Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: Dependence of resistive Wall stabilization on Equilibrium Configuration

OP-XP-210	**Revision: v1.0**	Effective Date: 02/21/02 *(Ref. OP-AD-97)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Author: F. Paoletti	Date
ATI - Task Force Leader: D. Gates	Date
RLM - Run Coordinator: R. Maingi	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

Maingi, Kaye, Bell, Sabbagh, Menard

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

<u>Title</u>: Dependence of Resistive Wall stabilization on Equilibrium Configuration

<u>Authors</u>: F. Paoletti, S.A. Sabbagh, J. Bialek, C.E. Bush, D. Gates, S.M. Kaye, R. Maingi, J. Manickam, J. Menard, D. Mueller, A. Turnbull, A. Glasser, etc.

1. Overview of planned experiment

Describe the scientific goals of the experiment.

In conventional aspect ratio tokamaks (PBX-M, HBT-EP, and DIII-D), low toroidal mode number kink/ballooning pressure driven instabilities have been successfully stabilized with the use of conducting structures surrounding the plasma. Still at these conventional aspect ratios the values of normalized beta β_t, experimentally achievable are relatively low. Low aspect ratio configurations appear to be more attractive because low l_i,, high β_t,, and high bootstrap fraction configuration are found to be stable against ideal MHD modes in the presence of a conducting wall.

The study of the stabilization of pressure driven instabilities by conducting structures is, therefore, a central research topic in present research and is setting the foundation for more advanced endeavors such as the design of active feedback mode stabilization systems that will be able actively control such instabilities. The conducting structure allows plasma operation above the no wall β-limit (the ideal MHD limit calculated without any conductor placed near the plasma). In the presence of conducting structures with finite resistivity, the ideal kink mode is stabilized but another mode arises: the resistive wall mode (RWM) which has been recently observed on NSTX[1]. As β is increased another limit is found where even the ideal kink mode is again destabilized even in the presence of a conducting structure. This is the with wall β-limit. Therefore plasma operation can only be successful between these two limits provided that the RWM is also stabilized. Successful operation above the no wall β-limit requires the separation between no wall and with wall β-limits to be finite.

The present experiment aims to investigate the effectiveness of resistive wall stabilization in different plasma regimes and characterize the dependence of no wall / with wall β-limits vs. plasma configuration and parameters. Different paths providing access to elevated β_N and low internal inductance will be experimentally explored. The dependence of no-wall and with-wall β_N-limits vs. equilibrium configuration parameters such as current peaking, (parameterized by l_i,); total pressure peaking, $F_p \equiv p(0) / \langle p \rangle$; and plasma shape will be studied and compared with theoretical expectations.

The potential outcomes of this XP are:

- Determine the dependence of the experimental no-wall and with wall β-limits as a function of current profile shape parameterized with l_i in configurations with reduced F_p. Variations in boundary shape will be used essentially to help control of profile shaping.
- Create a plasma with reproducible RWM onset and measurable difference between wall and no wall β-limits.

[1]"Beta-limiting Instabilities and Global Mode Stabilization in NSTX", S.A. Sabbagh, *et al.*, submitted to *Physics of Plasmas*.

- Make initial assessment of the effect of error field reduction on rotation damping at marginal RWM stability, and duration of pulse at $\beta_N > \beta_N$(no-wall)
- Determine no-wall to with-wall β-limits in diverted (LSN or DN) configuration, considering that transitioning to a diverted configuration will help to clamp, or even decrease l_i,. Measure the variation of the rotation damping rate and critical rotation frequency in the new configuration to examine the effect on stability as l_i is decreased.
- Attempt to reach values of β_N above $\beta_N \sim 6\ l_i$ operating significantly above the no-wall β-limit. As highlighted in Figure 2 at $F_p \sim 2.6$ – typical of H-mode operation in NSTX – values of $\beta_N \sim 10\ l_i$ appear to be accessible through wall stabilization.
- Examine stability as high-β plasma becomes more diamagnetic.
- Develop and or utilize techniques to vary l_i and F_p including H-mode, (κ, δ) variation (XP 38 – D. Gates, et al.), I_p ramp-up, large bore startup, and early HHFW heating.
- Compare expectations of mode structure, dynamics, and stability limits between theory and experiment.

2. Theoretical/ empirical justification

Brief justification of activity including supporting calculations as appropriate

Analysis performed to date indicates specific routes toward the optimized, high β target proposed in the conceptual design of NSTX. This target, with $\beta_N = 8$, $\beta_t = 40\%$, and $l_i = 0.35$ can only be reached if the plasma is wall stabilized. Results from the analysis of the data collected in previous NSTX experimental campaigns are shown in Figure 1 where the maximum β_N values achieved are plotted vs. l_i across the present database of reconstructed equilibria. The plot shows that the conceptual design target cannot be reached if l_i is too large, the modes show an internal structure, and do not couple to conducting structure.

At small l_i, the ideal no-wall β limit is typically crossed before the mode balloons and couples to conducting structure. In an ST geometry, the n=1 mode cannot couple efficiently to the passive conducting structure unless it balloons in the outboard of the poloidal cross-section therefore leading to a perturbation of long poloidal wavelength. This occurs generally for NSTX plasmas at levels of $\beta_N \sim 3$ and greater. This is typically larger than in an equivalent, moderate aspect ratio, advanced tokamak equilibrium. In the case where the ideal no-wall limit is not violated until β_N is sufficiently large, even at low l_i, the mode starts ballooning therefore allowing coupling to the conducting structure and wall stabilization. High β_N can also be reached without wall stabilization at medium l_i, ~ 0.7 however, it is expected from our present theoretical analysis and experimentation that the maximum β_N that can be reached will be lower that the optimized, wall stabilized target value. Also, the lower l_i solution is more attractive since it provides a large amount of boostrap aligned current (~70% in the case of the optimized target).

Another important variable that regulates the stability properties of an ST plasma is the shape of the pressure profile, parameterized in these studies by the peaking factor F_p.

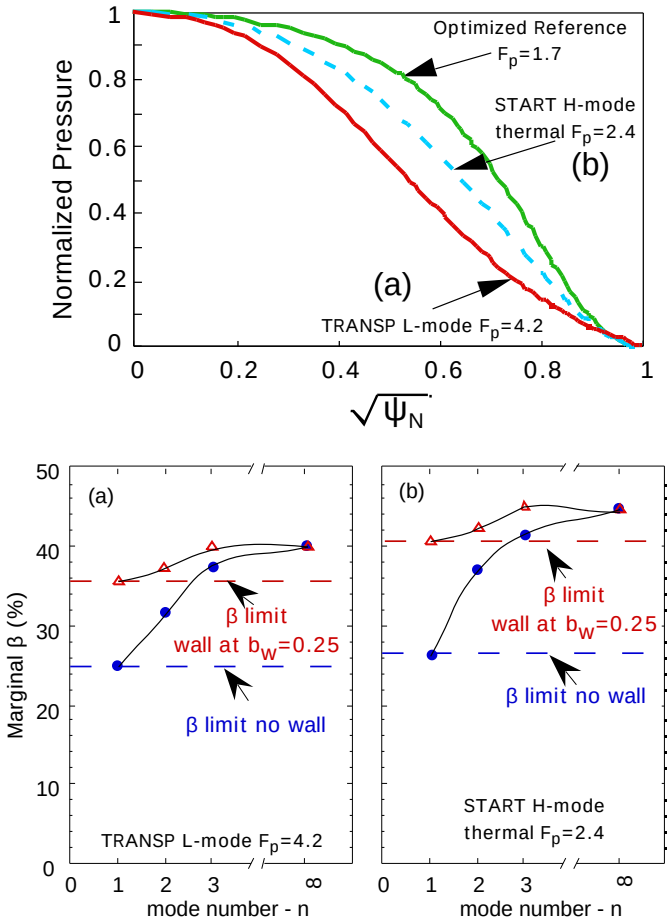

Figure 1: Calculated β-limits for a set of P profile variations starting from the optimized reference case

Theoretical/computational analysis performed to date[2, 3] shows that stability is degraded as F_p is increased. In particular, the study presented in reference[3] highlights the fact that the gap between wall and no-wall β-limits increases as F_p is decreased. An example is given in Figure 1 where the β-limits are compared for two configurations obtained from the optimized reference target replacing the P profile. Case a) pertains to a more peaked P profile F_p ~ 4.2 for a TRANSP simulation of an L-mode type plasma in NSTX. The dashed P profile – see case b) – is a typical H-mode case from the START spherical torus experiment constructed using the thermal contribution to the electron and ion pressure. It is important to notice that the peaking factor of the START H-mode P profile (F_p ~ 2.4) is in the same range of the values observed in NSTX during H-mode operation (F_p ~ 2.6). it is also important to notice that the large separation between no-wall and with-wall β limits in the case a) with high F_p ~ 4.2 is due to the fact that current density profile is broad and internal inductance is low (l_i = 0.35). As l_i is increased the separation between no-wall and with-wall β limits decreases.

Figure 2 shows the results of a computational study aimed at defining an accessible path to high-β_N low- l_i operation in NSTX. The no-wall and with-wall ideal MHD limits are calculated along the trajectory using the DCON code. Each point along the trajectory is obtained starting from the experimental reconstructed equilibrium of shot 106165 at t = 192ms which is the time at the maximum of β_N ~ 2.8 in the presence of a RWM. Each equilibrium is obtained through a linear merging of the P and FF' profiles of the experimental staring point and the reference target highlighted on the top-left of the graph with a star. As β_N is increased along the trajectory, the value of the pressure peaking factor decreases while the separation gap between the calculated no-wall and with-wall β limits increases. This particular feature shows that operation at values of β_N largely above the no-wall β limit is accessible when moving along a trajectory such as the one shown in Figure 2. The general goal of this experiment is to follow specific trajectories in (l_i, F_p, β_N) space

[2] J. Menard, et al., *Nucl. Fus.* **37** 595 (1997).

[3] Impact of MHD Equilibrium Input Variations on the High-Beta Stability Boundaries of NSTX, F. Paoletti, *et al.*, *Nucl. Fus.*, in press.

that are theoretically stable, in the attempt of reaching the optimized target equilibrium therefore documenting the instabilities that appear in these attempts.

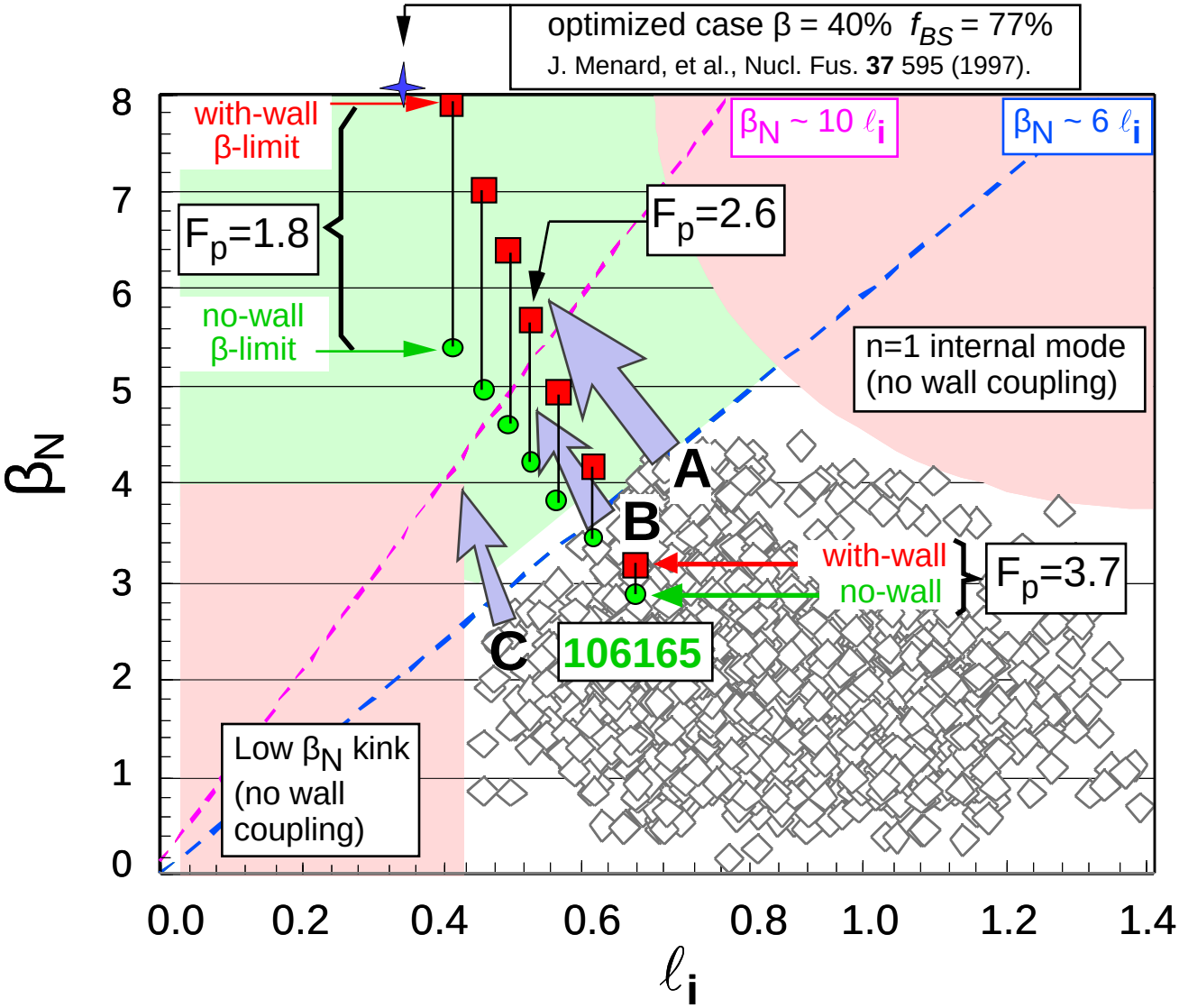

Figure 2 No-wall and with-wall (conformal wall with r_w=1.25a) β_N-limits along the identified trajectory to high-β_N wall stabilized operation on NSTX

The experimental observation of the RWM on NSTX (see CY 2001 experiment - XP 17), set the foundation for this exploratory campaign which will start from shot 106165 where RWMs lasted for up to 3.5 conducting plate wall times. The reduced error field configuration of the present machine should increase the duration of the discharge. The effects of configurational changes on the toroidal rotation damping (-300 kHz/s observed in XP 17) and the coupling of the plasma to the passive plate structure will be a central point of investigation in this experiment. Shot 106165 was run in a limiter configuration, exhibited a very fast toroidal rotation damping (~ -300 kHz/s) and operation was estimated to be very close to the calculated with-wall ideal stability limit. Figure 2 shows the no-wall and with wall β limits in the proximity of the experimental point.

The first goal of this XP is to attempt recreating this plasma in the present reduced error field machine configuration. The second goal of the XP is to generate new plasma configurations which allow following the three trajectories outlined in Figure 2 with the letters (A) (B) and (C). The first attempt (phase 1) will be done starting from one of the highest β_N points in Figure 2 (see for example XP 38 by D. Gates, et al.; shot 106385 @ t = 241 ms reached β_N ~ 4.5; β_T ~ 26%; l_i. ~ 0.66; and a broad pressure profile with peaking factor F_p. ~ 2.6). Another remarkable feature of these high-β_N low- F_p. plasmas is that as long as only one NBI source is used, the value of the central safety factor q_0 remains above 1 (for shot 106385 @ t = 241 ms, q_0 ~ 1.45 as calculated by EFIT) with clear beneficial effects on stability.

The series of shots like 106385 where run in inner limited configuration. Converting from inner limited to lower single null (LSN) operation has shown to broaden the current density profile therefore decreasing l_i,. Such a transition, combined with other measures aimed at broadening the pressure profile, should result in a path along the trajectory (A) outlined in Figure 2. One of the natural tools that provide broader pressure profiles is H-mode operation. Although H-mode operation is not specifically required for this experiment, it would be highly desirable since it has led to pressure peaking factors in the range of F_p ~ 2.6 where, according to the results shown in Figure 2, the separation between no-wall and with-wall β limits is large, theoretically allowing access to values of β_N ~ 10 l_i. Broader pressure profiles will lead to increased induced bootstrap current, which, in turn, will help to further decrease l_i therefore moving along the trajectory of Figure 2. Further decrease of l_i could be achieved through NBI power step down following and trying to accelerate the natural evolution of the l_i trace vs. time which tends to saturate in present RWM discharges before their termination (see for example shot #106165). An example of the possible waveforms is given in the bottom part of Figure 3.

Further broadening of the current density profile could be achieved using different I_p ramp-up sequences. In particular, variation of the I_p time evolution which provides increases in current at high stored energy. In phase 2, with the aim of following the trajectory labeled (B) in Figure 2, different I_p ramp-up schemes will be applied to the best discharge produced in phase 1. This is outlined in Figure 3 where a sketch of the anticipated I_p waveforms is shown starting from a template provided by discharge 106818 (this is a plasma obtained in the reduced error field configuration of the present run). In shot 106818 the current is ramped at a rate of 5MA/s and diverted right after reaching 1MA. During the I_p ramp l_i slowly rises up to values of l_i ~ 0.57 and after the plasma is diverted it starts decreasing as expected. The strong increase in l_i observed after t ~ 180 ms is due to the fact that I_p has now reached its flattop value and no additional current is fed from the edge with the result of a peaking of the current density profile. To avoid this rapid increase in l_i,, different I_p ramp-up sequences will be tried (see Figure 3) starting from I_p ~ 0.8 MA at t ~ 140 ms and approaching the target time of interest (t ~ 240 ms) at different rates. For example, the green trajectory in Figure 3 has a 2.5 MA/s I_p ramp-rate in the second portion of the ramp. The timing of transition from inner limited to diverted is also another important knob to reduce l_i. Different attempt will be made to identify the best setup as shown in Figure 3. Characterization of RWM onset will be carried out through a scan of NBI power/timing as done in phase 1 (see Figure 3 for anticipated timing and sources use).

High β_N wall stabilized operation in NSTX will be attempted by varying timing and applied NBI power (see Figure 3), and the effect on the toroidal rotation damping rate and critical mode rotation frequency in the presence of a resistive wall will be measured. If high-β_N – high-β_p regimes are accessed in this experiment a initial characterization of the transition from paramagnetic to diamagnetic plasma will also be a possible outcome.

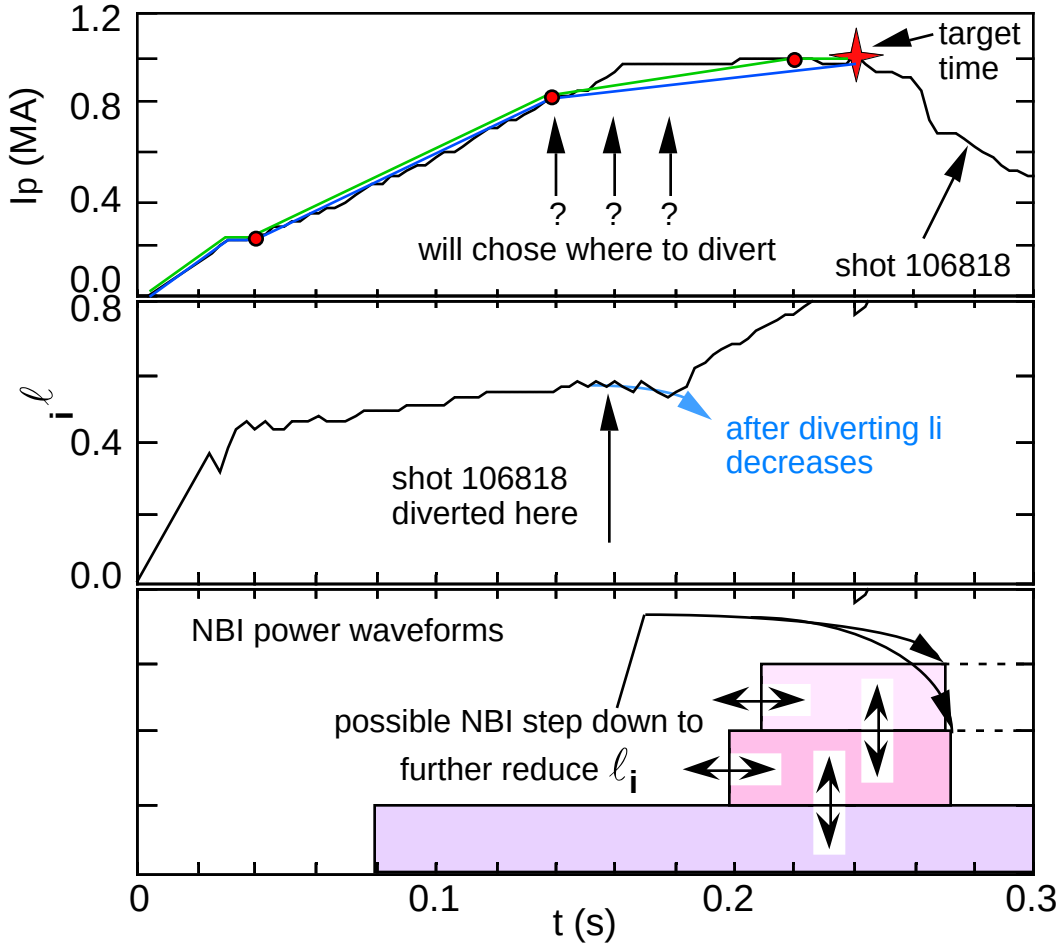

Figure 3 Proposed waveforms for the Second Phase of the XP, where different I_p ramp-up sequences will be used to attempt broadening of the current density profile (reduction in l_i). The NBI power waveforms or similar setups shown at the bottom of the figure will also be used in the First Phase of the XP.

Another possible path to high-β_N – low-l_i operation could start directly from existing low-l_i discharges. Operation in the new low error field environment should be beneficial here as well. The plan for phase 3, and 4 of this experiment is to adopt different startup techniques to generate low-l_i targets and then follow the steps highlighted in the previous section (H-mode and LSN operation) to generate broader pressure profiles and further reduce l_i. Two different techniques will be used to create the initial targets:

1) Starting with a large bore plasma to produce a low-l_i configuration. Previous attempts to adopt this kind of startup configuration have possibly failed due to the presence of a high error field affecting the edge of the plasma. In the present reduced error field configuration it should easier to produce these targets avoiding disruptive locked modes.
2) Early application of HHFW, as demonstrated in XP 25 by J. Menard, *et al.* will tend to freeze the current density profile providing low-l_i and q_0 >> 1 (see for example shot #104403).

Finally, the use of LSN plasma with cross sections of comparable size to those that could be generated of the DIII-D tokamak will aid the selection of a target configuration to be used in the NSTX / DIII-D RWM similarity experiment proposed for the NSTX CY 2002 run.

3. Experimental run plan

Describe experiment in detail, including decision points and processes

The run plan would proceed as follows:

FIRST DAY

FIRST Phase: (20 shots) - Approaches paths (A) & (B) of Figure 2. Follow path to high β_N low l_i starting from medium/high l_i and low F_p study effect of equilibrium variations.

GOALS

(1) Reproduce low F_p type shots (ex. 107125) and move on path (A) of Figure 2 attempting to create a plasma with reproducible RWM onset and measurable difference between wall and no wall β-limits.

(2) Evaluate effect of reduced error field configuration on RWM type shots (ex. 106165) and possibly start moving on path (B) of Figure 2.

- **Use H-mode (if available) to produce lower F_p targets.**

	Task	Number of Shots
1)	Restore shot 107125, (XP 38, CS limited, @ t = 242 ms: I_p = 1.2 MA, β_T = 3.0 kG, F_p ~ 2.66, l_i ~ 0.7, q_0 ~ 0.95, κ ~ 1.72, δ ~ 0.51, out gap ~ 5 cm)	
	→ run larger cross section plasma (k ~ 2.2), lower out-gap ~ 2 cm for better passive plate coupling and flattop I_p = 1.0 MA. Possibly switch to β_T = 3.5 kG for longer pulse.	6
	→ Apply I_p ramp-up (see Figure 3); this should prevent fast l_i increase observed during I_p flattop.	3
	→ Scan beam power to find RWM onset.	2
	→ Take lower β control shot without RWM.	1
2)	Reproduce RWM shot 106165 to evaluate effect of reduced error field (CS limited, I_p = 1.0 MA, β_T = 3.5 kG, F_p ~ 3.7, l_i ~ 0.70, q_0 ~ 1.02, κ ~ 2.0, δ ~ 0.47, out-gap = 1.6 cm).	6
	→ Scan beam power to find RWM onset	2
	→ Take lower β control shot without RWM	1
	Total:	20

Total number of shots (day 1): 20

Total number of shots for XP 210: 20

4. Required machine, NBI, RF, CHI and diagnostic capabilities

Describe any prerequisite conditions, development, XPs or XMPs needed. Attach completed Physics Operations Request and Diagnostic Checklist

The list of diagnostics:

- Flux loop and plasma current data are required.
- Integrated poloidal Mirnov coil data is required.
- CHERS toroidal rotation measurements are required.
- Locked mode detector is required.
- Thomson scattering is required.
- Measurement of the shaping and OH coil currents are required.
- Toroidal Mirnov coil data is highly desired.
- USXR is highly desired.
- The diamagnetic loop is required for partial kinetic EFIT reconstruction.
- Fast camera is highly desired.
- Measurements of currents in passive conducting plates is highly desired.
- D_α , C_{III} measurements are highly desired.

5. Planned analysis

What analysis of the data will be required: EFIT, TRANSP, etc.

Shot-to-shot equilibrium (EFIT) + stability (DCON) analysis would be desirable to provide guidance to the run. DCON and GATO will be used to determine the ideal stability analysis. In particular, GATO will be used in the post-run analysis to determine internal mode structure. Outputs from DCON will be used in the VALEN code to study the effectiveness of passive wall stabilization as well contribute to the design of an active mode feedback control system on NSTX.

6. Planned publication of results

What will be the final disposition of the results; where will results be published and when?

The results from this experiment will be considered as the core subject of an astract submission for invited talk at the 2002 APS Meeting in Orlando (FL). Publication of the results in a peer reviewed journal such as Nuclear Fusion, Physics of Plasmas is also expected. Depending on the caliber of the obtained results publication in Physical Review Letters is also considered.

PHYSICS OPERATIONS REQUEST

Title: Dependence of Resistive Wall stabilization on Equilibrium Configuration **XP No.: 210**

Machine conditions (indicate range where appropriate):

TF: Flattop (T) ≤ 0.45T__ Flattop start/stop (s) _____

I_p:Flattop (kA) ≥ 0.7 - 1.0 MAFlattop start/stop (s) _REQUIRED: ability to perform I_p ramps

Position: R (m) _____ Z (m) _____ Boundary shape: CS, LSN, DND_

Gas: Prefill D___ Puff _____

NBI:Power (MW) _full (5MW)_ Start / stop (s) _____ Voltage (kV) _____

RF:Power (MW) _< 6 MW__ Start / stop (s) _____ Frequency (MHz) _____

CHI: (Off) Off / Start-up / Ramp-up / Sustainment

If this is a continuation of a previous run or if shots from a previous run are similar to those needed, provide shot numbers for setup

---

If shots are new and unique, sketch desired time profiles and shapes. Accurately label the sketch so there is no confusion about times or values. Attach additional sheets as required.

DIAGNOSTIC CHECKLIST

Title: **Dependence of Resistive Wall stabilization on Equilibrium Configuration** **XP No.: 210**

Diagnostic system	**Need**	**Desire**	**Requirements** (timing, view, etc.)
Magnetics	✓		
Fast visible camera		✓	
VIPS-1		✓	
VIPS-2		✓	
SPRED		✓	
GRITS		✓	
Visible filterscopes		✓	
VB detector		✓	
Midplane bolometer		✓	
Diamagnetic flux	✓		
Density interferometer (1mm)		✓	
FIReTIP interf'r/polarimeter		✓	
Thomson scattering	✓		
CHERS	✓		
NPA			
X-ray crystal spectrometer		✓	
X-ray PHA		✓	
EBW radiometer			
Mirnov arrays	✓		
Locked-mode detectors		✓	
USXR arrays	✓		
2-D x-ray detector (GEM)		✓	
X-ray tangential camera		✓	
Reflectometer (4 ch.)			
Neutron detectors		✓	
Neutron fluctuations		✓	
Fast ion loss probe		✓	
Reciprocating edge probe			
Tile Langmuir probes			
Edge fluctuation imaging			
H-alpha cameras (1-D)		✓	
Divertor camera (2-D)			
Divertor bolometer (4 ch.)			
IR cameras (2)		✓	
Tile thermocouples			
SOL reflectometer			