Report of Progress on Grant

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High Beta and Confinement Studies on TFTR

15 April 1992 to 14 April 1993

by

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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 most of the second budget period of the three year grant (6/25/92 to 6/24/93).

During the approved three year project period we proposed 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 \( \geq 2 \) 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 significant progress in the first three of these four areas through the submission, approval, and execution of 3 TFTR Experimental Proposals using a total of 7 run days during the August 1992 to November 1992 TFTR run. The full text of these Experimental Proposals (XPs) is included in Appendix A of this report. The title and run time allocated to each is listed below:
XP403:
“Enhanced High Poloidal Beta Operation in TFTR with Deuterium Pellet Injection”
Experiment carried out 11-12 September 1992

XP413:
“Approaching High Q by Utilizing High $\beta_p$ Operation in TFTR”
Experiment carried out 31 August 1992

XP415:
“Advanced Tokamak Regime Experiment”
Experiment carried out 16 September 1993

XP403/413:
“Second Regime Studies at Large Major Radius High $\beta_p$ Plasmas”
Experiments carried out 30 October 1992 and 7 November 1992

Analysis of the data taken during these experiments as well as continuing analysis of earlier data led to a number important results described in publications in the past year including two invited presentations at the 1992 American Physical Society Division of Plasma Physics Meeting in Seattle (with full papers published in *Physics of Fluids B*), an oral presentation at the 1992 IAEA Meeting in Würzburg, Germany, and a *Physical Review Letter*. These results included extending the high $\beta_p$ regime to 1.2 MA current and neutron production rates to more than $3 \times 10^{16}$ sec$^{-1}$; the first experiments with 4 sec neutral beam injection on TFTR; the creation of the first beam and bootstrap current sustained plasmas on TFTR for more than a current relaxation time scale; the first observation of ideal MHD ballooning modes in a large tokamak; and production of plasmas with the inner 3/4 of the plasma in or with stable access to the second stability regime. The principal results of these papers and supporting theory work are summarized below.
High Q Operation in TFTR: We have extended our previous work in this area through the TFTR Experimental Proposal No. 413 (TFTR XP413) titled: “Approaching High Q by Utilizing High $\beta_p$ Operation in TFTR” (copy attached in Appendix A) which was approved by the TFTR Task Force Council on 8/21/92 and resulted in a 1 day run on 8/31/92. These experiments extended our previous high $\varepsilon\beta_p$ results from 1.0 MA to 1.4 MA operation with a peak neutron production of $2.9 \times 10^{16}$ sec$^{-1}$ for a 1.2 MA discharge at $\beta_N = 2.8$. Previously obtained best results with supershots at this modest 1.2 MA plasma current were $2.0 \times 10^{16}$ sec$^{-1}$ at $\beta_N = 2.35$. Attempts to further increase neutron production in 1.4 MA discharges were not completely successful due partly to power limitations: it requires an increasing auxiliary heating power level to access the high $\beta_p$ regime with good confinement. At 1.4 MA, more than 30 MW of heating would be needed and this was not available to us during this experiment. Also, at the higher currents and corresponding lower edge $q$, increasing difficulties were encountered with beta-collapse phenomena. These new results together with further analysis of earlier results at 0.85 MA and 1.0 MA were the basis for an IAEA paper for the 14th Conference on Plasma Physics and Controlled Nuclear Fusion titled “Achieving High $Q_{DD}$ Operation in High Poloidal Beta Discharges in TFTR” by M. E. Mauel, G. A. Navratil, S. A. Sabbagh, M. G. Bell, et al. (copy attached in Appendix B).

Work on extending our high $Q_{DD}$ and high neutron production rate experiments will continue during the next TFTR run period beginning May 1993 to extend these high $\varepsilon\beta_p$ plasmas to 1.4 MA with neutron production rates and $Q_{DD}$ values as close to the best supershot performance levels preparatory for carrying out these experiments in DT.

Study of High $\varepsilon\beta_p$ Plasmas on Current Relaxation Time Scale: During the previous budget period TFTR XP322 titled “Long Pulse High Poloidal Beta Experiment” (copy attached in Appendix B) was approved 12/2/91 and was executed on 17 January 1992 resulting in the first experiments with 4 seconds of neutral beam injection on TFTR. As a follow-on to these successful experiments XP415 titled “Advanced Tokamak Regime Experiment” was approved 8/7/92 and run on 9/16/92. These experiments led to an Invited Paper at the 1992 APS-DPP Meeting in Seattle presented by J. Kesner and the publication in July 1993 of the paper “High Poloidal Beta Long Pulse Experiments in the Tokamak Fusion Test Reactor” (copy attached in Appendix C).
The primary purpose of TFTR XP322 and XP 415 was to study the effects of plasma current equilibration in high bootstrap fraction discharges. We expected to observe changes in both confinement and stability properties as the current profile evolved on the characteristic skin time. Previous high $e\beta_p$ experiments were maintained for 0.5 to 1 second, too short a time to observe current relaxation. In these experiment we created high $e\beta_p$ plasmas using 0.4 to 0.6 MA discharges with neutral beam injection pulses of up to 4 seconds with up to 90% bootstrap and beam driven current. These discharges have been maintained for a constant-current electric field relaxation time. The current profile immediately after the ramp-down phase of the discharge contained a negative current in the outer region which contained 15-25% of the total plasma current. The current profile in the outer region typically relaxed on a time scale of the order of 0.7 seconds while the current profile in the core of the plasma took several seconds to equilibrate.

High normalized beta ($\beta_N > 3$) could not be sustained in TFTR for longer than 0.8 sec, which is approximately the period for the relaxation of the outer portion of the plasma current. The accessibility of the high normalized beta regime in $e\beta_p \sim 1$ discharges appears to be a result of the current profile created by the current ramp-down and is characterized by a negative edge current, increased magnetic shear, and high internal inductance. Lower $\beta_N$ plasmas could be sustained for the full 4 sec duration of the heating pulse although, as the current density profile broadens within the plasma core, beta collapses were often observed to occur near $\beta_N \sim 1.5$.

Energy confinement did not degrade as the current profile relaxed in these high $\beta_p$ discharges. The current ramp-down formation process appears to provide access to a confinement regime in which the plasma current profile does not affect confinement for either the thermal or supra-thermal species.

The results of XP 322 and XP 415 imply that maintenance of high normalized beta values can be obtained in high $\beta_p$ plasmas if current profile control is applied to maintain the strongly peaked current profiles generated in the current ramp-down formation process. The broad current profiles that are present with high bootstrap fractions are subject to beta collapses at reduced levels of $\beta_N$.

Effect of Bootstrap Current on Tokamak Performance: Theoretical work was carried out to identify the scaling of the poloidal beta with bootstrap fraction for a general tokamak operating in steady state. In this work, the 'seed' current profile was specified, but no assumptions are made regarding the functional form of the total current profile. This new scaling relation, which holds for a wide class of density and
temperature profiles, was found to have a quadratic dependence of the poloidal beta on bootstrap fraction. A paper on this work was published in *Phys. Fluids* in July 1992 (copy attached in Appendix D) and this work was also included as part of an IAEA paper for the 14th Conference on Plasma Physics and Controlled Nuclear Fusion titled “Theoretical Basis for Advanced Plasma Configurations” by S. C. Jardin, A. Bhattacharjee, M. S. Chance, S. C. Cowley, *et al.*

**High \(q_o\), Second Regime Experiments:** The TFTR Experimental Proposal 403 titled “Enhanced High Poloidal Beta Operation in TFTR with Deuterium Pellet Injection” was approved 8/21/93 and run on 9/11-9/12/92 with a follow-on experimental run in conjunction with XP 413 on 10/30/92 and 11/7/92. This series of experiments has led to a number of exciting results connected with the production of high \(q_o\) plasmas near second regime operation and pressure profile effects on the stability properties of high \(\beta_p\) plasmas. By operation of TFTR with larger major radius plasmas (\(R = 2.6\) m rather than 2.45 m) the profile of beam driven current was found to significantly broaden the current profile in the ohmic target plasma and aid the production of \(q_o > 2\) plasmas with high \(\beta_p\). In these experiments \(q_o\) values as high as 2.5 were obtained with \(\epsilon \beta_p \leq 1.25\) with over 70% of the plasma minor radius computed to be either in or with direct access to the second stability regime. The availability of accurate \(q\)-profile information from multi-point MSE measurements by F. Levinton has greatly increased the confidence in our modeling of the expected stability properties of these discharges. Variations in current ramp-down control access to this high \(\epsilon \beta_p\) regime of near second stability operation. Without current ramp-down a lower limit of \(\epsilon \beta_p \sim 0.7\) is observed concurrent with the onset of measured high-\(n\) electromagnetic fluctuations whose characteristics are consistent with high-\(n\) ballooning instabilities. An article for *Physical Review Letters* describing these results is currently being prepared for submission.

Another area of study from this series of experiments is the effect of equilibrium profile modification caused by injection of deuterium pellets into high \(\beta_p\) plasmas in TFTR. Pellet deposition was altered in these plasmas by varying the timing of a multiple pellet injection sequence. Broad pellet deposition reproducibly excited large \(m/n = 2/1\) and 3/1 modes which accompany a large collapse in the plasma stored energy. As the pellet deposition is made more peaked, a hot core forms in the plasma with no collapse in stored energy. Analysis of these discharges reveals that the central safety factor increases and transiently forms an inverted central \(q\)-profile.
High Beta and Confinement Studies on TFTR

Analysis of these results is still in progress and a paper for submission to *Physics of Fluids* is currently in preparation.

**Observation of Ballooning Modes in TFTR:** Analysis of fluctuation data in the high $\beta_p$ plasmas in the current and previous budget periods on TFTR has resulted in the first observation of ballooning instability in the interior of a large, collisionless tokamak plasma. These results were presented by Y. Nagayama in an Invited Paper at the 1992 APS-DPP Meeting, were the subject of a *Physical Review Letter* (copy attached in Appendix E), and described in a full paper in *Physics of Fluids* to be published in July 1993.

**PBX-M Collaboration:** Our primary activity in this period has been implementing the adaptation of our TokaMak equilibrium reconstruction code which previously ran only on Apple Macintosh machines to run on a VAX. The code is now operational and will be applied to PBX-M as well as TFTR data analysis in the next budget period.

**List of Publications**


Appendix A — TFTR Experimental Proposals:

XP 403
XP 413
XP 415
TFTR EXPERIMENTAL PROPOSAL

Title: Enhanced High Poloidal Beta Operation in TFTR with Deuterium (or Tritium) Pellet Injection

Proposal No. 403 (Version 1.2)

Authors: S. Sabbagh, K. Owens, G. Schmidt, P. Efthimion, Date: 8/18/92
D. Mansfield, M. Bell, R. Budny, C. Bush, F. Levinton, K. McGuire,

1. Overview of planned experiment:
(include how it fits into the run strategy)

The purpose of this experiment is to optimize the flexibility and enhance the performance of high \( \beta_p \) TFTR plasmas in preparation for DT operation. The injection of deuterium pellets (or tritium pellets during the DT phase) will be used to i) establish a model operating scenario for high \( \beta_p \) TFTR plasmas with increased plasma profile control and ii) attempt to further enhance the stability, confinement, and/or neutron production of these plasmas. The addition of pellet injection will add the ability to modify the density (pressure) profile and central \( q \) profile to the standard \( I_p \) ramp-down technique used to modify the edge \( q \) profile. This additional profile modification capability will be used to influence confinement and stability limits in an effort to improve plasma performance. First, the pressure profile can be altered to improve the ideal MHD stability of the bulk plasma to low-\( n \) modes. Second, \( q_0 \) can be increased in order to obtain improved energy confinement/stability by suppressing sawteeth, attaining second stability to high-\( n \) modes, or creating a pellet enhanced performance (PEP) mode which is thought to be caused by an inversion of the \( q \) profile. High \( \beta_p \) TFTR plasmas provide a good starting point to create these conditions. Increasing \( q_0 \) at high \( \beta_p \) facilitates reducing the size or completely removing the high-\( n \) ballooning mode unstable region. Also, the high \( \beta_p \) plasmas in TFTR have attained large bootstrap current fractions which has been reported to be important in producing the PEP regime in JET. Finally, sawtooth suppression has already been demonstrated at high \( I_p \) in TFTR with pellet injection.

This proposal has particular relevance to the DT phase of TFTR. In summary, the main goals of the experiment are to:

- Demonstrate simultaneous pressure and \( q \) profile modification (with pellets and \( I_p \) ramp-down) for bulk plasma stability studies in DD (collective alpha effects in DT) at high \( \beta_p \).
- Attain higher neutron rates and/or \( Q \) by creating an additional increase in confinement and/or stability (by profile modification) to an already high performance operating regime.
- Gain experience with fueling high \( Q \), high \( \beta_p \) discharges with pellets. This is important since tritium fueling with pellets is much more efficient than with neutral beams (see the DT plan, pages 1-22, 1-38, 2-11).
- Determine the optimal pellet injection timing for top performance in high \( I_p \) discharges.
- Control/suppress MHD activity (i.e. sawteeth, locked modes) which has been detrimental to high \( I_p \), high \( \beta_p \) plasmas. Stabilization of sawteeth has already been demonstrated in high \( I_p \) plasmas with pellet injection.
- Determine the effect of pellet injection on the transition to the limiter H-mode, which has been observed in plasmas with \( I_p \) ramp-down and used as a mechanism to avoid disruptions at high stored energies.
- Examine the behavior of pellet density pumpout as a function of plasma current.
The present experiment will be able to directly address the impact of the imposed density, pressure, and $q$ profile variations on the bulk DD plasma stability. This study will also show to what extent the equilibrium profiles can be modified for stability studies involving collective alpha effects during the DT phase of TFTR (i.e. the ability to change the Alfven velocity profile).

This experiment will also attempt to improve the neutron production of $\beta_p$ plasmas. Since the neutron rate increases as approximately the square of the plasma stored energy, producing a modest increase in energy confinement and/or stability with pellet injection in higher current ($I_p \geq 0.85$ MA, $\tau_e/\tau_e^{\text{ITER-89P}} \sim 3$), high $Q$, high $\beta_p$ plasmas could result in a significant increase in neutron production and/or $Q$. At present, $Q_{DD} = 1.3\cdot 10^{-3}$ has been reached in a 1MA high $\beta_p$ plasma in TFTR, which is 70% of the highest value obtained in TFTR supershots at any current. In addition, creating radially localized enhanced performance regions in the high $\beta_p$ TFTR plasma (as demonstrated in DIII-D and JET) would also help provide a better understanding of the underlying physical mechanisms responsible for the observed improved confinement and/or stability.

2. Theoretical / Empirical justification:
(include figures of previous data from TFTR and / or other machines as appropriate)

The suppression of MHD (i.e. sawteeth) at high current, the modification of the central $q$ profile, and the modification of the pressure profile are the major new features that will be added to the standard high $\beta_p$ plasma current ramp-down technique in order to improve plasma performance. These modifications will all be attempted with the use of D (or T) pellets of various size and quantity injected at various times throughout the discharge. Therefore, for a given plasma current waveform, the experiment will primarily involve varying the pellet injection timing and the number of pellets injected (to change the profile shape) at fixed neutral beam heating power.

1) Sawtooth Suppression: First, the baseline case will be to inject the minimum size and amount of pellets that will suppress sawteeth. Sawtooth suppression by pellet injection has already been performed in XP238 (see Fig. 1). The plan is to use similar relative timing between pellet injection and beams as used in that experiment.

2) Central $q$ profile variation: The pellet timing will then be varied, initially starting before the time of maximum injected beam power and then moved earlier in time. Injecting the pellet early in the discharge will produce the lowest density target plasmas for beam heating and will result in peaked density profiles. In this configuration, the objective is to drive a higher percentage of bootstrap current closer to the magnetic axis, and perhaps enter an enhanced performance mode as found in JET (i.e. see M. Hugon, et al., Nucl. Fusion 32 (1991) 33, Fig 5 - reprinted here as Fig. 2). As the pellet injection time is moved closer to the start of maximum neutral beam power, the plasma target density will be progressively increased, and the beam power to a greater extent will become screened from reheating the magnetic axis until the added density has pumped out. These higher density plasmas with more central pellet deposition will be achieved by the injection of two pellets. A pellet deposition of $r/a \sim 0.2$ will be used for this configuration. The objective is to create a large increase in $q_0$, similar to that observed in TFTR shot 44961. This change is expected to improve stability to high-$n$ ballooning modes. Ideal MHD stability calculations show that a second region equilibrium (to high-$n$ modes) exists with $\epsilon \beta_p = 1.14$, $\beta_N = 2.41$ (already achieved in TFTR) that is also stable to the $n=1$ kink/ballooning mode if $q_0 = 2.8$ can be reached in a broad current profile. In a more peaked profile, a substantial reduction in size of the high-$n$ unstable region can be achieved if $q_0 \sim 3$ can be reached.
3) **Pressure profile variation:** Ideal MHD stability calculations based on TRANSP simulations of existing high $\beta_p$ discharges in TFTR also show that the combination of a broad pressure profile and a peaked current profile can dramatically increase the stability of the $n=1$ kink/ballooning mode (see Fig. 3). Therefore, a tradeoff will be made between extreme pressure profile peakedness and increased MHD stability to find if high neutron production can be obtained in a plasma with broader pressure profile and increased $\beta_N$. The variation in pressure profile shape will be produced by changing the pellet deposition. For the target ohmic electron temperatures being considered, one pellet will fully ablate before reaching the plasma core, producing a broad density profile. A pellet deposition of $r/a \sim 0.5 - 0.7$ will be used to create this profile. Such deposition led to pressure peaking factors as low as 3 in shot 44961.

4) **Existing data:** The increase in $q_0$ anticipated with the injection of D (or T) pellets in this experiment was calculated to have occurred in TFTR shots 44961 and 55053. Results from TRANSP reconstructions of these shots in which multiple D pellets were used to increase the plasma density show that the pellets had the additional effect of raising $q_0$ by a factor of 1.5 - 1.7 by preferential cooling of the magnetic axis. Two key characteristics to the success of shot 44961 in producing a large amplification of $q_0$ seems to be i) central (or near central) deposition of the injected pellet, coupled with ii) densities large enough to screen out neutral beam heating from the plasma center. The key result of these two effects was the production of a hollow $T_e$ profile that was maintained during the reheat phase of the discharge. Production of the hollow $T_e$ profile and the increase in $q_0$ will be monitored using the ECE and MSE diagnostics.

In shot 55053, an increase in $q_0$ and an inversion of the $q$ profile are calculated to have occurred during the ohmic phase, following the injection of the second D pellet and an inversion in the $T_e$ profile. An enhancement in plasma performance may not have been produced in these discharges since the beams were injected after the density (the beam heating was not screened from the magnetic axis) and the central $q$ had decreased significantly by the time of maximum stored energy (Fig. 4). Also, the bootstrap fraction was calculated to be less than 25% (at maximum) in this discharge. Coupling the pellet injection technique to raise $q_0$ with the increased bootstrap fraction of the high $\beta_p$ plasma may provide the necessary complement in achieving enhanced confinement. The plasma current ramp-down should also allow enhanced stability (high $\beta_N$ operation) to help exploit any increase in confinement that may be produced. Finding the optimal timing between pellet injection, $I_p$ ramp-down, and beam injection will be emphasized in the experiment. Injecting the beams closer to the time of pellet injection may result in a larger $q_0$ due to the screening of the reheat of the magnetic axis. An inversion of the central $q$ profile may be sustained by the earlier development of a large fraction of bootstrap current.

The present proposed experiment is a significantly upgraded continuation of XP319 which was started on 1/16/92. Since the D pellet injector was not available during the last TFTR run, the central current profile modification was attempted using the impurity pellet injector. These experiments were successful in achieving an inversion of the electron temperature profile, however the effect could not be maintained, lasting for only 10-20 milliseconds. Creation of the hollow $T_e$ profile which will be used to elevate $q_0$ will not require the plasma density to be as large as that obtained in shot 44961. Experience from shots 44961, 55053 and XP319 indicate that electron densities of about $1 \times 10^20$ m$^{-3}$ should be adequate to reduce $T_e(0)$ and screen the central reheat of the plasma.
3. Experimental Run plan:
(describe groups of shots as appropriate, assume 20-25 shots on a good day)

As discussed in the last section, the pellet and beam deposition are key components to this experiment. Luckily, TFTR pellet injection data (from XP238 - "Supershots and Pellets") exists in the range of current and density proposed for this experiment. These data will be used to set up default values for the pellet injection timing. The structure of this experiment consists of varying the pellet timing and the number of injected pellets for two different plasma current waveforms. The first plasma current used will be 0.85MA, which is the lowest current at which nominal supershot neutron production has been attained at high $\beta_p$. The power level will be near the maximum injected into existing 0.85MA, high $\beta_p$ plasmas (~ 21 MW). During the plasma current ramp-down, one co-source (2.5 MW) will be injected to help prevent high density disruptions. Two baseline shots will be taken without pellet injection. The next shot will be taken as a sawtooth stabilization shot using pellet sizes and timings similar to those used in XP238. The following set of shots has one injected pellet programmed for shallow penetration ($r/a = 0.5 - 0.7$) in order to broaden the density (and pressure) profile. The second set of shots will involve injection of two pellets to attain central deposition of the second pellet ($r/a = 0.2$) and to adequately densify the plasma to block an immediate reheat of the magnetic axis by the beams. In each of these cases, the relative pellet injection timing will be changed to examine the effect of the profile modification on the plasma confinement and stability. The run plan is schematically illustrated in Fig. 5 and listed in tabular form on page 5. The plasma current will then be increased to the maximum current ramp-down condition ($I_p = 2.0$MA, ramp-down to 1.4MA) and the scan in pellet injection timing will be repeated. Careful set-up shots will be required to attain 2 MA operation without causing locked modes (using shot 55051 as a default). If sawteeth and locked modes can be suppressed at $I_p = 2.0$MA, the initial plasma current will be raised to examine if performance can be improved by ramping down from a larger $I_p$ (≤ 2.4 MA). However, if locked modes cannot be avoided at 2 MA and above, the initial plasma current will be reduced to 1.9 MA (or less) until locked modes are no longer a problem for the plasma initiation. If after performing the indicated scans the plasma exhibits improved stability for a particular profile modification, this plasma will be rerun at increased beam power.

D-T Run Plan: This experiment is designed as a D-D prerequisite for an equivalent D-T experiment. It could be reproduced in the D-T phase of TFTR by replacing deuterium pellet injection with tritium pellet injection. The experiment need not use tritium beams and therefore could be substantially more efficient in delivering tritium to the plasma. As outlined in section 2 of the D-T plan, fueling TFTR using tritium pellets will increase the number of allowable D-T shots taken in a run week from 8 (beam fueled) to 32 (pellet fueled) shots.

Since this experiment has not yet been performed, it is difficult to estimate with certainty the neutron production and $\beta_\alpha$ levels that will be obtained. However, as mentioned earlier, the existing high $\beta_p$, high $I_p$ discharges have reached nominal supershot neutron production levels for a given input power. Since $n_e$ and $T_e$ are also similar, it is anticipated that the alpha slowing down time and $\beta_\alpha$ will be similar to that of an equivalently powered supershot, with the advantage of having both pressure and profile control. It is also hoped that this added control will also be able to produce more favorable alpha physics parameters by increasing the bulk plasma performance.

The transient nature of the profile modification will need to be carefully addressed for the actual DT run. The alpha slowing down time (~ 0.35 - 0.5 s) is of the same order as the density profile and current profile relaxation time (~ 0.5 s). For the high temperature plasmas that are planned in this experiment, the current profile relaxation may not be a problem. If the density profile relaxation is too short to perform alpha physics studies, then additional pellet injection could be used to prolong the effect.
High Poloidal Beta with Pellet Injection - Run plan

<table>
<thead>
<tr>
<th>(I_p) pedestal</th>
<th>(I_p) initial</th>
<th>(P) (MW)</th>
<th>pellets</th>
<th>Inject (Te(0))</th>
<th># shots</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85 MA Sequence: (Note: pellet injection times are relative to main beam start)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>850 kA</td>
<td>1.7 MA</td>
<td>18</td>
<td>None</td>
<td></td>
<td>1</td>
<td>Check (\beta_N)</td>
</tr>
<tr>
<td>850 kA</td>
<td>1.7 MA</td>
<td>21</td>
<td>None</td>
<td></td>
<td>1</td>
<td>Reference shot</td>
</tr>
<tr>
<td>850 kA</td>
<td>1.7 MA</td>
<td>21</td>
<td>3.43 mm, -250 ms</td>
<td>(\sim 5) keV</td>
<td>1</td>
<td>Stabilize sawtooth</td>
</tr>
</tbody>
</table>

Broad \(n_e\) cycle: \((r/a \sim 0.5 - 0.7)\)
| 850 kA | 1.7 MA | 21 | 3.43 mm, -50 ms | \(\sim 5\) keV | 1 | Examine reheat |
| 850 kA | 1.7 MA | 21 | ?4.0 mm, 150 ms | \(\geq 5\) keV | 1 | Broad \(n_e\) profile |
| 850 kA | 1.7 MA | 21 | ?4.0 mm, 50 ms | \(\sim 5\) keV | 1 | |
| 850 kA | 1.7 MA | 21 | None | | 3 | Interspersed |

Increase \(q_0\) cycle: \((r/a \sim 0.2)\)
| 850 kA | 1.7 MA | 21 | Two 3.43 mm, 1st at - 50 ms \(\sim 5\) keV | 1 | Central pellet deposition and high \(n_e\), raise \(q_0\) |
| 850 kA | 1.7 MA | 21 | 2nd at 150 ms \(\sim 3\) keV | 1 | |
| 850 kA | 1.7 MA | 21 | None | | 1 | |

Repeat above cycle, each time increasing the interval times (3) If \(T_e\) inversion between pellet injection and beam injection (-50, -150, subtotal: 6 is not attained, use 4mm as 2nd pellet).

1.4 MA Sequence: (Initial \(I_p = 2.0\) MA or greater: Requires set-up: use shot 55051)
| 1.4 MA | 2.0 MA | 22, 25 | None | | 2 | Set-up shots |
| 1.4 MA | 2.0 MA | 25 | None | | 1 | Reference shot |
| 1.4 MA | 2.0 MA | \(\geq 25\) | 3.43 mm, -600 ms \(\sim 6.5\) keV | 1 | Stabilize sawtooth |
| 1.4 MA | 2.0 MA | \(\geq 25\) | 3.43 mm, -400 ms \(\sim 3\) keV | 1 | |

Broad \(n_e\) cycle: \((r/a \sim 0.5 - 0.7)\)
| 1.4 MA | 2.0 MA | \(\geq 25\) | 3.43 mm, -50 ms \(\sim 6\) keV | 1 | Examine reheat |
| 1.4 MA | 2.0 MA | \(\geq 25\) | ?4.0 mm, 150 ms \(\geq 6.5\) keV | 1 | Broad \(n_e\) profile |
| 1.4 MA | 2.0 MA | \(\geq 25\) | ?4.0 mm, 50 ms \(\sim 6\) keV | 1 | |
| 1.4 MA | 2.0 MA | \(\geq 25\) | None | | 3 | Interspersed |

Increase \(q_0\) cycle: \((r/a \sim 0.2)\)
| 1.4 MA | 2.0 MA | \(\geq 25\) | Two 3.43 mm, 1st at - 50 ms \(\sim 6\) keV | 1 | Central pellet deposition and high \(n_e\), raise \(q_0\) |
| 1.4 MA | 2.0 MA | \(\geq 25\) | 2nd at 150 ms \(\sim 3\) keV | 1 | |

Repeat above cycle, each time increasing the interval times (3) If \(T_e\) inversion between pellet injection and beam injection (-50, -150, subtotal: 6 is not attained, use 4mm as 2nd pellet).

Extra shots included for tuning pellet timing, etc.: 6 Includes 3 cleanup
Increase beam power in optimal conditions: 4 Includes 2 cleanup

Total number of shots (5 ref/set-up + 17 cleanup + 19 pellet shots) 41
Note that approximately one “cleanup" shot (i.e. a shot without pellets) has been planned to be performed for each pellet shot taken. These shots will be taken after each pellet shot to maintain good machine conditioning and to provide reference shots without pellets for each condition.

4. **Required Machine, Beams, ICRF and Diagnostics Capabilities:**
(Machine conditions which are required, and impact of experiment on conditioning. Complete the two forms attached)

This experiment should have conditions similar to those that existed for XP313 (1/10-11/92) with the following amendments/additions:

1. A well conditioned machine (Target \(n_e I \sim 2.2 \times 10^{15} \text{cm}^{-2}\) at 1.6 MA)
2. Availability of greater than 25 MW of balanced NBI for 1.0 sec.
3. D pellet injector for profile modification, up to two pellets/shot (3.43 & 4.0mm, low speed).
4. \(T_e\) permissive for pellet injection highly desired, but not required.
5. Highly desire MSE diagnostic for measurement of the \(q\) profile.

See attached forms for complete description of machine and diagnostics capabilities needed.

5. **Estimated neutron budget:**
(include basis for budget calculation, can use:- neutrons = \(2.7 \times 10^{15} \Delta t \text{sec} P(\text{MW}) Q\))

    Shot 55853, which ramped the plasma current down from 1.65 MA - 1.0 MA, produced \(8.5 \times 10^{15}\) total neutrons. If the planned high neutron producing shots are successful, the expected amount of neutrons/shot would be about a factor of two larger. If all shots produce this level of neutrons, then \(< 7 \times 10^{17}\) total neutrons will be produced.

6. **Planned analysis:**
(include estimated time and manpower requirements)

    If measurements of the internal magnetic field using MSE can be made, free-boundary equilibrium analyses using the TokaMac code will also be performed to calculate the global equilibrium parameters and the \(q\) profile. TRANSP simulations of these discharges will be essential. Ideal MHD stability analysis will follow using the TRANSP pressure and \(q\) profiles, and outer boundary shapes. This analysis will determine how the high-\(n\) unstable region has been modified and the low-\(n\) kink stability of these plasmas.

7. **Experimental results summary:**
(due 4 weeks after the experimental run)

    Will give a summary in four weeks.
Title: High $\beta_p$ with D(or T) pellet injection

Proposal: 403

Machine conditions (indicate range where appropriate):

$I_p$(MA) $2.4 - 0.85$ MA  $R$(m) $2.45$,  ($a = R - 165.5\text{cm}$ for BL and $= 359.8 - R\text{cm}$ for RFL)

OH Flattop start/stop ~ 2 to 2.5 sec,  $I_{TF}$(kA) $68$, Gas Species $D$, Pellets(D) [D or T]

Beams: Power > 25 MW, duration 1.0 sec, voltage 100 - 110 keV

ICRF: Power______, duration__________

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

List of previous shot numbers for setup 0.85 MA: 60542, 60545; 1.4 MA: Startup - 55051.

_plasma current ramp-down - 60523 - also see Fig. 5 for sketch of waveforms._

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

(Attach additional sheets as required)
Fig. 1
Fig. 5. Computed and measured profiles for pulse No. 23100 at $t = 6.605$ s: (a) $q$-profile calculated using IDENTD and rational $q$-values determined from soft X-ray data analysis; (b) current density profile, averaged over the flux surfaces, obtained from IDENTD and the bootstrap current contribution to the total current. The indicated dark area reflects the uncertainty in the bootstrap current calculated from the local gradients of the measured LIDAR density and temperature profiles; (c) LIDAR electron density profile; (d) LIDAR electron pressure profile.
The combination of $J_P$ ramp-down and broad $p$ profile shape leads to a significant improvement in the $n = 1$ kink stability.
Fig. 4

1. Peak in stored energy
2. Start of beam heating
3. Peak in stored energy

$q_0$

Q PROFILE (Q VS TIME)

$q$ profile inversion at $t = 2.6$ s (TRANS)
**High Poloidal Beta with Pellet Injection**

**Run Plan**

- Pellet Injection Into Current Ramp-Down:
  
a) 1.7 MA - 0.85 MA Ip Ramp-down
  
b) 2.0 MA - 1.4 MA Ip Ramp-down

1) Sawtooth Suppression:

- 3.43 mm Pellet
- One co-source @ start of ramp-down
- Main NBI @ 2.45 s
- Extend Beam Pulse if WE Saturation is not reached

2) Broad density (pressure) profile:

- One co-source @ start of ramp-down
- Main NBI @ 2.45 s
- Peak β
- Extend Beam Pulse if WE Saturation is not reached

**Reference shot(s) & Comments**

- Pre-fill only
- TF: 68 kA
- 60542, 60545

Start-up: 55051
Ip ramp: 60623

**Pellet timing**

One pellet, vary timing (3 shots)
3) **Increase central \( q \) (two pellets/shot):**

- **Main NBI** @ 2.45 s
- **One co-source** @ start of ramp-down
- **Extend Beam Pulse if WE Saturation is not reached**
- **Peak \( \beta \)**
- **Pellet timing**
- **Two pellets/shot** (3 shots)
- **High density target**

**Reference shot(s) & Comments**
Title: Approaching High Q by Utilizing High $\beta_p$ Operation in TFTR

Authors: M. Mauel, G. Navratil, S. Sabbagh, (Columbia U.) Date: 8/18/92
J. Kesner (MIT), M. Bell, C. Bush, E. Fredrickson, K. McGuire,
M. Zarnstorff, (PPPL)

1. Overview of planned experiment:
(include how it fits into the run strategy)

By making use of a rapid plasma-current ramp-down, high $\epsilon \beta_p$ discharges have been produced in TFTR with $Q_{DD}$ up to $1.3 \times 10^{-3}$, $S_n$ up to $2.9 \times 10^{16}$, and stored energy up to 3.4 MJ. Since the current and pressure profiles of these discharges differ from supershot profiles, these high $\beta_p$, $I_p$ ramp-down shots provide TFTR with a unique opportunity to investigate the roles of changing profiles on DT performance and plasma stability in the presence of alpha particles. At somewhat lower currents, these high $\beta_p$ discharges have also given TFTR the ability to investigate confinement and fluctuations in diverted discharges and in the presence of high bootstrap current fractions.

The purposes of this XP are (1) to collect additional data further documenting our highest $Q_{DD}$ discharges produced with the rapid $I_p$ ramp-down technique, (2) to vary the timing of the NBI in order to "optimize" the stabilizing effects of the $I_p$ ramp-down by making nearly coincident the maximum $\beta_N$ with the maximum $I_p$, and (3) to demonstrate disruption avoidance at high $\beta_p$ so that we can use with confidence this shot formation technique during the DT phase. The first two of these goals will result in data that will be made part of our IAEA paper this fall. As will be explained in the following section, we believe the second task may raise further the levels of $Q_{DD}$ that TFTR can achieve using the rapid $I_p$ ramp-down.

2. Theoretical / Empirical justification:
(include figures of previous data from TFTR and / or other machines as appropriate)

As described in XP 313, when we extrapolated the early results and performance of relatively low current $I_p$ ramp-down discharges from 0.6-1.0 MA up to 1.4 MA, it appeared that discharges of this type may obtain $S_n$ and $Q_{DD}$ above those achieved so far with supershots in TFTR. However, when XP 313 was executed (Jan. 10 & 11, 1992, shots 60508-655), confinement did not increase in proportion with increasing current and the maximum attainable $\beta_N$ did not exceed 2.7. The onset of ELMs and/or MHD activity appeared to contribute to reduced confinement and/or a beta collapse. Figure 1 summarizes the waveforms for the 1.6 MA $\rightarrow$ 1.0 MA ramp-down shots, and Figure 2 summarizes some waveforms for representative 1.75 MA $\rightarrow$ 1.2 MA shots. As indicated, when $I_p$ increased, the L-mode confinement time multiplier decreased, and this reduced $Q_{DD}$ somewhat. However, by injecting 28 MW to reach $\beta_N = 2.7$ at $I_p = 1.2$ MA, XP 313 succeeded to create record stored energy and neutron production at this current level. Furthermore, the ELMs associated with the limiter/high...
$\beta_p$ H-mode seemed to act as a $\beta_N$ limiting process, none of these discharges disrupted despite being above the beta limit usually observed for supershots.

In preparation for this run period, we have considered carefully possible modifications to the rapid $I_p$ ramp-down technique that may allow operation at $\beta_N \geq 3$ with good confinement at higher current levels, $I_p \sim 1.4$ MA. One possibility was suggested by the DIII-D experiments conducted by J. Ferron. These experiments resembled the L-mode current ramp experiments conducted by M. Zarnstorff except Ferron injected sufficient NB power to reach DIII-D's highest recorded value of normalized beta, $\beta_N = 6$.

In the DIII-D experiments, a nearly circular discharge ($\kappa = 1.2$) having $I_p = 0.8$ MA ($q_{95} = 3.5$) was rapidly ramped-down to 0.4 MA ($q_{95} = 6$). Figure 3 summarizes the DIII-D results. This current ramp was similar to the 1.75 to 1.2 MA TFTR discharges performed in XP 313; however, Ferron "pre-heated" the pre-ramp plasma with 75% of the power injected during the post-ramp phase of the discharge. In addition, the DIII-D experiments were conducted with L-mode conditions while our current ramp-downs usually entered the H-mode (at modest power) or a "high $\beta_p$" confinement mode (at larger power levels). Thus, the density profiles during TFTR's ramp-downs are more peaked than DIII-D's. Ferron noticed that $\beta_N$ scaled linearly with $l_i$. As $l_i$ increased from 1 to 2, $\beta_N$ increased from 3 to 6. Stability analysis verified the linear dependence of $\beta_N$ with $l_i$ for these profiles. The confinement time also seemed to scale with $l_i$, and, since Ferron noticed that these shots always seemed to "track" the marginal stability boundary, he suggested that the data shows a link between stability and confinement.

We are not certain why DIII-D was able to achieve twice the $\beta_N$ that we have been able to produce in TFTR at $q_{95} = 6$, but their results suggest that "pre-heating" the pre-ramp-down plasma may also contribute to higher $\beta_N$ limits in TFTR. In addition, by heating the plasma through the $I_p$ ramp-down, the time at which peak $\beta_N$ occurs will more closely coincide with the peak in $l_i$.

We have also numerically solved the 1D magnetic diffusion equation for TFTR parameters (as in Mikkelsen, 1989) in order to illustrate the role of increasing $T_e$ on the edge global shear, $s = (r / q) dq/dr$, and $l_i$. As expected, as $T_e$ increases (for example, after the NB "pre-heat"), the $I_p$ ramp-down modifies the current profile within a thinner region at the surface of the plasma. This increases $l_i$ and the magnitude of the edge shear. Since higher $l_i$ and shear is usually stabilizing, "pre-heating" the plasma before the rapid $I_p$ ramp-down might increase our operational beta limit. The simulation results and the time-variation of $l_i$ as calculated by TRANSP are shown in Figure 4.

The higher edge shear may also improve energy confinement. One popular hypothesis for the improved confinement observed during the high $l_i$ mode is that the increased edge shear allows a higher $p'$ at the edge while remaining within the first stability regime. (This is the opposite of the popular explanation for the VH-mode which might be explained due to a lower edge shear allowing access to the second regime at the edge.)

Switching on the neutral beams before and during the ramp-down moves the time of peak stored energy earlier and may allow us to coincide the peak $\beta_N$ with the peak $l_i$ and $s$ (which always occurs at the end of the $I_p$ ramp). This was briefly attempted during XP 149 and 160 (performed on Feb. 1, 1990 shots 46429-97) but with mixed results. In discharges having a 0.85 to 0.4 MA current ramp, we attempted to move the peak beta ($\beta_N = 3.6$) from 350 msec after the peak $l_i$ to one peaking only 100 msec from the peak $l_i$. As we moved the start-time of the NBI 100 msec before the completion of the $I_p$ ramp, we observed the highest value of $\beta_N \sim 4.5$ obtained during the run. Figure 5 shows the waveforms for these shots. However, when the NBs were injected even earlier during the $I_p$ ramp-down (shots 46471 & 3), disruptions occurred at $\beta_N < 2$. After careful examination, these two disruptions appeared to result 50 msec after the radiated power rose to a level equaling the injected beam power. Since these two shots
were made in dirty machine conditions and after a long sequence of Li-pellet injections into diverted, $\varepsilon \beta_p > 1$, discharges, we believe they should not reflect negatively on this proposal. For this run period, we will operate at much higher current levels. Indeed, we speculate that "pre-heating" will allow higher NBI powers by helping to prevent beta-driven disruptions by increasing $I_i$, $s$, and the limiting $\beta_N$ as observed in DIII-D.

We have reason to believe that one additional modification to our $I_p$ ramp-down technique may further improve performance. We noticed some time ago (XP 221 and 222, performed Aug 21, 1990, shots 52270-336) that small changes in the co-counter- beam mix can change and even stabilize the MHD activity observed in high $\beta_N$ discharges. Probably one of the best examples of this effect is the pair of shots 52335 and 52336. By changing the co-counter-mixture from (10 MW, 8 MW) to (8 MW, 10 MW), the beta collapse occurring at $\beta_N \approx 3.3$ was stabilized. TRANSP analysis indicated a significantly different beam-driven current profile between the two otherwise identical shots. Apparently, similar effects have been seen during 1 MA supershots (XP 131, performed Oct. 19, 1989, shots 42924-61). In this run, co-injection tended to increase the toroidal mode number of the continuous MHD activity.

Variation of the co-counter-mixture may also help to avoid the H-mode in our higher current $I_p$ ramp-down shots. As pointed out by C. Bush, 1990, the limiter H-mode in TFTR can be usually prevented by strongly unbalanced NBI. When the "pre-heat" consists of only co- or counter-beam injection, we will likely not enter the H-mode until well after the $I_p$ ramp-down has been completed. Since the ELMs associated with the H-mode appeared to limit confinement in our higher current $I_p$ ramp-down shots, an unbalanced "pre-heat" should optimize confinement. In addition, H-mode ramp-down experiments conducted by Ferron did not show a significant confinement improvement or increase in the operational beta limit.

Although we are not certain whether co- or counter- or balanced injection "optimizes" performance of TFTR's $I_p$ ramp-down discharges, we propose to vary the co-counter mixture of the "pre-heat" injection and observe experimentally which mixture "optimizes" performance either by reducing MHD activity or improving confinement. We will also monitor the time history of the central $T_e$ in order to determine whether or not sawteeth can be stabilized or the deleterious effects of sawteeth minimized. We have reason to believe from a comparison between shots 60542 and 60544 that higher $q(0)$ may improve performance. In these shots, we decreased the interval of the ohmic pedestal before the $I_p$ ramp, and this delayed the onset of sawteeth and improved confinement. Since TRANSP simulations have indicated a gradual reduction in $q(0)$ during the ohmic pedestal, the discharges having a shorter pedestal were also likely to have high $q(0)$.

3. Experimental Run plan:
(describe groups of shots as appropriate, assume 20-25 shots on a good day)

As described in XP 313, a major concern in this run plan is to avoid disruptions (which require a long clean-up period) while, at the same time, exploring new advanced regions of operating space. To date, all of the record high $Q_{DD}$ and high $S_n$ discharges obtained following a rapid $I_p$ ramp-down ended in a beta collapse or a disruption. However, as demonstrated in XP 313, at higher currents, by limiting the injected NB power, all discharges also made a transition to a limiter H-mode. The onset of ELMs and an increase in the observed $D_\alpha$ light at the end of the H-mode phase both appeared to limit the shot's stored energy and neutron rates. On the other hand, when ELM's appeared, no disruptions were observed.

In order to achieve the three goals for this experiment, we must decide early whether or not NB "pre-heat" extends the TFTR beta limit as seen on DIII-D. If the NB "pre-heat" is
successful, we will have demonstrated $\beta_N \geq 3$ performance with currents as high as 1.2 MA to 1.4 MA. This will lead to record neutron rates, and we will probably devote most of the run time to exploring these higher current regimes. On the other hand, if high $\beta_N$ discharges can not be produced at higher $I_p$, then we will focus on the high $\epsilon\beta_p$, high $Q_{DD}$ discharges obtained previously at 1.0 MA.

This strategy leads to a run plan that can be stated as follows...

1. Setup a 1.75 MA to 1.2 MA rapid ramp-down discharge similar to shot 60544 or 60615.
2. Investigate NBI “pre-heat”. We must determine first whether or not co-injection-only (in order to raise $q(0)$ and eliminate earlier H-modes), counter-injection only, or balanced-injection for the “pre-heat” optimizes confinement. Secondly, we must determine how much “pre-heat” power is required.
3. We must next determine at which time the full NB power should be applied. By initiating the full-power phase of the NBI earlier in the $I_p$ ramp-down, we will better coincide the peak stored energy with the maximum modification of the current profile.
4. Finally, we will examine the results from this initial sequence for an indication of (i) sawteeth, (ii) MHD activity, and (iii) ELMs/H-mode transitions. Based on these results, we will select the optimum beam timing, and gradually increase the power to the maximum available or until indications of MHD activity are observed.
5. Based on our experience at 1.2 MA, we will next setup a 2.0 MA to 1.4 MA rapid ramp-down. We will use the same NBI timing as determined previously. This will include the NB “pre-heat” and a gradual power scan.
6. At the end of the run, we will quickly review our data and select the “best results” (as defined by high $S_n$ or high $Q_{DD}$) and collect supporting data for our IAEA paper and to help plan for the DT runs.

A detailed outline of our proposed shot list is...

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<th>$I_p$ initial ($q_a$)</th>
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<th>$F I_p$ # shots</th>
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Subtotal | 7

- Choose best approach for low MHD and sawtooth suppression
- Choose earliest NBI start time with good performance

- Move NBI earlier in 0.1 sec increments

- Shift balance to 2 co; 6 counter sources

- Shift balance to 6 co; 2: counter sources

(check effect on pressure profile; broader & higher $\beta_N$ limit)
Choose best combination of preheat; earlier NBI; & co/counter and push power to 30 MW

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Subtotal 4

Use results of 1.2 MA operation to set up 2.0 MA to 1.4 MA rampdown

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Subtotal ≤10

Second Stage of Run: (6 shots)

Review data to select the “best results” as defined by \( S_n \) and \( QDD \) to collect supporting data for our IAEA paper and to help plan DT experiments. These include exploration of the following (i) longer beam pulses at 1.2 MA or 1.4 MA, (ii) higher power at 1.2 MA or 1.4 MA, or (iii) higher power “pre-heat”.

The required shots will maximum of 38 shots (1 reference and 37 research shots).

4. Required Machine, Beams, ICRF and Diagnostics Capabilities:
(Machine conditions which are required, and impact of experiment on conditioning. Complete the two forms attached)

This experiment should have conditions similar to those existing for XP 313 (Jan. 10, 1992). In addition, we would prefer to have NBI capability greater than or equal to 28 MW. The machine should be relatively clean and well-conditioned with an integrated target density near \( 2.0 \times 10^{15} \text{ cm}^{-2} \) at a discharge current of 1.4 MA. It would be highly desirable to have available MSE, CHERS, and BES diagnostics.

5. Estimated neutron budget:
(include basis for budget calculation, can use:- neutrons = \( 2.7 \times 10^{15} \Delta t \text{(sec)}P(\text{MW}) Q \), assume \( Q \propto \text{Power} \))

Shot 60554, which ramped the plasma current down from 1.75 MA \( \rightarrow \) 1.2 MA, produced \( 1.1 \times 10^{16} \) total neutrons at 28 MW. We plan \( \approx 17 \) 20 MW shots and \( \approx 21 \) 22–30 MW shots. If we are successful, the high-power shots would be a factor of 2-3 times larger than the neutrons recorded in 60554. Based on this estimate, the level of neutrons produced from the shots in this proposal would be less than approximately \( 9 \times 10^{17} \) total neutrons produced.
6. **Planned analysis:**
(include estimated time and manpower requirements)

Estimates of the energy confinement time will be made using M. Bell's filament code. TRANSP simulations of these discharges will be essential. Ideal and resistive MHD stability analyses will follow using the TRANSP pressure and $q$ profiles, and outer boundary shapes. TRANSP simulations of the best shots as might be observed with D-T will be performed. Kinetic instabilities driven by alpha particles will be investigated.

If measurements of the internal magnetic field using MSE can be made, free-boundary equilibrium analyses using the TokaMac code will also be performed to calculate the global equilibrium parameters and the $q$ profile.

7. **Experimental results summary:**
(due 4 weeks after the experimental run)

Will give a summary in four weeks.
PHYSICS OPERATIONS REQUEST

Title: Approaching High $Q$ by Utilizing High $\beta_p$ 
Operation in TFTR

Proposal: 413

Machine conditions (indicate range where appropriate):

$I_p$(MA) 1.0 - 2.0 MA  $R(m)$ 2.45 ,  (a = R-165.5cm for BL and = 359.8-Rcm for RFL)

OH Flattop start/stop  $\sim 2.2$ to $\sim 2.5$ sec,  $I_T$(kA) 68 ,  Gas Species D,  Pellets(D) No

Beams: Power Max ($\geq$28 MW), duration 0.75 - 1.0 sec,  voltage 95 to 110 keV

ICRF: Power , duration .

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

List of previous shot numbers for setup 60554, 55051, and schematic below.

If this is a series of shots that are new and unique, sketch the desired profiles. It is important to accurately label the sketch so there is no confusion about times or values.

(Attach additional sheets as required)
### DIAGNOSTIC CHECKLIST

**Proposal Title:** Approaching High Q by Utilizing High $\beta_p$ Operation in TFTR  
**Proposal No.:** 413

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**Comments / Times of Interest:** Desire MSE, CHERS, BES, and Fast MIRI diagnostics.  
We will adjust NB timing as appropriate.
'BEST' 1.2 MA KAMP-Down $\sim 2.9 \times 10^4$

$1.75 \rightarrow 1.2$ MA Ramp Down

$T_e \lesssim 140$ msec

NOT AS GOOD for 1.2 MA

$\zeta \sim 1.8$

$\beta_n \sim 2.7$
$\beta_N$ GREATER THAN 6
REACHED BY INCREASING $\ell_i$

- Strong negative current ramp raises $\ell_i$ above 2.
- $\beta_N$ decays on the time scale of the current profile ($\ell_i$) relaxation, longer than $T_E$.
- Near-circular, limiter discharge.

The $\beta_N = 6$ discharge has $\beta_p = 3.6$

- Negative current near the edge results from the negative current ramp.
\[ \frac{2E}{2\epsilon} = \frac{1}{6} \frac{1}{\epsilon^2} \left( \frac{\partial^2 }{\partial \epsilon^2} \right) \]
Our previous attempt at "pre-heat"...

Plasma Current $I \sim 2.8$

Neutral Beam Power Summary Waveform Beams #7744 #15703

BD/DT 25-35 KHz

NBI 100 mSec Earlier

Beta N

Large increase in $\beta$ limit (and improved confinement!)

Ant 46466 02/01/90 18:22 46474

Cijlot 07/28/92
TFTR EXPERIMENTAL PROPOSAL

Advanced Tokamak Regime Experiment


August 6, 1992

1. Overview

This proposal is a follow-on to XP222 (performed 8/22/90) and XP322 (1/17/92) and is particularly relevant to the understanding of high-bootstrap-fraction long-pulse tokamak phenomena. XP322 was a 4 second high-bootstrap-fraction experiment. In this experiment we successfully used rampdown techniques to create discharges with very high bootstrap fractions and held these discharges until they ended in beta collapses and in some cases disruptions. There were 2 discharges, #’s 61124 and 61148 that were of particular interest in terms of high non-inductive current fraction. Both of these discharges had sister shots which collapsed early indicating that we were operating close to a stability boundary.

The purpose of this XP is to perform a follow-on experiment with the following goals:

- Reproduce the high bootstrap fraction discharges from XP322 to obtain more data under these conditions.
- Vary ramp timing to control early beta collapse. Document beta collapse dependence on $q_0$ (or alternately $\chi_0$). Obtain more MSE current profile measurements.
- Vary plasma current waveform to extend shot to the full 4 seconds while avoiding a beta collapse, i.e. obtain true steady state.
- Vary co/counter mixture to change current profile. Obtain full non-inductive current drive.
- Add neutral beam power late in discharge (when $q_0 > 2$) to test for second stability effects.
2. Justification

XP322 created high-bootstrap-fraction 4 second discharges. In these discharges the plasma current is initially typically twice the final value and the current is rapidly ramped down prior to neutral beam injection. Thus the beams are injected into an initially high $I_i$ plasma.

We observed that the discharges pass through several phases as the bootstrap current diffuses and $q_0$ rises. Initially the neutral beams heat the plasma up to $\epsilon \beta_p \sim 1$. Non-inductive (bootstrap and beam driven) current of > 80% was seen in discharge 61148 and the non-inductive current causes the current profile to broaden and $\ell_i$ to drop with time. Confinement is seen to fall with time throughout this phase of the discharge which includes an H-mode transition and the appearance and then disappearance of a 3/2 mode. The plasma current profile was predicted by TRANSP (61148A03) and was also measured by the MSE diagnostic. The analysis of the MSE data is not yet complete.

Theoretical arguments appear in the literature to the effect that with a broad current profile the normalized beta should properly be $q_0 \beta_N$ or $\beta_N/\ell_i (1/2)$. From the TRANSP simulation we observe that although $\beta_N \equiv \beta a B/I_p$ decays with time both $q_0 \beta_N$ and $\beta_N/(\ell_i - 1/2)$ rise as the current profile broadens.

Fig 1a shows temporal measurements of the a) plasma current and b) neutral beam power c) $T_e$, d) $(n_e \ell_i)$, e-f) Mirnov signals for discharge 61148. The plasma current is rapidly ramped-down from 850 to 400 KA prior to neutral beam injection. After the beams turn on the plasma heats up rapidly to $\epsilon \beta_p \sim 1$. At the point of peak beta $q_0$ is near 1 and the high $\ell_i$ current profile typical of a ramp-down plasma is believed to be present. However the bootstrap current is also high and as it broadens the current profile (on a resistive skin time scale) the discharge is seen to pass through several phases. A measure of the broadening of the current profile is the axial q value, $q_0$, and according to TRANSP $q_0$ rises steadily up to $q_0 \sim 2.2$. After 2.5 seconds of beam heating when the plasma current profile is close to equilibrium a beta collapse is observed. Fig. 2 shows the plasma current profile just prior to the beta collapse at $t=5.3$ sec. Except for the vicinity of the magnetic axis the current is largely maintained by bootstrap current. (On axis there is some neutral beam current drive present). The specific phases observed in this discharge are as follows:

- After reaching the peak beta ($t=3.2$ sec) we observe a separatrix limited plasma for a short duration.

- The discharge drops into a high confinement limiter L-mode with the turn-on of a 30 KHz, $m/n=3/2$ mode (fig. 1d) at $t=3.3$ sec. This mode decays with time and disappears after $t=4.5$ sec. During this phase of the discharge density rises and $\beta$ decays slowly.

- At $t=4$ sec a transition into a limiter H-mode discharge is observed. The density reaches steady state and large elms appear.
At \( t=4.5 \text{ sec} \) the 30 KHz mode disappears. The disappearance is consistent with \( q_0 > 1.5 \) at this time. At this point the density rises and beta flattens near \( \epsilon \beta_p \sim 0.9 \). Elms continue to be observed.

At \( t=5.3 \) a beta collapse is observed and \( \epsilon \beta_p \) drops to \( \epsilon \beta_p \sim 0.4 \). Fig 3 shows clearly the 5 KHz signal rising at this time. This mode remains present in the plasma until the beams shut off at \( t=6.7 \text{ sec} \).

We observe that although plasma pressure is dropping with time the shear is also dropping which is bringing us up to a stability boundary. Detailed calculations using the PEST stability code with the pressure and current profiles gotten from TRANSP indicate that at the time of the beta collapse the discharge becomes unstable to both the high-\( n \) and \( n=1 \) ideal modes. We observe that the \( n=1 \) mode is predicted to contain a large 3/1 component (as was observed on the Mirnov array.)

The TRANSP simulation indicates that although we are close to equilibrium \( q_0 \) is still rising with time (shear is falling with time) at the time of the beta collapse. We would like to reach a steady state or at least prevent the beta collapse from occurring during the extent of the discharge.

Initially we will use the same neutral beam sources as were found to be successful in XP322. In this XP we observed, for example, switching the time order of 5B and 4B (which were run in a staggered fashion for 2 sec at 95 KeV) significantly effected confinement. This might be an indication of the sensitivity of the location of the beam footprint to the mode rational surfaces.

The two major difficulties which we had in these experiments were 1) Early time \( (q_0 \sim 1, \ell_i > 1.5) \) beta collapses due to 2/1 and 3/2 modes, 2) Late time beta collapses \( (q_0 > 1.5, \ell_i < 1) \). We will attempt to eliminate these problems in the following ways:

- To avoid early beta collapse we will try to vary the length of time of the high current plateau. This will vary the position of the 3/2 and 2/1 surfaces with respect to the peak in pressure gradient, which may cause beta collapse when it lines up with the neutral beam footprint.

- To avoid late-in-time beta collapse we will raise the plasma current. After repeating the 850 \( \rightarrow \) 400 KA rampdowns we will set up a 900 \( \rightarrow \) 500 \( \rightarrow \) 400 (Sabbagh slow ramp), 900 \( \rightarrow \) 450, and 1000 \( \rightarrow \) 500 KA rampdown. At fixed power the higher current will move us away from the stability boundary.

3. Experimental Plan

Describe goals of shots, assume 20-30 shots per good day. In the experimental program plan care will be taken to

- Obtain the same well conditioned wall conditions as present in XP-322, namely \( \langle n_{\ell} \rangle < 2.8e15 \text{ cm}^{-2} \).
Use the same neutral beam sources and timings as used in shot 61148. We observed above that when we switched the relative timing of sources 5B and 4B, (which were staggered because the MSE required that 5B be run at 95 KeV which limited its duration to 2 seconds), the discharges exhibited more virulent early time beta collapses.

• Arrange the fast and long-fast windows to coincide with the probable times of the beta collapses.

• Vary the current profile by producing 3/1 and 1/3 co/counter discharges.

The initial timing sequence will be approximately as follows:

Current ramp-up (0-1000 KA), time 0 → 1 sec,
Flattop high current operation, 1 → 2.5 sec,
Current rampdown to 600 KA, 2.5 → 2.7 sec,
Neutral Beam injection 2.7 → 3.7-6.7 sec,
Final current rampdown, 6.7 → 7.2 sec.

SHOT SEQUENCE
1 shot; Ohmic reference, 850 → 400 kA.
8 shots; 4 sources, 2/2 co/counter mix. Begin with 1 second beams and extend in 1/2 second steps out to 4 second pulse length. Take two 4 second shots.
1-4 Shots; If early beta collapse occurs decrease high-current flattop time to 1.25 sec.
4-6 Shots; If beta collapse occurs late in time switch current waveform to try 900 → 500 → 400 KA, 900 → 450 and 1000 → 500 rampdowns.
2 shots; For best sequence switch to 3/1 co/counter mix.
2 shots; For best sequence perform to 1/3 co/counter mix.
2 shots; In late-time-beta-collapse shot add additional 6 MW of power after the collapse.
2 Shots; Constant current at high and low currents respectively.

4. Required Capabilities

Include impact of ram on conditioning. Also see two forms attached.

• $I_{TF}=68$ KA.

• A sufficiently well conditioned machine to maintain $(n_e\ell) < 3 \times 10^{15}$ cm$^{-2}$. 
• Capability to run 4 second beam pulses with \(\approx 9\) MW of balanced neutral beam injection power. Prefer use of 2A, 2C, 4A as 4 second sources (to reproduce conditions of discharge 61148). (Would like but do not require 4 additional sources for 2 higher power discharges.)

The long beam pulses may require a recalibration of the diamagnetic loop.

• 95 KeV on beams 5B and 4B for operation of the MSE diagnostic.

• CHERS measurement.

• Diagnostic set should include fast diagnostics that measure internal fluctuations including:
  - Interferometer with fast fringe counters.
  - Grating Polychromator.
  - Mirnov loops
  - Soft X-Ray arrays.
  - BES

• Microwave scattering may shed light on confinement reduction as current profile relaxes.

5. Planned Analysis

Include estimated time and manpower requirements.

Unfold current and q profiles from MSE.

Compare measured current profile with TRANSP simulations with and without bootstrap current. Also do comparison in shots with and without beta collapse.

Check stability against PEST predictions.
Title: Advanced Tokamak Regime Experiment

Machine conditions (indicate range where appropriate):

\[ I_p (\text{MA}) \ 0.4 - 1.0 \ \text{MA} \quad R (\text{m}) \ 2.45 \quad (a = R - 165.5 \text{cm for BL and } = 359.8 - R \text{cm for RFL}) \]

OH Flattop start/stop \ ~ 1 \text{ to } 5 \text{ sec} \quad I_T (\text{kA}) \ 6.8 \quad \text{Gas Species } D \quad \text{Pellets (D) No} \]

Beams: Power \ 10 - 18 \text{MW} \quad \text{duration } 4 \text{ sec} \quad \text{voltage } 80 - 95 \text{ keV} (5b @ 95\text{keV})

ICRF: Power_____, duration______.

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

List of previous shot numbers for setup 61145

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

(Attach additional sheets as required)
Appendix B —

"Achieving High $Q_{dd}$ 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 Nuclear Fusion Research 1992*
Appendix C —

“High Poloidal Beta Long Pulse Experiments in the Tokamak Fusion Test Reactor”

J. Kesner, M. E. Mauel, G. A. Navratil, S. A. Sabbagh, M. Bell, R. Budney, et al.,

*Physics of Fluids B* to be published July 1993.
Appendix D —

"Poloidal Beta Scaling for a Bootstrapped Tokamak"

R. Iacono and A. Bhattacharjee

Appendix E —

“Observation of Ballooning Modes in High-Temperature Tokamak Plasmas”


DATE
FILMED
8 / 16 / 93
END