NSTX

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NSTX Operator Training: 3-D Field Detection and Application + Beta Control

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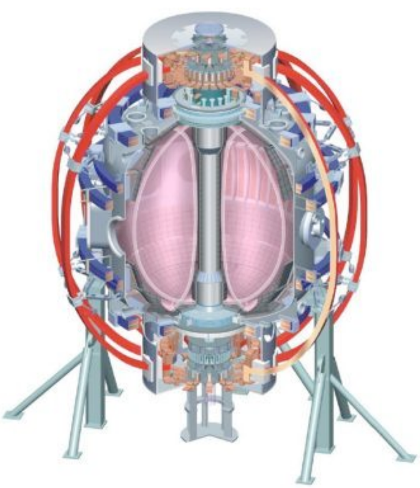

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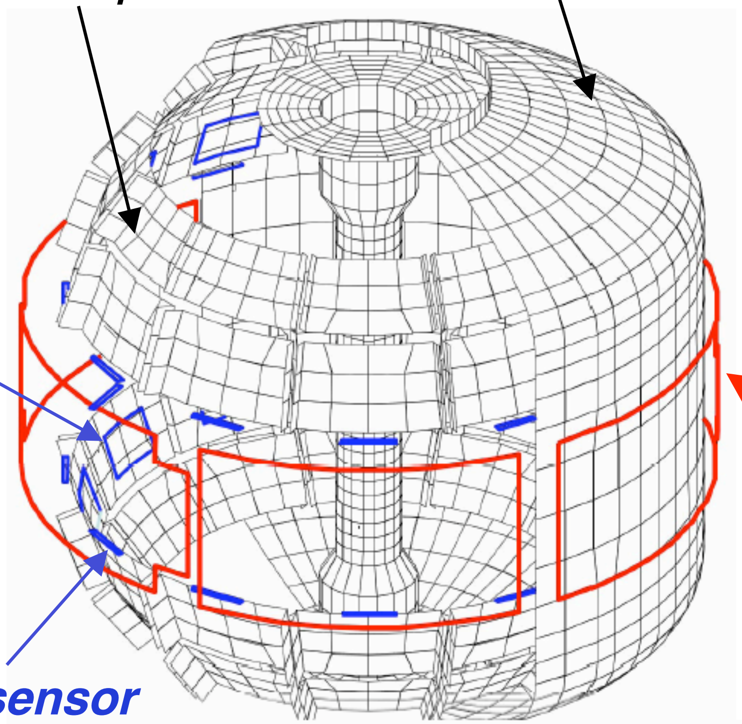
Topics

- Motivation for 3-D field sensors and coils.
- Overview
  - Layout of sensors and coils
  - Overall scheme for mode detection, feedback, and pre-programmed 3-D field application
- How to detect a mode
  - Sensor compensation
  - Mode Identification
- How to get current in the coils
  - RWM feedback/DEFC & pre-programmed coil currents
- State Space Controller
- NB Control From PCS
  - Introduction and methods
  - Technical Considerations
  - Examples

Why Do We Have 3-D Field Detection and Application?

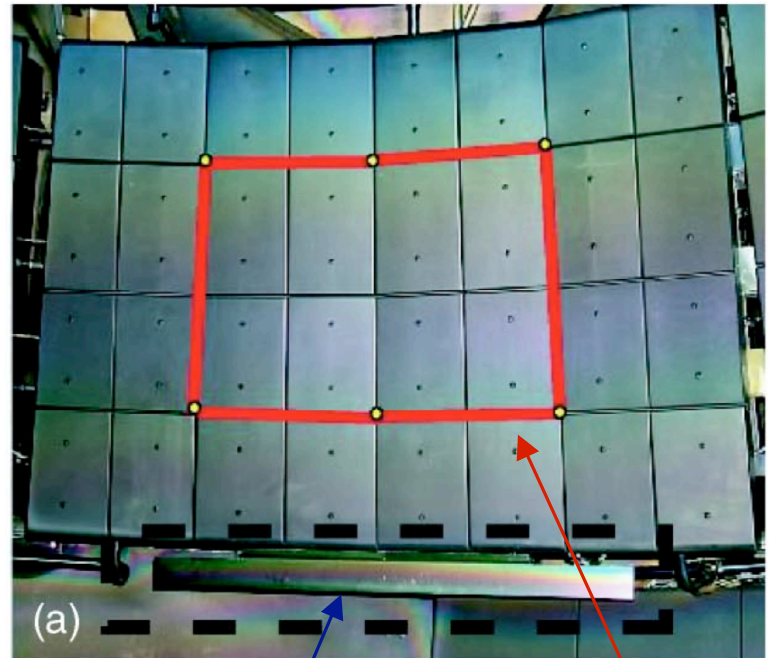
- Deliberately apply fields as perturbations:
  - Locked mode thresholds vs. density, field,…
  - Magnetic braking to study “stuff” as a function of rotation.
  - (N)RMP for modifications to pedestal transport & ELM suppression.
    - or ELM triggering.
  - Strike-point splitting, 3-D effects on divertor loading, “homoclinic tangles”
- Control of Error Fields
  - Small non-axisymmetries in machine construction lead to error fields.
  - Plasma can amplify the error field (RFA), causing their effect to become stronger….effect is stronger at higher β.
  - Detect the amplified error field and suppress it with feedback
    - Called “dynamic error field correction” (DEFC).
    - Only detect and correct n=1 fields.
- Suppression of Resistive Wall Modes.
  - RWM=external kink instability modified by the resistive wall.
    - Both pressure and current driven kinks can become RWMs.
  - Grows on the scale of the wall time=L/R time for dominant eddy current patterns. (10 msec).
  - Detect and suppress it.
    - Call this “fast” n=1 feedback.

Midplane External Coils and Off-Midplane Sensors



VALEN Model of NSTX (Columbia Univ.)

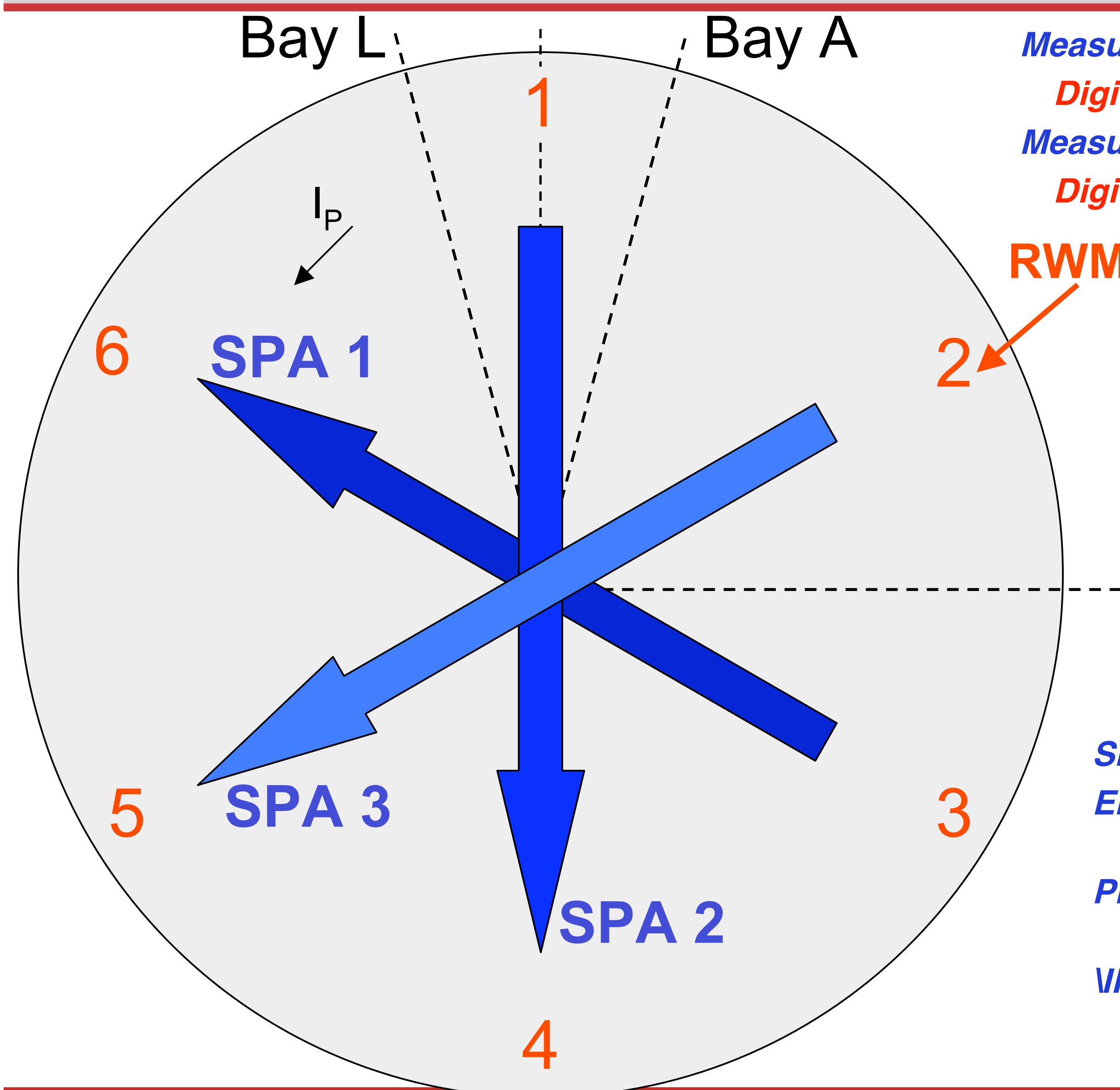
Sontag et al., Physics of Plasmas **12** 056112 (2005)



B_P Sensor in a Sealed Stainless Box

B_R Sensor as a loop behind the tiles, but in front of the plate.

Each SPA is (Usually) Connected to a Pair of Anti-Series Coils



Measure currents at the SPA

Digitize these in CAMAC and PCS

Measure currents at the coils

Digitize in CAMAC

SPA Subunit	Coils
1	-3,+6
2	-1,+4
3	-2,+5

Special connections available on request

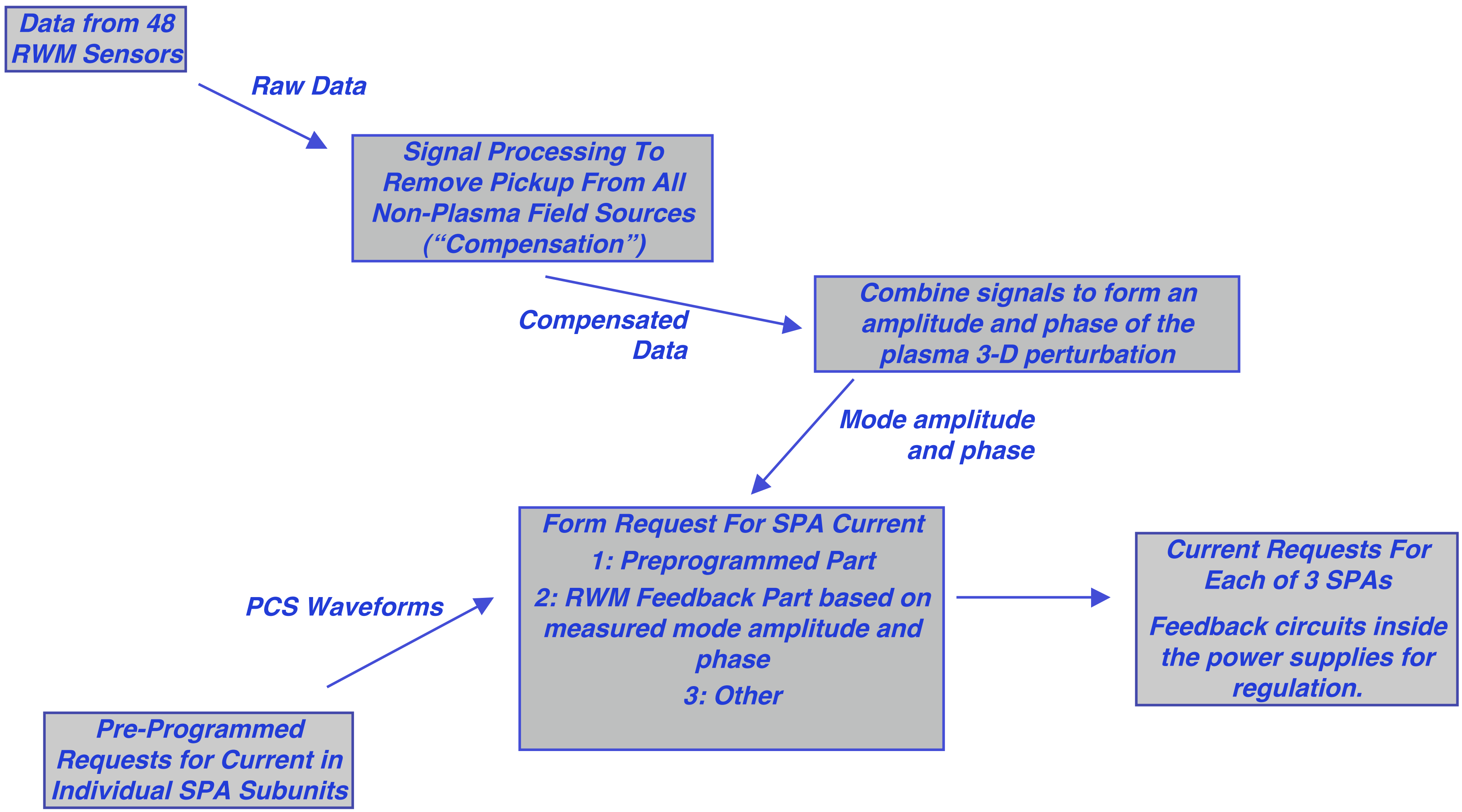
Sign conventions:

Engineering: Positive current is clockwise as you view the coil.

Physics: Positive current makes radial field pointing away from the vessel.

\RWM1, \RWM2,… signals use the physics convention.

Overall Scheme



Signal Compensation For RWM Coils

- Any given sensor detects the field from the plasma perturbation, plus other sources.
  - Other sources include direct coil pickup, the tilting TF coil, eddy currents.
- For each sensor, find a mathematical model for that pickup and subtract.

Static

Direct pickup between coil and sensor. $P_{i,j}$ are mutual inductances

$$C_{i,static} = \sum_{j=0}^{NumCoils-1} p_{i,j} I_j$$

816 Coefficients

OHxTF

Direct n=1 pickup from the tilting TF coil

$$f_i = LPF\left(I_{OH} \times I_{TF}; \tau_{OHxTF,i}\right)$$

$$f_i = \frac{f_i}{1 + \beta_i f_i}$$

$$\textbf{if } f_i > 0 \textbf{ then } C_{OH\times TF,i} = r_{p,i} f_i$$

$$\textbf{if } f_i < 0 \textbf{ then } C_{OH\times TF,i_i} = r_{n,i} f_i$$

96 Coefficients

AC Compensation For Fluctuating RWM Coil Currents

Eddy currents driven by RWM coils make fields…subtract these out.

$$C_{AC,i}(t) = \sum_{j=0}^{5} \sum_{k=0}^{k_{\max}} p_{i,j,k} LPF\left(\frac{dI_{RWM,j}(t)}{dt}; \tau_{AC,i,k}\right)$$

504 Coefficients

Final Field For Plasma Mode Identification

$$B_{i,plasma} = B_i - C_{i,static} - C_{i,OH\times TF} - C_{i,AC}$$

Process for Mode Identification

- The mode has an amplitude (A_{RWM}) and phase (ϕ_{RWM})

$$B = A_{RWM}\cos(\phi - \phi_{RWM})$$

- At the i[th] sensor, the measured amplitude is:

$$B_i = A_{RWM}\cos(\phi_i - \phi_{RWM}) \Rightarrow$$
$$B_i = A_{RWM}\cos(\phi_{RWM})\cos(\phi_i) + A_{RWM}\sin(\phi_{RWM})\sin(\phi_i) \Rightarrow$$
$$B_i = C_{RWM}\cos(\phi_i) + S_{RWM}\sin(\phi_i)$$

- Many sensors…build a matrix and invert it!

$$\begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_N \end{bmatrix} = \begin{bmatrix} \cos(\phi_1) & \sin(\phi_1) \\ \cos(\phi_2) & \sin(\phi_2) \\ \vdots & \vdots \\ \cos(\phi_N) & \sin(\phi_N) \end{bmatrix} \begin{bmatrix} C_{RWM} \\ S_{RWM} \end{bmatrix} = M \begin{bmatrix} C_{RWM} \\ S_{RWM} \end{bmatrix}$$

$$\begin{bmatrix} C_{RWM} \\ S_{RWM} \end{bmatrix} = M^{-1} \begin{bmatrix} B_1 \\ B_1 \\ \vdots \\ B_N \end{bmatrix}$$

$$A_{RWM} = \sqrt{C_{RWM}^2 + S_{RWM}^2}$$
$$\phi_{RWM} = a\tan\left(S_{RWM} / C_{RWM}\right)$$

- Many more details in reality, but this is the idea.

Algorithms for Mode Identification: mid

- mid="Mode Identification" (modeid Category)
- Applies "static compensation only".
- Inputs:
  - Rezeroing time (time at end of I_p flat top where sensor values are reset to zero).
  - The Matrix (2x24): see previous slide.
    - Actual numbers come from Stefan, Steve, or Jon.
- Outputs:
  - Passed within PCS to RWM feedback algorithms.
  - Amplitude and phase of mode as detected by B_P sensors.
  - Amplitude and phase of mode as detected by B_R sensors.
  - Amplitude and phase of mode as detected by B_R + B_P sensors.

Algorithms for Mode Identification: miu New for 2010!

- miu="Mode Identification Upgrade" (modeid Category)
- Applies three levels of compensation:
  - Static compensation.
  - OHxTF compensation (with an on/off switch).
  - AC compensation (with an on/off switches).
- Inputs:
  - Rezeroing time (time at end of I_p flat top where sensor values are reset to zero).
  - Switches to turn off various compensations
  - The Matrix (2x24): see previous slides.
    - Actual numbers come from Stefan, Steve, or Jon.
- Outputs:
  - Passed within PCS to RWM feedback algorithms.
  - Amplitude and phase of mode as detected by B_P sensors.
  - Amplitude and phase of mode as detected by B_R sensors.
  - Amplitude and phase of mode as detected by $B_R + B_P$ sensors.
  - Compensated sensor data for the "advanced controller".

RWM/DEFC Feedback Methodology
“smf algorithm”

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the 3-D field.
- Apply an n=1 field with:
  - Amplitude proportional to the 3-D field amplitude: $G_{RWM}(t)\ L_{eff}^{-1}$
  - Fixed phase difference: $\delta(t)$

$$I_{SPA-1}^{B_P,RWM}(t) = G_{B_P}(t) B_{P1}(t) L_{eff}^{-1} \cos(300° - \theta_1(t) + \delta(t)) \quad \Rightarrow \quad K_{SPA-1}^{B_P,RWM}(t) = LPF\left(I_{SPA-1}^{B_P,RWM}(t);\tau\right)$$

$$I_{SPA-2}^{B_P,RWM}(t) = G_{B_P}(t) B_{P1}(t) L_{eff}^{-1} \cos(180° - \theta_1(t) + \delta(t)) \quad \Rightarrow \quad K_{SPA-2}^{B_P,RWM}(t) = LPF\left(I_{SPA-2}^{B_P,RWM}(t);\tau\right)$$

$$I_{SPA-3}^{B_P,RWM}(t) = G_{B_P}(t) B_{P1}(t) L_{eff}^{-1} \cos(240° - \theta_1(t) + \delta(t)) \quad \Rightarrow \quad K_{SPA-3}^{B_P,RWM}(t) = LPF\left(I_{SPA-3}^{B_P,RWM}(t);\tau\right)$$

- Generate similar requests based on the B_R sensors:

$$K_{SPA-1}^{B_R,RWM}(t)\ ,\ K_{SPA-2}^{B_R,RWM}(t)\ ,\ K_{SPA-3}^{B_R,RWM}(t)$$

- Can also request pre-programmed SPA currents:

$$I_{SPA-1}^{\mathrm{Pre-Prog}}(t),\ \ I_{SPA-2}^{\mathrm{Pre-Prog}}(t),\ \ I_{SPA-3}^{\mathrm{Pre-Prog}}(t)$$

- OH x TF EF correction algorithm:

$$I_{SPA-1}^{OH\times TF}(t),\ \ I_{SPA-2}^{OH\times TF}(t),\ \ I_{SPA-3}^{OH\times TF}(t)$$

- Total current request:

$$I_{SPA-1}^{\mathrm{Pre-Prog}}(t) = I_{SPA-1}^{OH\times TF}(t) + K_{SPA-1}^{B_P,RWM}(t) + K_{SPA-1}^{B_R,RWM}(t) + I_{SPA-1}^{\mathrm{Pre-Prog}}(t)$$

There Are Many More Algorithms in the RWM Category

- "spa"=SPA
  - Pre-programmed EFC coil currents only.
- "fec": Field Error Correction
  - Pre-programmed currents
  - Currents in EFC coils $\propto$ PF coils and voltages on certain flux loops.
- "imf"=Initial Mode Feedback
  - First generation of RWM control.
  - No low-pass filtering.
  - No separate gains for B_P and B_R perturbations.
- "smf"=Second mode feedback
  - This is almost always the correct choice.

Advanced RWM Controller

- Development effort lead by Oksana Katsuro-Hopkins of CU.
  - Others: S. A. Sabbagh, J. Bialek, S.P. Gerhardt.
- State-Space implementation of RWM feedback.
  - "State" is a mathematic representation of the system status
    - Plasma surface currents to represent the RWM.
    - Vessel and plate currents (VALEN EM model).
    - Coil currents.
  - Solve a linearized version of the dynamical system equations to determine optimal correction currents.
    - A true model of the RWM is built into the controller.
    - No PID…"Gains" are numbers in a bunch of matrices.
  - Will generate requests for currents: $I_{SPA-1}^{State-Space\ RWM}(t),\ I_{SPA-2}^{State-Space\ RWM}(t),\ I_{SPA-3}^{State-Space\ RWM}(t)$
- Add the optimal controller request to other requests.
  - Preprogrammed, Proportional feedback,…
- May be tested in the upcoming run.

Beam Control from PCS

- This remains a development effort…what I say here may change.
- Why?
  - Would like to be able to restore the beam waveforms from previous shots.
  - Would like to be able to regulate the β_N values so as to avoid instability.
  - Would like to turn off beams before (automatically) ramping down I_P.
- How?
  - Preprogrammed modulations (what we know before the shot)
    - Are entered as waveforms into PCS.
    - Info send to the EPICS beam control software via an EPICS-PCS link.
    - Changes must be “approved” by NB operators pressing a button on their screens.
  - Feedback (changes we can’t time before the shot).
    - Parameters that govern the feedback are PCS waveforms and parameter data.
      - Target waveforms, gains, deadbands, batting order,…
    - Issue “blocks” through a FOM-D into the TFTR β-feedback chassis at the D-site 138’ level.
  - EPICS turns the beams on, and PCS may then block them.
    - Only allowed 20 blocks per shot, with 10 msec minimum on/off times.

Implementation of β_N Control in NSTX

- Compare filtered β_N value from rtEFIT to a request, and compute an error.

$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

- Use PID on the error to compute a new requested power.

$$P_{inj} = P_{\beta_N}\overline{C}_{\beta_N}e + I_{\beta_N}\overline{C}_{\beta_N}\int edt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

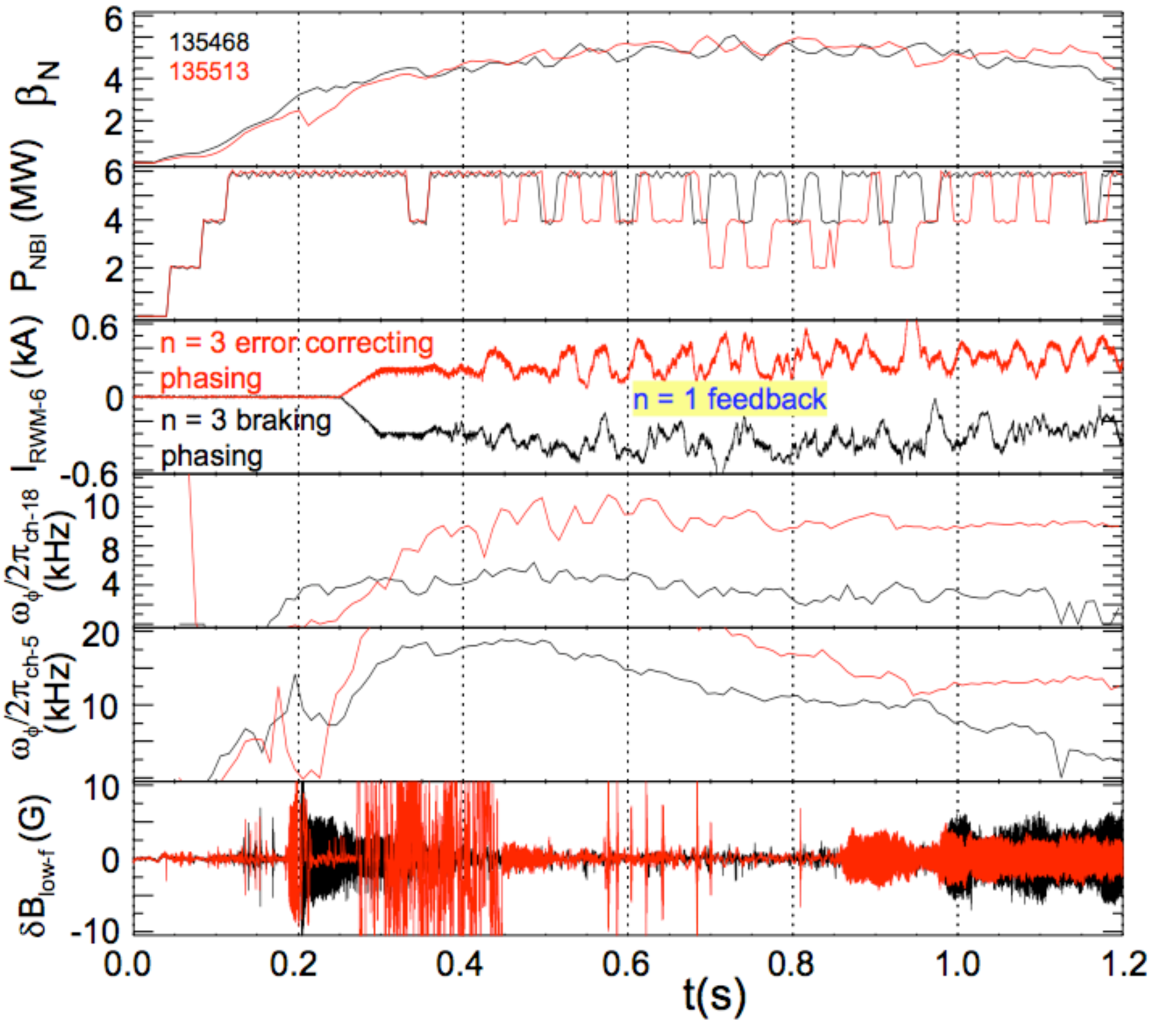
$$\overline{C}_{\beta_N} = 1000\cdot\tau\cdot\frac{I_P V B_T}{200\mu_0 a}$$

- Use power from the PID operation, source powers, and "batting order" to determine the duty cycles for each source.
- Use the duty cycles and min. on/off times to determine when to block.
- NB controls at D-site turn the beams on, and we issue requests to turn the beams off.
  - PCS is allowed to block the beam up to 20 times per discharge, with 10 msec minimum on/off times.

Many Available Adjustments For β_N Control (i.e. PCS Waveforms)

- Filter time constant on the β_N value sent from rtEFIT.
  - Useful for smoothing transients and “noise” in the rtEFIT β_N.
- Proportional, integral, and derivative gains.
  - Determines the response of the system to transients.
- Batting order array.
  - Determines which sources modulate
  - Switch to a different source if a given source reaches the maximum number of blocks.
  - *Also able to prevent A modulations, to keep MSE and CHERS.*
- Source powers
  - Can be adjusted in order to prevent modulations.
- Minimum Source On/Off Times.
  - Smaller values will lead to better control, but possibly at the expense of source reliability.
  - 20 msec. has been used so far, with reasonable success (still rather coarse compared to the confinement time).
- Explicit injected power request.
  - Request a power waveform, and PCS determines modulations to achieve it.
- This is all part of the “bnf”=“beta normal feedback” algorithm.

β_N Control Has Been Demonstrated in 2009



- ***β_N algorithm compensates for loss of confinement with n=3 braking.***
- ***But not done:***
  - ***Gains were not optimized.***
  - ***Modified the PID operator for the 2010 run…need to re-tune.***
  - ***XMP to finish this task in 2010.***

Modifications to the rtEFIT Basis Functions Resulted in Improved Real-time Reconstructions

- Occasional poorly converged equilibria lead to incorrect outer gap, β_N
  - Kick off an deleterious transient in the vertical field coil current.
  - Edge current not allowed
- New basis function model based on those developed for off-line magnetics-only reconstruction (Columbia University)
  - Tested on literally > 2 million equilibria
  - Finite edge current through ff'(ψ_n)
- Considerable real-time reconstruction improvement
  - Reduction in β_N “noise” indicative of improved reconstructions

$$p'(\psi_n) = a_1\psi_n(1-\psi_n)$$

$$ff'(\psi_n) = b_0 + b_1\psi_n\left(1-\frac{1}{3}\psi_n^2\right) + b_2\psi_n^2\left(1-\frac{2}{3}\psi_n\right)$$

rtEFIT, Old Basis Functions *rtEFIT, New Basis Functions* ***Offline Calculation***