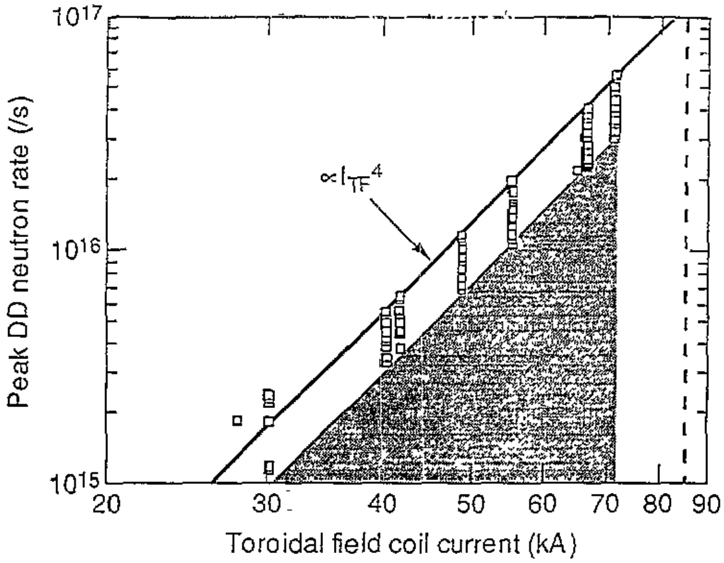

Figure 12. The DD neutron emission plotted as a function of the current in the TFTR toroidal magnetic field coils.

## Acknowledgment

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| Parameter | Units | JET DT | TFTR DD | TFTR D-T |
|---|---|---|---|---|
| Central density $n_e(0)$ | $10^{19}m^{-3}$ | 3.6 | 7.7 | 7.6 |
| Effective charge ($Z_{eff}$) | | 2.4 | 2.4 | 2.3 |
| Electron temperature $T_e(0)$ | keV | 9.9 | 9.2 | 10.8 |
| Ion temperature $T_i(0)$ | keV | 18.8 | 25.6 | 33.0 |
| Energy replacement Time ($\tau_E$) | seconds | 0.9 | 0.145 | 0.176 |
| Central alpha density | $10^{19}m^{-3}$ | 0.0029 | --- | 0.013 |

**Table 1.** Parameters for DD and DT Comparison Plasmas

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