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Report of Progress on Grant

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High Beta and Confinement Studies on TFTR

25 September 1991 to 24 April 1992

by

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Report of Progress 25 September 1991 to 24 April 1992

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 D^T phase of operation was approved by the DOE and this is a report of our progress during the first 9 month budget period of the three year grant (9/25/91 to 6/24/92).

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 seven month period covered by this report we have made progress in each of these four areas through the submission of 4 TFTR Experimental Proposals and the partial execution of 3 of these using a total of 4.5 run days during the August 1991 to February 1992 TFTR run.

High Q Operation in TFTR: We have extended our previous work in this area through the TFTR Experimental Proposal No. 313 (TFTR XP313) titled: "Approaching High Q by Utilizing High β_p Operation in TFTR" (copy attached in Appendix A) which was approved by the TFTR Task Force Council on 9/12/91 and resulted in a 2 day run on 10-11 January 1992. These experiments extended our

previous high $\epsilon\beta_p$ results from 1.0 MA to 1.2 MA operation with a peak neutron production of $2.9 \times 10^{16} \text{ sec}^{-1}$ at a $\beta_N = 2.8$. Previously obtained best results with supershots at this modest 1.2 MA plasma current were $2.0 \times 10^{16} \text{ sec}^{-1}$ at a $\beta_N = 2.35$. 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 QDD 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 A) which was selected by the DOE IAEA selection panel to be submitted to the international selection panel.

A related area we have begun to explore is the use of high $\epsilon\beta_p$ discharges in TFTR for collective alpha particle instability studies during DT operation. Because the higher l_i current profiles generated with current ramp-down formation in high $\epsilon\beta_p$ plasmas have larger shear at the plasma edge relative to a normal supershot, theory predicts that enhanced continuum damping will occur which may prevent alpha-destabilization of TAE modes.

Work on TFTR XP313 will continue during the next TFTR run period beginning May 1992 to continue to extend these high $\epsilon\beta_p$ plasmas to 1.4 MA with neutron production rates and QDD values as close to the best supershot performance levels preparatory for carrying out these experiments in DT.

Study of High $\epsilon\beta_p$ Plasmas: Two TFTR Experimental Proposals were submitted and approved in this area. 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. TFTR XP327 titled "Perturbative Transport in High $\epsilon\beta_p$ Plasmas" (copy attached in Appendix B) was approved 1/7/92 but has not yet been allocated run time.

The primary purpose of TFTR XP322 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 $\epsilon\beta_p$ experiments were maintained for 0.5 to 1 second, too short a time to observe current relaxation. In this experiment we created high $\epsilon\beta_p$ 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.

The current ramp-down during the ohmic phase of the discharge created highly peaked initial current profiles with $I_i \geq 3$ and during the NBI phase achieved β_N up to 3.5 and $H > 3$ for periods up to 0.5 seconds. As time progressed, the current profile broadened significantly due to the bootstrap and beam driven current and confinement gradually decreased. For a 0.6 MA discharge heated with 9 MW of NBI, a sudden disruption occurred at $\beta_N \sim 2$ and for a 0.4 MA discharge heated with 8.5 MW of NBI, high $\epsilon\beta_p$ operation was terminated by a beta collapse at $\beta_N \sim 1.5$. In both cases, the current relaxation and the magnitude and profile of the m =non-inductive currents were modeled with TRANSP. These equilibria reconstructed by TRANSP were analyzed for ideal MHD stability. Although the initial plasma profiles are stable and far from stability boundaries, as the profiles evolve, both $n=1$ and high- n instabilities are predicted to become unstable near the observed onset of disruption and beta collapse. These results on TFTR dramatically demonstrate the importance of current profile control to maintain high performance, high $\epsilon\beta_p$ discharges combining both high β_N and good confinement.

The plasma current profile was measured by F. M. Levinton using a motional Stark effect (MSE) diagnostic during these experiments although the analysis of this data is not yet complete. When this information is available it will be compared with the TRANSP predictions of a central q value above 2, developing during these long pulse experiments of XP322.

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 accepted for publication in *Phys. Fluids* and this work was 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.* (copy attached in Appendix B) which was selected by the DOE IAEA selection panel to be submitted to the international selection panel.

High q_0 , Second Regime Experiments: A TFTR Experimental Proposal XP319 titled "Exploring Second Stability Region Operation in TFTR with Impurity Pellet Injection" (copy attached in Appendix C) was approved by the Task Force Council on

12/7/91 and executed 15-16 January 1992. As described in the attached XP319, this experiment used lithium pellet injection to cool the plasma center and thereby elevate the q_0 as the current broadens due to the higher resistivity in the now cooler central plasma. Preliminary analysis of the results from this XP319 show that indeed the pellet injection resulted in an electron temperature profile with a depressed central core temperature for a period of about 50 msec. Analysis of the current profiles measured in these discharges with the MSE diagnostic are not yet available. This work is planned for continuation during the next TFTR run period using deuterium pellet injection as well as lithium pellet injection.

PBX-M Collaboration: PBX-M has begun operation again after a long shut-down during the 7 months covered by this report. Our primary activity in this period has been the adaptation of our Tokamak equilibrium reconstruction code which now runs only on Apple Macintosh machines to run on a VAX. When implemented on the VAX this code will allow better equilibrium reconstruction of PBX-M plasmas for further analysis with stability codes.

List of Publications

1. "Operation at the Tokamak Equilibrium Poloidal Beta Limit in TFTR," by M. E. Mauel, G. A. Navratil, S. Sabbagh, M. G. Bell, *et al.* to be published in *Nuclear Fusion*.
2. "Poloidal Beta Scaling for a Bootstrapped Tokamak," R. Iacono and A. Bhattacharjee, to be published in *Physics of Fluids*.
3. "The Use of High $\epsilon\beta_p$ Discharges to Study α -particle Physics During DT Operation in TFTR," M. E. Mauel, M. Bell, E. Fredrickson, A. Janos, J. Kesner, K. McGuire, G. A. Navratil, S. Sabbagh, S. Zweben, *Bull. Am. Phys. Soc.* **36**, 2377 (1991).
4. "Enhanced Ideal MHD Stability of TFTR Discharges at High Poloidal Beta," S. A. Sabbagh, M. E. Mauel, G. A. Navratil, R. V. Budny, P. C. Efthimion, J. Manickam, *Bull. Am. Phys. Soc.* **36**, 2445 (1991).
5. "Electron Thermal Conduction in High $\epsilon\beta_p$ TFTR Plasmas," J. Kesner, M. Mauel, G. Navratil, S. Sabbagh, R. Budny, M. Bell, K. McGuire, M. Zarnstorff, *Bull. Am. Phys. Soc.* **36**, 2446 (1991).
6. "Simulations of DT Experiments in TFTR," R. Budny, H. Biglari, C. Z. Cheng, D. R. Mikkelsen, S. A. Sabbagh, D. A. Spong, M. C. Zarnstorff, S. J. Zweben, *Bull. Am. Phys. Soc.* **36**, 2453 (1991).

7. "Variation of Ignition Requirements and α Parameters with Density Profile Shapes in a Tokamak," R. Budny, D. McCune, S. J. Zweben, S. A. Sabbagh, *Proc. 1992 Sherwood theory Meeting*, Santa Fe, 6-8 April 1992.
8. "Effect of Bootstrap Current Modified profiles on Ideal MHD Stability Limits for Long Pulse, High Poloidal beta Equilibria in TFTR," S. A. Sabbagh, M. E. Mauel, G. A. Navratil, M. G. Bell, *et al.*, *Proc. 1992 Sherwood theory Meeting*, Santa Fe, 6-8 April 1992.
9. "Supershot-like Profiles in Tokamak Reactors," R. Budny, R. J. Hawryluk, D. L. Jassby, J. Manickam, D. McCune, K. M. McGuire, S. A. Sabbagh, S. D. Scott, W. Stodiek, *et al.*, to be presented at the 1992 International Conference on Plasma Physics, Innsbruck, Austria, 29-3 July 1992.
10. "Theory of Thermonuclear Instabilities in High Beta Plasma Regimes," H. Biglari, R. Budny, L. Chen, C. Z. Cheng, G. Y. Fu, J. Manickam, G. Rewoldt, F. Zonca, S. A. Sabbagh, submitted by DOE for oral presentation at the 14th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 30 Sept. - 7 Oct. 1992.
11. "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.*, submitted by DOE for oral presentation at the 14th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 30 Sept. - 7 Oct. 1992.
12. "Theoretical Basis for Advanced Plasma Configurations" by S. C. Jardin, A. Bhattacharjee, M. S. Chance, S. C. Cowley, *et al.*, submitted by DOE for oral presentation at the 14th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 30 Sept. - 7 Oct. 1992.

Appendix A — High Q in TFTR

TFTR EXPERIMENTAL PROPOSAL

APPROVED XP #	313
DATE	9/12/91

Title: Approaching High Q by Utilizing High β_p Operation in TFTR

Proposal No. 313
(Version 1.3)

Authors: G. Navratil, S. Sabbagh, M. Mauel, (Columbia U.)
M. Bell, C. Bush, E. Fredrickson, K. McGuire, M. Zarnstorff, (PPPL)
J. Kesner (MIT) **Date:** 9/10/91

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

During the 1990 run, the TFTR high β_p regime began to be used as an operating condition for plasmas with high neutron production and fusion power gain. High β_p and β_N operation with significant neutron production was achieved at $I_p = 1.0$ MA during XP 221, performed on 8/27/90, using a plasma current ramp-down technique. However, due to time constraints, only 8 high power shots were taken, and the original run plan of XP221 was never completed. The purpose of this experiment is to extend the results of XP221 to larger values of I_p to further increase Q at high β_p . In addition, experience will be gained in operating high β_p TFTR plasmas at larger stored energy and I_p . Attention will be placed on avoiding disruptions that have terminated experimental runs in the past.

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

When projected to larger I_p , the present high β_p database of shots utilizing an I_p ramp-down technique to reach high β_N indicates that this type of discharge may attain S_n and Q_{dd} above those already achieved in TFTR. If S_n scales as the stored energy, W_E , squared, and if energy confinement scales as I_p and $(1/\sqrt{P_{beam}})$, a linear increase in S_n as a function of $I_p^2 P_{beam}$ is expected. Existing data shows that the dependence of S_n on I_p and P_{beam} is less strong and actually closer to $I_p^{1.69} P_{beam}^{0.84}$. An extrapolation of S_n to higher I_p is shown in Fig. 1 using high β_p cases with beam power above 15 MW and ramp factors $F_{I_p} = (I_{p\ initial}/I_{p\ final})$ above 1.2. In order to obtain S_n near $5 \times 10^{16} \text{ sec}^{-1}$, present operation will have to be extended from $I_{p\ final} = 1.0$ MA to about 1.4 MA and a beam power of 28 MW. At this pedestal current, Q_{dd} projects to be about 0.002, as shown in Fig. 2.

This experiment will provide important information and experience with high β_p and β_N operation at relatively large values of I_p :

(1) The high β_p discharges created to date have been able to produce more neutrons for a given I_p than supershots, since the former can handle higher power levels and reach higher values of stored energy before disrupting. We need to see if this trend continues at larger values of I_p .

(2) The scaling of τ_e can be determined in this parameter regime. To date, it is unclear whether τ_e will scale as $I_p/P_{beam}^{0.5}$ as in high β_p shots at lower I_p , or if it will be essentially independent of these parameters, as in standard supershots.

(3) The stability of these discharges can be assessed and compared to the low I_p counterparts, which have shown increased stability properties.

Since this proposal is an extension of XP221, the technique involves the familiar I_p ramp-down procedure with additional constraints placed on the neutral beam power in many of the discharges to avoid disruptions. These changes are described in the following section

3. Experimental Run plan:

(describe groups of shots as appropriate, assume 20-25 shots on a good day)

The brief run day of XP221 on 8/27/90 included discharges with $I_p \leq 1$ MA. Before this, XP221 was conducted on 9/17/90 and included plasmas with $I_p \leq 0.85$ MA. The operational strategy and results of these run days were similar. A limited set of I_p ramp-down conditions was set up, and the beam power levels were increased. The results were similar: all discharges made a transition to the limiter H-mode, accompanied by ELM's, after reaching large values of stored energy and neutron rate. The last discharge of each run day, (the largest beam power) had reduced ELM activity. These discharges produced the largest S_n and β_N of their type, but they also terminated in disruption. The disruptions occurred at values of $\beta_{N\ dia}$ that were not excessively large for the F_{I_p} specified for the discharges. In fact, shot 55884, the disruption at $I_p = 1$ MA occurred at a $\beta_{N\ dia}$ that had been exceeded at lower power in 0.85MA plasmas without disruption.

The large stored energies associated with higher I_p operation necessitate reducing the risk of disruption in these discharges. Past experience has shown that high β_p discharges that have made a transition to a limiter H-mode with ELM's rarely end in disruption. Therefore, in the initial stage of the run, discharges will be constrained to remain below the expected stable value of $\beta_{N\ dia}$ for a given F_{I_p} as in XP221, and also be limited to beam power levels less than or equal to that required to exceed limiter H-mode/ELM operation (shown in Fig. 3). This will decrease the likelihood of disruption in these plasmas at the cost of not fully optimizing plasma parameters. Nevertheless, these plasmas are projected to have among the best neutron production and stored energy in TFTR before the transition to the ELMing phase of the H-mode is made. Proceeding in this way will allow us to gain necessary experience with the high β_p discharges at higher plasma current, so that optimal operating conditions for maximum neutron production (avoidance of sawteeth, optimal F_{I_p}) can be determined.

Ultimately, the suppression or significant delay in the onset of ELM's and an increased value of the $\beta_{N\ dia}$ limit will be important to fully optimize plasma performance. Therefore, the second stage of the run will consist of gentle (~ 0.5 MA/sec) I_p ramps, both positive and negative, during the beam phase to investigate these issues. The purpose of the ramp-down is to help keep the product (ℓI_p) from decaying during the beam phase. Both TFTR and DIII-D data indicates that this product is proportional to the β limit. TRANSP simulations of TFTR discharges shows that (ℓI_p) increases transiently with a ramping down of the plasma current. The purpose of the ramp-up is to delay the transition to the H-mode and create a plasma in

which the neutron rate saturates before the onset of ELMs. The gentle current ramp up will be reversed to aid the H-mode/ELM transition after the time of peak neutron rate. In addition, ideal MHD stability calculations based on TFTR high β_p equilibrium profiles indicate that a broader pressure profile should increase the $\beta_{N\ dia}$ limit. So if $\beta_{N\ dia}$ constrains the beam power, an increase in target density of up to $4 \times 10^{15} \text{ cm}^{-2}$ will be used to help broaden the pressure profile during the beam phase.

The run will consist of various current ramp-down scenarios in a well-conditioned machine using neutral beam power up to about 30MW with a pulse duration of 0.5 - 1.0 sec. The discharges will begin with 0.75 sec beam injection pulses. It may be necessary to extend the NBI pulse to 1.0 sec to allow β_p to saturate in these plasmas if confinement is enhanced significantly over anticipated values. The beam pulse length should be kept to a minimum to help/avoid disruptions due to relaxation of the ramped-down current profile.

The run plan focuses on plasmas with pedestal plasma currents of 1.2 and 1.4 MA. The first shots start from an initial I_p of 1.65MA to a pedestal value of 1.0MA with 18MW of NBI to reproduce shot 55883 at slightly lower power. The new sets of parameters start from an initial I_p of 1.75MA to keep q_a above 4, circumventing the problem of having this rational surface entering the plasma. Sawteeth should also be less of a problem at this initial current. The plasma current ramp ratio, F_{I_p} , for these discharges is low. Since the value of $\beta_{N\ dia}$ at which TFTR can be operated increases with F_{I_p} (Fig. 4), the initial plasma current will be raised to 2MA and the scans will be repeated. If $\beta_{N\ dia}$ still poses a limit for these cases, and if sawteeth haven't devastated the plasma performance at 2 MA, the initial plasma current will be increased to 2.2MA if possible. Increasing the neutral beam power will stop and the next condition will be tried when the beam power levels equal or exceed that required to provide limiter H-mode/ELM transition, or the $\beta_{N\ dia}$ limit is reached (see run plan table). Once the specified conditions are tried, the gentle I_p ramps and increase in target density will be performed on the scenario yielding the best performance. These conditions would be run at the same beam power as the original case, and then repeated at higher power to obtain maximum neutron production.

We hope to avoid the sawtooth problems experienced in XP203. The present experiment will utilize a faster I_p ramp-down rate, better machine conditioning, higher power levels, and a shortened ohmic phase to minimize the time during which the central q can evolve before beam heating. These changes should help alleviate the sawtooth problem.

I_p pedestal	I_p initial (qa)	P (MW)	F_{I_p}	# shots	Comments
First Stage of Run:					Beam pulse ≤ 0.75 s
1.00 MA	1.65 MA (4.54)	18	1.65	2	Reference shots for 55883 (XP221)
1.20 MA	1.75 MA (4.29)	18	1.46	1	Increase beam pulse if W_E not saturated
1.20 MA	1.75 MA (4.29)	21	1.46	1	Increase power if $\beta_N < 3.1$
1.20 MA	1.75 MA (4.29)	24	1.46	1	and $P_{beam} < 24$ MW
1.40 MA	1.75 MA (4.29)	21	1.25	1	
1.40 MA	1.75 MA (4.29)	24	1.25	1	Increase power if $\beta_N < 2.8$
1.40 MA	1.75 MA (4.29)	27	1.25	1	and $P_{beam} < 28$ MW
1.20 MA	2.00 MA (3.75)	21	1.67	1	Increase power if $\beta_N < 3.5$
1.20 MA	2.00 MA (3.75)	24	1.67	1	and $P_{beam} < 24$ MW
1.40 MA	2.00 MA (3.75)	24	1.43	1	Increase power if $\beta_N < 3.1$
1.40 MA	2.00 MA (3.75)	27	1.43	1	and $P_{beam} < 28$ MW
* 1.20 MA	2.20 MA (3.41)	24	1.83	1	*Do this only if 2 MA shots do not have sawteeth that degrade confinement Increase power if $\beta_N < 3.8$ and $P_{beam} < 24$ MW
** 1.40 MA	2.20 MA (3.41)	27	1.57	1	**Do this only if 2 MA shots do not have sawteeth that degrade confinement Increase power if $\beta_N < 3.3$ and $P_{beam} < 28$ MW
Second Stage of Run:					
1.20 MA	[Gentle I_p ramp-down during beams]				*** Do this if the best scan above is limited by β_N constraint.
***Choose best condition from above that was limited by β_N constraint.				1	- at highest beam power used in first stage
				3	- Change ramp rate of second I_p ramp / increase beam power.
1.20 MA	[Gentle I_p ramp-up during beams]				*** Do this if the best scan above is limited by power constraint.
***Choose best condition from above in which S_n has not saturated before ELM's.				1	- at highest beam power used in first stage
				3	- Change ramp timing of second I_p ramp / increase beam power.
1.40 MA	[Repeat gentle I_p ramps]			4	Use best conditions from above
****Choose best condition from above. Increase target density.					****Do this if the best scan above is limited by β_N constraint.
				2	Increase beam power.
Total number of shots				28	(Note: the number will be less than this since the data from stage 1 will dictate which cases to pursue as the run evolves)

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 shot 55882 (12/27/90), in particular:

- (1) A well-conditioned machine ($n_e l = 2.0 - 3.0 \times 10^{15} \text{ cm}^{-2}$)
- (2) Ability to ramp up to large ($\sim 2\text{MA}$) plasma currents at 1MA/sec .
- (3) Ability to ramp down from large I_p to $1.0 - 1.4 \text{ MA}$ at $- 2.5 \text{ MA/sec}$.
- (4) Availability of maximum ($\sim 30 \text{ MW}$) of balanced NBI for $0.75 - 1.0 \text{ sec}$.

The beams should be staggered, co-only first, then balanced, as in the previous shots (see shot 55882, for example).

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

5. Estimated neutron budget:

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

Shot 55883, a $1.65 - 1.0\text{MA}$ I_p ramp-down case, produced 8.5×10^{15} total neutrons. If each planned shot were to be successful, the average neutron production per shot would be about twice this amount. Therefore, if the entire XP were to be performed as planned, about 3.6×10^{17} neutrons would be 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.

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 β_p
Operation in TFTR

Proposal: 313

Machine conditions (indicate range where appropriate):

I_p (MA) 1.0 - 2.2 MA R(m) 2.45, ($a = R - 165.5\text{cm}$ for BL and $= 359.8\text{-Rcm}$ for RFL)

OH Flattop start/stop ~ 2.0 to ~ 3.0 sec, I_{TF} (kA) 68, Gas Species D, Pellets(D) No

Beams: Power Max (~30 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 see the "Physics operations daily comment log book" in the control room to find machine parameter to those desired that have been saved on disk (circled in the log book). If similar shots were r past, but not saved on disk, a couple of hours lead time may be needed to have the requir restored and marked to be saved.

List of previous shot numbers for setup 55882, and schematic below

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)

DIAGNOSTIC CHECKLIST

Proposal Title: **Approaching High Q by Utilizing
High β_p Operation in TFTR**

Proposal No. 313

			Need	Desire	Comments
Magnetics:	Magnetics (MB,MD,MR,MV)		✓		
T_e and n_e:	Thomson Scattering	TS	✓		
	Thomson Scattering	TV		✓	
	Radiometer	YS	✓		
	Michelson	YM		✓	
	1 mm Interferometer	YI			
	MIRI Interferometer	FM	✓		
T_i:	X-ray Crystal	XC,XV	✓		
	CHERS (beam stops)	SW	✓		
	Diag. Neutral Beam	EN		✓	
Spectroscopy:	HAIFA (H _{α} and VB)	SH	✓		
	SPRED (UV)	SP	✓		
	VIPS (H/D ratio)	SV			
	SOXMOS (XUV)	SX	✓		
	X-ray PHA	XP	✓		
	Hard X-rays	XH			
Particles:	Epithermal Neutrons	NE	✓		
	Charge Exchange	EV		✓	
	Neutron Activation	NA			
	Fusion Products	N _f		✓	
	Lost Alphas	NL			
	Neutron Collimator	NM	✓		
	Neutron Fluctuations	NS	✓		
Waves: (timing of fast channels)	Mirnov Coils	MM	✓		
	X-ray Array	XI	✓		
	RF Probe	RP		✓	
	Grating Polychromator	YG	✓		
	Microwave Scattering	YU	✓		
Edge:	Bolometer	BR	✓		
	Plasma TV	VP	✓		
	Edge Thomson	TE			
	Impurity Injection	WI			
	Lithium Pellet	LP			
	Edge Probe	WE			

Comments / Times of Interest: Desire BES diagnostic

Fig. 1

X SHOT<54025
 □ SHOT>=54025

PBMAX MW>15.0
 RAMP_FACTOR>1.2

I_P**1.69*PBMAX_MW**0.836

Fig. 2

X SHOT<54025
 □ SHOT>=54025.

PBMAX MW>15.0
 RAMP_FACTOR>1.2

Y = (1.386549E-13 +/- 1.182E-14)
 X + (3.418802E-05 +/- 3.353E-15)
 R^2 = 0.729 msr/var = 0.271 s^2 = 3.006E-08 n = 53

I_P**1.69/PBMAX_MW**0.164

1.5
 1.0
 0.5
 0.0

QDDN_EBB_0

1.0

0.5

0.0

QDDN_EBB_0

first observation
LMs, with an

FIG. 4. (a) Plot of P_b vs I_p for the TFTR limiter H mode. Data for supershots are also included (but only a small fraction of the TFTR supershot database). An apparent threshold power dependence on I_p is indicated. (b) τ_E from magnetics

the plasma edge
plane of an 80-
, soft-x-r , and

Fig. 4

X DISRUPTION < 0.1
 □ SHOT = 54025
 + DISRUPTION > 0.1

SHOT > 46457
 DELT_BEAMS > 0.1

Appendix B — High $\varepsilon\beta_p$ Plasmas

1

APPROVED XP #: 322

DATE: 12/2/91

TFTR EXPERIMENTAL PROPOSAL

Long Pulse High Poloidal Beta Experiment

Proposal 322

J. Kesner, M. Mauel, M.G. Bell, F. Levinton, K. McGuire, G.
Navratil, S. Sabbagh, M.C. Zarnstorff

November 20, 1991

1. Overview

Include how it fits into the overall Run Strategy.

We hope to observe the resistive relaxation of the current density profile and the associated effects on stability and transport by extending the length of the neutral beam injection pulse in rampdown experiments. Operation at the low current end of the high poloidal beta regime ($I_p \sim 400 - 500$ KA) should produce a high bootstrap current fraction while staying away from problems associated with beta collapse and disruptions. Furthermore in lower current discharges with $T_e \sim 5$ KeV the plasma is sufficiently resistive to permit the plasma current to diffuse within the 4 to 5 seconds of the beam heating pulse.

Using current ramp-downs prior to neutral beam injection, we have been able to obtain discharges with $\epsilon\beta_p > 1$ and $\nu_e \ll 1$. The total plasma current is sufficiently low that we may expect the equilibrium current density profile to be dominated by the bootstrap current. As these discharges approach equilibrium they may reverse ∇q near the magnetic axis and we will observe the effect of this reversal. We hope to obtain a better understanding of the confinement and MHD stability of these high poloidal beta mostly non-inductively driven discharges. This experimental proposal is a follow-on to XP-222.

In summary the main goals of this proposal are as follows:

- Internal measurement of the current density profile in a high poloidal beta plasma having a large bootstrap fraction.
- Observation of the relaxation of the current density profile and the effect of the resulting profile on a) Stability, b) Transport.

2. Justification

Include previous data as appropriate.

The low current, high poloidal beta plasmas obtained in ramp-down shots on TFTR have run for an insufficient time to obtain an equilibrium current profile. Furthermore attempts to run longer pulse lengths (XP 222 which was run on 8/22/90) have been hindered by beta collapses, due to 2/1 and 3/2 modes.

To get around this problem we plan to start the long pulse shots at relatively low power and to use relatively low currents (< 600 KA). Below about 500 KA the equilibrium limit is reached before the disruption limit (and the separatrix enters the plasma). By running at sufficiently low current we can stay away from both disruptions and the low- m beta collapses that occur as the disruption limit is approached. /

Additionally we have observed that when the counter injected neutral beam current is equal to or greater than the co-injection current the discharge is less likely to exhibit MHD behavior. In high beta ramp-down experiments we maintained close to balanced beams. However when an odd number of beams were used with a net co-injection balance the resulting discharges tended to more often exhibit beta collapses at high beta than for net counter discharges. (This is observed for example in shots 52335 and 52336). Counter beam driven current can be a significant fraction of the bootstrap current and thus counter-injection reduces the total fraction of non-inductively driven current.

In experiments to date we observe a drop in ℓ_i as the edge current density rises. In long time discharges the plasma inductance ℓ_i will also relax as the bootstrap driven current density broadens. This appears to lead to a beta collapse or a disruption. Thus these experiments will provide insight into the current density profile and ℓ_i dependence of stability.

The proposed experiments require moderate power neutral beam injection. As a compromise between power and pulse length we will attempt to inject less than 16 MW at pulse lengths of 4 sec.

In experiments on 8/21/90, discharge 52328, we did a $1 \rightarrow 0.6$ MA rampdown with 16 MW balanced (3/3) injection. On shot 52336 we injected 18 MW of net counter (3/4) injection. These discharges were quiet during 0.75 sec, exhibited $\Lambda > 5$ with ~ 1.4 MJ of stored energy. TRANSP simulations showed a bootstrap fraction $> 60\%$ for 52336. Fig 1 shows relevant cuplot data for shot 52336. Fig 2 shows the total currents vs time for this shot as calculated in TRANSP. Notice that the bootstrap current rises up to 60 % of the total current. Fig 3 shows the current profiles at the time of the peak bootstrap fraction. We observe that the total current density (the solid line) is still centrally peaked at this time. A measure of the change of the central current density is shown in fig 4 which shows q_0 rising with time. In the 0.5 seconds of heating it appears to rise from 0.97 up to 1.17, i.e. at a rate of 0.4 /sec and we thus we can expect a significant rise in 4 sec. Finally fig 5 shows the change of internal inductance during the shot. A close inspection of the profiles indicates that the decay observed between 3.5 and 4 sec is largely the result of a bootstrap driven edge current and not a general current broadening.

Shot 46465 (2/1/90), is a good example of a low current ramp-down discharge. In this discharge current was ramped from 850 $\rightarrow$ 400 KA with 18 MW of neutral beam injection. We obtained $\beta_p \sim 5$ with a surface voltage of -1 V during neutral beam injection. However although this shot exhibited a higher poloidal beta than 52336 the bootstrap fraction was lower due to a increased collisionality. In this shot $n_e \ell \sim 3.7 \times 10^{15} \text{ cm}^{-2}$. To increase the bootstrap fraction in lower current shots we would endeavor to keep $n_e \ell \sim 3 \times 10^{15} \text{ cm}^{-2}$.

In a resistive diffusion time ($\tau_{res} \approx 2-10$ sec) we expect the current density profile to relax significantly. Since poloidal beta is very high the final profile should be characteristic of a bootstrap driven and *not* an inductively driven discharge. A significant fraction of plasma current can also be driven by neutral beams in either co or counter direction. If there is a small or negative loop voltage in equilibrium this would indicate a large fraction of current is being driven by non-inductive means.

If there is insufficient "seed" current from inductive or NB current drive, q should evolve to having a minimum off axis. The reversed q gradient has been hypothesized to improve confinement in the JET "PEP" (pellet enhanced performance) shots as well as in DIII-D experiments. On the other hand such a q profile could give rise to double tearing modes.

A low beta limit has been observed in JT-60 in low current bootstrap dominated discharges due to MHD activity. We would like to determine if this is a universal consequence of a bootstrap current driven current density profile.

3. Experimental Plan

Describe groups of shots, assume 20-25 shots per good day.

- Set up a $I_p = 840 \rightarrow 500$ KA rampdown experiment with a similar time sequence to shot 52336 and with $I_{TF} = 56$ KA. Adjust gas puffing to obtain $\langle n_e \ell \rangle \sim 4.5 \times 10^{15} \text{ cm}^{-2}$. We want to obtain $\beta_p \approx 3$ discharges that reach steady state without a disruption.

The timing sequence will be approximately as follows:

Current ramp-up (0-1000 KA), time 0 $\rightarrow$ 1 sec,

Flat top high current operation, 1 $\rightarrow$ 2.5 sec,

Current rampdown to 600 KA, 2.5 $\rightarrow$ 2.7 sec,

Neutral Beam injection 2.7 $\rightarrow$ 3.7-6.7 sec,

Final current rampdown, 6.7 $\rightarrow$ 7.2 sec.

- SHOT SEQUENCE

Bring up beam power to beta collapse limit.

1 shot; Ohmic reference, 840 $\rightarrow$ 500 kA with new timing.

2 shots; 10 MW 0.5 sec.

EXTENDED BEAM PULSE

5 to 10 shots; Choose sequence of shots leading up to the maximum pulse length (4 sec) 500 KA discharge at 10 MW.

4 shots; Gradually gradually raise power in long pulse shots, possibly up to 16 MW, to observe beta collapses. 16 MW utilizes 3 co and 3 counter beams.

2 shots - When beta collapse is encountered reduce NB power by 1 source (keeping counter $\geq$ co) 1/2 second prior to collapse time.

- SECOND SEQUENCE - Rampdown shots with lower current and higher initial ℓ_i . These shots will resemble the 850 $\rightarrow$ 400 KA, 18 MW rampdown (46465). Maintain $\langle n_e \ell \rangle \sim 3 \times 10^{15} \text{ cm}^{-2}$.

5 shots; Choose sequence of shots leading up to maximum pulse length (4 sec) discharge at 12 MW.

4 shots; Raise power to beta limit.

- OBSERVE
 - a. Confinement time changes on the resistive time scale.
 - b. The loop voltage. In steady state a negative loop voltage indicates $I_{\text{boot}} + I_{\text{beam}} > I_p$.
 - c. Stability limits for long pulse discharges.

4. Required Capabilities

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

- A sufficiently well conditioned machine to maintain $\langle n_e \ell \rangle \sim 4.5 \times 10^{15} \text{ cm}^{-2}$.
- Capability to run 4 second beam pulses with ≈ 16 MW of balanced neutral beam injection power.

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

- MSE diagnostic for internal magnetic field measurement.
- Microwave scattering may shed light on confinement reduction as current profile relaxes.
- CHERS measurement.
- Diagnostic set should include fast diagnostics that measure internal fluctuations including:

Interferometer with fast fringe counters.

Grating Polychrometer.

Mirnov loops.

Soft X-Ray arrays.

BES

5. Planned Analysis

Include estimated time and manpower requirements.

Confinement time estimates use M. Bell's filament code.

Unfold current and q profiles from MSE with Mauel's free boundary reconstruction code.

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

ANT52336 08/21/90 20:52

CUPLOT 10/18/91

Time (Seconds)

TFTR.90 52336A06 PAGE 1
 $\times 10^6$ IND(RBOUN) = 1.0000E+00

TFTR.90 52336A06 PAGE 4
 TIME = 3.9500E+00 SECONDS

PLASMA CURRENTS (PCURS) VS RADIUS (RZON)

PHYSICS OPERATIONS REQUEST

Title: Long Pulse High Poloidal beta Experiment

Proposal: 322

Machine conditions (indicate range where appropriate):

I_p (MA) 0.4 - 1 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 1 to 5 sec, $I_{TF}(kA)$ 56, Gas Species D, Pellets(D) No

Beams: Power 18 MW, duration 4-4.5 sec, voltage 80 to 95 keV

ICRF: Power _____, duration _____.

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

List of previous shot numbers for setup 46464 - 46470 and 52328-52336

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.

DIAGNOSTIC CHECKLIST

Proposal Title: **Long Pulse High Poloidal
Beta Experiment**

Proposal No. **322**

			Need	Desire	Comments
Magnetics:	Magnetics (MB,MD,MR,MV)		✓		
T_e and n_e:	Thomson Scattering	TS	✓		
	Thomson Scattering	TV		✓	
	Radiometer	YS	✓		
	Michelson	YM		✓	
	1 mm Interferometer	YI			
	MIRI Interferometer	FM	✓		
T_i:	X-ray Crystal	XC,XV	✓		
	CHERS (beam stops)	SW	✓		
	Diag. Neutral Beam	EN		✓	
Spectroscopy:	HAIFA (H _α and VB)	SH	✓		
	SPRED (UV)	SP	✓		
	VIPS (H/D ratio)	SV			
	SOXMOS (XUV)	SX	✓		
	X-ray PHA	XP	✓		
	Hard X-rays	XH	✓		
Particles:	Epithermal Neutrons	NE	✓		
	Charge Exchange	EV		✓	
	Neutron Activation	NA			
	Fusion Products	NF		✓	
	Lost Alphas	NL			
	Neutron Collimator	NM	✓		
	Neutron Fluctuations	NS	✓		
Waves: (timing of fast channels)	Mirnov Coils	MM	✓		
	X-ray Array	XI	✓		
	RF Probe	RP		✓	
	Grating Polychromator	YG	✓		
	Microwave Scattering	YU	✓		
Edge:	Bolometer	BR	✓		
	Plasma TV	VP	✓		
	Edge Thomson	TE			
	Impurity Injection	WI			
	Lithium Pellet	LP			
	Edge Probe	WE	✓		
	MSE		✓		Should be operating well

Comments / Times of Interest: 3, 4.5, 6, 7.7 sec

TFTR EXPERIMENTAL PROPOSAL

K. H. Hoffman
APPROVED XP #: 327

DATE: 1/7/92

Title: Perturbative Transport in High $\epsilon\beta_p$ Plasmas Proposal No. 327

Authors: P. Efthimion, E. Synakowski, D. Mansfield, Date: 12/1/91
A. Bhattacharjee, R. Iacono, M. Mauel, G. Navratil, S. Sabbagh

1. Overview of planned experiment:

(include how it fits into the run strategy)

Perturbation techniques have now been used to study ohmically-heated, L-mode, and supershot plasmas in TFTR. In each case, perturbative analysis has complimented the equilibrium analysis and provided measurement of the particle transport of the electrons and helium ions. The interest is now to extend the work to include high $\epsilon\beta_p$ plasmas. It would be particularly interesting to measure the perturbative transport coefficients from a scan of $\epsilon\beta_p$ by performing a power scan with the same current waveform programmed for each power. This scan was previously completed in XP 221 that studied the equilibrium characteristics. The discharges are formed by bringing the current waveform to a flat top of 1.0 MA and then ramping down to 0.7 MA at a rate of 2.5 MA/s. After the current has been ramped down to 0.7 MA, the neutral beam sources are sequentially turned on. The power scan will be 10, 15 and 23 MW and the $\epsilon\beta_p$ previously obtained was 0.6, 0.9, 1.27, respectively. The confinement time mildly degraded over this power scan while L-mode plasmas have their usual confinement degradation. Thus, $\tau_e/\tau_{L\text{-mode}}$ increases with $\epsilon\beta_p$.

2. Theoretical / Empirical justification:

(include figures of previous data from TFTR and / or other machines as appropriate)

Perturbative transport studies of these high $\epsilon\beta_p$ plasmas have not been completed yet and therefore there are no estimates of the electron and helium ion particle transport coefficients. Considering how difficult it is to perform an equilibrium power balance analysis for these discharges, additional information about the plasma transport derived with other techniques is very helpful. There already exist perturbative transport coefficients for L-mode and supershots at 1.0 MA to compare to. It will be interesting to see how the transport coefficients depend on $\epsilon\beta_p$.

Recent studies have identified resistive ballooning turbulence as a possible candidate for the thermal diffusivity. The theoretical models also predict the parametric dependencies of the particle diffusion coefficient. Hence,

perturbative measurements of the particle diffusivity can shed light on whether resistive ballooning can govern the transport in these plasmas.

3. Experimental Run plan:

(describe groups of shots as appropriate, assume 20-25 shots on a good day)

The experiment will consist of a power scan at 10, 15, and 23 MW with the same current waveform. The current waveform reaches 1.0 MA, the current is held constant for 2.0 s, then ramps down to 0.7 MA at a rate of 2.5 MA/s, and is held constant for approximately 1.5 seconds. The neutral beams are injected in a sequential fashion during the 0.7 MA flattop with no beam pulse longer than 1.0 s. The machine should be somewhat well conditioned to reproduce the operating conditions from XP221 (target $n_e L \sim 2 - 3 \times 10^{15} \text{ cm}^{-2}$).

The perturbation techniques require 10 reproducible shot per beam power condition for a total of 30 good shots.

In XP221 the operating toroidal field coil current was 68 kA. It is preferred to operate under the same machine parameters. If a cautious approach to machine operation dictates 56 kA, then the current waveform will be reprogrammed to initially reach 825 kA and then will be ramped down to 560 kA to maintain the same safety factor as in the 68 kA case. In addition the neutral beam power can be scaled down to 7, 10.5, 16 MW to maintain a similar range in $\epsilon \beta_p$ during the scan.

The sequencing of the neutral beam sources will be the same used in XP221. The first co-source is on at 3.4 s, the other co-sources are then staggered on one at a time every 30 ms, then all of the counter sources are turned on 30 ms after the last co-source has done so, and all of the sources are turned off at 4.4 s. The perturbation will be a helium gas puff starting at 4.0 s for 25 ms at a fueling rate of 10 t-l/s.

Shot 52336 can be used for the machine waveforms, but the flattop needs to be extended an additional 0.5 s out to 4.5 s.

4. Required Machine, Beams, ICRF and Diagnostics Capabilities:

(Machine conditions which are required, and impact of experiment on conditioning. Complete the two forms attached)

If the experiment is performed at 68 kA coil current, then 23 MW of nearly balanced neutral injection is required. If 56 kA current is preferred, then 16 MW of nearly balanced injection is sufficient. The longest beam pulse will be 1.0 s. High beam reliability will minimize the number of shots required to obtain the 30 good shots desired. A well-conditioned machine is required to match the conditions in XP221 (target $n_e L \sim 2 - 3 \times 10^{15} \text{ cm}^{-2}$).

In terms of diagnostics, Chers and Miri are essential for the experiment, and a full set of diagnostics for confinement studies is desirable.

5. Estimated neutron budget:

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

The neutron yield on other $\epsilon \beta_p$ discharges of similar beam power yielded 1.3×10^{15} neutrons. The desired 30 good shots would then produce less than 4×10^{16} neutrons for the experiment.

6. Planned analysis:

(include estimated time and manpower requirements)

Estimates of energy confinement time will be made using M. Bell's filament code. Transp analysis will be attempted and are important for the electron particle transport analysis. The usual perturbative analysis will be completed on these discharges.

7. Experimental results summary:

(due 4 weeks after the experimental run)

The equilibrium analysis of these discharges will be completed within 4 weeks. The perturbative analysis will be completed within 6 weeks.

PHYSICS OPERATIONS REQUEST

Title: Perturbative Transport in High $\epsilon\beta_p$ Plasmas Proposal: 327

Machine conditions (indicate range where appropriate):

I_p (MA) 1.0 to 0.7 R (m) 2.45, ($a = R - 165.5$ cm for BL and $= 359.8 - R$ cm for RFL)

OH Flattop start/stop 1/4.5, I_{TF} (kA) 68 kA, Gas Species D, Pellets(D)

Beams: Power 23 MW, duration 1.0 s, voltage

ICRF: Power , duration ,

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

List of previous shot numbers for setup Shot 52336 can be used for setup, but the end of the current flattop has to be extended from 4.0 s out to 4.5 s

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

He
puff

DIAGNOSTIC CHECKLIST

Proposal Title: Perturbative Transport in High

Proposal No. 327

			Need	Desire	Comments
Magnetics:	Magnetics (MB,MD,MR,MV)		x		
T_e and n_e:	Thomson Scattering	TS	x		
	Thomson Scattering	TV			
	Radiometer	YS	x		
	Michelson	YM		x	
	1 mm Interferometer	YI			
	MIRI Interferometer	FM	x		
T_i:	X-ray Crystal	XC,XV			
	CHERS (beam stops)	SW	x		
	Diag. Neutral Beam	EN			
Spectroscopy:	HAIFA (H _α and VB)	SH	x		
	SPRED (UV)	SP			
	VIPS (H/D ratio)	SV			
	SOXMOS (XUV)	SX			
	X-ray PHA	XP			
	Hard X-rays	XH			
Articles:	Epithermal Neutrons	NE		x	
	Charge Exchange	EV			
	Neutron Activation	NA			
	Fusion Products	NF			
	Lost Alphas	NL			
	Neutron Collimator	NM			
	Neutron Fluctuations	NS			
Waves:	Mirnov Coils	MM			
(timing of fast channels)	X-ray Array	XI			
	RF Probe	RP			
	Grating Polychromator	YG	x		
	Microwave Scattering	YU		x	
Edge:	Bolometer	BR	x		
	Plasma TV	VP			
	Edge Thomson	TE			
	Impurity Injection	WI			
	Lithium Pellet	LP			
	Edge Probe	WE			

Comments / Times of Interest: _____

Appendix C — High q_o , Second Regime

TFTR EXPERIMENTAL PROPOSAL

APPROVED XP #: 319

DATE: 12/7/91

Title: Exploring Second Stability Region Operation in TFTR with Impurity Pellet Injection **Proposal No. 319**
(Version 1.3)

Authors: S. Sabbagh, P. Efthimion, J. Snipes, M. Bell, **Date:** 10/21/91
K. Owens, H. Park, C. Bush, S. Scott, F. Levinton, K. McGuire, G. Navratil,
J. Kesner, E. Marmor, M. Mauel, S. Paul, J. Terry, and M. Zarnstorff.

1. Overview of planned experiment:

(include how it fits into the run strategy)

TFTR high β_p experiments (XP's 146, 208, 221, 222) have extended the machine's operating range in the parameters β_p and β_N , and have shown improved confinement (enhancement factors of τ_e over L-mode values of greater than 3). These plasmas have all been computed to be in the first stability region to high- n ballooning modes. Many of these plasmas have pressure gradients that are marginally stable at the first region boundary.

The goal of this experiment is to combine the effects of pellet injection to raise q_0 , and a modest I_p ramp to decrease the edge shear, in order to explore a transition to the second stability region to high- n modes. The reduction, or complete removal of the high- n ballooning mode unstable region caused by the resulting current profile modification may produce TFTR plasmas with improved confinement and stability.

2. Theoretical / Empirical justification:

(include figures of previous data from TFTR and / or other machines as appropriate)

Using the results of the high β_p experiments performed during the last run, a postulated second region equilibrium that has global parameters $\epsilon\beta_p$ and β_N within the present TFTR operating space, has been computed. The modification of the profiles needed to produce this equilibrium is thought to be feasible in TFTR using the superposition of pellet injection and modest I_p ramping. This plasma was modelled by using the equilibrium data from a TRANSP simulation of TFTR shot 46494, which had a modest I_p ramp-up, and results from TRANSP reconstruction of TFTR shot 44961, in which multiple D pellets were used to increase the plasma density, and had the additional effect of raising q_0 by a factor of 1.5 - 1.7 by preferential cooling of the magnetic axis. A new q profile was generated by superimposing these two effects, and the pressure profile was scaled up to produce a second region plasma at $I_p = 0.67$ MA with only a small unstable region in p' space (Fig. 1). The global equilibrium parameters $\epsilon\beta_p = 1.14$ and $\beta_N = 2.41$ are well within the present TFTR operating space. Another very important feature of this equilibrium is that it is also stable to the free-boundary $n=1$ kink/ballooning instability. In fact, it is found that by scaling up the pressure, the plasma remains kink stable at least to $\beta_N = 3.4$, and at this value, no high- n unstable region exists at any value of p' .

Since the D pellet injector will not be available during the present run, the central current profile modification will be achieved using the impurity pellet injector. Experiments have already been conducted to improve supershots by injecting Li pellets into the ohmic phase of the discharge in order to enhance density profile peakedness (shots 43293-43340). The pellets were

observed to suppress the ohmic sawteeth by greatly reducing the central electron temperature, which probably raised q_0 above one. Fig. 2 shows a case in which the pellet reduced the electron temperature, and the sawteeth were stabilized for a few hundred milliseconds.

Two key characteristics to the success of shot 44961 in producing a large amplification of q_0 seems to be i) 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 is the production of a hollow T_e profile that is maintained during the reheat phase of the discharge (250ms between pellets). The impurity pellet injector has not yet been used to create such hollow T_e profiles. However, some simple modelling and comparisons to existing TFTR data show that such profiles could be created with Li pellet injection. Three important aspects to consider in determining the success of raising q_0 with pellet injection are: a) pellet deposition, b) beam deposition/plasma reheat, and c) density limits. Each of these points were considered for this proposal. The results indicate that the desired effects might be achieved with Li pellet injection.

a) Pellet Deposition: The largest Li pellets available (2.54 mm long) are planned to be used. These pellets contain about 3 times fewer electrons/pellet than the largest D pellets fired into discharge 44691. The ablation of these pellets was modelled for both the plasma current ramp-up (using data from shots 46493, 46494), and ramp-down conditions specified for this experiment using J. Terry's pellet ablation code (Parks penetration model). The results show (Fig. 3) that a deposition profile that is peaked slightly off-axis (15cm) can be created when a 2.54mm pellet is injected into a 0.5 MA plasma (profiles from shot 46494) with $T_e(0) = 2870$ eV (at time 1.7s). Injecting into this plasma at lower $T_e(0) = 2600$ eV (at 1.65 s) led to a deposition profile that was peaked on-axis. This pellet introduces $1.2e21$ electrons into the plasma. When added to the original electron content of shot 46494, the total number of electrons is $2.2e21$ at the time of injection. Note that at temperatures obtained during the ohmic phase of the discharge ($T_e(0) = 1250$ eV), the pellet is calculated to go through the plasma.

b) Beam Deposition / Plasma Reheat: Shot 44961 achieved hollow T_e profiles because $T_e(0)$ was lowered when the plasma had sufficient density to screen out the neutral beam deposition from the center of the plasma, precluding a strong reheat of the axis. TRANSP simulations of 44961 show that the beam deposition profile becomes inverted after each injection of a D pellet. The simulation also shows that at 3.0s, when the central pellet deposition is achieved and q_0 rises, the added Ohmic heating of the cooler plasma core increases, but not enough to make up for the loss of centrally deposited beam power. Therefore, if Li pellet injection is to produce the desired result, there needs to be a sufficient off-axis increase in density to screen the beams (producing a hollow beam deposition profile) and sufficient on-axis density to cool the axis.

The conditions of creating a hollow beam deposition profile were investigated using both existing TFTR data and Steve Scott's empirical fit of the beam deposition profile peakedness $h(0)$ from SNAP data. Consider the evolution of the beam deposition profile for shot 44961 (Fig. 4a). Also shown in Fig. 4b is the evolution of the line average electron density. The density increases in large steps as the D pellets are injected, and relaxes between pellets. Notice that after each injected pellet, the beam deposition profile becomes inverted. For pellets injected before $t = 2.7$ s, the inverted profile relaxes back to a centrally peaked profile. However, after 2.7s, the pellets have sufficiently densified the plasma so that the beam deposition profile remains inverted before the time of the subsequent pellet injection. By this simple analysis, the

line average density that is required to produce an inverted deposition profile is about $7.5 \times 10^{19} \text{ m}^{-3}$.

However, it is not only the absolute value of the density, but also the density profile shape that dictates the shape of the beam deposition profile. In shot 44961, the pellets injected at $t \leq 2.75 \text{ s}$ were fully ablated before they reached the axis, creating broad or hollow density profiles. These profiles are more effective in screening out the beams from reheating the axis. A model for $h(0)$ that folds in the effect of density profile shape has been produced by Steve Scott from a fit to the SNAP database of TFTR shots,

$$h_{fit}(0) = \frac{2.601 \exp \left(\frac{-0.259 \bar{n}_e (10^{19} \text{ m}^{-3})}{P_{ne}} \right) E_{beam} (\text{keV})^{0.0675}}{(a (\text{m}) - a_{shift} (\text{m}))^{1.13}},$$

where P_{ne} is the density peakedness factor. In shot 44961, only $\bar{n}_e$ and P_{ne} vary considerably. Upon substituting the remaining variables, the expression reduces to

$$h_{fit}(0) = 5.581 \exp \left(\frac{-0.259 \bar{n}_e (10^{19} \text{ m}^{-3})}{P_{ne}} \right).$$

This fit function is compared to the TRANSP calculation of $h(0)$ in Fig. 5. The $h_{fit}(0)$ disagrees significantly with $h(0)$ during the very high density phase of the discharge ($t > 3.0 \text{ s}$), but this might be expected, since the fit was compiled from plasmas with lower densities. The agreement is better during the lower density portion of the discharge, especially in predicting the inversion of the beam deposition profile ($h(0) < 1$). The fit overestimates $h(0)$ throughout, and thus provides an upper bound to this quantity.

The function $h_{fit}(0)$ has been used to indicate the inversion of the beam deposition profile for existing TFTR high β_p shots, and also to calculate what conditions would be needed to produce profiles with $h(0) \leq 1$ in the present experiment. Using the data from shot 46494, the value of $\bar{n}_e$ required to reach values of $h(0) = 0.5, 1.0$ are shown for various P_{ne} in the table below.

Line Averaged Densities Required to Produce Various $h(0)$

Condition	P_{ne}	$\bar{n}_e (10^{19} \text{ m}^{-3}) @$	$h_{fit}(0) = 0.5$	$h_{fit}(0) = 1.0$
1) No Pellet	1.25		11.0	8.3
2) Pellet 15 cm off axis	0.67		6.0	4.4
3) Pellet on axis	4.0		35.0	27.0

Consider the injection of a 2.54 mm Li pellet, producing a plasma with 2.2×10^{21} total electrons (as calculated in part a) above). For shot 44961, this corresponds to an $\bar{n}_e$ of $1 \times 10^{20} \text{ m}^{-3}$. Using the

chart above, we see that this density is sufficient to obtain a beam deposition profile that is peaked off-axis, as long as the pellet ablation does not peak on axis. The existing low current TFTR high β_p discharges with Li pellet injection (1.52mm pellets) do not reach a transient density that is large enough to screen the beams from heating on-axis. However, the shots with the largest transient density do show a significant flattening of the T_e profile right after pellet injection, even though the pellet is deposited on-axis. The reheat of such a shot (46448) is shown in Fig. 6.

The operational scenario for pellet injection will consist of the injection of two Li pellets. The initial setup will be to inject the first pellet to have peak deposition about 15 cm off-axis, and then to follow this after sufficient reheat of the plasma ($T_e = 2.8\text{keV}$) by a second pellet with about the same deposition. This shot will be checked to find out if the T_e profiles were inverted during the reheat phase. Adjustments of the pellet timing will then be made optimize the T_e profile inversion.

c) Density Limits: Injecting the large Li pellet into low current plasmas leads to transiently large values of the ratio of average density to the Greenwald limit. However, the ratio considered for the present experiment has been surpassed in previous TFTR high beta poloidal discharges with Li pellet injection. Many low current (0.3MA - 0.5MA) discharges have had Li pellets injected for the purpose of q profile measurement. These plasmas did not disrupt, even though transient densities of 4-5 times the Greenwald limit have been obtained (see table below). Many of the 0.3 MA discharges had the beams shut down because the pellet perturbation led to a decrease of I_p below permissive. Although the beams were shut down, the plasma current continued in the discharges. The 0.5 MA discharges with injected pellets did not suffer a beam permissive shut down, and did not disrupt.

At 0.5 MA, the planned maximum transient line averaged density of $1.0 \times 10^{20} \text{ m}^{-3}$ is 3.7 times the Greenwald limit. The table below shows that this factor has been reached in existing TFTR high β_p discharges immediately following Li pellet injection.

Shot	Max. $n_e l$ (10^{15} cm^{-2})	I_p (MA)	P_{beam} (MW)	$(n_e l / 2a) / (I_p / \pi a^2)$
45665	7.4	0.278	13.0	3.23
45739	9.3	0.488	18.6	2.32
45740	8.6	0.485	18.6	2.17
46433	8.7	0.273	16.8	4.30
46448	11.0	0.280	9.2	4.75
46450	12.0	0.283	9.5	5.15

3. Experimental Run plan:

(describe groups of shots as appropriate, assume 20-25 shots on a good day)

This experiment attempts to establish the calculated second region plasma with $I_p = 0.65\text{MA}$ (see Fig. 7 for schematic). An ohmic plasma at low current (0.5MA) will be established, then neutral beam injection will begin with co-injection only, followed by balanced, or near balanced injection at 18 - 20 MW. The impurity pellet will be injected into a $T_e(0) = 2.85 \text{ keV}$ plasma, which occurs approximately 200 ms after the start of NBI. At the same time, the plasma current will be ramped-up to 0.65MA to reach the target plasma conditions. TRANSP calculations were used as a guide to determine this specific timing of Li pellet injection

and I_p ramp-up. The T_e profiles during the reheat phase will be examined to see if they have been made hollow. We will then know how long it will take the plasma to reheat (100 ms is expected). On subsequent shots, a second impurity pellet will be injected after reheat for additional profile modification. This second pellet can also be used as a diagnostic to measure the q profile at this time (this has already been performed in XP146). Once this baseline case is set-up, the timing of the pellet injection and I_p ramp-up will be varied to produce an optimum configuration. For example, the pellet injection timing will be varied to produce density profiles that maximize the hollowness of the T_e profile, and the current ramp will be varied to produce a broad current profile without deleterious MHD. At this point, the beams will be started with counter-injected sources turned on first. If there is a significant improvement in plasma performance, the beam initiation will be kept this way in the following shots. In addition, D_2 gas puffing may be used to increase the plasma density before pellet injection. The experiment will then be repeated using a lower initial plasma current (0.3 MA).

The current profile modification via impurity pellet injection will also be tried on the plasma current ramp-down plasmas, which have had success in raising β_N in TFTR (see Fig. 8 for schematic). MHD stability calculations indicate that the large edge shear in these plasmas restrict direct access to the second stability region near the plasma edge. However, raising q_0 in these plasmas can significantly alter the stability of the plasma core. Such a configuration may lead to increased pressure gradients on axis while maintaining a first-stability profile at the plasma edge. In addition, if the central current density can be significantly altered in these plasmas at relatively constant I_i , the question of whether or not stability and/or confinement depends on either q_0 or I_i might be better determined.

Experience during previous TFTR high β_p runs shows that some care needs to be taken in finding a successful plasma current ramp-up free of harmful MHD activity. During the run of XP146 (2/1/90), two shots were taken in which the plasma current was ramped up from a low ohmic value (0.3 - 0.5 MA) to a moderate value (0.85 MA) during neutral beam injection. The previous data shows that ramping I_p up too quickly during beam heating (shot 46493; $dI_p/dt \sim 1.5$ MA/sec) leads to deleterious MHD activity. TRANSP reconstruction of this shot shows the development of a non-monotonic q profile due to the fast current ramp-up. A ramp rate of 1.2 MA/sec (shot 46494) did not produce the MHD activity, and TRANSP modelling shows that the q profile remained monotonic in this case. Therefore, the initial set-up will have a 1.2 MA/sec ramp-up rate of I_p from the ohmic value to the final value. Since there has been much experience with the I_p ramp-down from 0.85 MA - 0.4 MA, it has been chosen as the low current configuration for the pellet injection/profile modification tests with I_p ramp-down.

The new operational aspect of this experiment is the coupling of the impurity pellet injection which will be used to raise q_0 , and the I_p ramp-up used to reduce the edge shear. Each of these techniques has already been used separately in previous TFTR experiments.

I_p pedestal	I_p initial	P (MW)	pellet (s)	# shots	Comments
650 kA	500 kA	18	None	1	Reference shot
650 kA	500 kA	18	1.7	1	First pellet - check reheat
650 kA	500 kA	18	1.7 & 1.8	1	Two pellet baseline case
650 kA	500 kA	18	vary	6	Vary pellet timing and I_p ramp timing relative to beams to optimize performance.
650 kA	500 kA	18	As above	2	Best of above with counter-injected beams first.
650 kA	300 kA	18	None	1	Reference shot
650 kA	300 kA	18	As above	3	Baseline at lower I_p initial
400 kA	850 kA	18	None	1	Reference shot
400 kA	850 kA	18	2.7	1	First pellet - check reheat
400 kA	850 kA	18	2.7 & 2.8	1	Two pellet baseline case
400 kA	850 kA	18	vary	5	Vary pellet timing and I_p ramp timing relative to beams to optimize performance.
Total number of shots				23	

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 shot 46494 (2/1/90) with the following amendments/additions:

- (1) A moderately conditioned machine (Target $n_e l = 3.0 \times 10^{15} \text{ cm}^{-2}$)
- (2) Availability of about 20 MW of balanced NBI for 1.0 sec.
- (3) Impurity pellet injector for current profile modification / measurement of q profile.
- (4) Desire MSE diagnostic for measurement of the q profile.

The beams should be staggered, co-only first, then balanced, as in the previous shots (see shot 46494, 46470 for example).

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

5. Estimated neutron budget:

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

Shot 46494, which ramped down up from 0.5 MA - 0.85 MA, produced less than 5.0×10^{14} neutrons for a 0.5 s pulse. If we use this as an average, and assume that 25 successful shots with a 1.0 s pulse duration can be obtained, then only 2.5×10^{16} total neutrons will be 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. If measurements of the internal magnetic field 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, whether or not the plasma has entered the second stability region, 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.

PHYSICS OPERATIONS REQUEST

Title: Second stability with impurity pellet.

Proposal: 319

Machine conditions (indicate range where appropriate):

I_p (MA) 0.3 - 0.85 MA R (m) 2.45, ($a = R - 165.5\text{cm}$ for BL and $= 359.8\text{-Rcm}$ for RFL)

OH Flattop start/stop ~ 0.5 to ~1.4 sec, I_{TF} (kA) 68, Gas Species D, Pellets(D) LI

Beams: Power ~20 MW, duration 0.75 - 1.0 sec, voltage 95 - 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 need the "Physics operations daily comment log book" in the control room to find machine parameter to those desired that have been saved on disk (circled in the log book). If similar shots were in the past, but not saved on disk, a couple of hours lead time may be needed to have the required restored and marked to be saved.

List of previous shot numbers for setup 46493, 46494, 48960, 48972, also see

Fig. 7-8 for sketch of waveforms.

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.

Time

(Attach additional sheets as required)

Time

DIAGNOSTIC CHECKLIST

Proposal Title: **Second stability in TFTR using impurity pellet injection.**

Proposal No. **319**

			Need	Desire	Comments
Magnetics:	Magnetics (MB,MD,MR,MV)		✓		
T_e and n_e :	Thomson Scattering	TS	✓		
	Thomson Scattering	TV		✓	
	Radiometer	YS	✓		
	Michelson	YM		✓	
	1 mm Interferometer	YI			
	MIRI Interferometer	FM	✓		
T_i :	X-ray Crystal	XC,XV	✓		
	CHERS (beam stops)	SW	✓		
	Diag. Neutral Beam	EN			
Spectroscopy:	HAIFA (H _α and VB)	SH	✓		
	SPRED (UV)	SP	✓		
	VIPS (H/D ratio)	SV			
	SOXMOS (XUV)	SX			
	X-ray PHA	XP	✓		
	Hard X-rays	XH			
Particles:	Epithermal Neutrons	NE	✓		
	Charge Exchange	EV		✓	
	Neutron Activation	NA			
	Fusion Products	NF		✓	
	Lost Alphas	NL			
	Neutron Collimator	NM	✓		
	Neutron Fluctuations	NS	✓		
Waves: (timing of fast channels)	Mirnov Coils	MM	✓		
	X-ray Array	XI	✓		
	RF Probe	RP		✓	
	Grating Polychromator	YG	✓		
	Microwave Scattering	YU	✓		
Edge:	Bolometer	BR	✓		
	Plasma TV	VP	✓		
	Edge Thomson	TE			
	Impurity Injection	WI			
	Lithium Pellet	LP	✓		
	Edge Probe	WE			

Comments / Times of Interest: Desire MSE, BES, and Fast MIRI diagnostics

Stability for Postulated 0.67 MA TFTR High β_p Second Stable Region Plasma

Fig. 1

- Equilibrium is stable to the $n = 1$ free boundary kink
- Stable to the $n = 1$ kink for highest β_N case tested ($\beta_N = 3.4$)

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CUPL0T 06/22/90

Fig. 2

Fig. 3

Density After Li Pellet

- Profiles correspond to time $t = 1.7\text{s}$ in shot 46494

RPLOT GENERATED PLOT 15-OCT-91 SHOT 44961

BEAM DEPOSITION (IONIZATION + CX

VS. RZON
AND TIME

TFTR.89 44961A05

Fig. 4b)

TFTR.89 44961A05 PAGE 1
IND(RBOUN) = 1.00000E+00

$\times 10^{14}$

LINE AVERAGE FROM IND(RBOUN) = 0.00000E+00
ELECTRON DENSITY (RMM00) VS TIME

TFTR.89 44961A05 PAGE 14
 IND(RBOUN)= 1.0000E+00

Fig. 5

TRANSP AND SNAP FIT H(O) (HOCOMP) VS TIME

TFTR 46448
 SHOTDATE: --/--/84TI

ELEC TEMP FEE DATA VS MAJOR RAD.

Fig. 6

Fig. 7.

XP 319 Run Plan

1) Set-up XP 319 :

- ITF = 68 kA
- $P_{beam} > 16.0$ MW
- $R/a = 245/80$ cm

a) He Conditioning Shots until $ne1 \leq 3.0e15$

2) Pellet Injection Into 500 kA Initial Current

- a) 500 - 670 kA I_p Ramp-up : (1 shot)
- b) One pellet at 1.7s : (1 shot)
- c) Pellets at 1.7 and 1.8s (vary): (7 shots)
- d) Counter-injected beams first: (2 shots)

3) Pellet Injection Into 300 kA Initial Current

- a) 300 - 670 kA I_p Ramp-up : (1 shot)
- b) Pellets at 1.7 and 1.8s (vary): (3 shots)

Reference shot(s) & Comments

shot 46494

NOTE: TF flattop
0.0 to 4.0 sec

$P_{beam} = 18$ MW

NOTE: Stagger co-
sources at 30 ms
intervals
starting at 1.5 s

$P_{beam} = 18$ MW

- Raise Initial I_p

- Extend beam
pulse length
to obtain WE
flattop

Fig. 8.

XP 319 Run Plan

4) Pellet Injection Into Current Ramp-Down

- a) 850 - 400 kA I_p Ramp-down : (1 shot)
- b) One pellet at 2.7s : (1 shot)
- c) Pellets at 2.7 and 2.8s (vary): (6 shots)

Reference shot(s) & Comments

shot 48972

NOTE: TF flattop
0.0 to 4.0 sec

Pbeam = 18 MW

NOTE: Stagger co-
sources at 30 ms
intervals
starting at 2.5 s

*Conf. paper
cycled approx
10*

END

**DATE
FILMED**

9/16/92