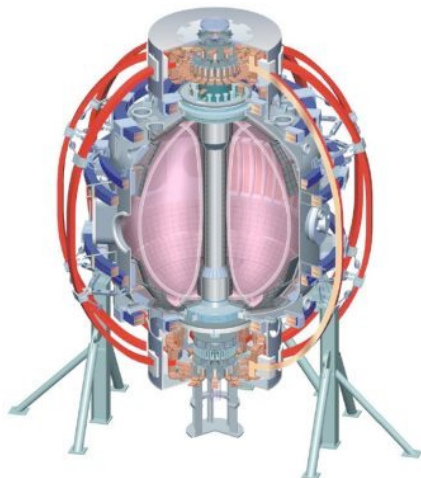


NSTX Operator Training: 3-D Field Detection and Application + PCS NB Control

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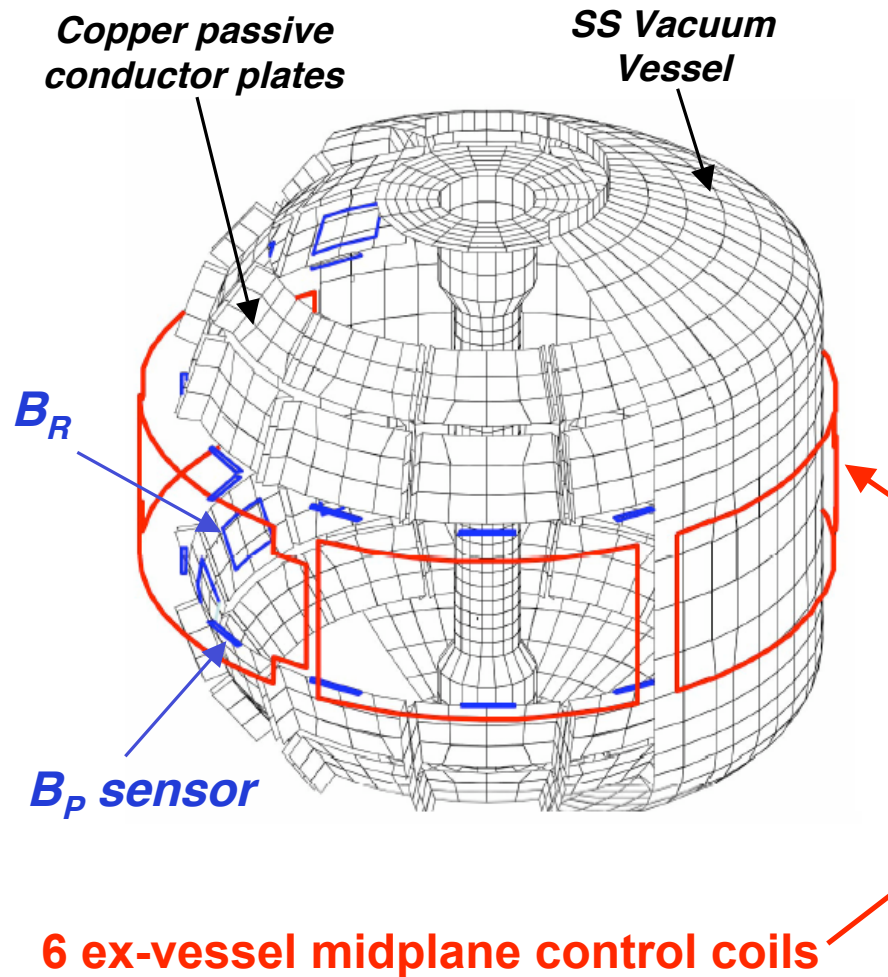
Topics

- 3-D Fields
 - Motivation for 3-D field sensors and coils.
 - Overview
 - How to detect an $n=1$ mode
 - What determines the currents in the coils
- Neutral Beams
 - Handy information about operation with beams
 - Overview of control of beams from PCS
 - Information about β_N -control

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

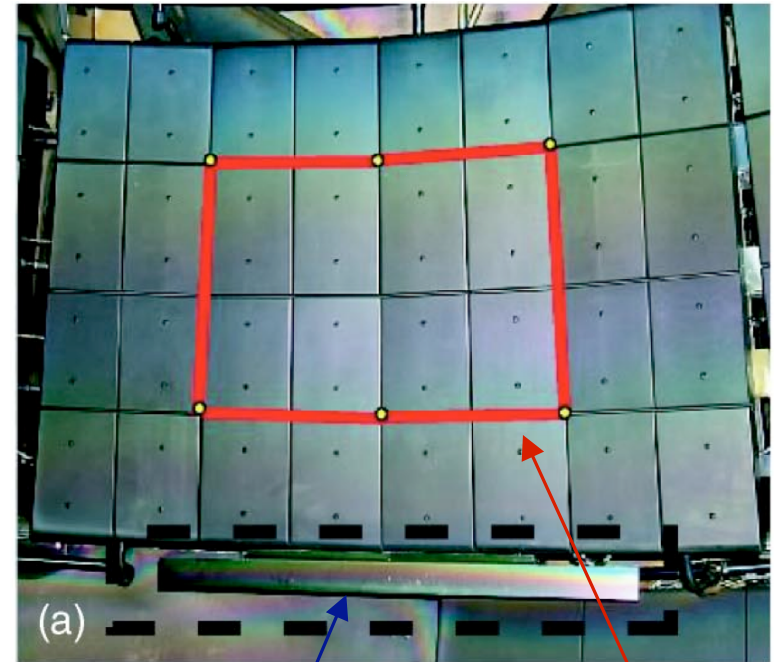
- Deliberately apply fields as perturbations:
 - Locked mode thresholds vs. density, field,...
 - Magnetic braking to study “stuff” as a function of rotation.
 - (N)RMP for modifications to pedestal transport & ELM suppression.
 - or ELM triggering.
 - Strike-point splitting, 3-D effects on divertor 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.)

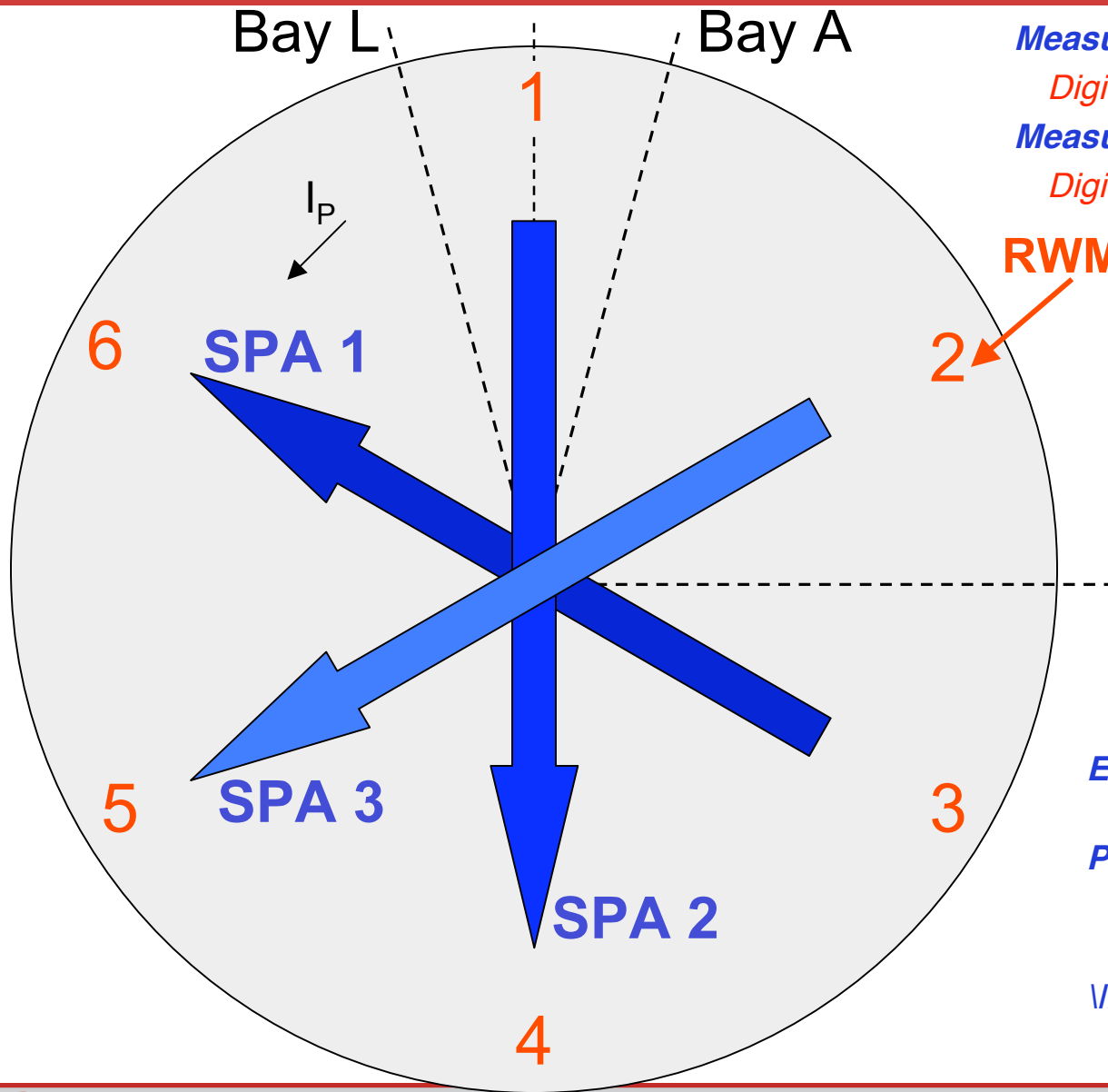
Sontag et al., Physics of Plasmas **12** 056112 (2005)



B_p Sensor in a Stainless Box

B_R sensor is 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

RWM/EF coil #

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

**Special connections
available on request**

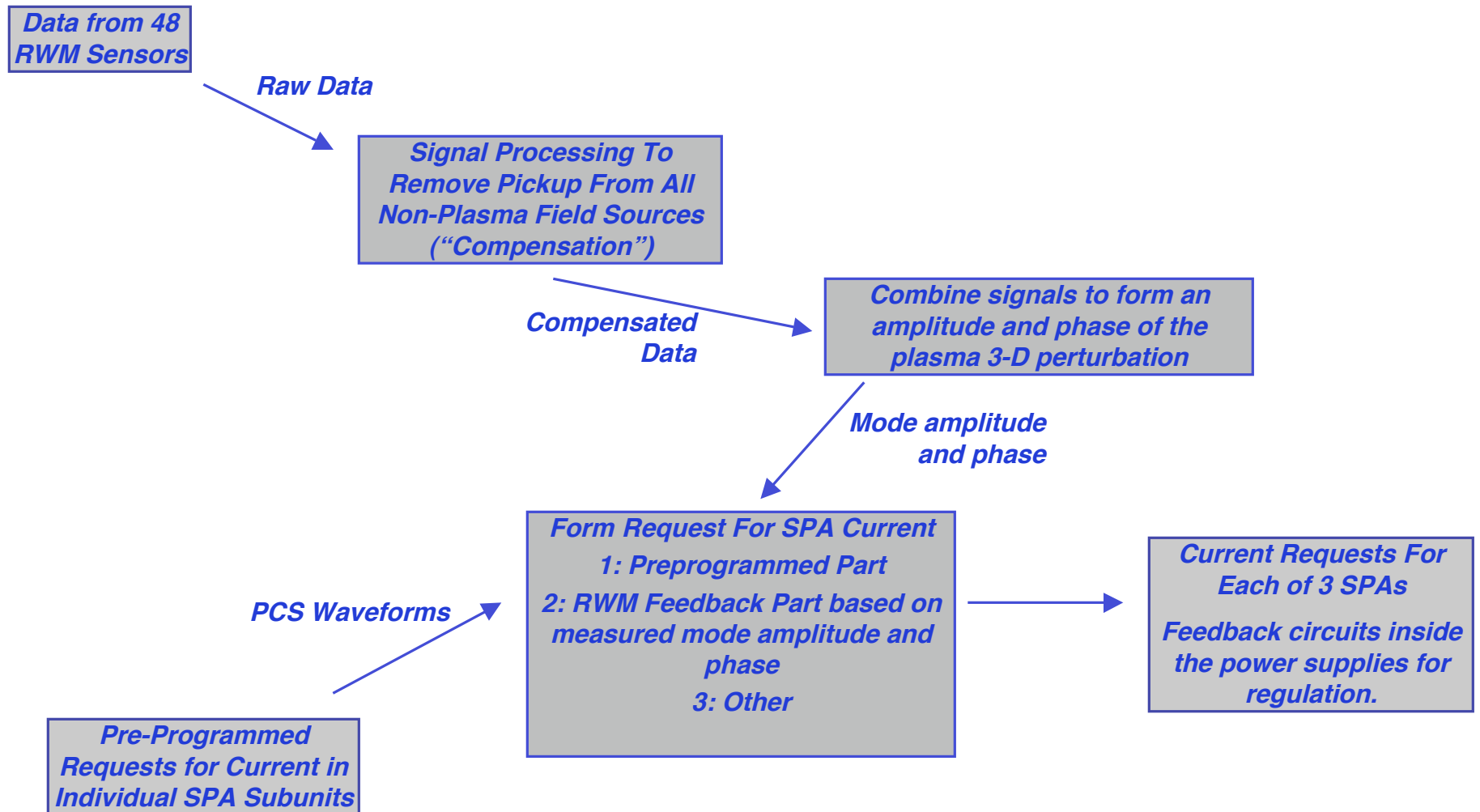
Sign conventions:

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

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

$\backslash$ RWM1, $\backslash$ 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.
- Subtract non-plasma pickup from each signal.
- Many coefficient involved, all in model tree.
 - Only read in to PCS/ACQ when ACQ is restarted

Static
 Direct pickup between coil and sensor. P_{ij} 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

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

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

if $f_i > 0$ then $C_{OHxTF,i} = r_{p,i} f_i$
 if $f_i < 0$ then $C_{OHxTF,i} = r_{n,i} f_i$

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

$$B_{i,plasma} = B_i - C_{i,static} - C_{i,OHxTF} - C_{i,AC}$$

In ACQ

In the modelD category

Process for Mode Identification

- The actual magnetic perturbation has an amplitude (A_{RWM}) and phase (ϕ_{RWM})

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

- How to determine A_{RWM} & ϕ_{RWM} ?
- We measure the plasma field:
 - Above and below the midplane
 - With B_R and B_P sensors
- Convert the sensor fields at each time point to amplitude and phase.
 - Assemble all the measured fields in a column vector [24x1].
 - Construct the mode-ID matrix [2 x 24]
 - Multiply these together...resulting [2 x 1] array contains (essentially) A_{RWM} & ϕ_{RWM}
- Matrix elements are a/the primary input to the algorithm.
 - Stored as “parameter data”
 - Restored with the shot.
 - GUI matrix editor for changing the values.
- Contents of matrix generally come from SPG, SAS, of JEM.

What is the mode-ID matrix?

- 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!

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

$$\begin{bmatrix} C_{RWM} \\ S_{RWM} \end{bmatrix} = M^{-1} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_N \end{bmatrix}$$

$$A_{RWM} = \sqrt{C_{RWM}^2 + S_{RWM}^2}$$

$$\phi_{RWM} = \text{atan}(S_{RWM} / C_{RWM})$$

- Matrix elements are a/the primary input to the algorithm.
- 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 mode-ID matrix (2x24): see previous slide.
- 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.
- 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 in the “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: $\delta(t)$

$$B_X = \{B_R, B_P\}$$

$$I_{SPA-1}^{B_X, RWM}(t) = G_{B_X}(t) B_{X1}(t) L_{eff}^{-1} \cos(300^\circ - \theta_1(t) + \delta(t))$$

$$I_{SPA-2}^{B_X, RWM}(t) = G_{B_X}(t) B_{X1}(t) L_{eff}^{-1} \cos(180^\circ - \theta_1(t) + \delta(t))$$

$$I_{SPA-3}^{B_X, RWM}(t) = G_{B_X}(t) B_{X1}(t) L_{eff}^{-1} \cos(240^\circ - \theta_1(t) + \delta(t))$$

- Apply a low-pass filter:

$$K_{SPA-1}^{B_X, RWM}(t) = LPF(I_{SPA-1}^{B_X, RWM}(t); \tau)$$

$$K_{SPA-2}^{B_X, RWM}(t) = LPF(I_{SPA-2}^{B_X, RWM}(t); \tau)$$

$$K_{SPA-3}^{B_X, RWM}(t) = LPF(I_{SPA-3}^{B_X, RWM}(t); \tau)$$

- Ultimately, generate requests based on both the B_P and B_R sensors:

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

- Separate gains and feedback phases for B_R and B_P sensors.

Total SPA Current is the Formed by Summing Requests

- Current requests from RWM feedback:

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

- Can also request pre-programmed SPA currents:
 - PCS waveforms, one per SPA

$$I_{SPA-1}^{Pr e-Pr og}(t), I_{SPA-2}^{Pr e-Pr og}(t), I_{SPA-3}^{Pr e-Pr og}(t)$$

- OH x TF EF correction algorithm (obscure, ask Jon):

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

- Total current request...sum them all up:

$$I_{SPA-1}^{Pr e-Pr og}(t) = I_{SPA-1}^{OH \times TF}(t) + K_{SPA-1}^{B_P, RWM}(t) + K_{SPA-1}^{B_R, RWM}(t) + I_{SPA-1}^{Pr e-Pr og}(t)$$

$$I_{SPA-2}^{Pr e-Pr og}(t) = I_{SPA-2}^{OH \times TF}(t) + K_{SPA-2}^{B_P, RWM}(t) + K_{SPA-2}^{B_R, RWM}(t) + I_{SPA-2}^{Pr e-Pr og}(t)$$

$$I_{SPA-3}^{Pr e-Pr og}(t) = I_{SPA-3}^{OH \times TF}(t) + K_{SPA-3}^{B_P, RWM}(t) + K_{SPA-3}^{B_R, RWM}(t) + I_{SPA-3}^{Pr e-Pr og}(t)$$

- This request is sent to PSRTC, then to the internal feedback circuit of the SPA.

There Are Many More Algorithms in the RWM Category

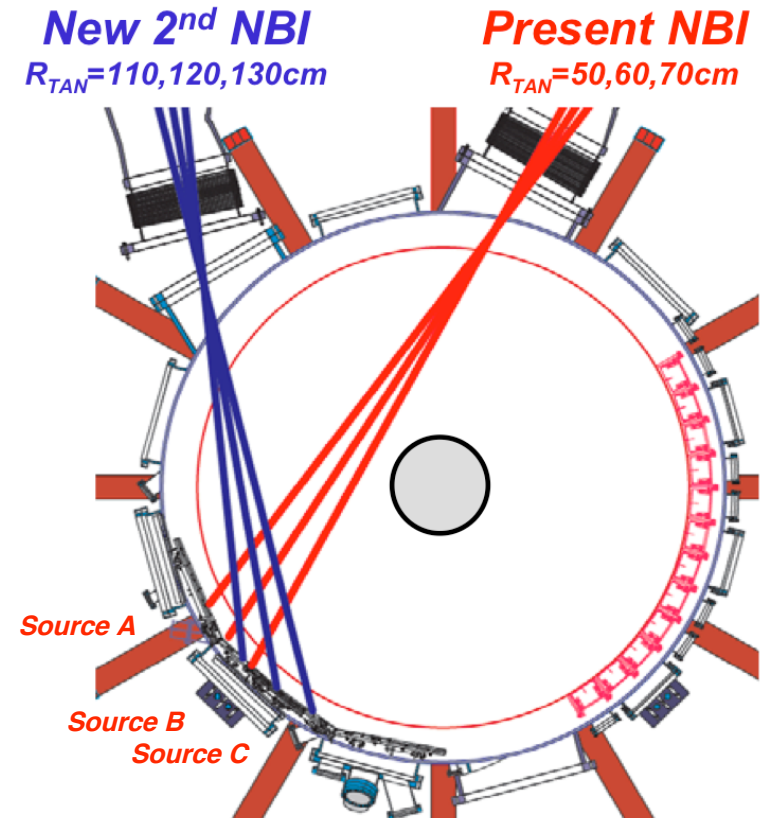
- “spa”=SPA
 - Pre-programmed EFC coil currents only.
- “fec”: Field Error Correction
 - Pre-programmed currents
 - SPA currents $\propto$ PF coils and voltages on certain flux loops.
- “imf”=Initial Mode Feedback
 - First generation of RWM control.
 - No low-pass filtering.
 - No separate gains for B_p and B_R perturbations.
- “smf”=Second Mode Feedback
 - ***This is almost always the correct choice.***
 - “Standard Error Field Correction” is implemented in this algorithm.
 - Pre-programmed correction of an $n=3$ error field (due to triangularity in PF-5).
 - $n=1$ feedback with 2msec time response.

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.

Overview of NBs...Physicist Perspective

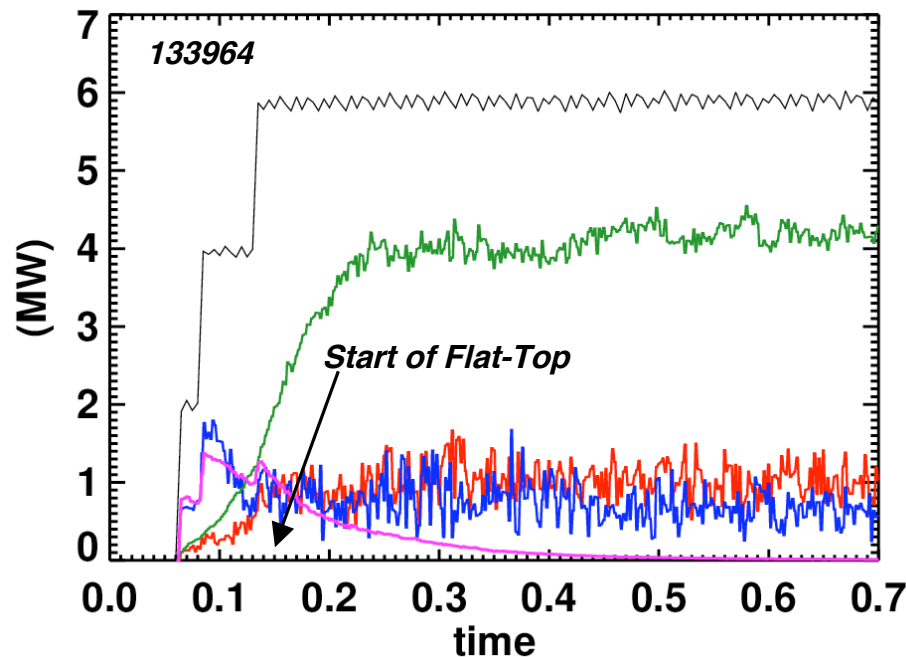
- Source A: $R_{\text{tan}}=70$ cm
 - Typically injected as early as 40 msec., when $I_p=350$ kA.
 - TRANSP indicates that it is mostly lost during this time.
 - Torque, and some heating, is very useful.
 - Must be at 90kV for MSE to work.
- Source B: $R_{\text{tan}}=60$ cm
 - Often goes in 40 msec after A.
- Source C: $R_{\text{tan}}=50$ cm
 - Most poorly confined...lots of loss power at/beneath 700 kA.
 - Short early blip of C often used to trigger H-mode transition (80-120 msec).
- 65-70 kV is a typical minimum voltage.
- 90-95 kV is a typical maximum voltage.



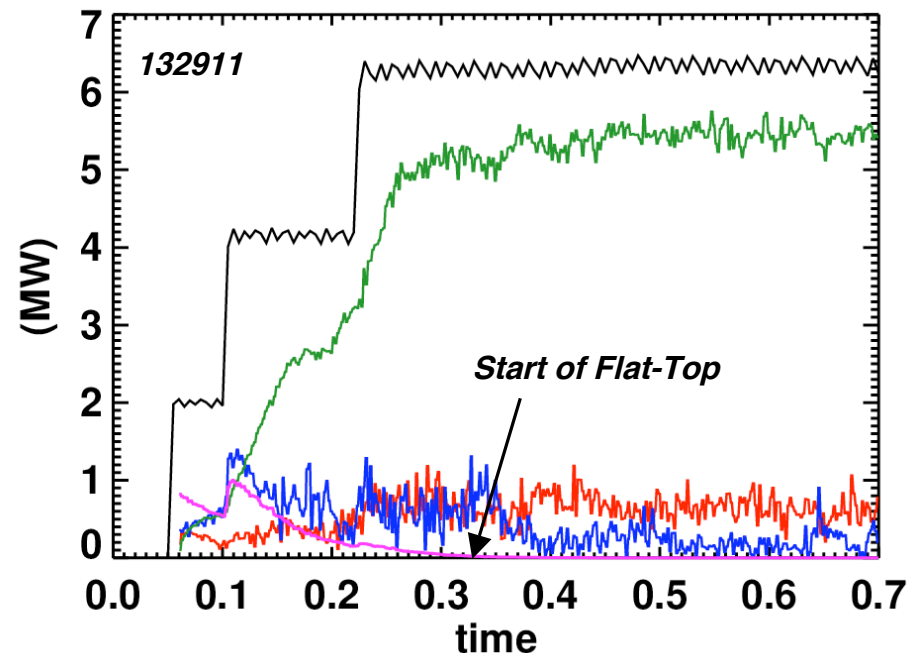
Beam Loss Power Depends on Plasma Current, Internal Inductance, and Outer Gap

Loss Power

Charge Exchange *Bad Orbit* *Shine Through* *Heating* *Total Injected*



$I_p=700$ kA
 $I_i=0.55$
15 cm outer gap
Voltages=[90,90,90] kV



$I_p=1300$ kA
 $I_i=0.4$
10 cm outer gap
Voltages=[90,95,95] kV

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 use feedback to regulate the β_N values so as to avoid instability.
 - Would like to turn off beams before/while (automatically) ramping down I_P .
- How?
 - Preprogrammed timing (what we know before the shot)...called over the phone, or...
 - Can be entered as waveforms into PCS.
 - Info send to the EPICS beam control software via an EPICS-PCS link.
 - Changes must be “approved” by NBOS pressing a button on their screen.
 - Feedback (changes we can’t time before the shot).
 - Parameters that govern the feedback are PCS waveforms and parameter data.
 - 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.
- What is NOT in scope for PCS beam control?
 - Source acceleration voltages.
 - Anything to do with the filament and arc supplies.
- Communication with NB operators is important.
 - We need to provide them with necessary information for reliable source operations.

Implementation of β_N Control in NSTX

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

$$e = \beta_{N,request} - LPF(\beta_{N,rtEFIT}; \tau_{LPF})$$

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

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

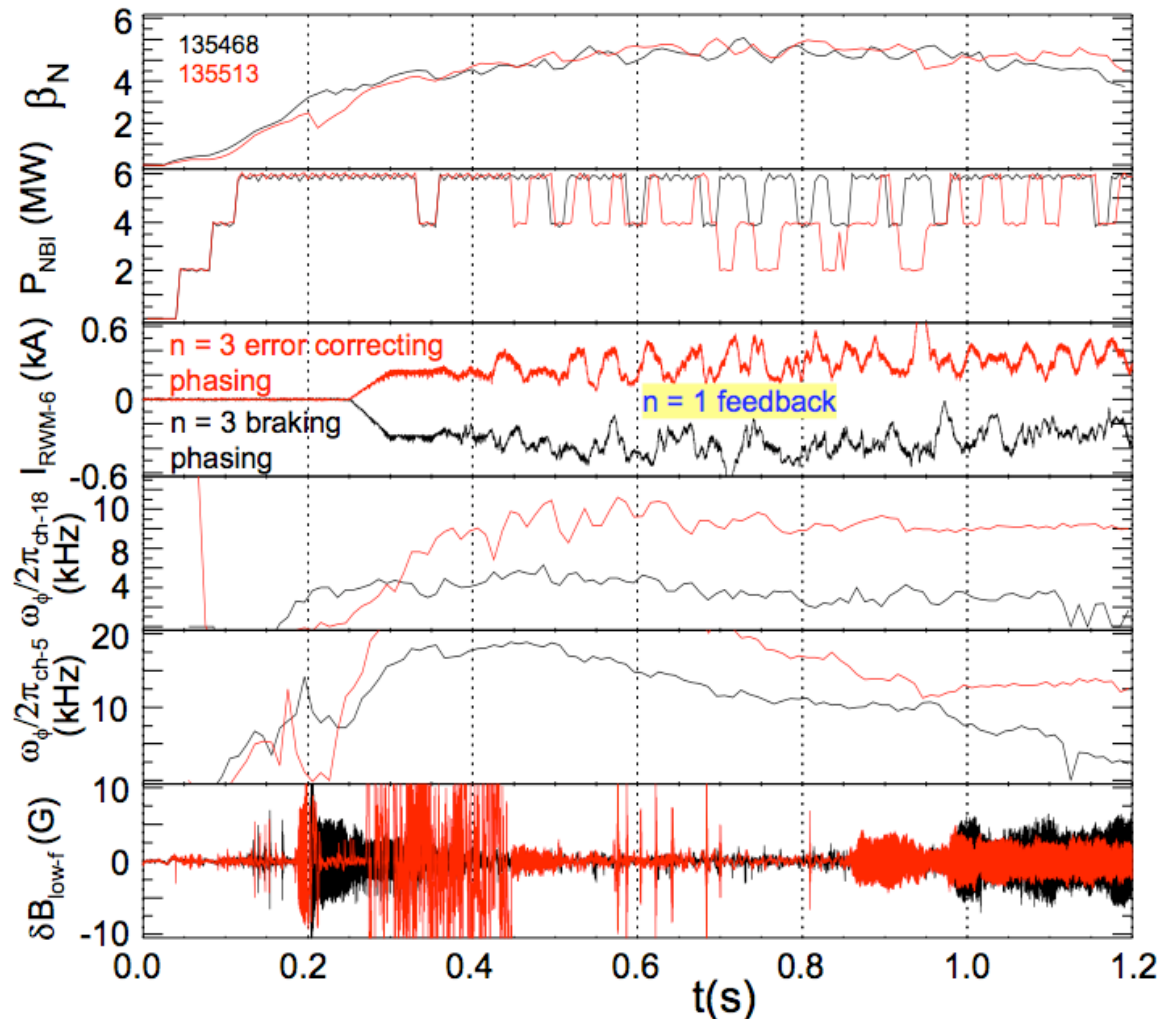
$$\bar{C}_{\beta_N} = 1000 \cdot \tau \cdot \frac{I_P V B_T}{200 \mu_0 a}$$

- 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 any given source up to 20 times per discharge, with 10 msec minimum on/off times.
 - Grid faults count toward the 20 blocks per discharges (?).

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.
 - ***No phase changes allowed in the NBI category!***

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 $ff'(\psi_n)$
- Considerable real-time reconstruction improvement
 - Reduction in β_N “noise” indicative of improved reconstructions

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

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

