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Report of Progress on Grant

DE-FG02-89ER53297

High Beta and Confinement Studies on TFTR

15 April 1993 to 14 April 1994

by

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Report of Progress

15 April 1993 to 14 April 1994

A new regime of high poloidal beta operation in TFTR was developed in the course of the first two years of this project (9/25/89 to 9/24/91). Our proposal to continue this successful collaboration between Columbia University and the Massachusetts Institute of Technology with the Princeton Plasma Physics Laboratory for a three year period (9/25/91 to 9/24/94) to continue to investigate improved confinement and tokamak performance in high poloidal beta plasmas in TFTR through the DT phase of operation was approved by the DOE and this is a report of our progress in the past 12 months which includes the third budget period of the three year grant (6/25/93 to 6/24/94).

During the approved three year project period we plan to (1) extend and apply the low current ($I_p \sim 1$ MA), high Q_{DD} discharges to the operation of TFTR using Deuterium and Tritium plasma; (2) continue the analysis and plan experiments on high poloidal beta phenomena in TFTR including: stability properties, enhanced global confinement, local transport, bootstrap current, and divertor formation; (3) plan and carry out experiments on TFTR which attempt to elevate the central q to values ≥ 2 where entry to the second stability regime is predicted to occur; and (4) collaborate on high beta experiments using bean-shaped plasmas with a stabilizing conducting shell in PBX-M.

In the twelve month period covered by this report we have made progress in each of these four areas through the completion of XP 403/413 during a 2 run day during October 1993 and through the submission, approval, and partial execution of the DT-33 Experimental Proposal (copy attached in Appendix A) using D-T fueled plasmas using a total of 10 DT plasma shots during a 3 day run in March 1994. The work carried out in the past 12 months has led to the presentation of an Invited Paper at the 1993 APS Division of Plasma Physics annual meeting in St. Louis and the selection by the DOE of a paper to be submitted for oral presentation at the 1994 IAEA Meeting in Madrid. Our work can be divided into two distinct parts: (1) deuterium plasma studies of the extension of our previous work on second stability region access and the observation of high- n ballooning

and (2) deuterium-tritium plasma experimental planning and execution. Each of these is summarized briefly below.

High q_0 , Second Regime Experiments

The completion of TFTR Experiment Proposal 403 (which was begun during a run on 7 November 1992) was carried out during experimental operation of TFTR on 20-21 October 1993 in deuterium plasmas. The objectives of this experiment was to extend our success in elevating the central q to values above 2 in plasmas with a larger major radius ($R = 2.6$ m instead of the $R = 2.45$ m used in most of our previous work). These plasmas were viewed as one of our best opportunities to explore the possibility of second regime access in TFTR.

High poloidal beta plasmas were produced with high central q values up to 2.6 as measured with the multi-point MSE system on TFTR in $R = 2.6$ m discharges. Discharges formed with a rapid ramp-down of the plasma current prior to application of full neutral beam heating power were found to reach values of $\epsilon\beta_p$ diamagnetic up to 1.25 with the appearance of an inboard separatrix. In contrast, similar high q_0 discharges where the plasma current was held constant encountered a soft-beta limit in stored energy with $\epsilon\beta_p$ diamagnetic = 0.8 remaining constant for injected neutral beam heating power ranging from 12 to 23 MW. The onset of measured high- n instabilities is concurrent with reaching this limit. The modes propagate in the ion diamagnetic drift direction, exhibit a ballooning character, and have a real frequency in the plasma frame near the ion diamagnetic drift frequency. These characteristics are consistent with the theory of high- n ballooning instabilities with kinetic effects included¹. By comparing the shift in mode frequency between plasmas of varying toroidal rotation velocity, an toroidal mode number of $n = 28 \pm 9$ was computed for a spectral peak in electron cyclotron emission measured at $R = 3.3$ m for a plasma with $R_0 = 2.62$ m. These discharges have been modeled with TRANSP and a free-boundary equilibrium code. The discharges which reach higher levels of $\epsilon\beta_p > 1$ with a current ramp-down were found to have a smaller magnetic field shear in the core and larger shear near the plasma edge than in cases where $\epsilon\beta_p$ was limited to 0.8. For the high $\epsilon\beta_p$ discharges where a soft beta limit is not observed, access to the second stability region is computed for over 70% of the minor radius. In the case of plasmas which encounter a soft-beta limit at $\epsilon\beta_p \sim 0.8$, the plasmas are computed to be near the marginal stability limit for high- n ballooning modes at a pressure gradient which is significantly smaller than the limit computed for TFTR plasmas with $q_0 \sim 1$. These experiments support the hypothesis that high- n ballooning modes can pose a beta limit in tokamak plasmas by causing a large decrease in confinement which can be avoided by operation in the second stability regime.

Experiments in Deuterium-Tritium Plasmas

As described in our DT Experiment Proposal DT-33 (copy in Appendix A), the goals of this experiment are to maximize neutron production in a TFTR DT plasma at high β_N and to determine any modifications to the plasma stability that alpha particle production may impart on optimally configured high β_p DT discharges as compared with comparable DD discharges. Approximately 1/3 of the planned work on DT-33 was completed during a 3 day run 9-11 March 1994 and we are anticipating the opportunity in the next budget period to complete the planned DT-33 experiments.

Deuterium-tritium plasmas with enhanced energy confinement and stability have been produced in the high poloidal beta, advanced tokamak regime² in our initial work on the DT-33 Experimental proposal. Confinement enhancement $H \equiv \tau_E / \tau_{E \text{ ITER-89P}} > 4$ has been obtained in a limiter H-mode configuration at moderate plasma current $I_p = 1.0 - 1.2$ MA. By peaking the plasma current profile, $\beta_{N \text{ dia}} \equiv 10^8 \langle \beta_{t \perp} \rangle a B_0 / I_p = 3$ has been obtained in these plasmas, exceeding the β_N limit for TFTR plasmas with lower internal inductance, l_i . Fusion power exceeding 4.2 MW with a fusion power gain $Q_{DT} = 0.18$ has been produced with reduced alpha particle first orbit loss provided by the increased l_i .

The peaked current profile was created by rapidly decreasing the plasma current in a deuterium plasma with $B_t = 4.8$ T from $I_p = 1.65 - 2.0$ MA to $1.0 - 1.4$ MA during a period of co-injected neutral beam heating (Fig. 1). Subsequent addition of counter-injected beams produced the desired power level $P_{NBI} = 16 - 29$ MW with a nominally equal number of deuterium and tritium sources.

Electron and ion temperatures reached 9 keV and 32 keV respectively with peak electron densities of up to $7 \times 10^{19} \text{ m}^{-3}$. Non-inductive current of up to 50% has been computed by the TRANSP code at $I_p = 1.2$ MA with a 35% contribution from the bootstrap current. Determination of the q profile using motional Stark effect measurements of the magnetic field pitch angle indicate that $q_0 \sim 1$ for these plasmas.

Producing enhanced energy confinement involved a reduction in particle recycling. This was obtained in both deuterium-only (D) and deuterium-tritium (DT) plasmas when the discharge made a transition to a limiter H-mode³, or by lithium pellet conditioning⁴ of the limiter. A greater increase in τ_E was attained during the ELM-free phase of the DT H-mode plasmas than in equivalent D plasmas (Fig. 1 (c-d)). The DT plasma shown in Fig. 1c reached a peak value of $H = 4.1$ (using an average isotopic mass of 2.3). At constant heating power, DT plasmas exhibited a greater drop in D_α emission during the ELM-free H-mode phase and an earlier onset time of ELMs than in D plasmas. These characteristics were also observed in D comparison plasmas created after, but not before a DT discharge

showing that retention of tritium in the vessel modifies H-mode behavior. These effects decreased as additional D discharges were run and tritium recycling was reduced.

Similar increases in τ_E have been observed in sequences of D plasmas which utilize lithium pellet conditioning before and/or after NBI. The greatest performance improvements were obtained when a pellet was injected before NBI. Use of lithium pellets in this manner has also been successful in delaying the ELMing phase of a discharge by up to 0.15 s.

Advanced tokamak operation (high H and β_N) in DT produced a relatively large alpha particle beta, β_α , for a given plasma current. Peak β_α of 1.6×10^{-3} is computed by TRANSP for the $I_p = 1.2$ MA DT plasma shown in Fig. 1. This value is the same as has been obtained in a constant current DT plasma with $I_p = 1.8$ MA. At $I_p = 1.2$ MA, the β_α profile is slightly broader. Due to the peaked current profile produced in the high β_p plasmas, first orbit losses are less than in a plasma with lower l_i and equal I_p . Modeling of experimental DT plasmas using TRANSP show that at $I_p = 1$ MA, 17% of the alpha particles are lost with $l_i = 2.2$ as opposed to 34% with $l_i = 1.2$.

Plasma stability was the limiting factor to obtaining greater improvement in τ_E in plasmas with high H factor. Peakedness of the DT neutron source strength from a neutron collimator (an indicator of the pressure profile peakedness) was found to be a useful diagnostic in examining the MHD stability. DT plasmas either disrupted or suffered a β -collapse when the neutron profile peakedness $P_{SN} \equiv S_N(0)/\langle S_N \rangle_{\text{volume}} \sim 10$ (Fig. 2). Such large values of P_{SN} were obtained only with DT operation or lithium pellet injection. These β -limiting events occurred at β_N less than the observed disruptive limit of D plasmas with less peaked pressure profiles. This observation is consistent with ideal MHD stability analysis of high β_p D plasmas which has shown that the increased β_N limit observed in high l_i plasmas is reduced if the pressure profile is sufficiently peaked.⁵

Characteristics of ELMs, precursor MHD activity to β -collapse, and disruption are generally similar in D and DT plasmas. Large amplitude, low frequency (~ 40 Hz) "giant" ELMs are more likely to occur in DT plasmas with relatively broad pressure profiles and high β_N (Fig. 1(d)). Small ($\sim 10\%$) fluctuations in fusion product loss are associated with these ELMs. A "secondary ballooning instability"⁶ was clearly observed as a precursor to the disruption. As in high performance, constant I_p DT supershots⁷, alpha-driven TAE instabilities have not yet been observed in the advanced tokamak DT plasmas. TAE mode stability analysis of these plasmas is presently underway.

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7. J. D. Strachan, H. Adler, P. Alling, *et al.*, *Princeton Plasma Physics Report* PPPL-2978, submitted to *Phys. Rev. Lett.*

Fig. 1. Time evolution of DT plasma parameters and comparison to an equivalent deuterium discharge.

Fig. 2. Time evolution of DT neutron peakedness in plasmas of varying MHD stability.

List of Publications

1. "High Poloidal Beta Long-Pulse Experiments in the Tokamak Fusion Test Reactor," J. Kesner, M. E. Mauel, G. A. Navratil, S. A. Sabbagh, *et al.*, *Physics of Fluids B* **5**, 2525 (1993).
2. "Investigation of Ballooning Modes in High Poloidal Beta Plasmas in the Tokamak Fusion Test Reactor," Y. Nagayama, M. Yamada, S. A. Sabbagh, *et al.*, *Physics of Fluids B* **5**, 2571 (1993).
3. "Neoclassical Tearing Dynamo and Self-sustainment of a Bootstrapped Tokamak," Y. Yuan and A. Bhattacharjee, *Physics of Fluids B* **5**, 3661 (1993).
4. "Overview of Recent TFTR Results," M. C. Zarnstorff, G. Bateman, S. H. Batha, *et al.* **Plasma Physics and Controlled Fusion Research 1992**, (IAEA, Vienna, 1993) Vol. 1, p111.
5. "Achieving High QDD Operation in High Poloidal beta Discharges in TFTR," M. E. Mauel, G. A. Navratil, S. A. Sabbagh, M. G. Bell, *et al.*, **Plasma Physics and Controlled Fusion Research 1992**, (IAEA, Vienna, 1993) Vol. 1, p205.
6. "MHD Constraints for Advanced Tokamak Operation" by S. C. Jardin, A. Bhattacharjee, A. Bondeson, *et al.*, **Plasma Physics and Controlled Fusion Research 1992**, (IAEA, Vienna, 1993) Vol. 2, p285.
7. "High- n Ballooning Instabilities and Access to the Second Stability region in TFTR," S. A. Sabbagh [Invited Talk], *Bull. Am. Phys. Soc.* **38**, 1984 (1993).
8. "Accuracy Estimates of Equilibrium Reconstruction of High Poloidal Beta Second-Regime Discharges in TFTR," M. E. Mauel, S. Sabbagh, L. Bai, *et al.*, *Bull. Am. Phys. Soc.* **38**, 2032 (1993).
9. "Search for Kinetic Ballooning Modes Driven by ICRH Minority Tail Ions in TFTR," H. Biglari, S. J. Zweben, M. Bell, *et al.*, *Bull. Am. Phys. Soc.* **38**, 2034 (1993).
10. "Improved Confinement in High I_p Lower Hybrid Driven Steady State Plasmas in Tore Supra," G. T. Hoang, G. Gil, E. Joffrin, ..., S. A. Sabbagh, *et al.* *Nucl. Fusion* **34**, 75 (1994).
11. "Preparations for Deuterium-Tritium Experiments on the Tokamak Fusion Test Reactor," R. J. Haryluk, H. Adler, P. Alling, ..., J. Kesner, ..., M. Mauel, ..., G. A. Navratil, ..., S. A. Sabbagh, ... *et al.* *Physics of Plasmas* **1**, 1554 (1994).

12. "Deuterium-Tritium TFTR Plasmas in the High Poloidal Beta Regime," S. A. Sabbagh, M. E. Mauel, G. A. Navratil, *et al.*; selected by DOE for submission as an oral presentation at the *1994 IAEA Meeting on Plasma Physics and Controlled Fusion*, Madrid.
13. "Characteristics of Confinement and Fusion Reactivity in JT-60 High β_p Discharges and TFTR Supershots with Deuterium Neutral Beam Injection," H. K. Park, M. Yamada, K. McGuire, M. Bell, S. Sabbagh, *et al.*; selected by DOE for presentation at the *1994 IAEA Meeting on Plasma Physics and Controlled Fusion*, Madrid.
14. "Confinement and heating of a Deuterium-Tritium Plasma," R. J. Haryluk, H. Adler, T. Alling, ..., S. A. Sabbagh, ...*et al.*, submitted to *Physical Review Letters*.
15. "Fusion Power Production from TFTR Plasmas Fueled with Deuterium and Tritium," J. D. Strachen, H. Adler, P. Alling, ..., S. A. Sabbagh, ...*et al.*, submitted to *Physical Review Letters*.

Appendix A — DT-33 Experiment Proposal

APPROVAL FORM FOR EXPERIMENTAL PROPOSALS

K. Maffei	
APPROVED XP #:	DT-33
DATE:	3/9/94

XP No. DT

TITLE OF XP: DT OPERATION IN OPTIMIZED HIGH β_p TFTR PLASMAS.

Prepared By: Steven Sabbagh 3/7/94
Authors Date

Reviewed By: DK Owens 3/8/94
Task Force Leader Date

Don M. H. 3-8-94
Physics Operation Branch Date

Approved By: K. Maffei 3/8/94 Date: Do higher I_p expt first K.I.
Physics Program Division Head

Approved By: Joel C. Hauer 3/8/94 Date: (intermediate rather than low is intended here) J. H. 3/8/94
Tokamak Operation Division Head

Approved By: Cl. Hauer Date:
TFTR Project Head (only for D-T XPs)

Approval for Operations

Run Date	Comments	Approved
	(Restrictions or minor modifications to XP)	(Tokamak Operations Division Head and Physics Program Division Head or designees)

Minor Modifications:

UNCONTROLLED

APPROVED XP #: DT-33

DATE 3/9/94

TFTR D-T Experimental Proposal

Title: DT Operation in Optimized High β_p TFTR Plasmas **Proposal:** DT-33

Authors: S. Sabbagh, G. Navratil, M. Mauel, K. Owens, M. Bell, R. Budny, S. Batha, F. Levinton, K. McGuire, J. Kesner, G. Rewoldt, M. Zarnstorff, and S. Zweben

Date: 16 Jul 93

Revised: 7 Mar 94

Version: V 1.4

1. Experimental Goals:

The goals of this experiment are to maximize neutron production in a TFTR DT plasma at high β_N and to determine any modifications to the plasma stability that alpha particle production may impart on optimally configured high β_p DT discharges, as compared to their DD counterparts.

2. Experimental/Theoretical Justification:

The high β_p plasma regime in TFTR has allowed the study of several interesting plasma physics phenomena and performance enhancement techniques during the DD phase of TFTR. These topics include high β_N operation by increasing current profile peakedness, the observation of intermediate- n ballooning modes during beta collapses, second stability region access at high q_0 , and the observation of high- n modes in high q_0 plasmas. Each of these existing TFTR DD plasmas would be useful to perform in the presence of alpha particles and could address the following topics:

- i) High DT fusion reactivity at high β_N and relatively low plasma current through current profile peakedness. This will be especially important if any gain in confinement can be achieved by isotope effects. Prototype DD plasmas have been produced in TFTR for plasma conditions planned for DT operation, except for the planned I_p ramp-down with an initial $I_p \sim 2.5$ MA (these initially high current plasmas will require DD setup XP's - see below).
- ii) Alteration of stability limits reflected in changes of relevant global (i.e. β_N, τ_E) and local (i.e. pressure gradient profile) parameters due to the presence of alpha particles.
- iii) Effect of alpha particles on β limiting phenomena including intermediate and/or high- n ballooning instabilities. (will require a DD setup XP or additional DD setup shots - see below)

The common link in these experiments is that they qualitatively involve the same basic plasma current waveform (that induced by plasma current ramp-down) and NBI timing. The main variations are the magnitude of the plasma current and the nominal major radius of the plasma.

The goal of high DT fusion reactivity at high β_N follows that of the existing TFTR high β_N DD plasmas. In most cases, small alterations of existing DD plasmas (see shot list) will be used as templates for DT operation. In addition, a new plasma current ramp-down scenario will be considered in which the initial plasma current of 2.5 MA is significantly larger than in previous experiments ($I_p = 1.6$ MA, $I_{TF} = -73$ kA, $R = 2.52$ m). This plasma will be a modification of the primary target plasma used in DT-8, "Maximum D-T Fusion Power from NB-Heated Supershots" (M.G. Bell, et al.) and is designed to be a high β_N analog to such shots. Because this operating scenario has never been attempted in TFTR (and is relatively unexplored even at constant current in supershots), the setup XP 512, "Development of 2.5 MA Supershot Targets" (M.G. Bell) is a prerequisite for operation of the 2.5 MA I_p ramp-down plasma.

A major portion of this experiment will be to investigate the theoretical prediction of altered stability limits in plasmas with hot alpha particle populations. For example, work by Spong, et al.¹, and Rewoldt² has shown that stability boundaries for both intermediate (toroidal mode number, $n \sim 10$) and high- n modes are both altered by alpha particles. The work of Spong et al. shows that the first stability boundary pressure gradient limit to high- n modes decreases as the relative amount of alpha particle pressure increases with respect to the bulk pressure. This work also indicates that access to the second stability region can be improved with alpha particles. The work of Rewoldt shows that a substantial reduction in the first region beta limit can be imposed by alpha particles for TFTR plasmas. Fig. 1 plots the growth rate as a function of local beta for an $n = 10$ mode in a modeled DT extrapolation of a TFTR DD supershot ($B = 5.2$ T, $I_p = 2.1$ MA, $R = 2.5$ m) at $r/a = 0.18$. The curve with the highest beta limit is the computed high- n ballooning mode first region boundary without kinetic effects included. The relevant curves to compare are those with kinetic effects included - one with alpha particles, and the other without. With alpha particles included, the local beta limit is reduced by a factor of 3.5 in this plasma.

Since both TFTR supershot and high β_p plasmas are computed to be near the first stability region boundary to high- n modes, a soft beta limit (that is, no increase in stored

¹D.A. Spong, D.G. Sigmar, K.T. Tsang, et al., *Physica Scripta* T16, 18 (1987).

²G. Rewoldt, *Nuclear Fusion* 31, 2333 (1991).

energy as input power is increased) would be theoretically expected if a substantial reduction in the first region pressure gradient would occur. This soft beta limit is not observed in TFTR DD supershots and high β_p plasmas with $q_0 \sim 1$, perhaps because these plasmas reach a disruptive limit before the entire pressure profile becomes marginally stable to intermediate or high- n modes. Because of this, the imposition of a soft beta limit generated by a reduction of the first stability region p' boundary (due to alpha particle effects, or otherwise) has been somewhat speculative. However, such a limit has been produced in TFTR constant current, high β_p , high q_0 plasmas. The reduction of the first stability region pressure gradient was due to the increase in q_0 and the associated change in the q profile rather than alpha particle effects in these plasmas, nonetheless, the theoretically anticipated soft beta limit was observed (a value of $\beta_{p \text{ dia}} = 1.9$ was reached at 12 MW NBI power, which remained constant as the beam power was progressively raised to 23 MW). In addition, high- n modes were observed in these plasmas, with $n = 28 \pm 9$ at $R = 3.3$ m measured from the Doppler shift in mode frequency for various toroidal rotation velocities (Fig. 2).

Therefore, the present experiment will focus on similar manifestations of modified local and global beta limits due to alpha particle effects, which may be observed in several plasma conditions tested. If a soft beta limit is encountered in any particular condition, the associated modes (if detectable) could then be analyzed. The study will also include high q_0 plasmas in which such modes have already been observed and identified in DD plasmas. However, for the latter case, additional experience of high β_p operation at $R = 2.6$ m will be required to determine the maximum plasma current that can be used while the modes are still observed. Some experience was gained during the brief runs of XP403/414 (10/30/92, 11/7/92) but additional setup shots or a devoted XP will be a necessary prerequisite in obtaining optimized $R = 2.6$ m plasmas for this XP.

3. Experimental Run Plan:

A) General Run Procedure:

The majority of the work involved with this experiment will be in the preparation of reliable, well-behaved DD plasmas operating at high β_p and near the β_N limit for a specified plasma current in both $R = 2.45$ m and 2.6 m plasmas. A well-defined DD target plasma performance will be established. The DT plasma shots will then be taken, data acquisition will be verified, and the experiment will proceed by moving on to the next pre-established plasma condition until the experiment is complete. Once this data is collected and analyzed, an

assessment will be made to determine whether or not the plasmas could be further optimized with respect to neutron production, or if observed instabilities have been significantly altered by alpha particle effects. If possible, a follow-on experiment could continue to investigate these issues.

Luckily, there exists an adequate amount of high β_N TFTR D data for $R = 2.45$ m plasmas in the appropriate range of plasma current to design a fairly well-optimized configuration with margin built-in to minimize the probability of disruption (XP's 221 (9/17/90, 10/27/90), 313 (1/10/92, 1/11/92) 413 (8/31/92)). However, high β_p operation at $R = 2.6$ m and operation of a fast I_p ramp-down from 2.5 MA will require setup XP's or additional setup shots as mentioned in the previous section.

The general run plan consists of reaching a reasonable target plasma density, injecting neutral beams and increasing power until the desired β_N is reached (checking that all requested diagnostics are functioning during this time), then taking the DT shots. The additional precaution of decreasing the beam power as the perturbation to the current profile begins to decay will be added to the standard "optimized" beam waveform to minimize the probability of disruption. The process is repeated for each desired plasma configuration.

Example: $R = 2.45$ m, I_p ramp-down 1.65 MA $\rightarrow$ 1.0 MA (patterned after shot 65558)

- a) 1.4 MA He conditioning until $n_e = 2.1 \times 10^{15} \text{ cm}^{-2}$.
- b) Install programmed waveforms for I_p ramp-down. Take 2 OH D shots to pump out helium. This will also serve as a test for the waveform programming.
- c) Start beam injection sequence - DD target plasma:
 - i) NBI timing will include a "preheat" of the plasma, which is an important component of performance optimization. In addition, NBI will be decreased as the edge current perturbation begins to diffuse in order to minimize the probability of disruption. Existing TRANSP runs will be used as a guide to estimate the current perturbation diffusion time.
 - ii) Start injection into DD plasma with 4 co / 3 ctr (21 MW) to check energy confinement and β_N . Increase power to reach within 10% of β_N limit (limit is 3.5 - stop at 3.15). If performance is similar to 65558, NBI power should be less than 27 MW (i.e. stop at 4 co / 4 ctr sources).

iii) Take additional DD shots to insure discharge reproducibility. Confirm that neutron rate does not vary by a great deal (i.e. less than 15%) for these plasmas.

d) Start beam injection sequence - DT plasma:

i) Choose T beam sources to inject during the preheat phase to maximize the time over which the alpha particle population will form.

ii) First T shot: Switch between 50 - 60% of the beam sources to T° injection (detail of which sources to switch will be discussed in the detailed spreadsheet for the run). Decrease the beam power (i.e by one source) so as not to exceed the β_N reached in the equivalent DD plasma. If not,

iii) Second T shot: Use this shot if β_N for the equivalent DD plasma is not reached, if NBI sources do not fire in the first attempt, or if critical data acquisition fails on the first attempt.

iv) Follow on with one identical DD shot to assess whether or not the DT plasmas have altered the diagnostic measurements.

e) Load new plasma configuration and repeat:

Repeat this sequence with a new plasma configuration until the tritium inventory is depleted. Since these plasmas will not all require 6 T° sources for each shot, the expected full power maximum of 18 T shots/Type B container or one U-bed (1.8 g of useable tritium) is more than adequate. The present plan incorporates seven different plasma current ramp-down waveforms plus two constant current comparisons, for a total of 43 shots (16 DT shots) not including OH or He conditioning shots.

B) Specific Discharges to be Run:

Each condition below represents the specific condition which will be run according to the general procedure above:

	I_p pedestal	I_p initial	P (MW)	R (m)	# shots	Comments
1)	1.4 MA	2.00 MA	full	2.45	5	DT version of 65554. Shot cluster includes 2 DT shots and 3 DD shots (see section 3A)
2)	1.2 MA	1.75 MA	~ 24 -27	2.45	5	DT version of 65547. Shot cluster includes 2 DT shots and 3 DD shots (see section 3A)
3)	1.0 MA	1.65 MA	~ 21-24	2.45	5	DT version of 65558.
4)	1.6 MA*	2.5 MA*	full	2.52	5	I_p ramp-down version of plasma considered for DT-8 (M.G. Bell) (DD setup XP <u>required</u>)
5)	0.8 MA	1.65 MA	~ 18-21	2.45	5	DT cousin of 54022.
6)	0.8 MA	0.8 MA	~ 10	2.45	4	Comparison shot (1 DT shot)
7)	0.6 MA**	1.20 MA**	~ 17-20	2.60	5	High β_p , high q_0 case (DD setup XP highly desired)
8)	0.6 MA***	0.6 MA***	~ 15	2.60	4	Comparison shot (1 DT shot) (Maximum alpha particle loss)
9)	Condition above which yields measurable high- n instabilities and acceptable alpha particle losses.		~ 10-14	2.60	5	Two extra shots to complete power scan (4 total) and establish n number from Doppler shift (DD setup XP highly desired)
Total number of shots					43	(16 DT shots)

*Note: Requires setup shots from XP 512 or DT-8.

**Note: If a dedicated setup XP is not run beforehand, approximately 6 - 8 DD shots will be required to develop an "optimized" waveform.

***Note: Use plasma current (during NBI) of "optimized" $R = 2.6$ m discharge with current ramp-down.

C) How the specific discharges contribute to meeting the goals:

- i) **High DT fusion reactivity:** The first three discharges are identical to optimized high β_p plasmas run at relatively high I_p during the 1992 TFTR run. They provide the basis for reaching maximum neutron rates in a high β_N plasma in TFTR. The fourth discharge is an extension of the ramp-down technique to improve the β_N limit of a high current plasma by maximizing the plasma current before the I_p ramp-down. The fifth discharge extends the range of plasma current and ramp ratio, $I_{p \text{ initial}}/I_{p \text{ pedestal}}$, and is nearly identical to many DD plasmas run over the past few years in TFTR.
- ii) **Effect of alpha particles on beta limit and instabilities:** The $R = 2.45$ m plasmas allow the investigation of global beta enhancement as well as effects on beta collapses (with associated intermediate- n ballooning modes) and/or the H-mode transition. A key purpose of the $R = 2.6$ m plasmas is to create a discharge similar to 69213-69217, in which high- n modes were actually measured, and then repeat the shots in DT to determine the effect of the alpha particles on the instabilities. As specified, a toroidal rotation scan will be necessary for this analysis.

In addition, the prescribed plasmas have a wide range of plasma current and plasma current ramp ratios. All of these shots will contribute to the investigation of alpha particle losses as a function of plasma current, and current profile peakedness. The expectation is that the alpha particle confinement will be significantly enhanced since the magnitude of the current density in the core of the plasma will be close to the pre-ramp-down current level. The constant I_p comparison shots at both R values will establish the alpha particle loss for plasma with decreased current profile peakedness at constant $I_{p \text{ pedestal}}$.

4. Required Machine, Beam, and Diagnostic Capabilities (General):

(Specific detail for each shot cluster will be outlined in the standard "spreadsheet" format for the run - see Appendix A for an example - shot 65558)

- i) **Machine** (nominal values - allowable range of values to be specified):
 - 1) Operation at $R = 2.45$ m, 2.52 m, and 2.6 m.
 - 2) TF = -68 kA and -73 kA (one 5 shot cluster at -73 kA)

- 3) Range of plasma current: 0.5 MA - 2.0 MA, plus the ability to run at, and rapidly ramp-down from 2.5 MA for one 5 shot cluster.
- 4) Ability to ramp down current at -2.5 MA/sec.
- 5) Target density: $n_e = 2.0 \times 10^{15} \text{ cm}^{-2}$ in a 1.4 MA He conditioning plasma
- 6) Li pellets for plasma conditioning and diagnostics

ii) Beams:

1) The $R = 2.45$ shots at 1.4 MA and the $F = 2.52$ m shots at 1.6 MA may require 12 beam sources to move within 10% of the beta limit, otherwise, the XP may be run if full power is not available.

2) Source 5b required to run in D for all shots in which MSE is required (see detail for specific shot cluster).

iii) Essential Diagnostics:

- 1) Lost alpha particle detectors
- 2) Neutron profile monitor
- 3) Alpha CHERS and standard CHERS (using at least source 5b in deuterium)
- 4) MSE (using source 5b in deuterium) required for $R = 2.6$ m plasmas and highly desired for all plasmas in which 10 beam sources or less are used.
- 5) ECE to examine high frequency T_e fluctuations (500 kHz sampling).
- 6) BES highly desired
- 7) Microwave reflectometer highly desired

See Diagnostic Checklist for entire list of diagnostics and detail of specific shot cluster for usage in a particular shot.

5. Estimated tritium budget:

Using the tritium beam consumption guidelines from L. Grisham's memo to R. Hawryluk dated 4/15/93, 215 Ci/source is consumed during 1s of beam operation. Based on this information, the present run plan consumes 14.6 kCi (1.46 g) of tritium (outlined below) assuming 1s T beam source operation.

	I_p pedestal	I_p initial	#DT shots	T source seconds	T (kCi) consumed per condition
1)	1.4 MA	2.00 MA	2	12	2.58
2)	1.2 MA	1.75 MA	2	10	2.15
3)	1.0 MA	1.65 MA	2	9	1.94
4)	1.6 MA	2.5 MA	2	12	2.58
5)	0.8 MA	1.65 MA	2	7	1.51
6)	0.8 MA	0.8 MA	1	2	0.43
7)	0.6 MA	1.20 MA	2	7	1.51
8)	0.6 MA	0.6 MA	1	3	0.65
9)	Complete power scan		2	6	1.29
Totals			16	68	14.6

6. Estimated neutron budget:

	I_p pedestal	I_p initial	neuts (DD)	#DT shots	est (DT)	Comments
1)	1.4 MA	2.00 MA	1.4e16	2	4.5e18	DD S_n taken from shot 65554
2)	1.2 MA	1.75 MA	1.5e16	2	4.8e18	DD S_n taken from shot 65547.
3)	1.0 MA	1.65 MA	0.9e16	2	2.9e18	DD S_n taken from shot 65558.
4)	1.6 MA	2.5 MA		2	4.8e18	DT S_n simulation of 68522 with TRANSP (1.0s NBI)
5)	0.8 MA	1.65 MA	0.9e16	2	2.9e18	DD S_n taken from shot 65558.
6)	0.8 MA	0.8 MA	0.5e16	1	0.8e18	DD S_n est. from shot 53985
7)	0.6 MA	1.20 MA	0.6e16	2	1.9e18	DD S_n est. from shot 52355
8)	0.6 MA	0.6 MA	0.3e16	1	0.5e18	DD S_n estimate
9)	Complete power scan		0.6e16	2	1.9e18	DD S_n estimate
Totals				16	2.5e19 neutrons	

7. Planned Analysis:

As usual, TRANSP will be a major component of the modelling of the high β_N plasmas. In addition to the standard computation of equilibria that is subsequently used in

Ideal MHD stability analyses, TRANSP will also be used for calculations of DT relevant parameters, such as β_{α} , for stability analyses extended to include kinetic effects.

Calculations of the free-boundary equilibrium, including the q profile, will be made using external magnetics, internal field pitch angle measurements from MSE, and pressure profile calculations from TRANSP by using the TokaMac code version 2, by Mike Mauel.

The neutron emission and q profiles will be used along with PPPL first orbit and ripple loss codes to determine the effect of current profile shape on alpha particle confinement.

6. Possible Publications:

If sufficient data can be gathered for each of the three topics outlined in Section 2, a separate publication might be considered for each topic. Achieving high fusion reactivity in a high β_N DT plasma is in itself an important verification of the fusion relevance of relatively low current tokamak plasmas. Modification of stability limits due to alpha particle effects would be another important and independent topic to address. Finally, if it can be shown that either high or intermediate- n modes are influenced by alpha particles, a publication on the resulting alteration of the stability of these modes would be possible.

PHYSICS OPERATIONS REQUEST

Title: DT Operation in Optimized High β_p TFTR Proposal: DT-33
Plasmas

Machine conditions (indicate range where appropriate):

$I_p(\text{MA})$ 0.6 - 2.5 MA $R(\text{m})$ 2.45, 2.52, 2.6 ($a = R - 165.5\text{cm}$ for BL and
 $= 359.8 - R\text{cm}$ for RFL)

OH Flattop start/stop ~ 2.5 to ~ 4.2 sec., I_{TF}(KA) 68.73, Gas Species D, Pellets(D) LI

Beams: Power Max (≥ 28 MW), source duration 1.0 sec, voltage 95 to 110 keV (for MSE)

ICRF: Power_____, duration_____

If this is a continuation of a previous run or if shots from a previous run are similar to those ne use the "Physics operations daily comment log book" in the control room to find ma parameters similar to those desired that have been saved on disk (circled in the log book). If s shots were run in the past, but not saved on disk, a couple of hours lead time may be need have the required shots restored and marked to be saved.

List of previous shot numbers for setup 65554, 65547, 65558, 54022; also see attached sheet and day of run spreadsheets for details of waveforms.

and day of run spreadsheets for details of waveforms.
If this is a series of shots that are new and unique, sketch the desired profiles. It is important you accurately label the sketch so there is no confusion about times or values.

Special Conditions: DT operation, rapid ramp-down of plasma current during NBI.

(Note: see Appendix for details of waveforms for each shot cluster)

Ballooning mode calculations with kinetic effects included show that a substantial reduction in the first region beta limit can be imposed by the presence of alpha particles

G. Rewoldt, et al., *Nucl. Fusion* 31 (1991) 2333.

- Local beta limit reduced by a factor of 3.5 in a 2.1 MA supershot

Fig. 1

Fig. 2

$n \sim 30$ is computed for these modes at $R \sim 3.3$ m, with a real frequency in the plasma frame near ω_{*ip}

Model: $\omega = \omega_{*ip} + k_{\phi} v_{\phi}$, $n = 2\pi R (\Delta f / \Delta v_{\phi})$

Summary of Results:

$R(m)$	n	$\omega_{*ip}/2\pi$ (kHz) (fit)	$\omega_{*ip}/2\pi$ (kHz) (TRANSP)
3.30	28 ± 9	84 ± 11	87
3.35	31 ± 14	66 ± 14	75
3.35	39 ± 9	82 ± 13	95

- ω_{*ip} (TRANSP) = $(k_{\perp} / L_{pi}) (T_i / eB)$, with $m = nq = rk_{\perp}$
(q taken from MSE data)
- $k_{\perp} \rho_i \sim 0.4$ for these cases.

Appendix A: Waveform Timing for High Poloidal Beta DT XP

(Example: DT Version of shot 65558)

1) Density Control:

No density feedback control, or gas puffing.

2) Toroidal Field Flattop Timing:

Flattop of TF is between 0.0 and 4.0 seconds (68 kA).

3) Plasma Current Waveform Timing (Rampdowns):

Obtain initial I_p	Start I_p ramp down	End I_p ramp down	End I_p flattop at	Setup shots
3) 1.65 MA at 1.60 s	at 2.74 s to 1.0 MA	at 3.0 s	4.2 s	65558

4) Times of Interest (initial settings):

Time of Interest	Initial setting (s)	Comment
1	2.90	During beam heated I_p ramp
2	3.30	End of peak injection power
3	3.60	During reduction of beam power
4	3.40	Peak in stored energy, also TS
5	3.80	During reduction of beam power

Waveform Timing for High Poloidal Beta DT XP

5) Neutral Beam Timing (DT version of shot 65558):

a) Startup:

Source 5b at 2.600 s
Source 4c at 2.620 s
Source 4b at 2.640 s
Source 4a at 2.680 s

Three counter
sources from
beamline one at 3.000 s

Three counter
sources from
beamline two at 3.020 s

Source 5c at 3.640 s

b) Shutdown:

Source 5c at 3.980 s
Source 5b at 3.600 s
Source 4c at 3.620 s
Source 2c at 3.920 s
Source 2a at 3.380 s
Source 2b at 3.480 s
Source 1c at 4.000 s
Source 1a at 3.940 s
Source 1b at 3.970 s
Source 4a at 3.680 s
Source 4b at 3.580 s

High Poloidal Beta DT XP
Waveform Timings
(Example : 65558 "DT version")

Specifications for Diagnostics (Example 65558 DT Version):

- 1) Polychromator:
 - Insure that setup is for 68kA on the TF.
 - Use 500kHz sampling, start at TOI4 or disruption trigger
- 2) MSE:
 - Needs 5b in deuterium (no 5a,5c preferred - notch 40-50ms at end if 5a, 5b used)
- 3) CHERS:
 - Uses source 5b only to be compatible with MSE
 - Notch in BL5, and BL5 turned off early to get background
(at t = multiple of 20ms)
- 4) MIRI:
 - (see D. Mansfield (x3238 or x2249) or L. Guttadoro (x3184))
 - a) Slow:
 - Monitor nel - profiles
 - b) Fast:
 - Not required
- 5) YS, YM:
 - Request profiles at TOI's from HLDAS operator for YS/YM
- 6) TV, TS:
 - Set TS to TOI4, TV to TOI5
- 7) BES:
 - (Needs 4a, 4b (and 4c is a bonus also))
 - Not required for shot 65558
- 8) Magnetics/MFAN:
 - Have MFAN running between shots.

Diagnostic Checklist

XP Title: **DT Operation in Optimized High Poloidal Beta TFTR Plasmas** XP No.DT33

			Need	Desire	Comments
Magnetics:	Magnetics MB,MD,MR,MV		✓		
	MSE	SQ	✓		
n_e and T_e:	MIRI Interferometer	FM	✓		
	Thomson Scattering	TS	✓		
	Thomson Scattering	TV		✓	
	Radiometer	YS	✓		
	Michelson	YM		✓	
T_i:	CHERS	SW	✓		
	X-ray Crystal	XC			
Spectroscopy:	HAIFA (H _α and UV)	SH	✓		
	SPRED (UV)	SP		✓	
	VIPS (H/D ratio)	SV		✓	
	X-ray PHA	XP		✓	
	Hard X-rays	XH		✓	
Particles	Alpha CHERS	SA	✓		
	Alpha CX	EA		✓	
	Epithermal Neutrons	NE	✓		
	Neutron Activation	NA	✓		
	Fusion Products	NF	✓		
	Neutron Collimator	NM	✓		
	Neutron Fluctuations	NS	✓		
	Lost Alphas	NL	✓		
Waves:	Mirnov Coils	MM	✓		
	X-ray Array	XI	✓		
	RF Probe	RP			
	Grating Polychromator	YG	✓		
	Microwave Scattering	YF		✓	
	Reflectometer	YR		✓	
	BES	SB		✓	
Edge:	Bolometer	BR	✓		
	Plasma TV	VP		✓	
	IRTV	VP			
	Edge Thomson	TE			
	Lithium Pellet	LP		✓	
	Edge Probe	WE			

	Toi 1	Toi 2	Toi 3	Toi 4	Toi 5
Times of Interest	2.900	3.300	3.600	3.400	3.800

DT - 33 Physics Shot List V1.0 : 3/9/94

sequence	shot	from shot	Major R(m)	Initial Ip (MA)	at t (s)	Start Ip ramp @ Ip (MA)	Pedestal at t (s)	D NBI (MW)	T NBI (MW)	Lj pellet timing (s) (pre-cued) (Alpha CX)	BN limit	comments
I - SET UP SHOTS												
3	D-1	65554	2.45	2.00	2.20	2.46	1.40	2.70	0	2.2	3.46	3.48 ~ 3 Initial TOI's: 2.6, 2.9, 3.3, 3.4, 3.45
2	D-2	65567	2.45	1.75	2.20	2.48	1.20	2.70	0	2.2	3.46	3.48 ~ 3 Initial TOI's: 2.6, 2.9, 3.3, 3.4, 3.45
1	D-3	65558	2.45	1.65	1.60	2.74	1.00	3.00	0	1.8	2.2	3.58 3.5 Initial TOI's: 2.9, 3.2, 3.3, 3.4, 3.45
6	D-4	54022*	2.45	1.65	1.70	2.68	0.85	3.00	0	2.2	2.5	3.86 3.6 Initial TOI's: 2.9, 3.4, 3.5, 3.6, 3.65
Initial TOI's (below): 3.7, 3.8, 3.9, 4.0, 4.2												
5	D-5	72010*	2.52	2.50	3.00	3.40	1.60	3.76	0	2.2	2.6	4.42 4.44 ITF = 72 kA : SIGNOFF:
4	D-6	69204*	2.60	1.20	1.60	2.46	0.60	2.70	0	1.8	2.2	R = 2.6m, high q(0) development (TAE)
		(q(0) scan)	2.60	1.40	1.60	2.38	0.60	2.70	0	1.8	2.2	Initial TOI's: 2.6, 2.7, 2.8, 3.0, 3.2
			2.60	1.65	1.60	2.38	0.85	2.70	0	1.8	2.2	3.38 q(0) comparison with R = 2.45 m case
II - TRITIUM SHOTS												
3	T-1	D-1	(as above)							(as above)		NOTE: Beam power will be determined
2	T-2	D-2	(as above)							(as above)		after DD setup shots are taken.
1	T-3	D-3	(as above)							(as above)		3.5
6	T-4	D-4	(as above)							(as above)		3.6
5	T-5	D-5	(as above)							(as above)		Use case with highest Initial Ip and acceptably high q(0) from D-6.
4	T-6	D-6										
* Indicates that waveforms need non-trivial modification Start all conditions at low power to check energy confinement All shots EXCEPT D,T-5 have 68kA TF. D,T-5 have 72kA TF.												
NOTE: If sawteeth occur in R=2.45m, extend preheat phase												

DT - 33 NBI Shot List V1.0 : 3/9/94

NBI Source Priority: (#8)																							
shot		Ip	P_NB	1A (1.74m)	1B (2.00m)	1C (2.23m)	2A (1.74m)	2B (1.99m)	2C (2.23m)	4A (2.28m)	4B (2.05m)	4C (1.80m)	5A (2.23m)	5B (1.99m)	5C (1.73m)								
	MA	MW	on	off	on	off	on	off	on	off	on	off	on	off	on	off							
I - SET UP SHOTS																							
3	D-1	1.40	25-30	2.72	3.30	2.72	3.30	2.70	3.30	2.40	3.40	2.40	3.40	2.40	3.36	2.40	3.36						
2	D-2	1.20	22-27	2.72	3.30	2.72	3.30	2.70	3.30	2.40	3.40	2.40	3.40	2.40	3.36	2.40	3.36						
1	D-3	1.00	20-25	3.02	3.40	3.02	3.40	3.00	3.40	2.60	3.50	2.60	3.50	2.60	3.46	2.60	3.46						
6	D-4	0.85	17-22	3.02	3.70		3.00	3.00	3.70	2.80	3.80	2.80	3.80	2.80	3.76	2.80	3.76						
5	D-5	1.60	30	3.78	4.26	3.78	4.26	3.76	4.26	3.36	4.36	3.36	4.36	3.36	4.32	3.36	4.32						
4	D-6	0.60	13-18				2.70	2.70	3.20	2.30	3.30	2.30	3.30	2.30	3.26	2.30	3.26						
		0.60	15-20				2.70	2.70	3.20	2.30	3.30	2.30	3.30	2.30	3.26	2.30	3.26						
		0.85	17-22	2.72	3.20		2.70	2.70	3.20	2.30	3.30	2.30	3.30	2.30	3.26	2.30	3.26						
II - TRITIUM SHOTS																							
3	T-1			D		T		D		T		T		D		T							
2	T-2			D		T		D		T		T		D		T							
1	T-3			D		T		D		T		T		D		T							
6	T-4			D				D		T		T		D		T							
5	T-5			D		T		D		T		T		D		T							
4	T-6			D				D		T		T		D		T							
Use sources in the order given by the "NBI Source Priority" above.																							

DATE

FILMED

7/21/94

END