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XP1022: RWM State Space Control in NSTX

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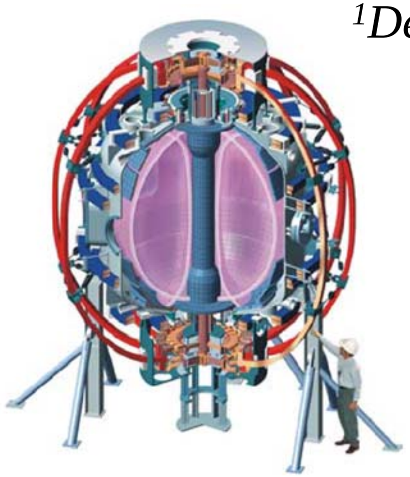

NSTX Team Review
August 17th, 2010
Princeton Plasma Physics Laboratory

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XP1022: RWM State Space Control in NSTX

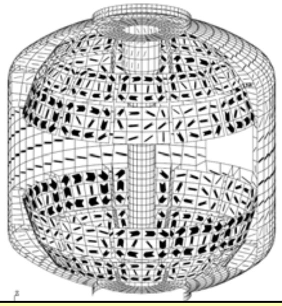
- Motivation
  - Present n = 1 RWM feedback control: limited ability to suppress mode onset and disruption - RWM coil external to vessel (SAS, et al. NF 44 (2004) 560)
  - Situation may be similar for next-step ST and advanced tokamaks
- Goals / Approach (two main goals: (i) improve control (ii) mode 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

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 feedback model 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
  - Controller (computes control currents)
    - Controller gain computed by established methods: gains for each coil and state
  - State space method amenable to expansion; useful as an analysis tool

RWM state space control reduces full 3D VALEN model to one tractable for real-time feedback control

Full VALEN model computed currents:



~3000+ states

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

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

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

sensor fluxes

mutual inductances

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

Balancing transformation

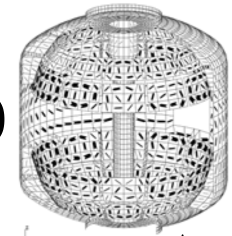
$$\hat{x} = \overleftrightarrow{T}\vec{x}$$

Balanced realization:

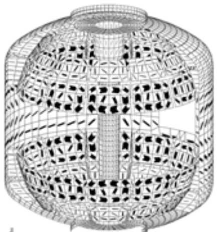
$$\left[\begin{array}{c|c} \overleftrightarrow{T}\overleftrightarrow{A}\overleftrightarrow{T}^{-1} & \overleftrightarrow{T}\overleftrightarrow{B} \\ \hline \overleftrightarrow{C}\overleftrightarrow{T}^{-1} & \vec{0} \end{array}\right] = \left[\begin{array}{c|c} \tilde{A} & \tilde{B} \\ \hline \tilde{C} & 0 \end{array}\right] = \left[\begin{array}{cc|c} \tilde{A}_{11} & \tilde{A}_{12} & \tilde{B}_1 \\ \tilde{A}_{21} & \tilde{A}_{22} & \tilde{B}_2 \\ \hline \tilde{C}_1 & \tilde{C}_2 & 0 \end{array}\right]$$

RWM eigenfunction (2 phases, 2 states)

$(\hat{x}_1, \hat{x}_2)$

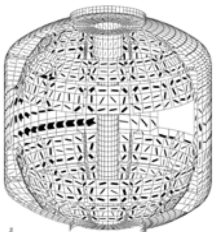


$\hat{x}_3$



$\hat{x}_4$

...



$\hat{x}_N$

Truncation

State reduction:

$$\left[\begin{array}{c|c} \tilde{A}_{11} & \tilde{B}_1 \\ \hline \tilde{C}_1 & 0 \end{array}\right] \equiv \left[\begin{array}{c|c} A & B \\ \hline C & 0 \end{array}\right]$$

N_r ~ 3-20 states

$(\hat{x}_1, \hat{x}_2, \hat{x}_3, \ldots, \hat{x}_{N_r})$

- Present state space controller uses
  - Two phases of n = 1 plasma eigenfunction to allow tracking of mode rotation
  - State derivative feedback method – suited to this specific application

O.N. Katsuro-Hopkins, et al., CDC conference, 2009 (Shanghai)

Advancing state vector provides closed-loop feedback

- State equations to advance

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

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

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 approach

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

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

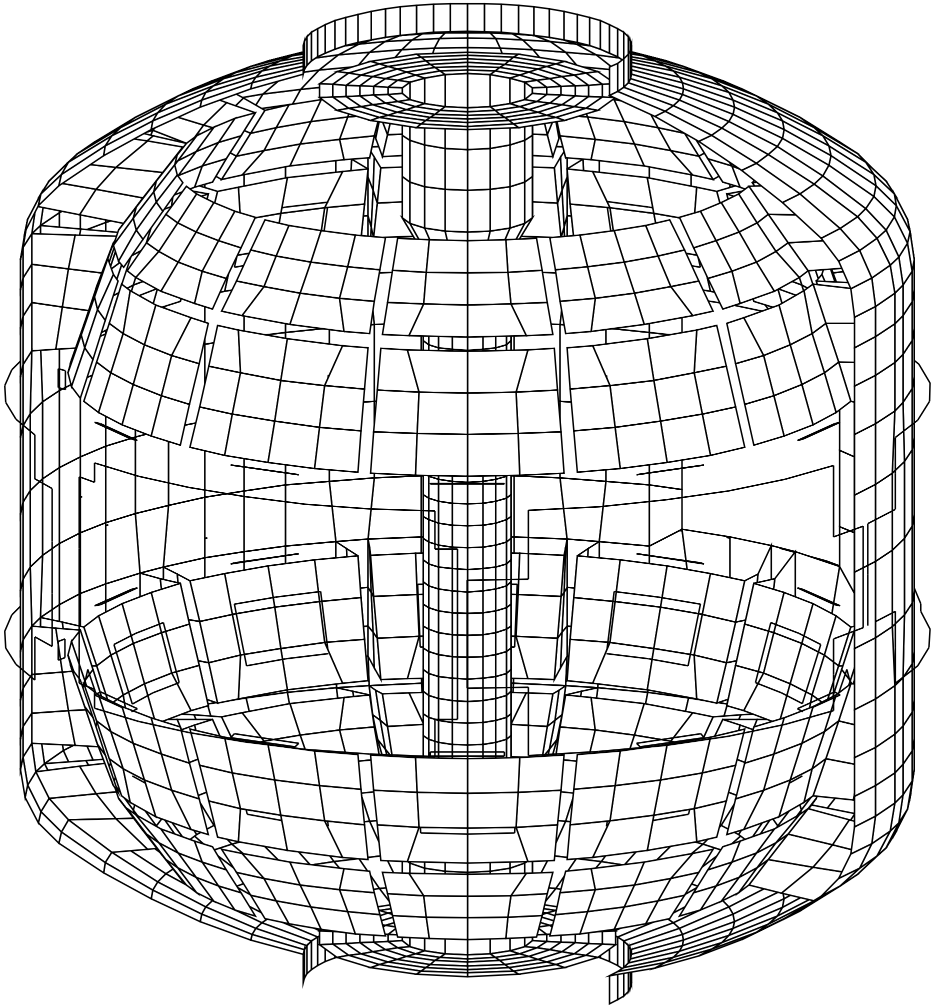
new "A" matrix, new "B" matrix = 0

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

RWM State Space Controller has many desirable characteristics

- Present RWM state space controller (SSC)
  - Includes plasma mode currents, plasma and control coil-induced wall currents
  - Plasma eigenfunction shape built into model
    - Phase relation between upper / lower sensor n = 1 decomposition is built-in
  - Mode rotation allowed
    - By using two orthogonal phases of eigenfunction (O.N. Katsuro-Hopkins, et al., CDC 2009 (Shanghai))
  - Complex, detailed 3-D conducting structure included in reduced form
    - Models effect of currents generated in the wall by applied field, plasma, etc.
  - A priori (theoretical) knowledge that gain matrices produce stable controller
    - Evaluation includes loss of sensors
  - Ability to offset control currents toroidally from controller solution (feedback phase); ability to turn off sensors and evaluate controller stability
  - Controller matrices contained in one ASCII file, can be pre-built for an XP, rebuilt in (tens of) seconds if needed, and read into the PCS, offline emulators from a common area
- Future development
  - Multiple modes input for higher-n mode stabilization, dynamic error field correction
    - E.g. adding n > 1 eigenfunctions will allow n > 1 mode detection, allow actuation of RWM coils with greater generality (e.g. use new SPA, recently delivered to PPPL, to actuate against n = 2)
  - RWM model development including additional real-time inputs
    - Simple differential equations describing RWM stability / dynamics could be included to allow model variation due to real-time β_N (now available), plasma rotation (available in near future)

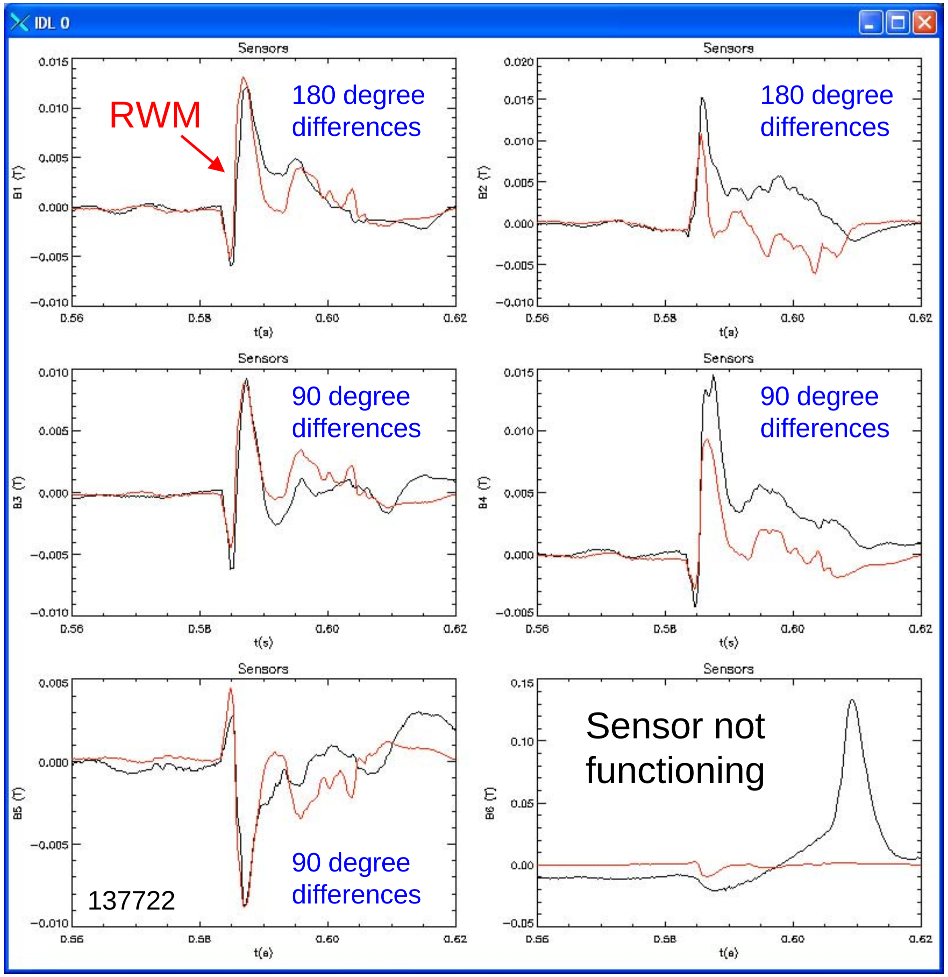
NSTX VALEN model updated for 2010



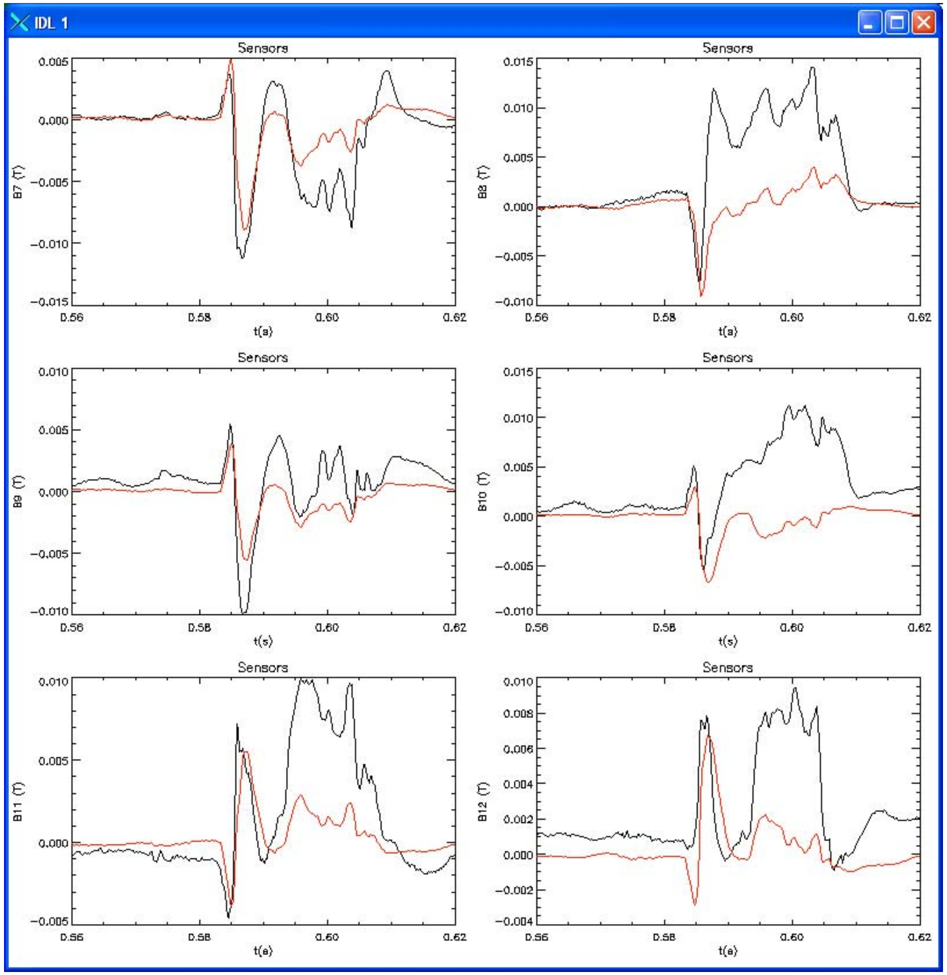
- RWM control coil model accurate for 2010
  - Incorporates coil modifications of the past few years
- B_p sensor finite poloidal angle added
- NBI port added
- Passive plate flanges removed
- Investigating addition of NBI armor

RWMSC observer with 2 states can reproduce sensors

Bp UPPER Sensor differences



Bp LOWER Sensor differences

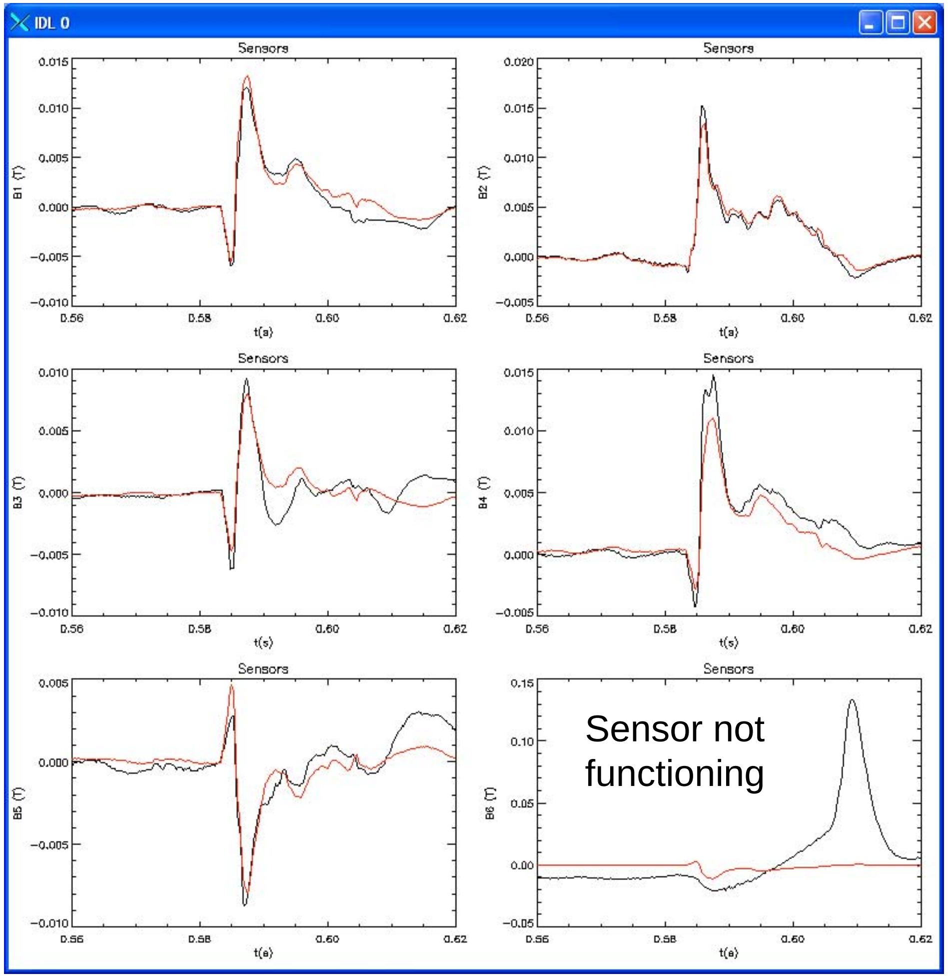


- RWMSC-07212010v11.dat (u/l sensors 7-11,19-24, 2 states), Q=1e8,R=1,V=1
- Reasonable match to all B_p sensors during RWM onset, large differences later in evolution

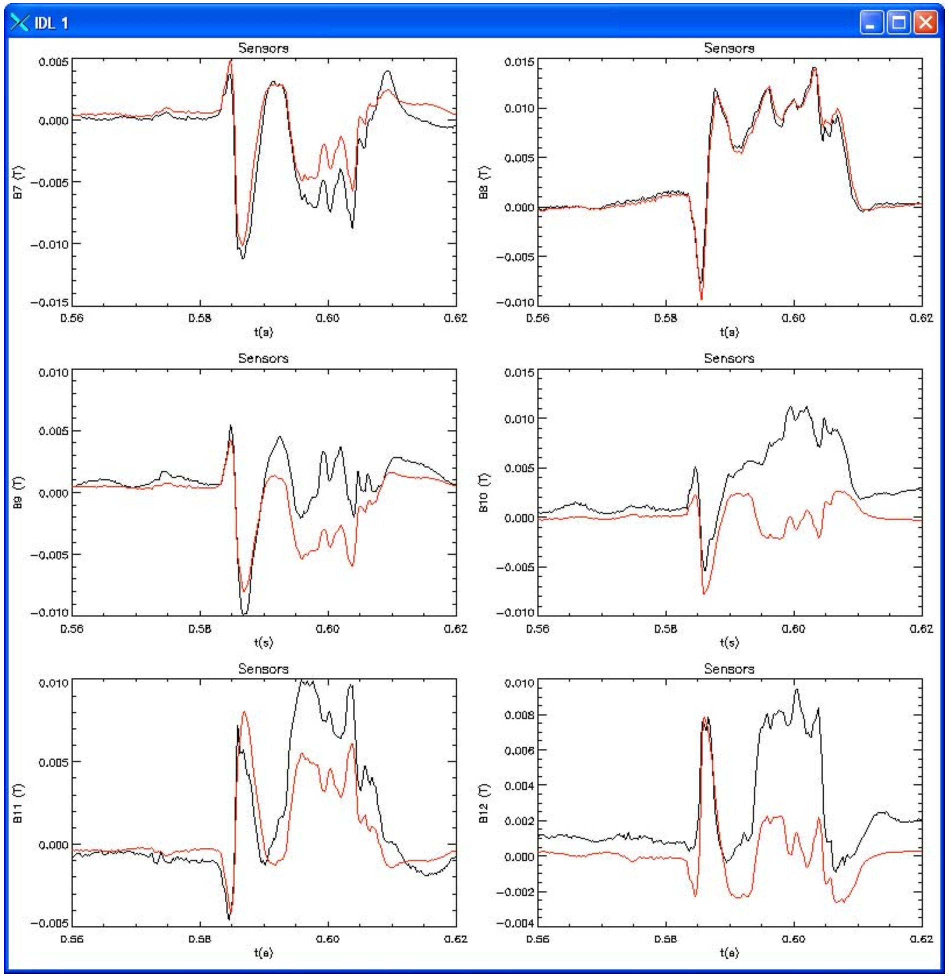
Black: PID
Red: offline RWMSC

RWMSC observer with 7 states improves match

Bp UPPER Sensor differences



Bp LOWER Sensor differences



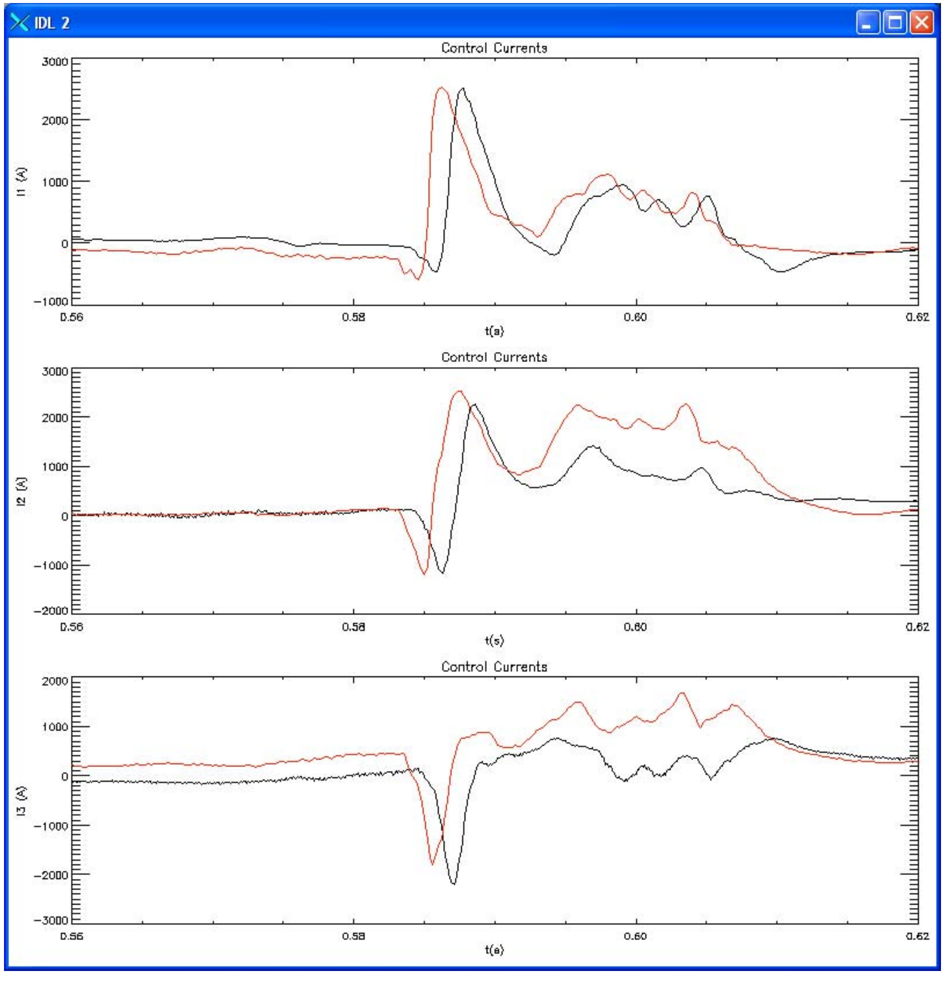
- RWMSC-07212010v22.dat (u/l sensors 7-11,19-24, 7 states), Qu=1e8,Qs=1e0,R=1,Vu=1,Vs=1e-4
- Better match to sensors, some mismatch to 90 degree sensors (n = 2 component?)

Black: PID
Red: offline RWMSC

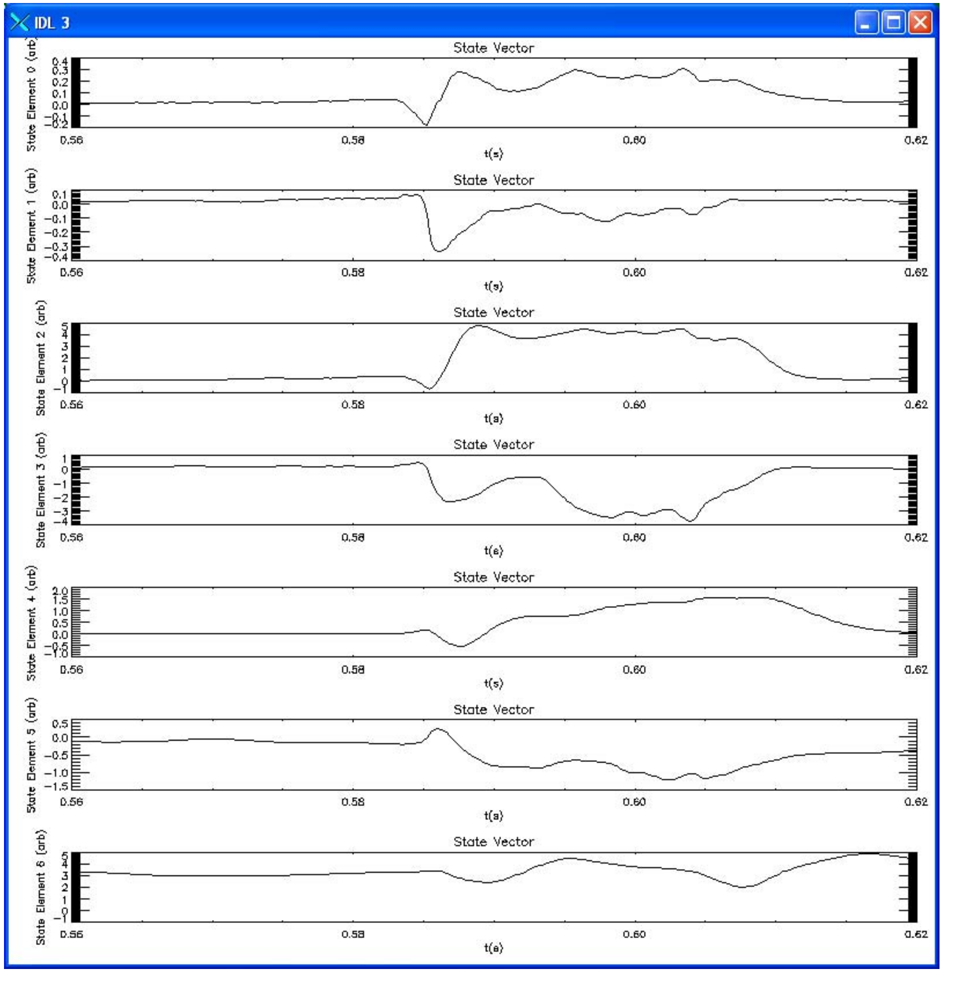
NSTX

RWMSC controller with 7 states can match PID

Control current



State vector evolution



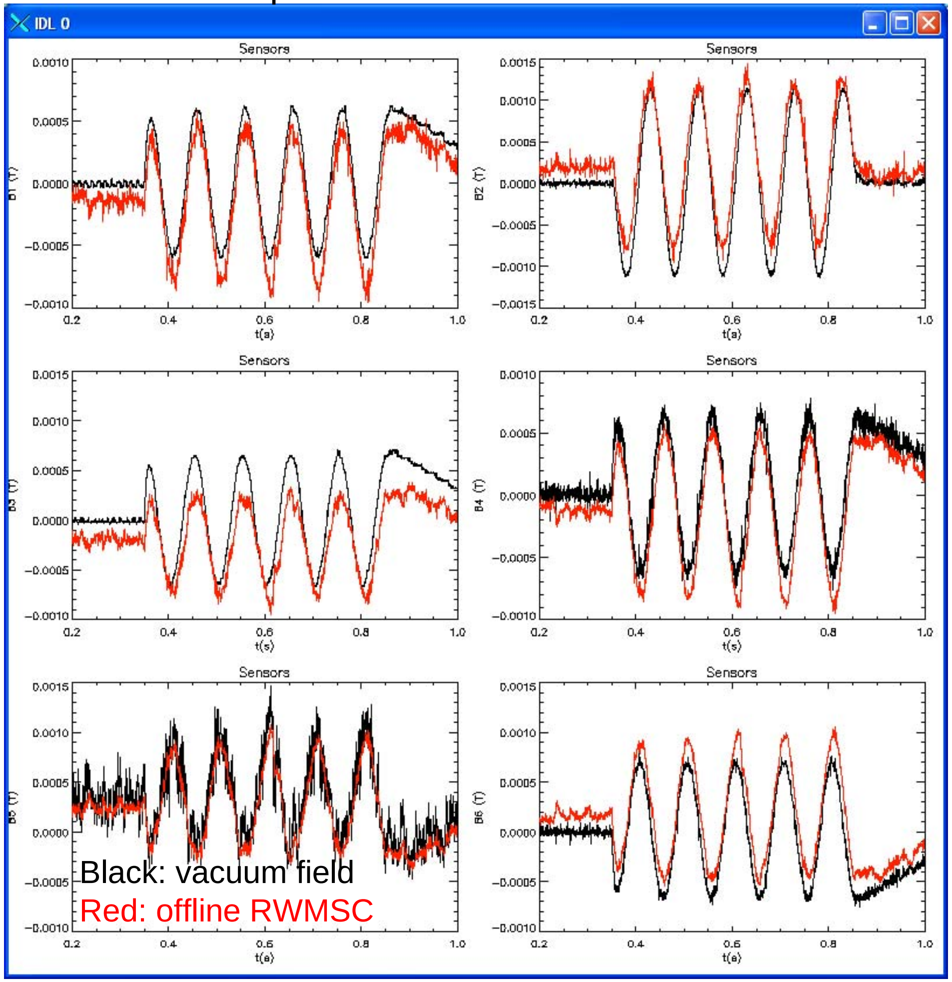
- RWMSC-07212010v30.dat (u/l sensors 7-11,19-24, 7 states), Qu=8e7,Qs=1e5,R=1,Vu=1,Vs=1e-5
- Better match to currents with stable states included
  - Controller gain for higher states turned down to best match PID result

Black: PID
Red: offline RWMSC

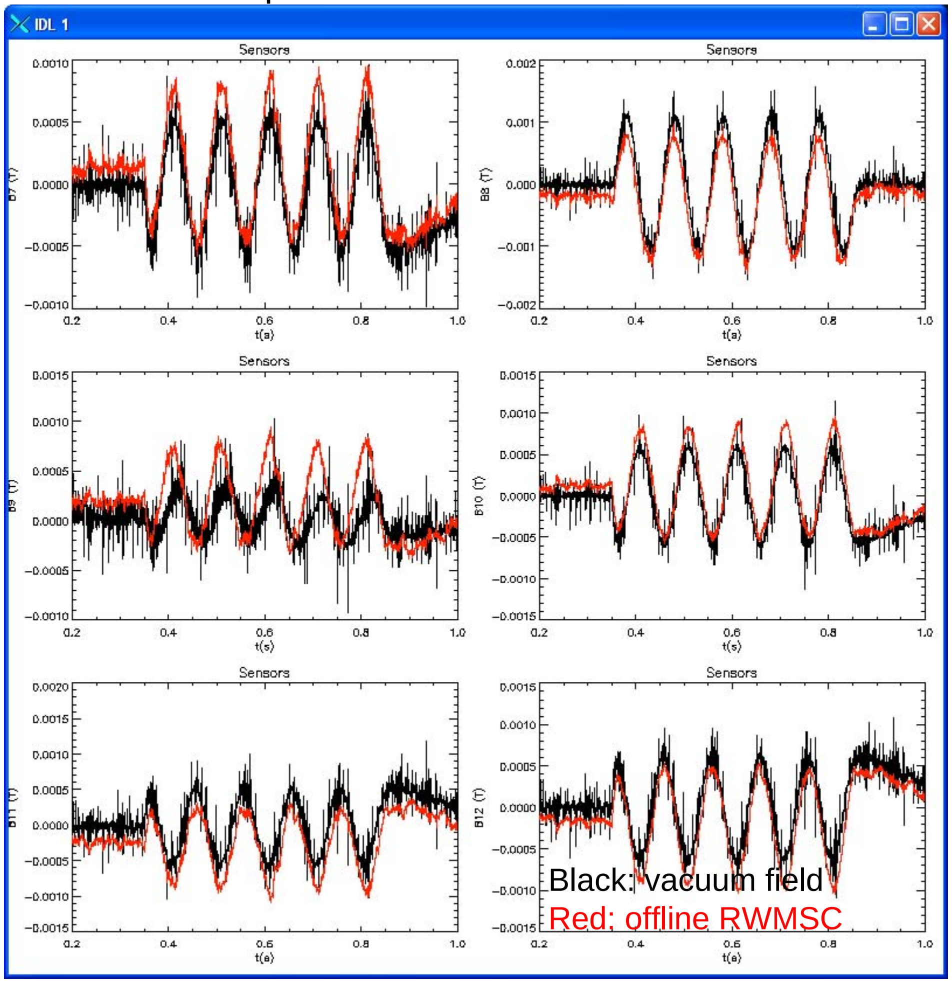
NSTX

118298 (-10Hz vacuum): 5 states, vacuum model

Bp UPPER Sensor Differences



Bp LOWER Sensor Differences



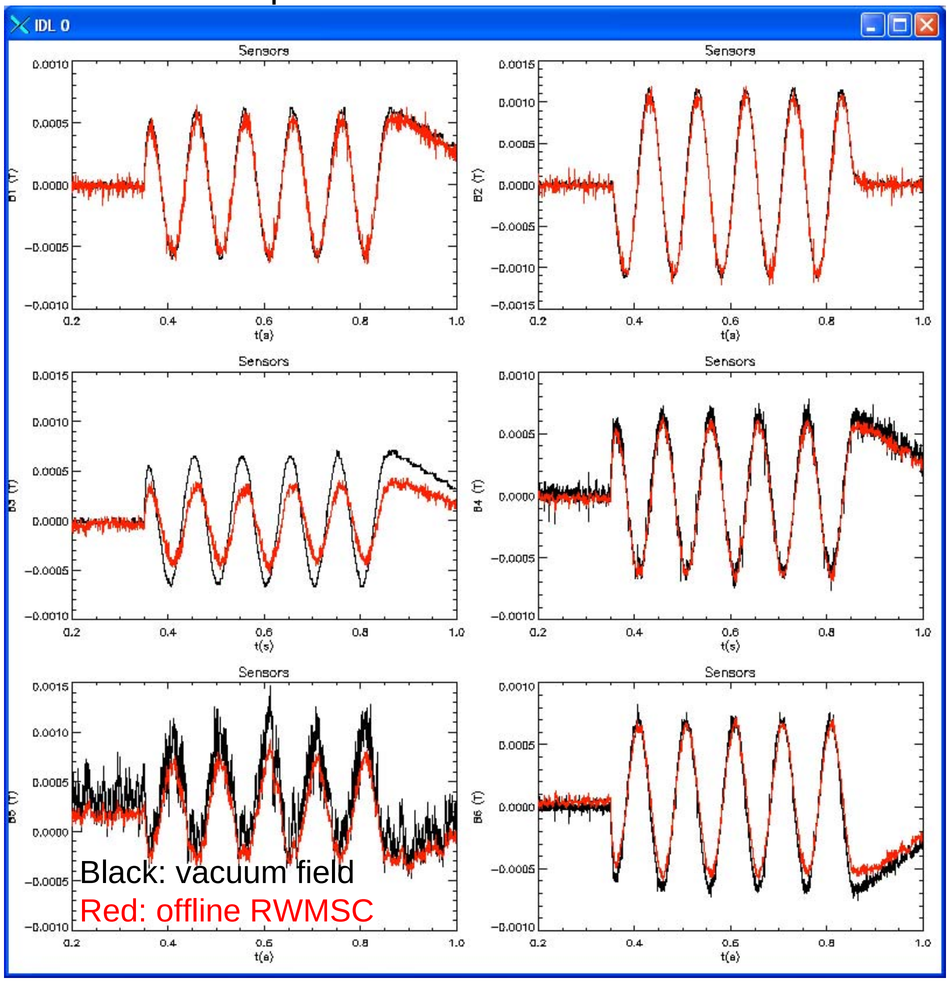
- RWMSC-VAC-07272010v13.dat (u/l sensors 7-11,19-24, 5 states), Q=8e4,R=1,V=5e-3, -180 phase shift
- -10Hz n=1 field (uncomp. sensors)

Will more states lead to a better match?

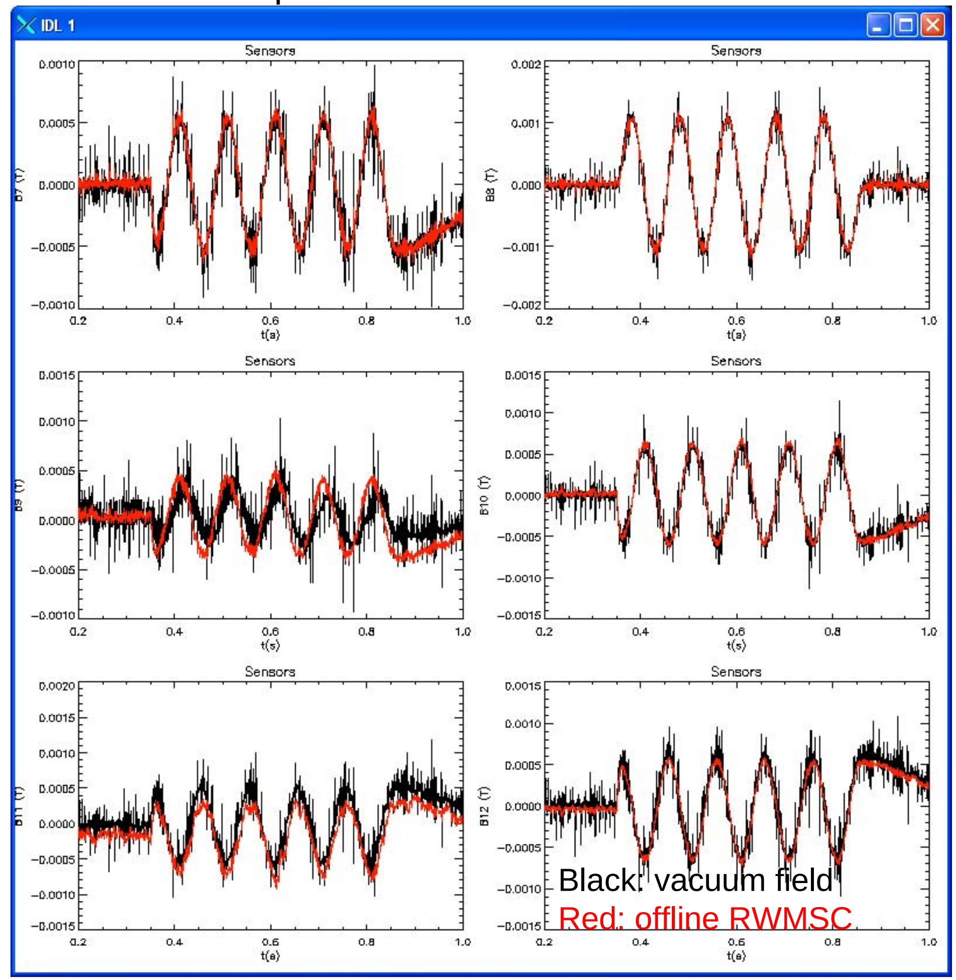
NSTX

118298 (-10Hz vacuum): 10 states, vacuum model

Bp UPPER Sensor Differences



Bp LOWER Sensor Differences



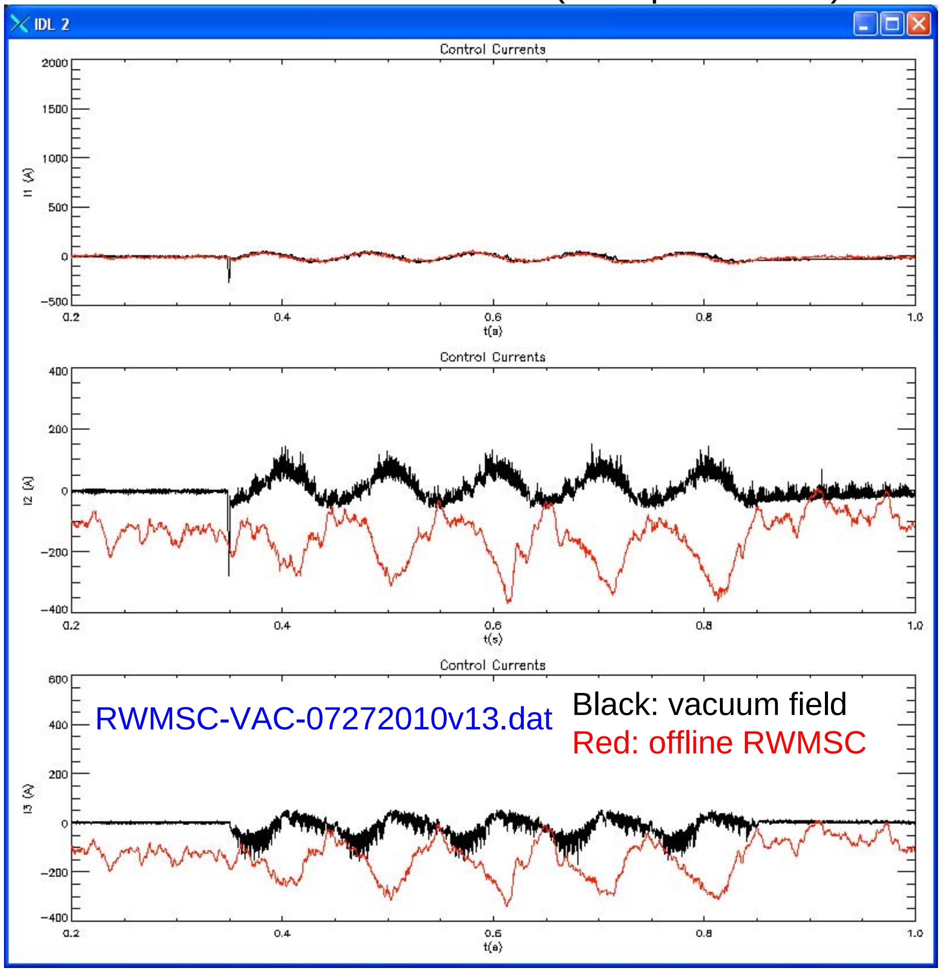
- RWMSC-VAC-07272010v16.dat (u/l sensors 7-11,19-24, 5 states), Q=2.5e5,R=1,V=2e-3, -180 phase shift
- -10Hz n=1 field (uncomp. sensors)

Far better match with 10 states vs. 5

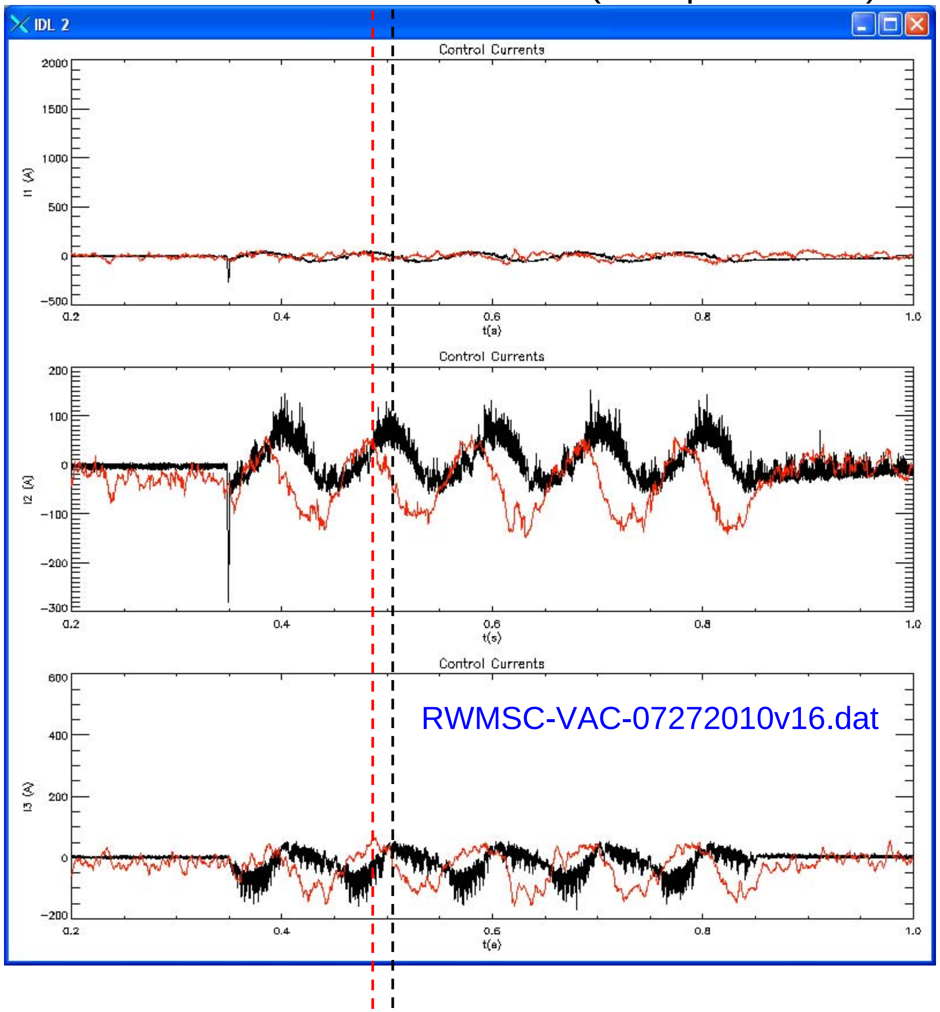
NSTX

118298 (-10Hz vacuum): 5 vs.10 states, vacuum model

Control currents – 5 states (-180 phase shift)



Control currents – 10 states (-180 phase shift)



- 10 states superior to 5 states
  - Clear phase shift with 10 states – for all 3 control currents (unclear for 5 states)
  - Far less "offset current" with 10 states vs. 5 states

XP1022 run plan: Overview

- Generate high normalized beta, and low l_i target plasmas with / without PID RWM control
- Determine ability of controller to suppress n = 1 RFA
- Determine controller compatibility with n = 3 magnetic braking
- Examine variation of RWM state space controller parameters
  - Number of states
  - Observer gain
  - Controller gain
    - N = 1 eigenfunction states
    - Other states
- Effect of other control parameters
  - B_p sensor baseline re-zeroing; new “MIU” AC and OHxTF compensations
  - Controller feedback phase
- Run optimal settings to demonstrate superior performance
- Repeat at reduced plasma rotation to make connection to ITER
- Add β_N feedback to best plasmas if needed / desired to reduce β_N fluctuations

XP1022: RWM State Space Control (RWMSC) shot plan

Task	Number of Shots
0) Generate targets	
(low l_i target (1 – 1.2 MA) from XP1023 (e.g. 139514); “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 and 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 B_p 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 RWMSC feedback phase to generate positive / negative feedback / determine best settings	8
B) Add n = 3 braking pulse to best settings above and ensure RWMSC response expected from (1A)	1
C) (optional) Introduce β_N feedback to to run steady, high $\langle\beta_N\rangle_{pulse}$ if desired	(2)
4) Generate high $\langle\beta_N\rangle_{pulse}$ 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 $\langle\beta_N\rangle_{pulse}$ if desired	(2)
	Total: 36; (4)

XP1022: RWM State Space Control – Diagnostics, etc.

- Required diagnostics / capabilities
  - New RWM sensor processing mode ID code "MIU" and RWM state space control code available in the PCS
  - RWM coils in standard n = 1,3 configuration
  - CHERS toroidal rotation measurement
  - Thomson scattering
  - MSE
  - Standard magnetics / diamagnetic loop
- Desired diagnostics
  - USXR
  - FIDA
  - FIReTip
  - Fast camera