Princeton Plasma Physics Laboratory
NSTX Experimental Proposal

Title: RWM Active Stabilization and Optimization – ITER Scenario		
OP-XP-728	**Revision: V1.0**	Effective Date: 5/8/07 *(Ref. OP-AD-97)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS	
Author: S.A. Sabbagh, et al.	Date:
ATI – ET Group Leader: S.A. Sabbagh / N. Gorelenkov	Date
RLM - Run Coordinator: D.A. Gates	Date
Responsible Division: Experimental Research Operations	

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

Title: RWM Active Stabilization and Optimization – ITER Scenario OP-XP-728

1. Overview of planned experiment

Briefly describe the scientific goals of the experiment.

The overall goal of the experiment is to actively stabilize resistive wall modes (RWMs) in NSTX plasmas that are above the ideal no-wall beta limit and well below the "critical plasma rotation frequency" for RWM stabilization, further optimizing the RWM control system from the initital experiments from XP615 in 2006 at low plasma rotation (Sabbagh, et al., PRL **97** (2006) 045004.) and to determine if low rotation states exist at high β_N that may be passively stabilized, similar to states found in DIII-D at lower β_N and low margins over the no-wall β_N limit, $\beta_N^{no\text{-}wall}$. (Reimerdes, et al. PRL **98** (2007) 055001.).

The specific goals of the experiment are:

1. Investigate variations of control sensor combinations to optimize RWM stabilization at low plasma rotation and plasma rotation, ω_ϕ (making stabilization more robust and enabling higher stable β_N).
2. Investigate active RWM stabilization of recent (CY 2007 plasmas) that exhibit unstable RWM activity leading to discharge termination at *high* ω_ϕ.
3. Explore possible stable region at low ω_ϕ with active feedback is turned off after this operational space is accessed.
4. Investigate RWM active stabilization and robustness of low ω_ϕ plasma with superposed time-averaged n = 1 error field correction + n = 3 magnetic braking.
5. Measure n = 2-3 RFA, attempt to destabilize n = 2 RWM with n = 1 stable.
6. Introduce and study effect of applied time delay on feedback (ITER support)
   (Depends on control system time delay capability in 2007).

This experiment will also provide important results for RWM stabilization physics and for ITER. The XP directly addresses a 2007 milestone for NSTX - R(07-2). It also addresses ITPA experiments MDC-2 on RWM stabilization physics, ITER issue card RWM-1, and contributes to the USBPO MHD task on a joint RWM/ELM/EF coil design. The goal of addressing stabilization with varying control system time delays addresses an NSTX PAC request for ITER support.

2. Theoretical/ empirical justification

Brief justification of activity including supporting calculations as appropriate

The goals of the experiment follow practically from both the initial RWM active feedback experiments on NSTX as well as results from DIII-D and JT-60U. Theory connected to each of these subjects has been relatively simple, but appears to be lacking based on the most recent experimental results. The present experiment will address several of these leading edge questions regarding RWM stabilization.

(a) Role of plasma rotation: The first key issue is RWM active stabilization in the presence of plasma rotation. Simple models of RWM passive stabilization typically describe a critical plasma rotation, usually at the plasma edge, or a low order rational surface, such as $q = 2$, below which the RWM becomes unstable at sufficiently high $\beta_N > \beta_N^{no\text{-}wall}$. However, data from NSTX has shown that the plasma rotation at the q = 2 surface can vary substantially at the onset of RWM destabilization. In addition, recent discharges with very high plasma rotation (core values of 40 kHz) and significant rotation at to the plasma edge (e.g. 123518) have become RWM unstable. Results of balanced NBI in DIII-D and low plasma rotation experiments in JT-60U have reported passive stabilization at very low plasma rotation $\omega_\phi < 0.01\ \omega_A$, although at low $\beta_N/\beta_N^{no\text{-}wall} < 1.2$. These plasmas in DIII-D were also shown to suffer RWM destabilization on the occurrence of non-axisymmetric field events, such as ELMs.

In the present experiments, we plan to investigate a more general hypothesis for the "critical rotation speed" by examining RWM stabilization at all levels of plasma rotation in NSTX that produce unstable RWMs. Active stabilization will be applied to the most recent result of RWM destabilization at high ω_ϕ. These results were obtained in plasmas exposed to the lithium evaporator, which also showed concurrent tearing mode and RWMs, which typically does not occur. This may give further clues to the underlying physics of RWM passive stabilization, which appears to depend on ion collisionality from 2006 results in NSTX. Along with high ω_ϕ, the entire range of ω_ϕ in NSTX will be scanned. Low ω_ϕ regimes will be accessed by actively stabilizing the plasma at ω_ϕ, and then switching off RWM active stabilization at levels of ω_ϕ that would be expected to be unstable to search for a passively stable regime at low and test its robustness to perturbations.

A general explanation of passive stabilization that incorporates these results would be a series of separate energy dissipation mechanisms each dependent on plasma rotation, ion collisionality, and perhaps several other key plasma parameters. Resonances at higher plasma rotation would include shear Alfven and sound wave resonances (A. Bondeson, M.S. Chu, Phys. Plasmas **3** (1996) 3013.) and at lower rotation $\omega_\phi < \omega_{*i}$, trapped particle precession drift resonances (Betti and Hu, PRL **93** (2004) 105002.). Unstable RWM activity at the highest ω_ϕ might be due to ineffective mode energy dissipation at these high levels. These theories, and others will be tested by simple analytic expressions, the MARS-F code, and codes to computed the Hu/Betti stability criterion. A conclusion that explained the inadequacy of a simple scalar critical plasma rotation for RWM stabilization would be a significant result leading toward a full understanding of RWM stabilization physics.

(b) RWM deformation during stabilization and δB_r vs. δB_p growth: The initial RWM active control experiments on NSTX sometimes showed poloidal deformation of the RWM. This may have occurred due to other stable RWM eigenfunctions becoming unstable during feedback control. This is shown in Fig. 3b of Sabbagh, et al., PRL **97** (2006) 045004. (attached to end of XP). In these cases, the mode amplitude measured by the upper B_p sensors, which were the only sensors used for feedback control in 2006, goes to zero, yet the mode still appears to grow in the B_r sensors. To attempt to combat this issue, the full sensor set of both upper and lower B_p and B_r arrays will be used to compute the RWM mode amplitude and phase for the plasma control system (PCS). The relative phase between the measured mode phase and the applied field phase will have to be varied for each new combination attempted.

(c) <u>*n* > 1 mode activity during stabilization</u>: The initial RWM active control experiments on NSTX stabilized the $n = 1$ RWM. During such periods, the $n = 2$ RWM amplitude was observed to sometimes exceed the $n = 1$ amplitude, but the mode never became unstable, up to values of $\beta_N = 5.6$. Instead, internal $n = 2$ kink modes were observed that rotated with the plasma rotation speed (Fig. 4 of Sabbagh, et al., PRL **97** (2006) 045004. (attached). These modes resulted in minor core collapses of stored energy, but the plasma current was not disrupted and the plasma reheated to high β_N. The present experiment will attempt to measure both $n = 2$ and $n = 3$ resonant field amplification at the highest β_N possible, and observe whether or not these modes become unstable. Theoretically, the plasmas were ideal MHD unstable to the $n = 2$ mode, so by present understanding the $n = 2$ mode was thought to be above the critical plasma rotation speed for the $n = 2$ mode. However, as discussed in Section 2(a), this may not be a satisfactory model for RWM stabilization. Destabilizing the n = 2 mode would give greater insight as to the general RWM stabilization physics.

(d) <u>Control system latency</u>: Once the NSTX RWM control system parameters are optimized, the control system latency could be increased to understand at what point RWM stabilization failed. This would be important input for ITER, whose control coil response may be slower than our present system, requiring at the very least a modification to the feedback control algorithm. This study was a specific request of the NSTX PAC. If the control system is modified before the end of the 2007 run to support this study, it would be performed, but that is not expected.

3. Experimental run plan

Describe experiment in detail, including decision points and processes

The experiment would be conducted in two parts. The first part will focus on reproducing active RWM stabilization with upper B_p sensors alone, then optimizing control by adding sensors and varying the relative phase between the measured n = 1 RWM phase and the applied field.

The specific shotlist is:

<u>PART I Run plan</u>: (24 shots)

Task	Number of Shots
1) Create target plasma	
A) Run active feedback in piggyback mode in prior experiments to verify operation	-
B) 3 NBI, $\kappa > 2.2$, $\beta_N > \beta_N^{\,no\text{-}wall}$ (control shot - 123529 as setup shot)	1
C) Drop I_p to 0.9 MA from 1.0 MA	1
2) Reproduce active RWM stabilization at low plasma rotation	
A) $n = 3$ braking, $n = 1$ feedback w/B_{pu} sensors, adjust $n = 3$ braking if $\omega_\phi > 0.5\ \Omega_{crit}$	2
B) Reproduce (2A) with $n = 1$ feedback off - demonstrate unstable RWM at low ω_ϕ	2

3) Optimize n = 1 feedback sensors at low ω_ϕ

A) Adjust relative phase between sensors / RWM coil current if (2A) <> shot 120717	3
B) Add B_{pl} sensors to feedback circuit	1
C) Use $B_{pu} + B_{pl}$ average (150 degree spatial offset)	1
F) Vary relative phase between sensors / RWM coil	4
D) Add upper/lower Br sensors to feedback circuit	1
E) Add $B_{ru} + B_{rl}$ average (260 degree spatial offset)	2
G) Vary relative phase / feedback parameters to further optimize performance	6
Total:	24

The second part will focus producing stabilized plasmas of varying plasma rotation profile, especially the very lowest rotation possible across the entire plasma. Active feedback will be gated off in some shots to explore the possibility of passive stabilization at low rotation. The additional goals of the experiment will be addressed with specific scans.

The specific shotlist is:

<u>PART II Run plan</u>: (18 shots)

Task	Number of Shots
4) n = 1 RWM stabilization with various rotation profiles < Ω_{crit} (best feedback settings from step (3))	
A) Vary n = 3 braking current to create scan of profiles $0 < \omega_\phi << \Omega_{crit}$ Gate off active feedback for many wall times (100 ms) to determine which, if any profiles are stable at low rotation without n = 1 feedback	8
B) If any ω_ϕ profiles are stable without n = 1 feedback in (5A), re-run shot with feedback turned off	2
5) Check pre-programmed average of n = 1 feedback current for stabilization	
A) Attempt stabilization using avg. n = 1 feedback current for best case of (3) above	2
B) If successful, vary plasma parameter(s) (e.g. κ) to test robustness of stabilization	2
6) Measure n > 1 RFA at maximum bN; attempt n = 2 RWM destabilization with n = 1 stable	
A) Take highest β_N stabilized plasma at low and run at maximum $\beta_N / \beta_N^{\text{no-wall}}$ (options: increase NBI power, optimize DRSEP, use lithium, drop I_p by 100A)	2
7) Examine feedback performance vs. feedback system latency	
A) Increase feedback system latency from optimized settings to find critical latency for mode stabilization	6

Total: 16 w/o latency scan; 22 with latency scan

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

NOTE: The lithium evaporator is highly desired for this experiment for maximum plasma performance, and is required if this experiment is to be run with 2 NBI sources instead of 3.

As usual, standard magnetic diagnostics are essential. Diamagnetic loop and Thomson scattering are required since partial kinetic EFIT reconstructions are needed for this experiment. CHERS and MSE are required for toroidal rotation, ion temperature, and internal magnetic field line pitch angle profile evolution. The NSTX RWM feedback control system will be required. The internal RWM sensor set will be required for RWM detection and operation of the RWM active feedback system.

5. Planned analysis

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

EFIT at all run levels, including MSE and flux isosurface constraint will be important for this experiment, and will be run for each shot of interest. DCON will be used to determine no-wall and with wall β_N limits and RWM mode structure. VALEN, including the effect of RWM mode rotation, will be used to model the performance of the feedback system and compared to the experimental results. MARS-F runs will be run to determine RWM stability with rotation and to test present code dissipation models for NSTX data. Codes by Hu and Betti to evaluate RWM stabilization due to trapped particle precession drift resonance will be run to determine of this mechanism could explain a passively stable operating regime for the RWM at low plasma rotation.

6. Planned publication of results

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

This experiment has the potential to provide key data in several leading areas of RWM stabilization physics research. If any of the more significant issues addressed in Section 2 could be clearly addressed and explained, the results would warrant rapid publication in Physical Review Letters. If incremental progress in improving the performance of the RWM control system could be clearly demonstrated, the results would also be quite important and would be appropriate for publication in Physics of Plasmas, or Nuclear Fusion.

PHYSICS OPERATIONS REQUEST

Title: <u>RWM Active Stabilization and Optimization – ITER Scenario</u> **OP-XP-728**

Machine conditions (specify ranges as appropriate)

I_{TF} (T): **0.35 – 0.45T** Flattop start/stop (s): _____/_____

I_P (MA): **0.8 – 1.0 MA** Flattop start/stop (s): _____/_____

Configuration: **Lower Single Null (minimize no-wall limit)**

Outer gap (m): 5**+/- 3 cm**, Inner gap (m): **5 +/-3 cm**

Elongation κ: **2.1 – 2.5**, Triangularity δ: **0.4 – 0.5**

Z position (m): **0.00**

Gas Species: **D**, Injector: **Midplane / Inner wall / Lower Dome**

NBI - Species: **D**, Sources: **A/B/C**, Voltage (kV): **max**; A at 90kV, Duration (s):

ICRF – Power (MW): ____, Phasing: **Heating / CD**, Duration (s): _____

CHI: **Off**

Either: List previous shot numbers: **<u>123529 (plasma), 120717 (RWM control)</u>**

Or: Sketch the desired time profiles, including inner and outer gaps, κ, δ, heating, fuelling, etc. as appropriate. Accurately label the sketch with times and values.

DIAGNOSTIC CHECKLIST

Title: RWM Active Stabilization and Optimization – ITER Scenario OP-XP-728

Diagnostic	Need	Desire	Instructions
Bolometer – tangential array			
Bolometer array - divertor			
CHERS	X		
Divertor fast camera			
Dust detector			
EBW radiometers			
Edge deposition monitor			
Edge pressure gauges			
Edge rotation spectroscopy			
Fast lost ion probes - IFLIP		X	
Fast lost ion probes - SFLIP		X	
Filtered 1D cameras			
Filterscopes			
FIReTIP		X	
Gas puff imaging			
Infrared cameras			
Interferometer - 1 mm			
Langmuir probe array			
Magnetics - Diamagnetism	X		
Magnetics - Flux loops	X		
Magnetics - Locked modes	X		
Magnetics - Pickup coils	X		
Magnetics - Rogowski coils	X		
Magnetics - RWM sensors	X		
Mirnov coils – high frequency		X	
Mirnov coils – poloidal array		X	
Mirnov coils – toroidal array	X		
MSE	X		
Neutral particle analyzer		X	
Neutron measurements		X	
Plasma TV		X	
Reciprocating probe			
Reflectometer – core			
Reflectometer - SOL			
RF antenna camera			
RF antenna probe			
SPRED			
Thomson scattering	X		
Ultrasoft X-ray arrays		X	
Visible bremsstrahlung det.			
Visible spectrometers (VIPS)			
X-ray crystal spectrometer - H			
X-ray crystal spectrometer - V			
X-ray PIXCS (GEM) camera			
X-ray pinhole camera			
X-ray TG spectrometer			