Princeton Plasma Physics Laboratory
NSTX Experimental Proposal

Title: **RWM State Space Control in NSTX**		
OP-XP-1022	Revision: **0**	Effective Date: *(Approval date unless otherwise stipulated)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible Author: S.A. Sabbagh	Date **8/10/10**
ATI – ET Group Leader: S.A. Sabbagh	Date
RLM - Run Coordinator: E. Fredrickson	Date
Responsible Division: Experimental Research Operations	

RESTRICTIONS or MINOR MODIFICATIONS
(Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

TITLE: **RWM State Space Control in NSTX** No. **OP-XP-1022**

AUTHORS: **S.A. Sabbagh, O. Katsuro-Hopkins, J.M. Bialek,Y-S. Park, S. Gerhardt, J. Berkery,…** DATE: **8/10/10**

1. Overview of planned experiment

Resistive Wall Mode (RWM) control for n = 1 modes using a proportional gain controller began in NSTX in 2006,[1] and began to be used routinely by NSTX experimenters a couple of years later. The control dynamics and physics of the RWM using this system continue to be studied.[2] The present experiment aims to introduce and study a completely new controller for the RWM in NSTX – a state space based controller that incorporates a physical model for the coupling of the RWM to NSTX conducting structure, and an electromagnetic model of the currents expected in the conducting structure derived from the RWM sensor measurements and RWM control coil currents. The RWM state space controller has several superior characteristics (examined further in section 2) to proportional gain controller, including the model of the conducting structure. This model may allow greater control of the RWM using coils that are exterior to significant conducting structure (e.g. the vacuum vessel in NSTX). This aspect alone is potentially very important for RWM control in future ST and Advanced Tokamak devices with high neutron fluence. Such devices may have to have control coils further separated from the plasma. In this way, NSTX is a perfect test bed for this controller, as the RWM control coils are external, but closely coupled to the device vacuum vessel. This would be the first application of such an RWM controller in a low collisionality, high beta tokamak device. The experiment will focus on examining basic parameter variations of the controller with the goals of (i) improving RWM control reliability and (ii) examining RWM physics related to the state space control model used. The XP addresses NSTX Research Milestone R(10-1), ReNeW Thrust 16.3, 16.4, and ITPA joint experiment MDC-2;

2. Theoretical/ empirical justification

The present n = 1 RWM proportional gain controller has been a successful workhorse for mode control in NSTX. The n = 1 Fourier decomposed amplitude and phase of the in-vessel RWM sensors provides input to controller. Favorable feedback settings actuate the RWM control coils to reduce the n = 1 amplitude and track the phase of rotating modes. However, the controller has no inherent model of the mode structure, conducting structure, or mode physics. Also, there is no a priori knowledge of the controller stability. Gain settings are made with caution, as past gain scans using the RWM Bp sensors have occasionally led to controller instability, which sometimes leads to blown fuses in the switching power amplifier (SPA) that powers the control system.

In comparison, the state space approach reproduces characteristics of a full 3-D feedback model[3] (VALEN[4]) and feedback control currents via matrix operations. The VALEN model is expressed in standard control theory form as coupled first-order differential equations:

$$\dot{\vec{x}} = \overleftrightarrow{A}\vec{x} + \overleftrightarrow{B}\vec{u}; \;\; \vec{y} = \overleftrightarrow{C}\vec{x} \qquad (1)$$

where

$$\vec{x} = \left(\vec{I}_w \ \ \vec{I}_{cc} \ \ I_d\right)^T; \ \ \vec{u} = \dot{\vec{I}}_{cc}$$
$$\vec{A} = -\overleftrightarrow{L}_1^{-1}\vec{R}; \ \ \vec{B} = \overleftrightarrow{L}_1^{-1}\overleftrightarrow{L}_2 \qquad (2)$$
$$\vec{y} = \vec{\Phi}_{sensors}; \quad \overleftrightarrow{C} = \overleftrightarrow{M}$$

The state vector, x, represents the conducting wall currents, feedback control currents, and plasma (dissipative) current. The control vector, u, is the derivative of the control currents. The plant matrix, A, and control matrix, B, are comprised of resistance and inductance values of model elements. The measurement vector, y, is comprised of measured RWM sensor fluxes. The measurement matrix, C, contains the mutual inductances between the sensors and the balance of the model elements. In the present controller, the prompt applied field of the control coils is subtracted from the sensor measurements. Therefore, the inductive coupling between the sensors and the control coils is zeroed out in the model. Typically, the state vector for this "full" model contains a few thousand elements. To be made practical for real-time controller use, the number of states is reduced by control theory techniques of balanced realization and balanced truncation. The reduced model contains roughly ten states, determined by the relative magnitudes of the Hankel singular values of the balancing transformation. This number of states is practical to use in a real-time control system, as the number of computations scale roughly as the number of states squared (Figure 1).

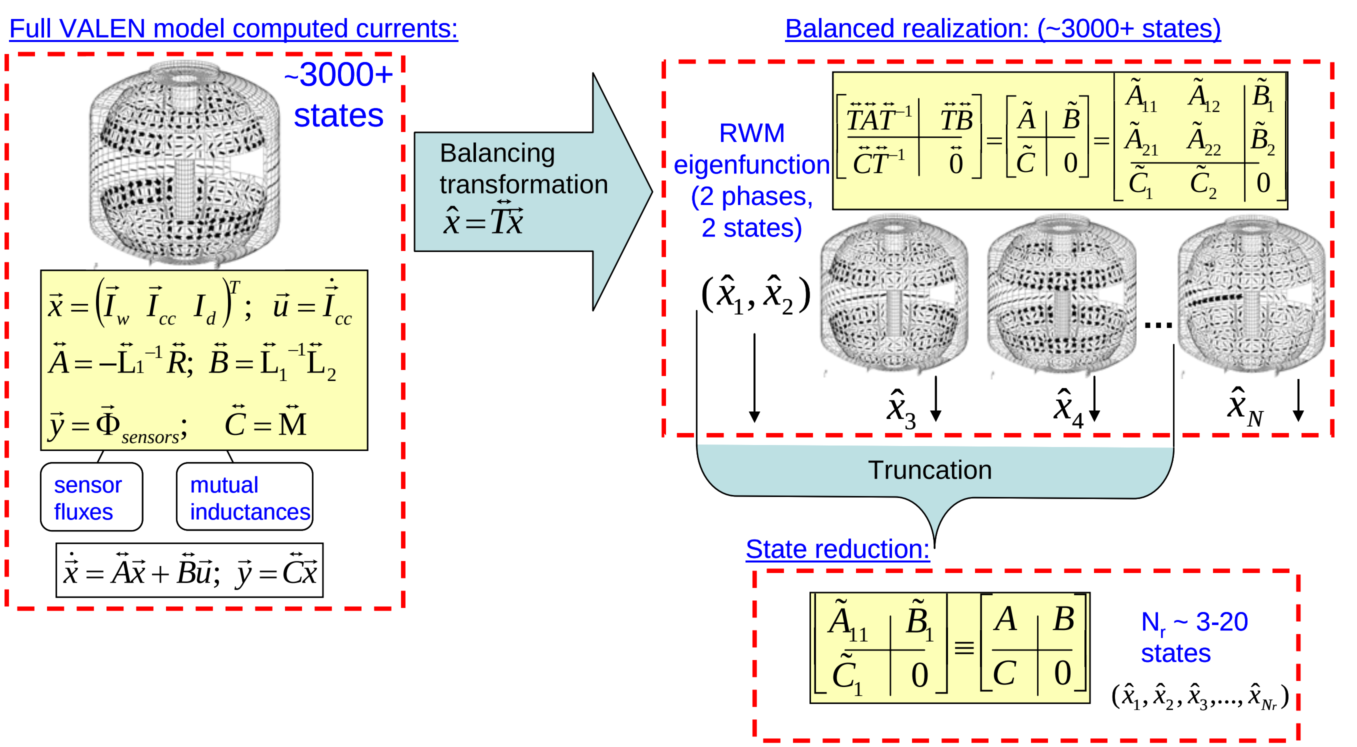

Figure 1: Reduction of full VALEN model of RWM feedback control to real-time model via balanced realization transformation and truncation based on Hankel singular values of the balancing transformation.

Real-time control is produced in two parts – a model that incorporates the electromagnetic coupling of the RWM, control coils, and conducting structure, and a model that computes an estimate of the field that is expected at the sensor positions (the "observer"). The difference between the observer and the actual sensor measurements is used to correct the model whenever the measurements are updated. The observer-adjusted model is used to advance the state vector by equation (1). A gain matrix – the observer gain, K_o - multiplies the difference between observer and measurements, and is computed by optimal control theory techniques.

The control equations (1) and (2) are not amenable to solution in the form presented, as the control vector is the time derivative of the control currents, while the desired quantities to control are the currents themselves. The technique of state derivative feedback[5] in control theory allows a transformation of equations (1) and (2) such that the control currents are the controlled quantity, computed directly from the states by the matrix equation

$$\vec{I}_{cc} = -\hat{K}_c \vec{x} \; . \qquad (3)$$

Here, the controller gain, K_c, is computed by optimal control theory techniques (Kalman filter). Both the controller and observer gains can be adjusted by setting parameters in a cost function for the former, and estimates of the model error covariance for the latter. Both of these are matrix quantities, and so allow a large flexibility in cost function and model error variation.

3. Experimental run plan

A real-time RWM state space controller (RWMSC) following the techniques outlined above has been built and installed in the NSTX plasma control system (PCS). This initial experiment will examine closed-loop operation of this controller for the first time. It will focus on examining basic parameter variations of the controller with the goals of (i) improving RWM control reliability and (ii) examining RWM physics related to the state space control model used.

The experiment will move toward maintaining long pulse plasmas at high β_N, possibly at low l_i with minimal fluctuation of β_N over the pulse. First, high normalized beta and low li target plasmas with or without PID RWM control will be created as fiducials. The ability of the controller to suppress n = 1 RFA (stable RWM error field amplification) will be demonstrated by applying a small n = 1 pre-programmed field and having the RWMSC reduce the amplified field. This is a desirable approach, as the n = 1 field can be applied in a known fashion. As n = 3 plasma rotation braking will be desirable in this experiment, the compatibility of the RWMSC with n = 3 magnetic braking will be tested.

Next, the primary RWM state space controller parameters will be varied. These will operate on high β_N plasmas subject to unstable RWMs, but will retain a period of n = 1 pre-programmed currents as a "tracer pulse" to ensure that useful response data of the RWMSC will be available on each shot. The number of states, observer gain, controller gain for the n = 1 mode eigenfunction states, and controller gain for the other states (the stable states) will be separately varied. The key control parameters outside of the primary state space variables will be varied including Bp sensor baseline re-zeroing time, inclusion of the new "MIU" OHxTF compensations, and omission/inclusion of MIU AC compensations. The controller “feedback phase”will be varied to demonstrate both positive and negative feedback, similar to earlier PID experiments.

Finally, optimal settings for the RWMSC will be run to demonstrate superior performance, and these settings will be used to examine the ability of the controller to stabilize plasmas at reduced rotation to make connection to ITER. Optionally, β_N feedback will be added to the best plasmas if needed / desired to reduce β_N fluctuations.

Task	Number of Shots
0) Generate targets	
(low li target (1–1.2 MA) of XP1023 (e.g. 139517); “higher l_i” (0.8 MA), high β_N target (e.g. 135462))	
A) Establish target plasmas (2 or 3 NBI sources), with/without n = 1 RWM PID feedback	4
1) RFA suppression of applied n = 1 field; effect on n = 3 applied field	
A) Apply n = 1; 3 DC pulses of increasing amplitude, determine state space controller response	2
B) Increase controller gain if response not observed; vary observer gain if needed	3
C) Apply n = 1 AC co/counter toroidally-propagating fields and determine RWMSC response	2
2) Control physics examination via controller parameter variations (n = 1 “tracer pulse” used)	
A) Vary number of SSC states – determine effect on observer and controller	3
B) Vary controller gain for n = 1 RWMSC states	3
C) Vary controller gain for other RWMSC states	3
D) Set Bp sensor baseline re-zeroing for best RWMSC settings above	2
E) Turn off AC compensation in mode-id upgrade algorithm for best RWMSC settings above	2
3) Control physics examination via controller parameter variations (n = 3 optimum/braking applied field)	
A) Vary feedback phase to generate positive / negative feedback / determine best settings	8
B) Add n = 3 braking to best settings above and ensure RWMSC response expected from (1A)	1
C) (optional) Introduce β_N feedback to to run steady, high $<\beta_N>_{pulse}$ if desired	(2)
4) Generate high $<\beta_N>_{pulse}$ at various ω_E	
A) Generate lowest possible ω_ϕ at high β_N using n = 3 braking with RWM SSC controller on	3
B) (optional) Introduce β_N feedback to (A) to run steady, high $<\beta_N>_{pulse}$ if desired	(2)
Total:	(4); 36

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

The new RWM mode ID upgrade “MIU” algorithm and the new RWMSC must be available and operational in the PCS. The RWM control coils must be in the standard odd parity n = 1, 3 configuration. Normalized beta feedback is also required. LITER operation is required. High power NBI operation (6 MW+) is desired to reach maximum β_N.

5. Planned analysis

NSTX EFIT reconstructions using MSE data will be used for ideal MHD stability analysis using DCON and as input to the VALEN code for RWM feedback analysis. Kinetic modification to ideal kink/ballooning stability analysis will be evaluated using the MISK code if the proximity to RWM marginal stability is needed. Offline analysis codes emulating the action of the controller will be used to determine details of control, including the evolution of the plasma and wall currents.

6. Planned publication of results

Successful experimental operation of the controller in maintaining high β_N plasmas and appropriate comparison to RWM stability theory will warrant publication in PRL. Also, a paper on the control theory approach is planned, focusing on the state derivative approach to this problem. Additional presentation of results is expected to be published as part of an APS DPP 2010 Invited Talk and associated Physics of Plasmas paper. If the XP is run early enough, initial results and analysis could appear in the oral 2010 IAEA Fusion Energy Conference submission on RWM stabilization. The results are also expected to be shown at the 2010 MHD Mode Control meeting and ITPA MHD meeting (if physics presentations are permitted at the fall meeting).

PHYSICS OPERATIONS REQUEST

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Brief description of the most important operational plasma conditions required:

- RWM coils configured for *n* = 1, 3 operation
- *n* = 1 RWM active feedback required (MIU algorithm, RWMSC, and PID controllers)
- β_N feedback system required (setup shot for β_N control: 139319)
- LITER required (~ 30 mg/min deposition rate)

Previous shot(s) which can be repeated: 139517, etc. (low l_i) from XP1023 (1 MA)

Previous shot(s) which can be modified: (high β_N e.g. 135462) and similar

Machine conditions *(specify ranges as appropriate, strike out inapplicable cases)*

I_{TF} (kA): **0.4 – 0.55T** Flattop start/stop (s):

I_P (MA): **0.7 – 1.2** Flattop start/stop (s):

Configuration: **Limiter / DN / LSN / USN**

Equilibrium Control: **Outer gap / Isoflux** (rtEFIT) / **Strike-point control** (rtEFIT)

Outer gap (m): **0.06-0.10** Inner gap (m): 0.04 Z position (m):

Elongation: **2.1 – 2.6** Triangularity (U/L): **0.45-0.75** OSP radius (m): **< 0.5m**

Gas Species: **D** Injector(s):

NBI Species: **D** Voltage (kV) **A: 90** **B: 90** **C:** 80-90 Duration (s): **~ 1.3**

ICRF Power (MW): Phase between straps (°): Duration (s):

CHI: **Off / On** Bank capacitance (mF):

LITERs: Off / On Total deposition rate (mg/min): **30 (same as in XP948)**

LLD: Temperature (°C): **optimal for density pumping**

EFC coils: Off/On Configuration: **Odd / Even / Other** *(attach detailed sheet)*

DIAGNOSTIC CHECKLIST

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Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
Beam Emission Spectroscopy		
Bolometer – divertor		**X**
Bolometer – midplane array		**X**
CHERS – poloidal		**X**
CHERS – toroidal	**X**	
Dust detector		**X**
Edge deposition monitors		
Edge neutral density diag.		**X**
Edge pressure gauges		**X**
Edge rotation diagnostic		**X**
Fast cameras – divertor/LLD		**X**
Fast ion D_alpha - FIDA		**X**
Fast lost ion probes - IFLIP		**X**
Fast lost ion probes - SFLIP		**X**
Filterscopes		**X**
FIReTIP		**X**
Gas puff imaging – divertor		**X**
Gas puff imaging – midplane		**X**
Hα camera - 1D		**X**
High-k scattering		**X**
Infrared cameras		**X**
Interferometer - 1 mm		**X**
Langmuir probes – divertor		**X**
Langmuir probes – LLD		**X**
Langmuir probes – bias tile		**X**
Langmuir probes – RF ant.		
Magnetics – B coils	√	
Magnetics – Diamagnetism	**X**	
Magnetics – Flux loops	√	
Magnetics – Locked modes	**X**	
Magnetics – Rogowski coils	√	
Magnetics – Halo currents		**X**
Magnetics – RWM sensors	**X**	
Mirnov coils – high f.		**X**
Mirnov coils – poloidal array		**X**
Mirnov coils – toroidal array	**X**	
Mirnov coils – 3-axis proto.		

Note special diagnostic requirements in Sec. 4

Diagnostic	**Need**	**Want**
MSE	**X**	
NPA – E||B scanning		**X**
NPA – solid state		**X**
Neutron detectors		**X**
Plasma TV		**X**
Reflectometer – 65GHz		**X**
Reflectometer – correlation		**X**
Reflectometer – FM/CW		**X**
Reflectometer – fixed f		**X**
Reflectometer – SOL		**X**
RF edge probes		
Spectrometer – divertor		
Spectrometer – SPRED		**X**
Spectrometer – VIPS		**X**
Spectrometer – LOWEUS		**X**
Spectrometer – XEUS		**X**
SWIFT – 2D flow		
Thomson scattering	**X**	
Ultrasoft X-ray – pol. arrays		**X**
Ultrasoft X-rays – bicolor		**X**
Ultrasoft X-rays – TG spectr.		**X**
Visible bremsstrahlung det.		**X**
X-ray crystal spectrom. - H		**X**
X-ray crystal spectrom. - V		**X**
X-ray tang. pinhole camera		**X**

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[1] S.A. Sabbagh, et al. Phys. Rev. Lett. **97** (2006) 045004.
[2] S.A. Sabbagh, et al., Nucl. Fusion **50** (2010) 025020.
[3] O.N. Katsuro-Hopkins, et al., CDC conference, 2009 (Shanghai).
[4] J.M. Bialek, et al., VALEN code, Phys. Plasmas **8** (2001) 2170.
[5] T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005.