NSTX

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

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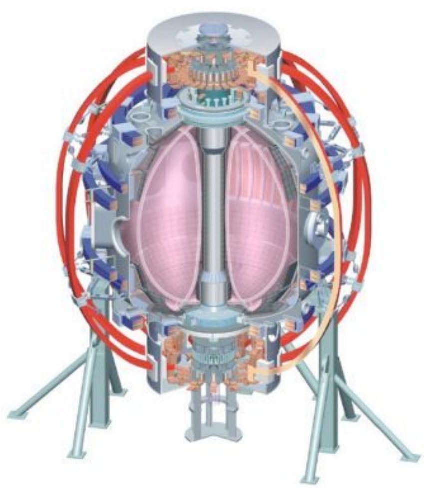

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Topics

- 3-D Fields
  - Motivation for low-frequency 3-D field sensors and coils.
  - Overview
  - How to detect an n=1 mode.
  - What determines the currents in the EFC coils?
  - High-frequency rotating MHD detection.
- 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?

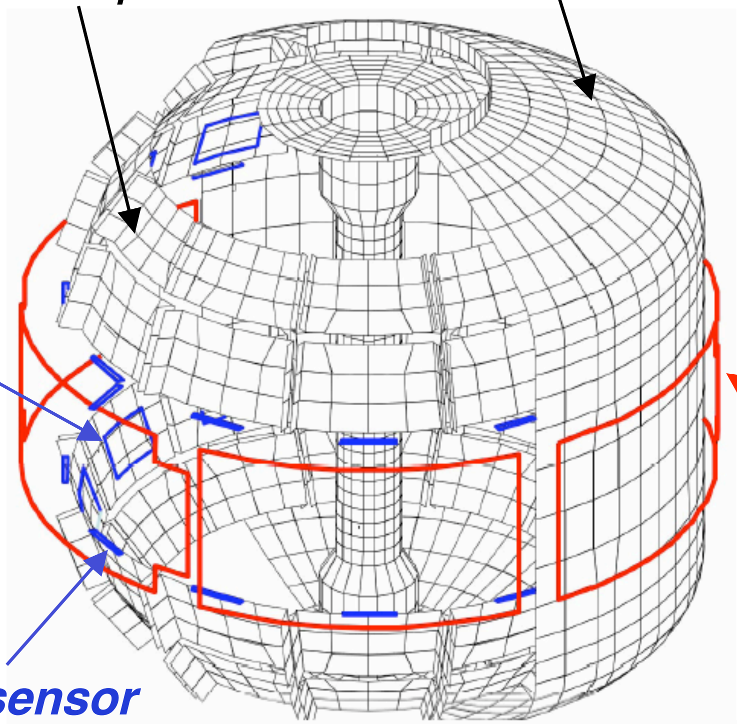
- Deliberately apply fields as perturbations:
  - Locked mode thresholds vs. density, field,…
  - Magnetic braking to study "stuff" as a function of rotation.
  - (N)RMP for modifications to pedestal transport & ELM suppression.
    - or ELM triggering.
  - Strike-point splitting, 3-D effects on divertor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

NSTX Has Midplane External Coils and Off-Midplane Internal Sensors

Copper passive conductor plates

SS Vacuum Vessel

B_R

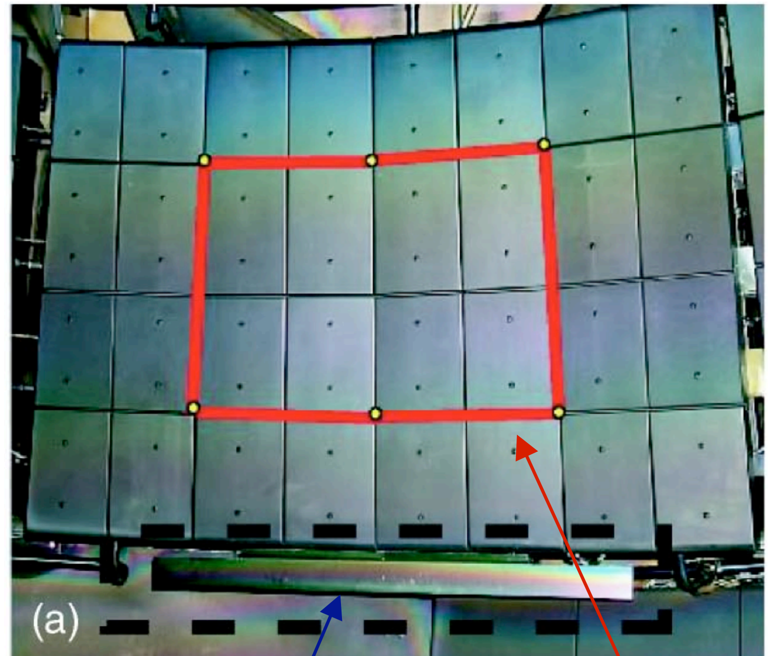


B_P sensor

6 ex-vessel midplane control coils

VALEN Model of NSTX (Columbia Univ.)

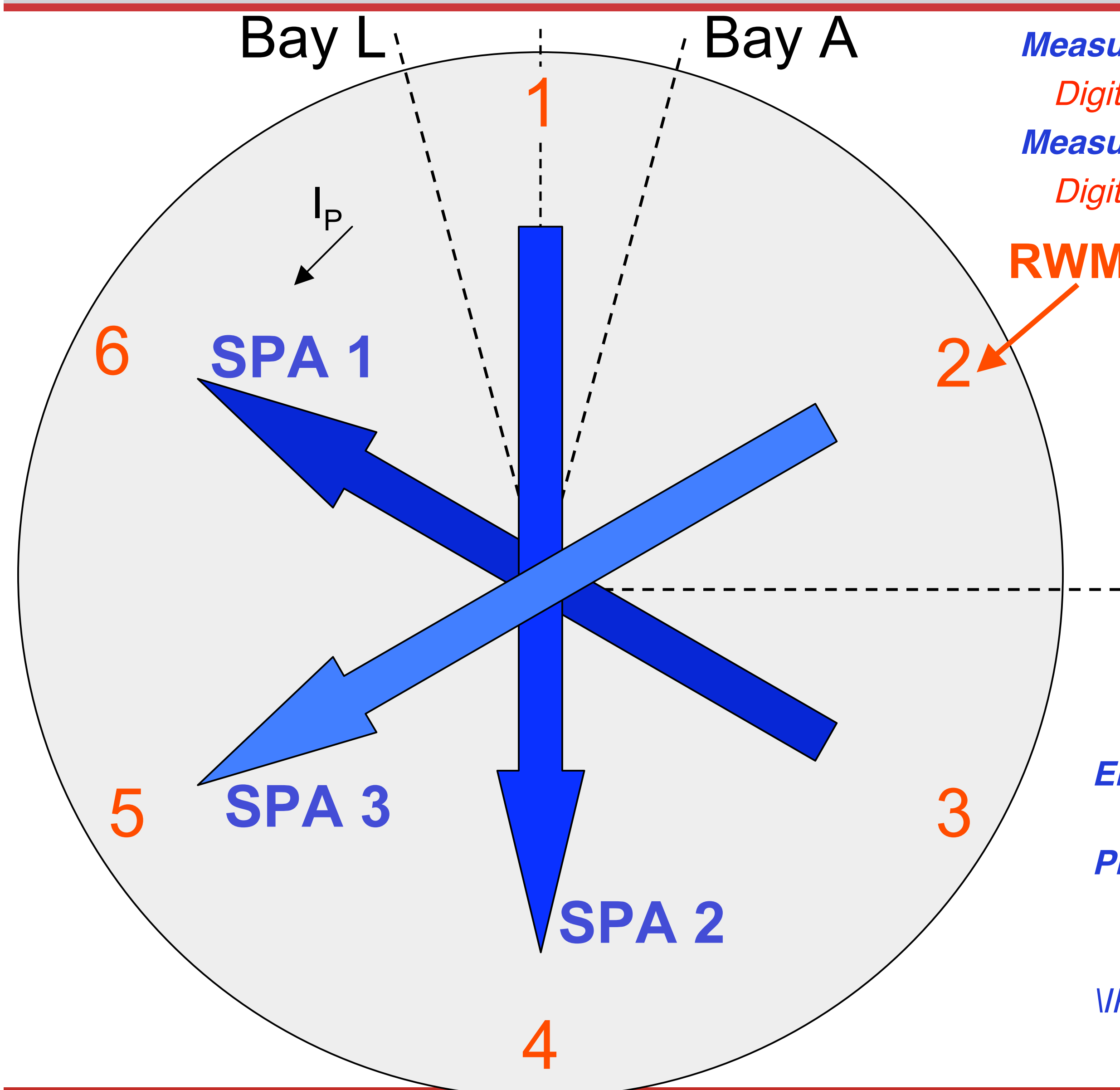
Sontag et al., Physics of Plasmas **12** 056112 (2005)



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

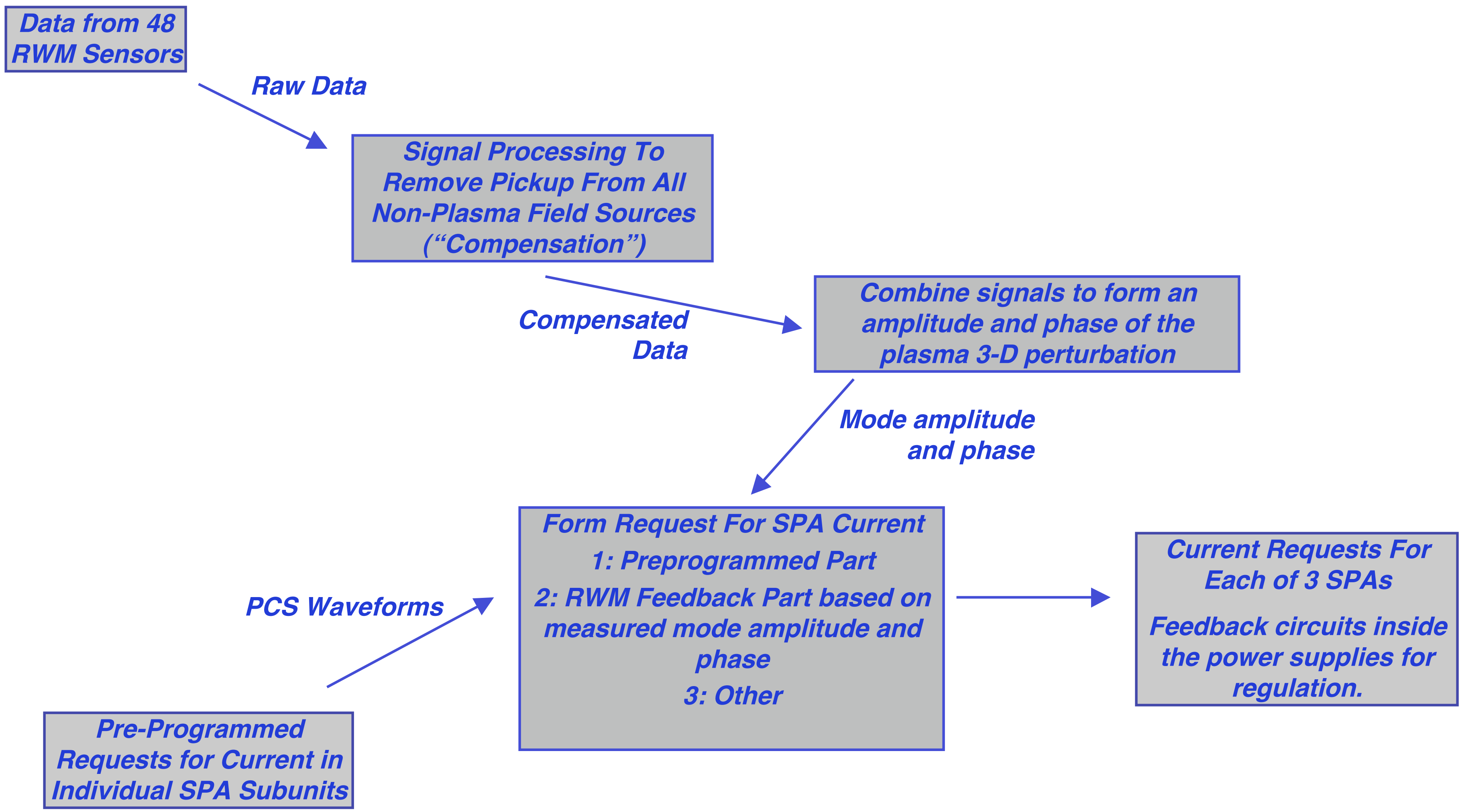
Sign conventions:

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

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

\IRWM1, \IRWM2,… 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. $P_{i,j}$ 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

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

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

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

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

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

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

In ACQ

In the modelID 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!

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

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

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

$$\phi_{RWM} = a\tan(S_{RWM} / C_{RWM})$$

  - 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: $\delta(t)$

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

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

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

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

- Apply a low-pass filter:

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

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

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

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

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

  - 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:

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

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

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

- 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:

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

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

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

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

There Are Many More Algorithms in the RWM Category

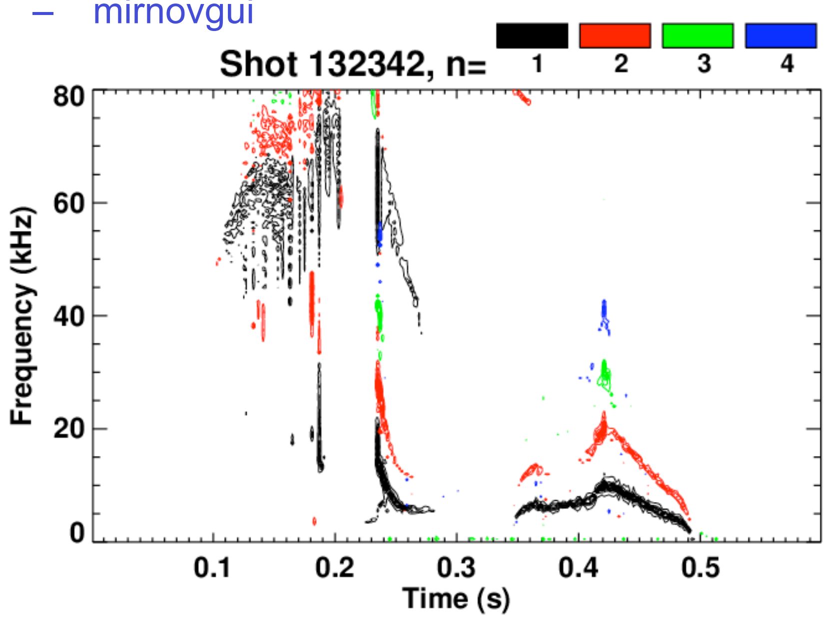
- "spa"=SPA
  - Pre-programmed EFC coil currents only.
- "fec": Field Error Correction
  - Pre-programmed currents
  - SPA currents ∝ PF coils and voltages on certain flux loops.
- "imf"=Initial Mode Feedback
  - First generation of RWM control.
  - No low-pass filtering.
  - No separate gains for B_P 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.

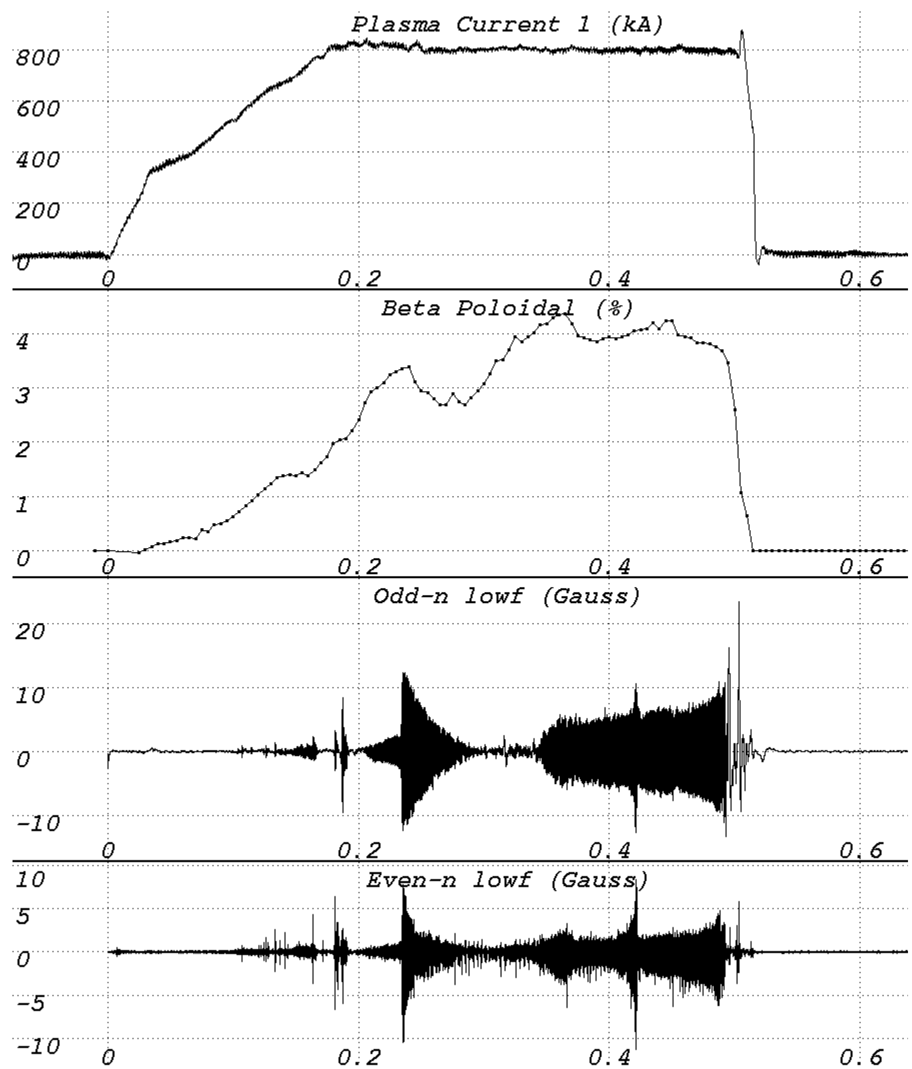
Advanced RWM Controller

- 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.

Detect Rapidly Rotating Modes With Smaller Internal Sensors

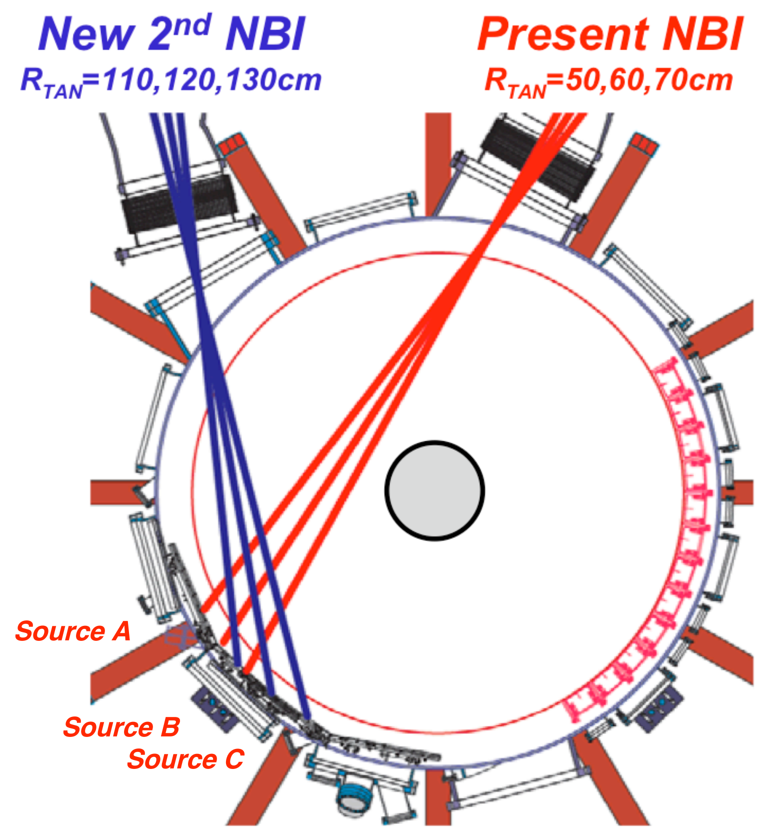
- High-n Array: Small B_P sensors mounted ~40 cm below the midplane.
  - Same sensors as for equilibrium field detection.
  - 12 sensors digitized in PCs at 4 MHz
  - No hardware integrators
- Pick 2 sensors 180º apart
  - Add the signals: Even-n magnetic signature.
  - Subtract the signals: Odd-n magnetic signature.
  - These signals written to the tree on every shot.
- Or, do a full decomposition in n-number….type in idl:
  - @/u/sgerhard/NSTX/idl/startup
  - mirnovgui





Overview of NBs…Physicist Perspective

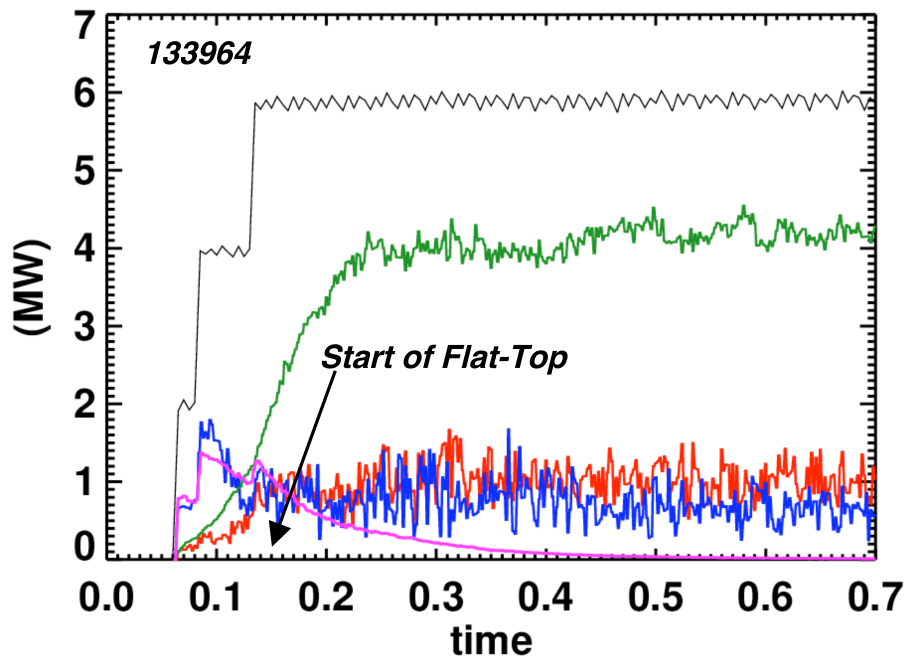
- Source A: R_{tan}=70 cm
  - Typically injected as early as 40 msec., when I_P=350 kA.
    - TRANSP indicates that it is mostly lost during this time.
    - Torque, and some heating, is very useful.
  - Must be at 90kV for MSE to work.
- Source B: R_{tan}=60 cm
  - Often goes in 40 msec after A.
- Source C: R_{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.



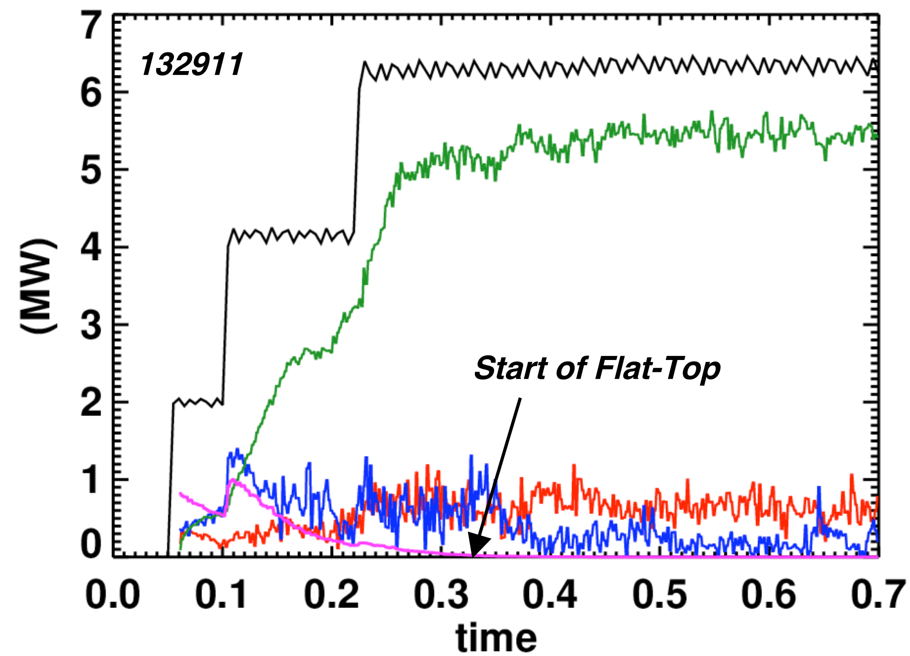
Beam Loss Power Depends on Plasma Current, Internal Inductance, and Outer Gap

Loss Power

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



I_P=700 kA
l_i=0.55
15 cm outer gap
Voltages=[90,90,90] kV



I_P=1300 kA
l_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.

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

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

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

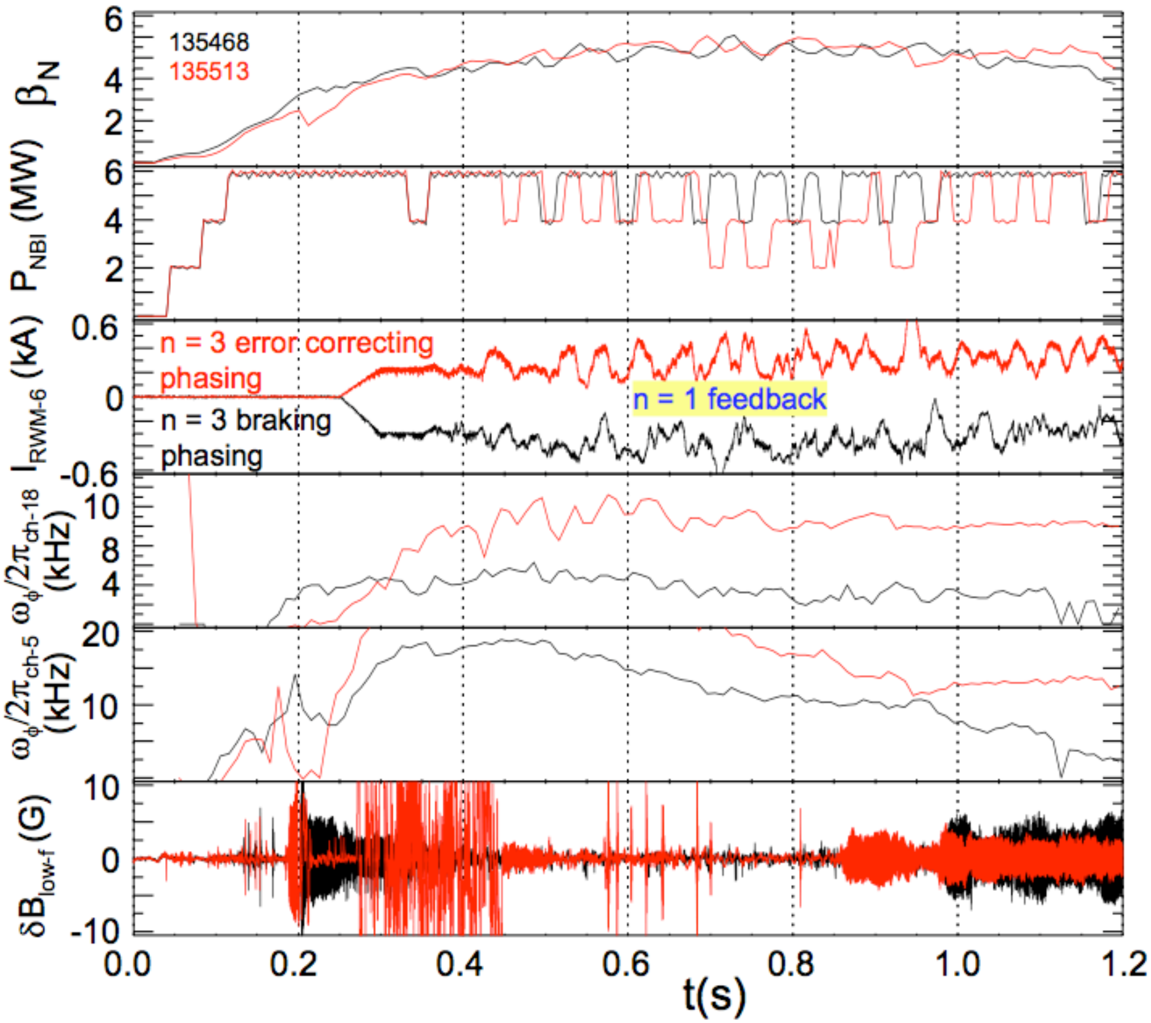
$$\overline{C}_{\beta_N} = 1000 \cdot \tau \cdot \frac{I_P V B_T}{200\mu_0 a}$$

- 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 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

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

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

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