Princeton Plasma Physics Laboratory
NSTX Experimental Proposal

Title: Physics of Passive RWM Stabilization		
OP-XP-619	**Revision: 0**	Effective Date: 4/30/06 *(Ref. OP-AD-97)* Expiration Date: 4/30/08 *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Author: A. Sontag	Date
ATI – ET Group Leader: J. Menard	Date
RLM - Run Coordinator: R. Raman (S. Sabbagh)	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

1. Overview of planned experiment

Briefly describe the scientific goals of the experiment.

The overall goal of this experiment is to determine the underlying physics which allow passive stabilization of the resistive wall mode (RWM) at high β_N, when the no-wall beta limit is exceeded.

Understanding the aspects of the RWM stability equation which allow the RWM to remain stable above the no-wall beta limit is important to optimize passive stabilization of the RWM, to scale results to future devices, and to determine requirements for active mode control. Current RWM theories employ toroidal rotation and some form of dissipation to allow this mode to remain stable above the no-wall limit, but the relative magnitudes and detailed nature of the inertial effects and dissipation mechanisms have yet to be determined. The strength of dissipation is tied to the rotation frequency in some cases. Also the simultaneous existence of other MHD modes may provide an effective dissipation that is not currently included in any theory.

The present experiment will consider the dissipative effects due to continuum damping, ion Landau damping, and neoclassical effects. Active braking of the plasma rotation by externally applied fields will be used to alter the RWM passive stabilization. The experimental results will be compared to analytic theories of RWM stability as well as to numerical computational results.

This experiment will study:

1) The stability dependence of the RWM on the Alfven frequency. Previous work has typically examined the rotation speed required for passive RWM stabilization in terms of the Alfven speed. This is because the rotation relative to the Alfven speed is predicted to affect the dissipative coupling of the RWM to the Alfven continuum. If the toroidal field is varied at fixed q (by also varying I_p), then the Alfven frequency can be varied while holding other parameters (such as the ion thermal speed) constant – allowing a clear examination of the effects of varying Alfven speed.
2) The stability dependence of the RWM on ion collision frequency. Dissipation is included in MHD models through modifications of the viscous stress tensor. Recent work on NSTX indicates that neoclassical toroidal viscosity (NTV) plays a dominant role in non-resonant rotation damping on NSTX. It follows that this viscosity model might be responsible for significant dissipation also. Both NTV and standard neoclassical effects depend on the ion collision frequency, so varying this frequency should vary the strength of these dissipation models.
3) The stability dependence of the RWM in relation to the existence of other MHD. Variations in RWM critical rotation suggests a correlation between the existence of other MHD in the plasma and RWM stabilization. It is hypothesized that other MHD

instabilities either alter the unstable drive of the RWM or provide a form of dissipation for the RWM. Magnetic braking to induce RWM instability during periods with and without this MHD will be used to test this hypothesis.

2. Theoretical/ empirical justification

Brief justification of activity including supporting calculations as appropriate

Several dissipation mechanisms have been invoked in the various RWM theories to explain the observed stability of plasmas with $\beta_N > \beta_N^{\text{no-wall}}$. Mechanisms such as dissipation of energy by other modes, or by the resistive wall have been suggested, but this experiment will focus on fluid models of dissipation dependent on the Alfven speed and ion collisionality. This experiment will vary plasma parameters in order to vary the relative strength of the proposed dissipation mechanisms and examine the variations in RWM stability.

Ion Landau damping is a dissipation mechanism which is often invoked in both analytic theories and in numerical calculations of RWM stability. This effect has been modeled with a sound wave approximation[1,2] and with a semi-kinetic damping model[3]. Increased ion thermal speed causes an increase in the strength of dissipation in the sound wave approximation which is taken to be proportional to $k_{\|} v_{ti} \rho v_{\|}$. The strength of the dissipation in the semi-kinetic model is strongly affected by the Alfven speed because this determines the degree of toroidal inertial enhancement. Toroidal inertial enhancement allows the RWM to more easily couple to the Alfven continuum and offsets the decrease in ion Landau damping due to trapped particles. The rotation frequency required for significant ion Landau damping in the semi-kinetic model is given by:

$$\omega_{rot} > \frac{\varepsilon^{1/2} v_{ti}}{qR} . \qquad [1]$$

The rotation frequency predicted by Bondeson and Chu for toroidal inertial enhancement is given by $\omega_{rot} > \omega_A/4q^2$. NSTX discharges which satisfy the criteria for toroidal inertial enhancement across the entire rotation profile have been shown to be stable to the RWM for long periods[4]. Recent NSTX work has shown that discharges with the region outside q=2.5 with very low rotation (not satisfying the inertial enhancement criterion) can also remain stable to the RWM for multiple wall times. This is consistent with global ion Landau damping, rather than damping only at rational surfaces, as predicted by the semi-kinetic model.

Much previous work has used the rotation speed normalized to the Alfven speed at the q = 2 surface as a determining factor in RWM stability. Comparisons of NSTX critical rotation profiles to DIII-D critical rotation profiles indicate that higher rotation is required in NSTX for passive RWM stability when both are normalized to the Alfven speed. This indicates that either an aspect ratio scaling is required, or the stabilization physics are not dependent on the Alfven speed. The critical rotation data for NSTX were obtained with only minor variations in the v_A, so it is desirable to examine the dependence of the critical rotation in NSTX on Alfven speed.

Dissipation effects are included in the MHD model as a parallel viscous term. Recent NSTX research has shown that significant rotation damping[5], especially when $\beta_N > \beta_N^{\text{no-wall}}$, can be accurately described by neoclassical toroidal viscosity[6] which is produced by toroidally asymmetric distortions of the magnetic field. This viscosity should also contribute to the stabilization of the RWM. In the collisionless regime which is dominant throughout most of the NSTX plasma, the torque from NTV has an inverse dependence on the ion-ion collision frequency. Variation of this collision frequency should alter the stabilization of the RWM due to NTV. Three dimensional field distortions give rise to the effects of NTV, but trapped particle effects also give a neoclassical parallel viscosity which is proportional to the ion-ion collision frequency[7]. Variation of the plasma density should allow a variation of this collision frequency. If the apparent dissipation varies with the collision frequency, then it should be possible to determine which of these models dominates the dissipation.

Some NSTX discharges remain stable to the RWM with lower rotation depending on the level of rotating MHD activity. Two discharges illustrating this are shown below in Figure 1. The discharges were part of a similarity experiment and have very similar time evolutions except for different applied n=3 braking fields (applied at 0.45 s). The discharge shown in Figure 1a (117291) experiences unstable RWM growth starting at 0.52 s, which correlates with the termination of the n=1-3 rotating MHD. The discharge shown in Figure 1b (117294) does not experience unstable RWM growth until 0.56 s, when the n=2 mode rotating at 40 kHz terminates. The normalized rotation at the q=2 surface in 117294 is significantly lower at the time of unstable RWM growth as compared to 117291. It is hypothesized that 117294 is able to remain RWM stable at lower rotation due to the presence of the 40 kHz n=2 mode which persists longer than in 117291.

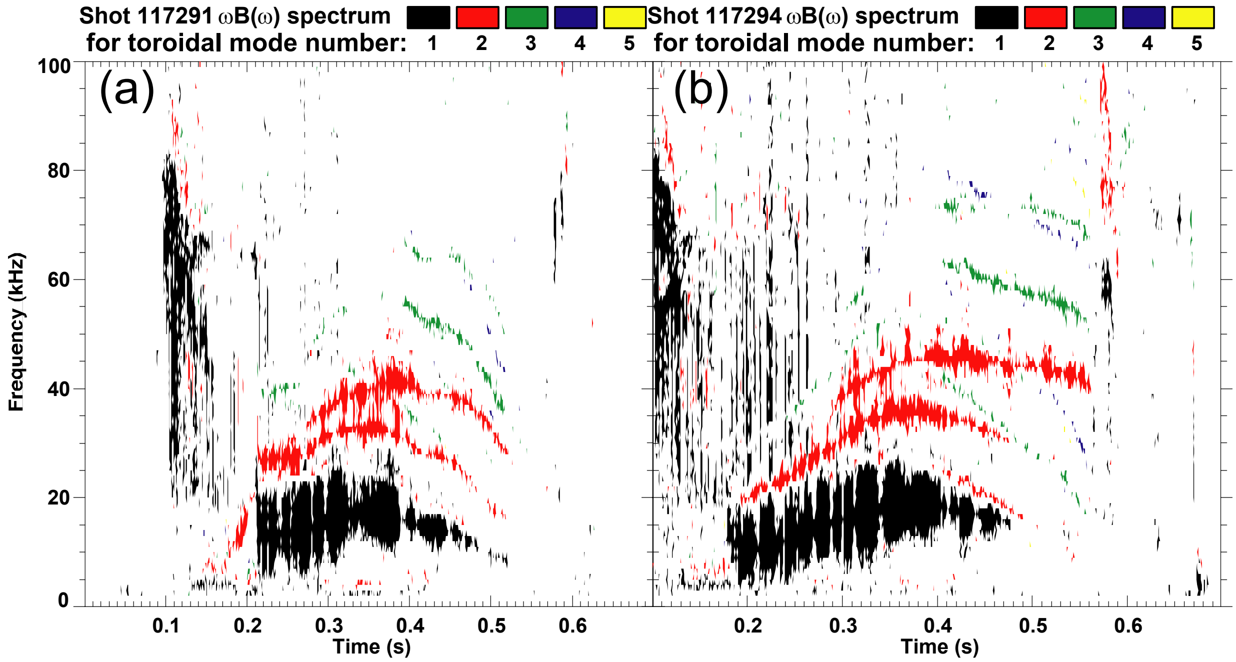

Figure 1: Toroidal mode spectrum for shots (a) 117291 and (b) 117294

The presence of this MHD could be either altering the unstable RWM drive, or providing a stabilizing source of dissipation. Applying rotation braking to induce RWM instability when this MHD is present should provide more insight into the nature of this interaction.

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[1] Hammet & Perkins, PRL **64** (1990) 3019
[2] Chu, et al., Phys. Plasmas **2** (1995) 2236
[3] Bondeson & Chu, Phys. Plasmas **3** (1996) 3013
[4] Sontag, et al., Phys Plasmas
[5] Zhu, et al., submitted to PRL
[6] Shaing, Phys. Fluids **29** (1986) 521
[7] Shaing, Phys. Plasmas, **11** (2004) 5525

3. Experimental run plan

Describe experiment in detail, including decision points and processes

It is desirable to vary the Alfven speed independent of other parameters which affect RWM stability. Operating at fixed q by varying B_0 and also varying I_p should make this possible. At fixed q, pressure, and fixed geometry, the quantity on the right hand side of equation 1 should vary as $1/n^{1/2}$, but the quantity ω_A/q^2 should vary as $B_0/n^{1/2}$. So lowering B_0 with q fixed will allow a scan of the Alfven frequency without affecting v_{ti} and therefore the ion Landau damping in the semi-kinetic model. Performing such scans at multiple values of q will ensure that any observed effects are indeed due to the changing field and not due to q alone. During the q scan the neutral beam power will be adjusted if necessary to avoid the with-wall β limit.

A density scan will allow variation of the ion-ion collision frequency. While it is difficult to actively control the density from shot to shot, the density does continue to rise throughout the discharge. Maintaining a longer discharge before the RWM collapse would allow for an effective density scan. Varying the strength and timing of the applied n=3 braking field will allow the timing of the RWM collapse to be varied. During the n=1 free window of the target discharge, the density rises by ~ 20% while the temperature is roughly constant. Longer glow might allow operation at lower density while maintaining performance. Alternatively, He conditioning shots could also be used to improve machine conditions to allow operation at lower density. Use of the SGI can also be attempted to increase the density during the shot.

Observing the variations in MHD activity will allow testing of the stabilizing effects of this MHD. The target discharge for this experiment has a window with little to no rotating MHD. Varying the timing of the rotation braking will likely alter the MHD causing it to extend into the MHD free window or for some modes to persist while others are stabilized. The natural variation of the MHD will provide information as to its stabilizing effects without dedicated shots.

Run Plan:

Task	Number of Shots
1. Control shot	2
a. 120705 with TF @ 0.5 T	
2. V_A scan at constant q – apply n=3 braking to induce RWM during MHD free window	
a. I_p = 0.89 MA, B_t = 0.5 T	2
i. increase TF from 120705 – may need higher density to get rid of n=1	
b. I_p = 0.71 MA, B_t = 0.4 T	3
i. 120327 with EFC off @ 0.5s & n=3 braking applied	
c. I_p =1.1 MA, B_t = 0.55 T	3
i. 120982	
3. lower-q	
a. I_p = 1.0 MA, B_t = 0.45 T	3
i. 119250	
b. I_p = 890 kA, B_t = 0.4 T	3
i. 120976	
c. I_p = 1.1 MA, B_t = 0.5 T	5
i. target development required – drop field from 120982	

   d. I_p = 780 kA, B_t = 0.35 T 5
      i. target development required – increase Ip from 120968
4. Density scan – vary timing of braking to delay onset of RWM until higher density, use baseline shot – alter fueling for wider density range
   a. beginning of n=1 free window – 0.5 s ($n_e\ell \sim 8.7e^{15}$) 2
      - use longer He glow to lower density
   b. end of n=1 free window – 0.7 s ($n_e\ell \sim 10.5e^{15}$) 2
      - add in SGI to raise density

Total: 30

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

All standard magnetic diagnostics are required as well as diamagnetic loop and Thomson scattering for partial kinetic EFIT reconstructions. CHERS is required since rotation profiles are an essential part of this experiment. The internal RWM sensors will be necessary to determine onset of RWM growth. MSE is highly desirable so NBI source A should remain fixed at 90 kV.

5. Planned analysis

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

Partial kinetic EFIT, including MSE and rotation effects will be performed for this experiment. DCON will be used to determine the no-wall and with-wall beta limits. MARS-F will provide detailed calculation of the magnitudes of the various dissipative and inertial terms, and their effects on stability.

6. Planned publication of results

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

This experiment involves detailed comparison between theory and experiment warranting publication in Physics of Plasmas or Nuclear Fusion. Success in definitively confirming or denying a specific dissipation mechanism would warrant publication in Phys. Rev. Letters. This work is in support of an IAEA FEC 2006 presentation.

PHYSICS OPERATIONS REQUEST

Physics of Passive RWM Stabilization **OP-XP-619**

Machine conditions (specify ranges as appropriate)

I_{TF} (kA): **3-5 kGauss** Flattop start/stop (s): _____/_____

I_P (MA): **<1.1 MA** Flattop start/stop (s): _____/_____

Configuration: **Inner Wall / Lower Single Null / Upper SN / Double Null**

Outer gap (m): _____, Inner gap (m): _____

Elongation κ: _____, Triangularity δ: _____

Z position (m): **0.00**

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

NBI - Species: **D**, Sources: **A/B/C**, Voltage (kV): _____, Duration (s): _____

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

CHI: **On / Off**

Either: List previous shot numbers for setup: **119250**

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

Physics of Passive RWM Stabilization **OP-XP-619**

Diagnostic	**Need**	**Desire**	**Instructions**
Bolometer - tangential array			
Bolometer array - divertor			
CHERS	✓		
Divertor fast camera			
Dust detector			
EBW radiometers			
Edge deposition monitor			
Edge pressure gauges			
Edge rotation spectroscopy			
Fast lost ion probes – IFLIP			
Fast lost ion probes – SFLIP			
Filtered 1D cameras			
Filterscopes			
FIReTIP			
Gas puff imaging			
High-k scattering			
Infrared cameras			
Interferometer – 1 mm			
Langmuir probes - PFC tiles			
Langmuir probes - RF antenna			
Magnetics – Diamagnetism		✓	
Magnetics – Flux loops	✓		
Magnetics – Locked modes	✓		
Magnetics – Pickup coils	✓		
Magnetics - Rogowski coils	✓		
Magnetics - RWM sensors	✓		
Mirnov coils – high frequency		✓	
Mirnov coils – poloidal array		✓	
Mirnov coils – toroidal array		✓	
MSE		✓	
Neutral particle analyzer			
Neutron Rate (2 fission, 4 scint)		✓	
Neutron collimator			
Plasma TV	✓		
Reciprocating probe			
Reflectometer - FM/CW			
Reflectometer - fixed frequency homodyne			
Reflectometer - homodyne correlation			
Reflectometer - HHFW/SOL			
RF antenna camera			
RF antenna probe			
Solid State NPA			
SPRED			
Thomson scattering - 20 channel	✓		
Thomson scattering - 30 channel		✓	
Ultrasoft X-ray arrays		✓	
Ultrasoft X-ray arrays - 2 color			
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			