NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

XP1022 RWM State Space Control in NSTX - Update

Y.S. Park[1], S.A. Sabbagh[1], O.N. Katsuro-Hopkins[1], J.M. Bialek[1], J.W. Berkery[1], S.P. Gerhardt[2], R.E. Bell[2], J.E. Menard[2], D.A. Gates[2], B.P. LeBlanc[2], D. Mastrovito[2]

[1]*Department of Applied Physics, Columbia University, NY, NY*
[2]*Plasma Physics Laboratory, Princeton University, Princeton, NJ*

NSTX Results / Theory Review

December 1st, 2010

PPPL

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
Sandia NL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

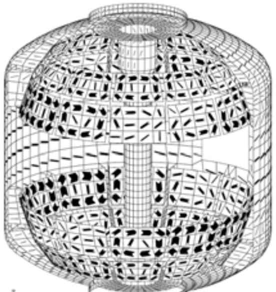
V1.0

XP1022: RWM State Space Control in NSTX

- Motivation
  - Present n = 1 RWM feedback control: limited ability to suppress mode onset and disruption - RWM coil external to vessel (SAS, et al. NF 44 (2004) 560)
  - Situation will be similar for next-step ST and advanced tokamaks
    - May allow control coils to be moved further from plasma, shielded
- Goals / Approach (two main goals: (i) improve control (ii) mode physics)
  - Improve RWM stabilization reliability using new RWM state space controller
    - Potential for improved stability at high β_N in NSTX (O.N. Katsuro-Hopkins, et al., CDC 2009 (Shanghai))
    - Inclusion of wall currents in feedback may improve RWM control (high β_N, β_N/l_i)
    - State-space formalism allows more confident tuning of controller for maximum performance (e.g. gain settings)
  - Examine RWM physics related to state space control model
    - First implementation of such control in a high beta collisionless tokamak plasma
    - Examine effect of "non-plasma" states in control physics, mode-induced current
    - Address differences in experiment vs. single mode vs. multi-mode RWM model
- Addresses
  - NSTX Research Milestone R(10-1), ReNeW Thrust 16.3, 16.4
  - ITPA joint experiment MDC-2; 2010 IAEA FEC, APS Invited talk submissions

New RWM state space controller implemented to sustain high β_N

Full 3-D model ~3000+ states



$$\vec{x} = \left(\vec{I}_w \;\; \vec{I}_{cc} \;\; I_p\right)^T; \quad \vec{u} = \dot{\vec{I}}_{cc}$$

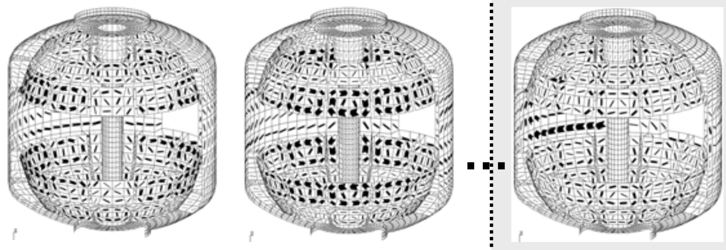
$$\overleftrightarrow{A} = -\overleftrightarrow{L}_1^{-1}\vec{R}; \quad \overleftrightarrow{B} = \overleftrightarrow{L}_1^{-1}\overleftrightarrow{L}_2$$

$$\vec{y} = \vec{\Phi}_{sensors}; \quad \overleftrightarrow{C} = \overleftrightarrow{M}$$

Balancing transformation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

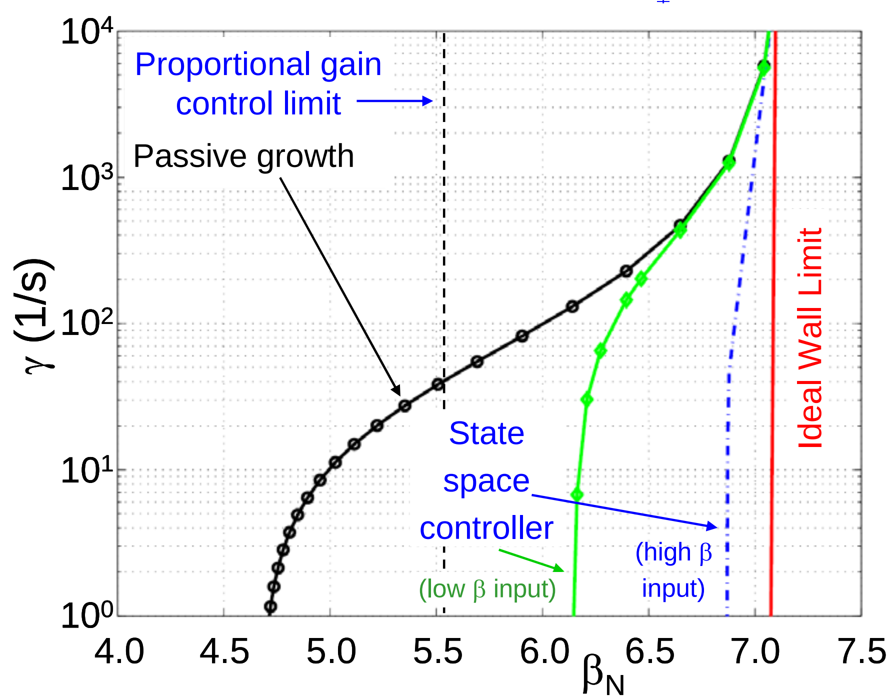


$(\hat{x}_1, \hat{x}_2)$ $\quad \hat{x}_3 \quad \hat{x}_4 \quad \ldots \quad \hat{x}_N$ truncate

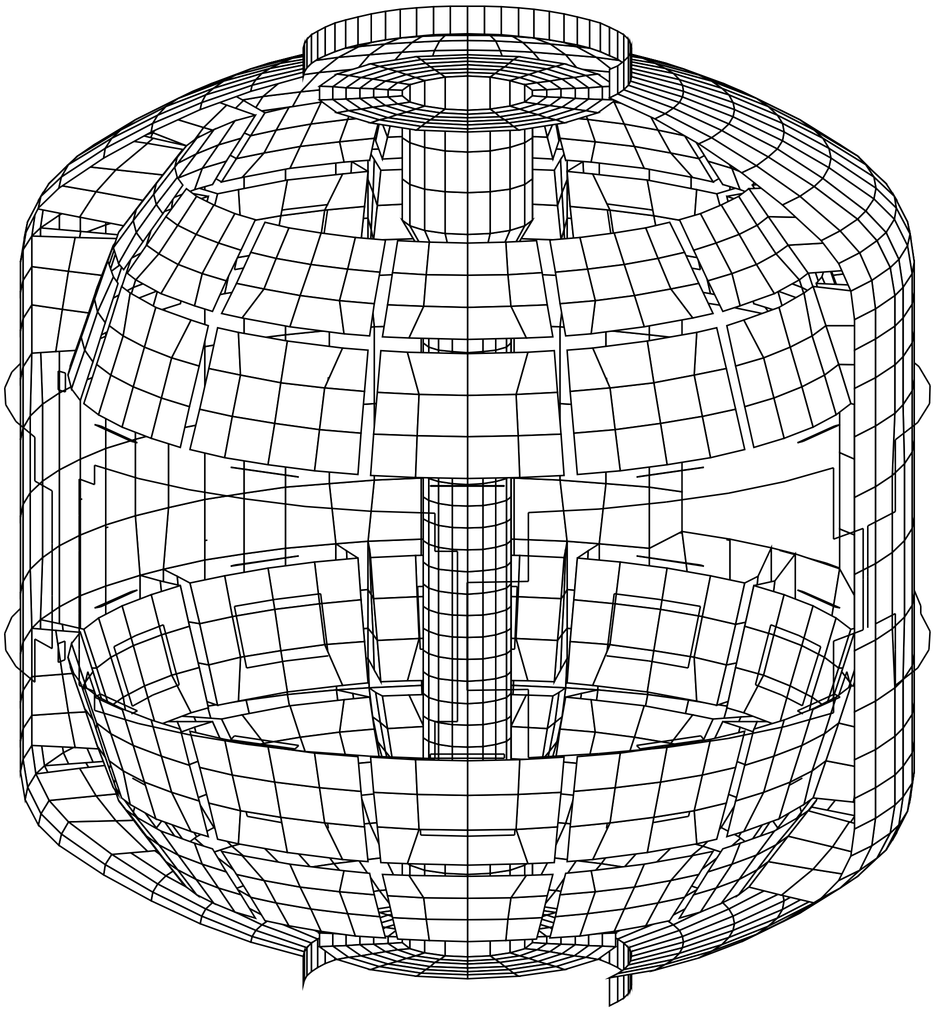
- Controller can compensate for wall currents
  - Including mode-induced current
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, shielded
  - Examined for ITER

Katsuro-Hopkins, et al., NF **47** (2007) 1157

Theoretical feedback performance (ω_ϕ = 0, 12 states)



NSTX VALEN model updated for 2010 – included in RWM state space controller



- RWM control coil model accurate for 2010
  - Incorporates coil modifications of the past few years
- B_p sensor finite poloidal angle added
- NBI port added
- Passive plate flanges removed
- Investigating addition of NBI armor

- NOTE: model without these features was run in XP for comparison

NSTX RWM state space controller advances present PID controller

- PID (our present, successful workhorse)
  - n = 1 phase/amplitude of RWM sensors provides input to controller
  - feedback logic operates to reduce n = 1 amplitude
  - No a priori knowledge of mode structure, physics, controller stability

- State space control
  - States reproduce characteristics of full 3-D model: conducting structure, plasma response, and feedback control currents via matrix operations
  - Observer (computes sensor estimates)
    - RWM sensor estimates provided by established methods (Kalman filter)
      - Allows error specification on measurements and model – full covariance matrix
    - Difference between sensor measurements and state space estimates are used to correct the model at each time point; useful as an analysis tool
  - Controller (computes control currents)
    - Controller gain computed by established methods: gains for each coil and state
  - State space method amenable to expansion

State Derivative Feedback Algorithm used for Current Control

- State equations to advance

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -K_c\vec{x} = \dot{I}_{cc}$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

Control vector, u; controller gain, K_c

Observer est., y; observer gain, K_o ; $D = 0$

K_c , K_o computed by standard methods (e.g. Kalman filter used for observer)

Advance discrete state vector

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$

"time update"

$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t)$$

"measurement update"

- State derivative feedback: superior control approach

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -\hat{K}_c\dot{\vec{x}} \longrightarrow \vec{I}_{cc} = -\hat{K}_c\vec{x}$$

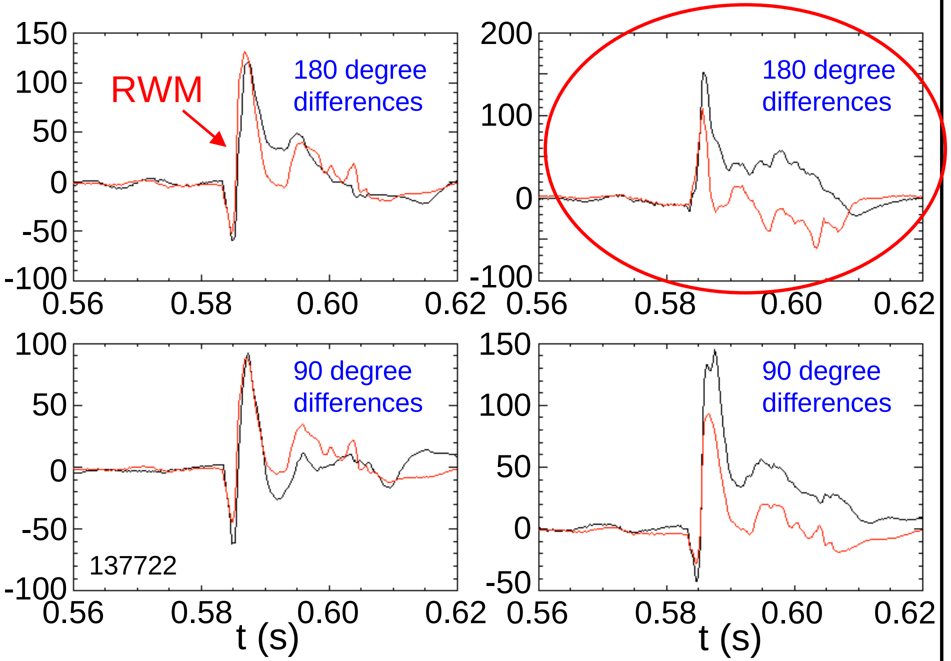
$$\dot{\vec{x}} = ((\mathrm{I} + B\hat{K}_c)^{-1}A)\vec{x}$$

  - new Ricatti equations to solve to derive control matrices – still "standard" solutions in control theory literature

    e.g. T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005

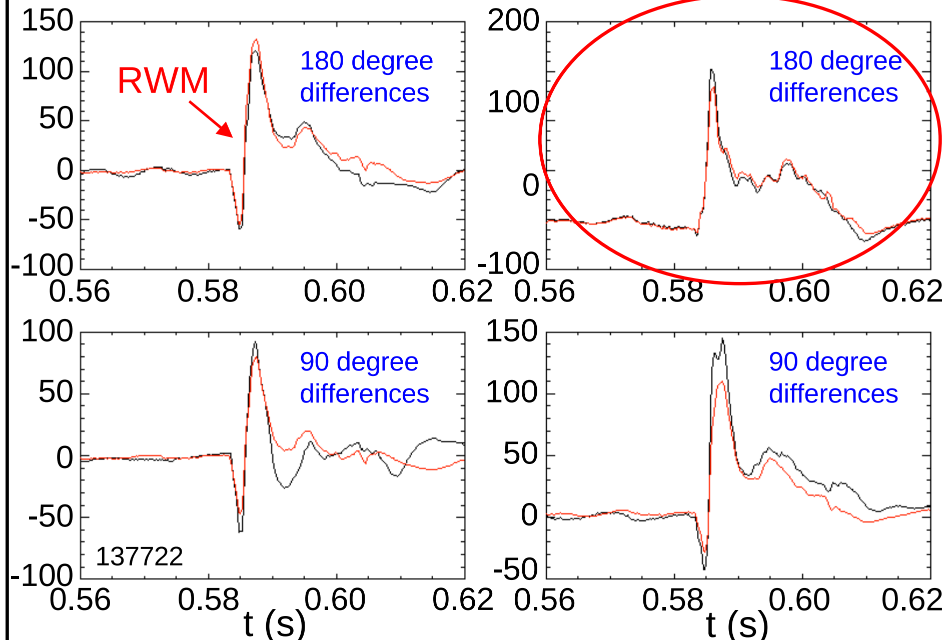
Increased number of states in RWM state space controller improves match to sensors over entire mode evolution

RWM Upper B_p Sensor Differences (G) – 2 States



- Reasonable match to all B_p sensors during RWM onset, large differences later in evolution

RWM Upper B_p Sensor Differences (G) – 7 States

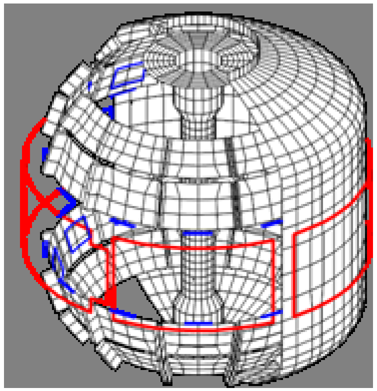


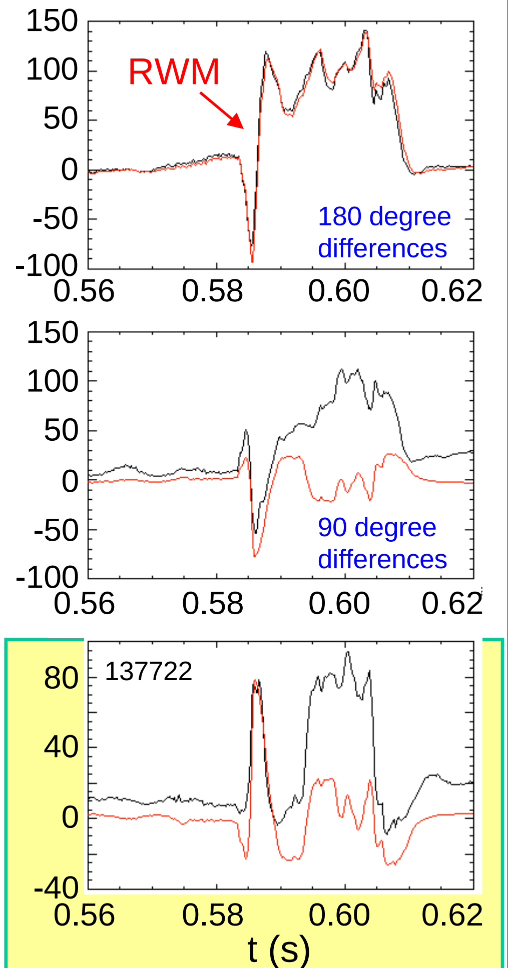
- Some 90 degree differences not as well matched
  - May indicate the need for an n = 2 eigenfunction state

Black: experiment Red: offline RWM state space controller

3-D conducting structure detail can improve RWM state space controller match to sensors

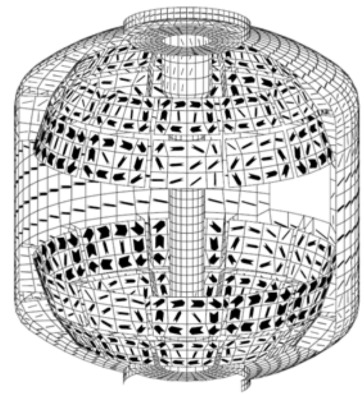
RWM Lower B_p Sensor Differences (G) – NO PORT

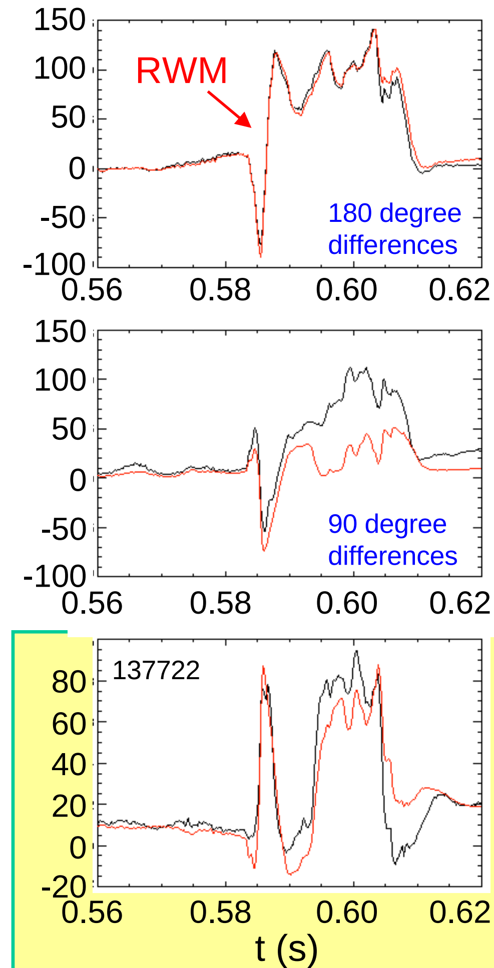




- Some 90 degree differences not well matched

RWM Lower B_p Sensor Differences (G) – NBI PORT



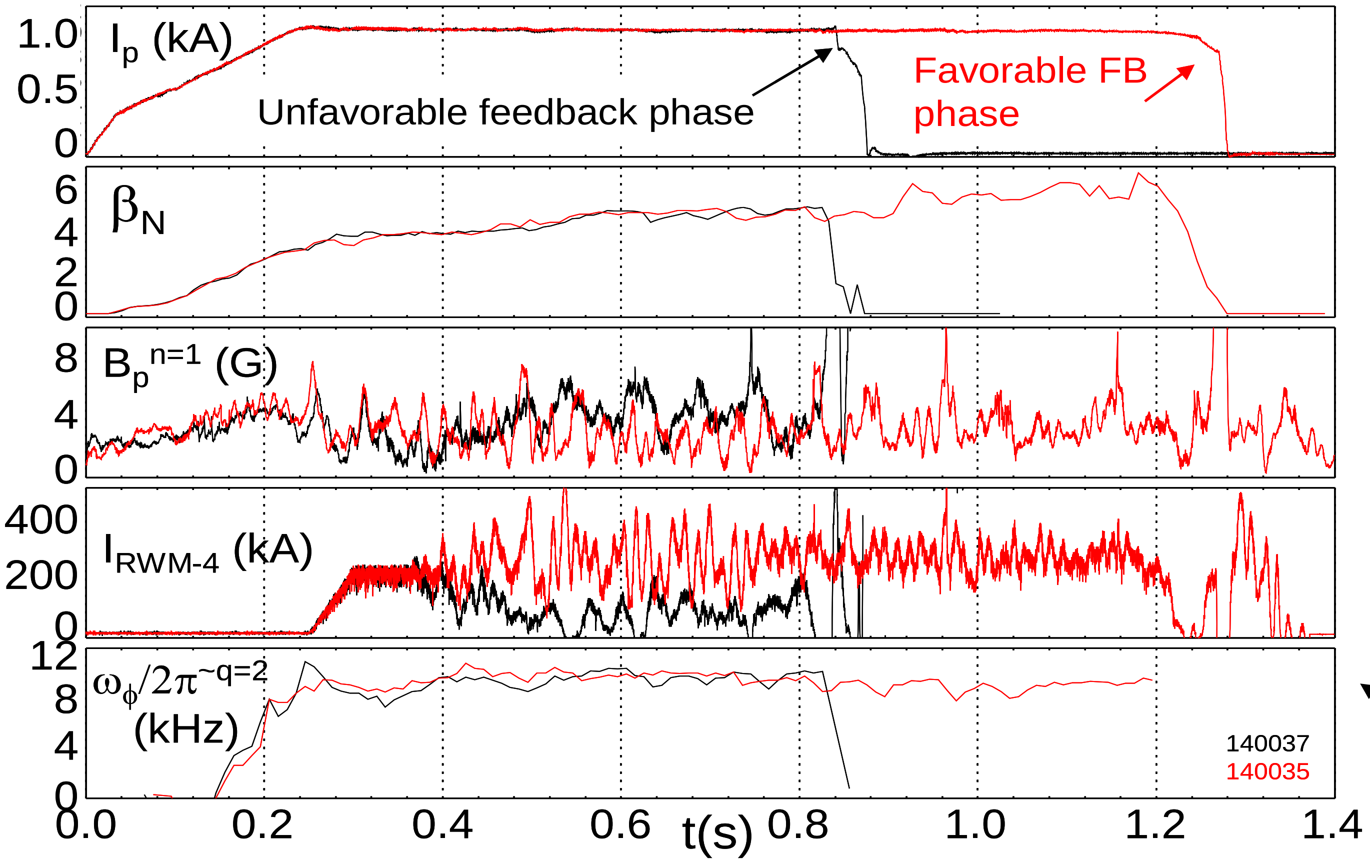


- Adding NBI port leads to greater match on some sensors

Black: experiment Red: offline RWM state space controller

New RWM state space controller sustains high β_N, low l_i plasma

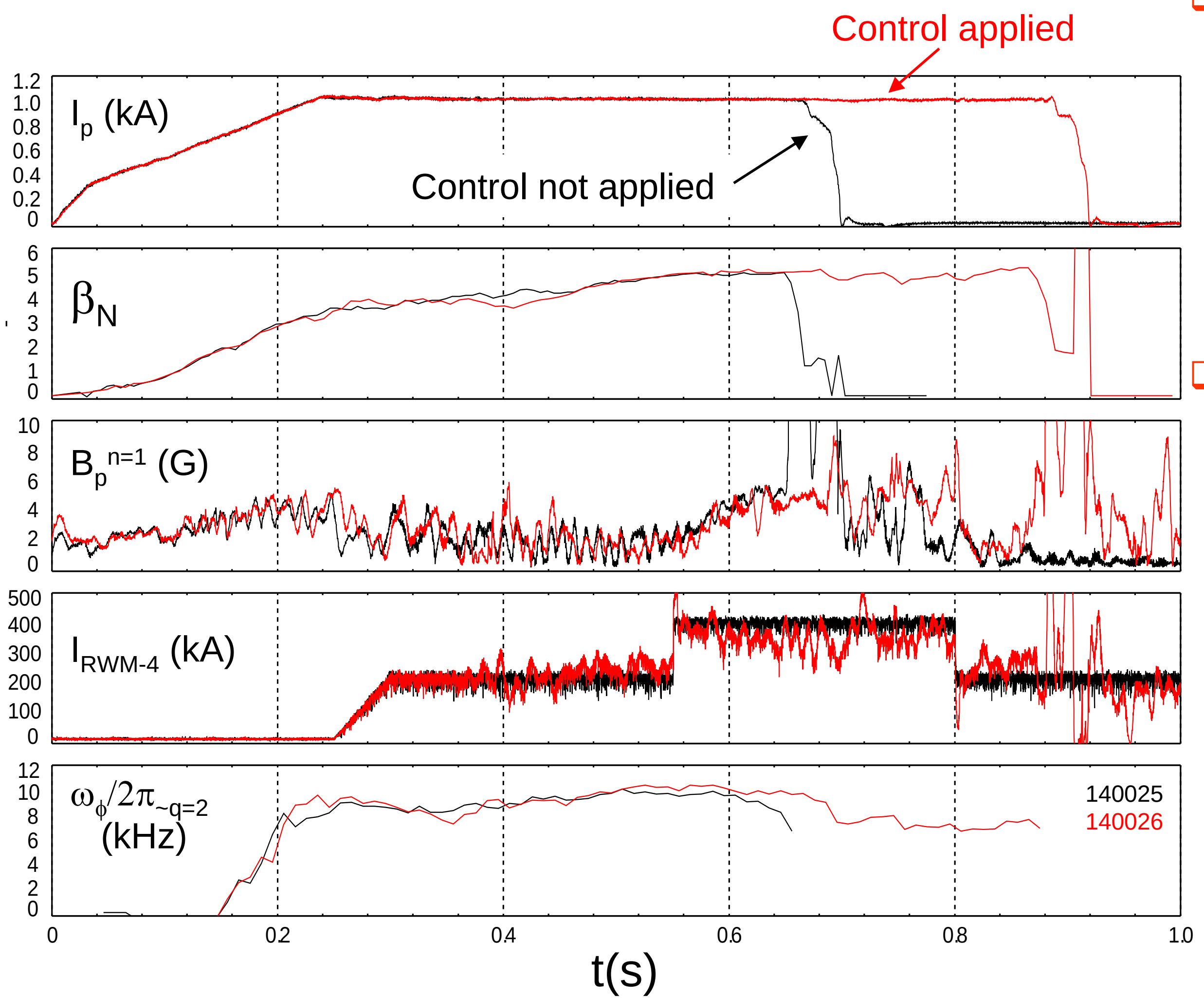
RWM state space feedback (12 states)



Successful First Experiments

- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field



- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

NSTX RWM state space controller successful in first run – analysis is just starting…

- Present results / analysis
  - New RWM state space controller operational, significant parameter variation
    - A key result – state derivative feedback approach important
    - Good match of observer to data
  - Control theory indicates superior performance over PID in NSTX
  - Controller sustains low l_i, high β_N plasma
    - Produced controlled long pulse, $\beta_N = 6.4$, $\beta_N/l_i = 13$
  - Controller suppressed n = 1 RFA from applied DC field
- Variation of RWM state space controller parameters includes
  - Number of states; conducting wall model
  - Controller gain
    - N = 1 eigenfunction states (~ unstable plasma states, RFA/wall response)
    - Other states (~ mostly wall response)
    - NOTE: Gains pushed to SPA current limits (up to a factor of 3), low frequency feedback instability generated (control lost) - but did not blow SPA fuses
  - Controller feedback phase
- Analysis to come includes
  - Determine role of wall/plasma response model, role of observer/controller gain settings, physics effects to explain observer differences to data