U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

3D Fields: Detection and Application

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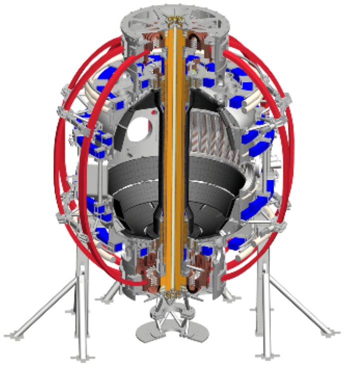
Phys. Ops. Course 2015

PPPL



Topics

- Motivation for low-frequency 3-D field sensors and coils.
- Application of low-frequency 3D fields
- Detection of low-frequency 3D fields
- Determination of the currents in the RWM coils
- High-frequency rotating MHD detection.

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

- 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”

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

- 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).

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

- 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. (~2-5 msec).
  - Detect and suppress it.
    - Call this “fast” n=1 feedback.

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

- Kink, Tearing, *AE
  - These show up as rapidly rotating/varying 3D perturbations.
    - 5 kHz -> 1s of MHz
  - Can only be detected with sensors inside the vessel
  - Tearing modes and kinks can degrade thermal confinement, stop the plasma rotation, modify the fast ion confinement and current drive.
  - Bursting TAE modes can eject (or steal energy from) fast ions, changing beam current drive.
  - GAE/CAE modes lead to PRLs.

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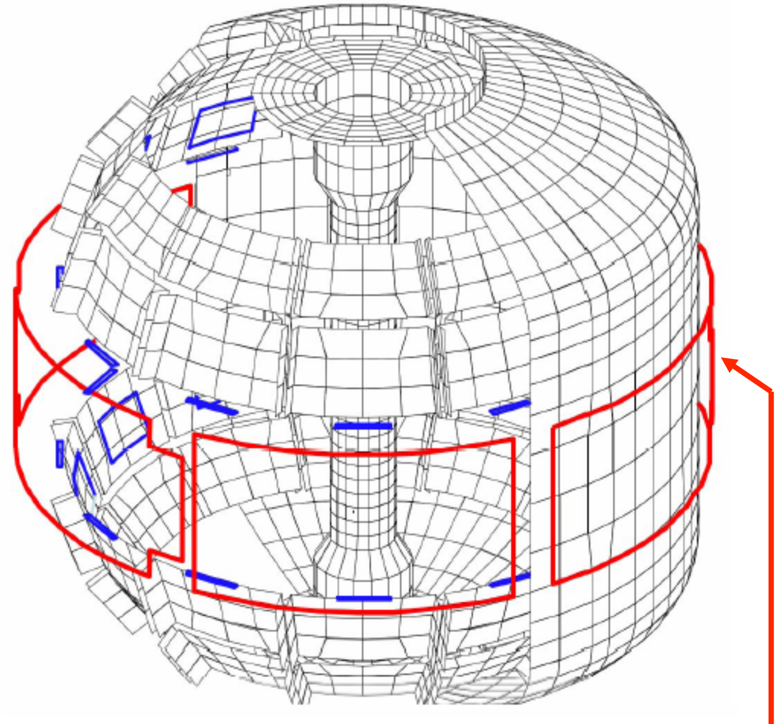
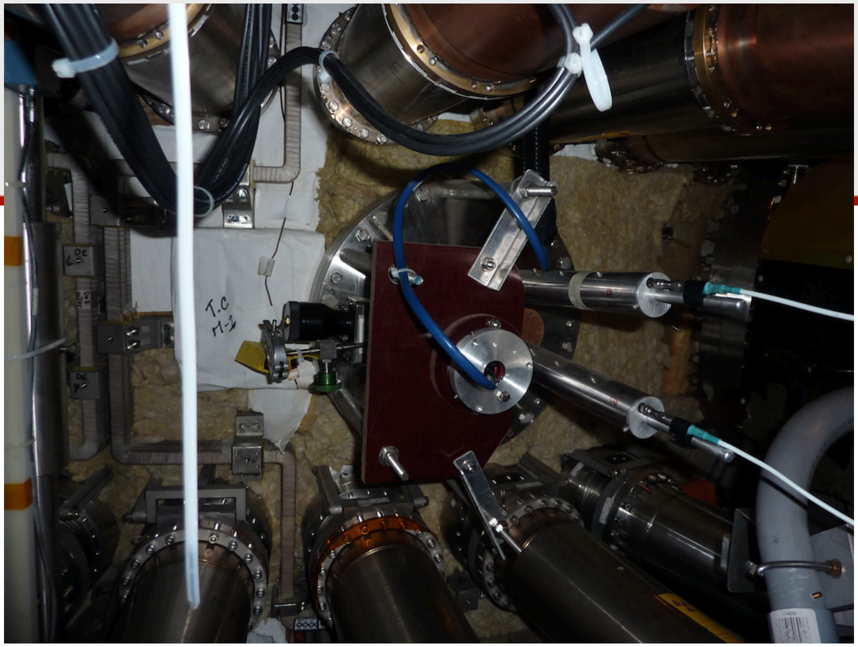
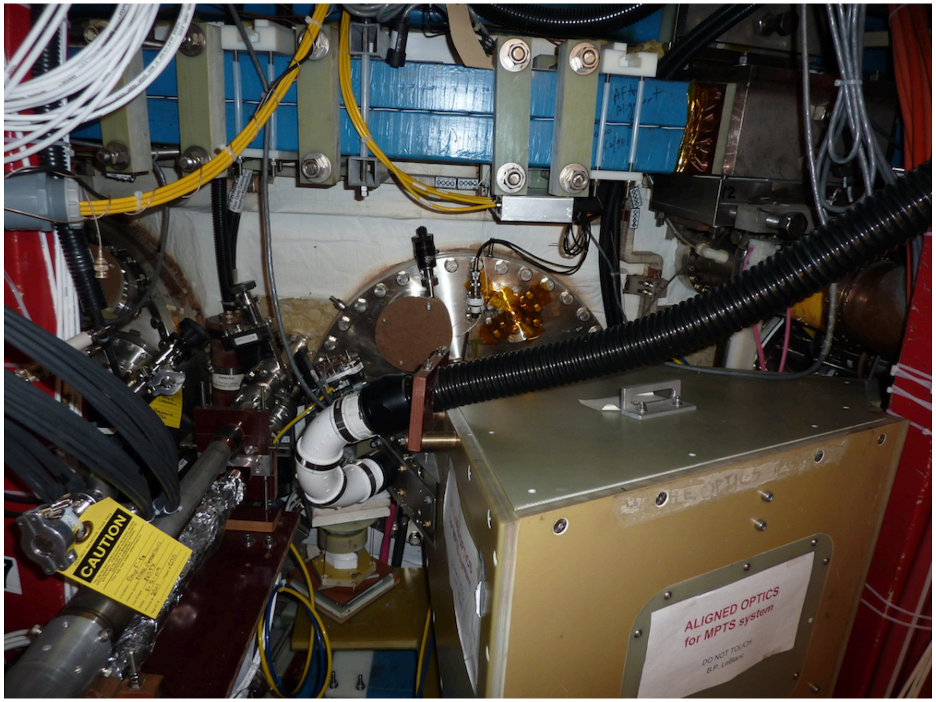
3D Fields Are Applied by the RWM Coils



6 ex-vessel midplane control coils

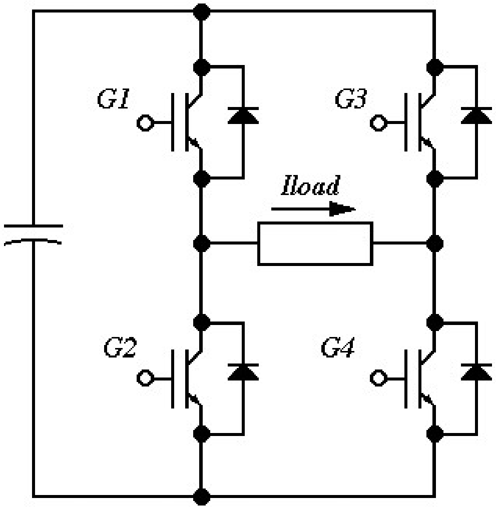
VALEN Model of NSTX (Columbia Univ.)



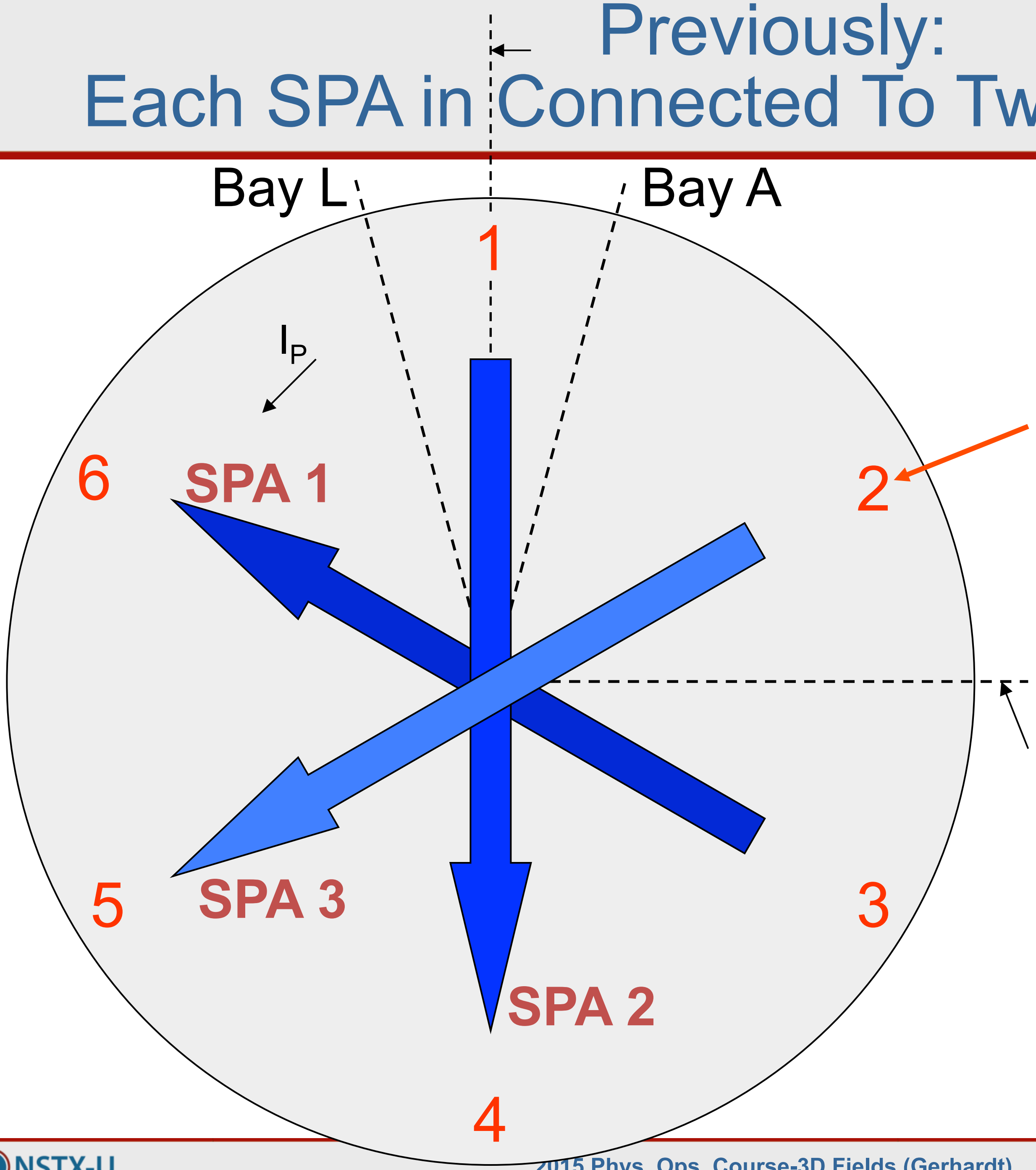


RWM Coil Current is Provided by the SPAs

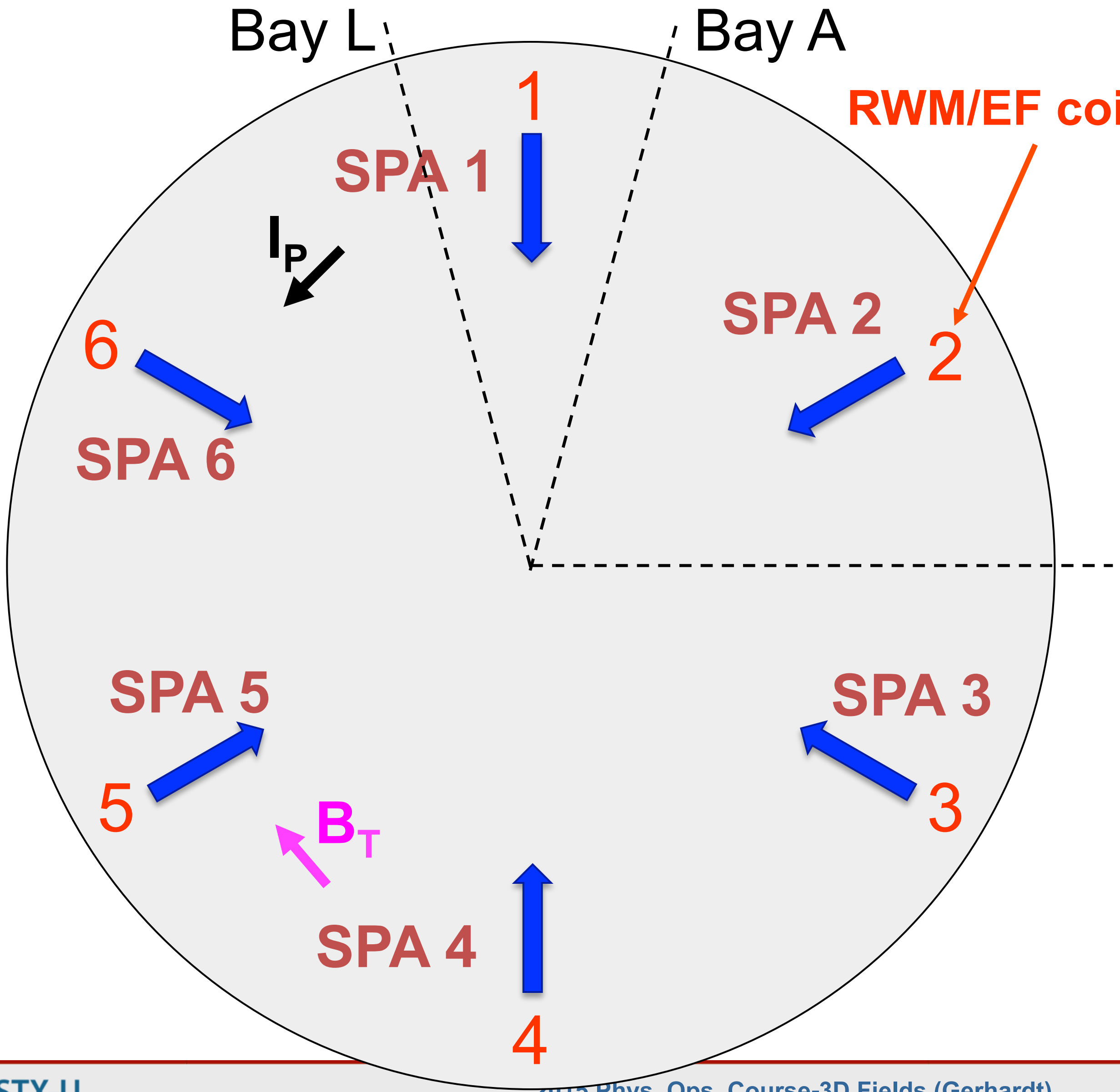
- SPAs are H-bridge power Supplies
  - Capacitor bank is a constant voltage
  - If G1 and G4 conduct, then load voltage is one polarity
  - If G2 and G3 conduct, load voltage has the other polarity.
  - Rapidly switch which IGBT conduct. This leads to regulation of the current.
- We rely on the on-board controller, and only issue a current request to the SPA.
- SPA cap bank is charged by "HF Supply"
  - If HF supply doesn't work, then neither will the SPAs



Previously:
Each SPA in Connected To Two RWM Coils



Now:
Each SPA in Connected To a Single RWM Coil



Positive SPA current makes:

- Field flowing CW in the RWM coil as you face the coil.
- This makes field pointing into the vessel

More on Signal Polarities

- Positive SPA *supply current* makes current flowing clockwise when viewed from outside NSTX-U.
  - This makes field that points into the vessel.
  - Hence, positive supply current makes field pointing into the vessel.

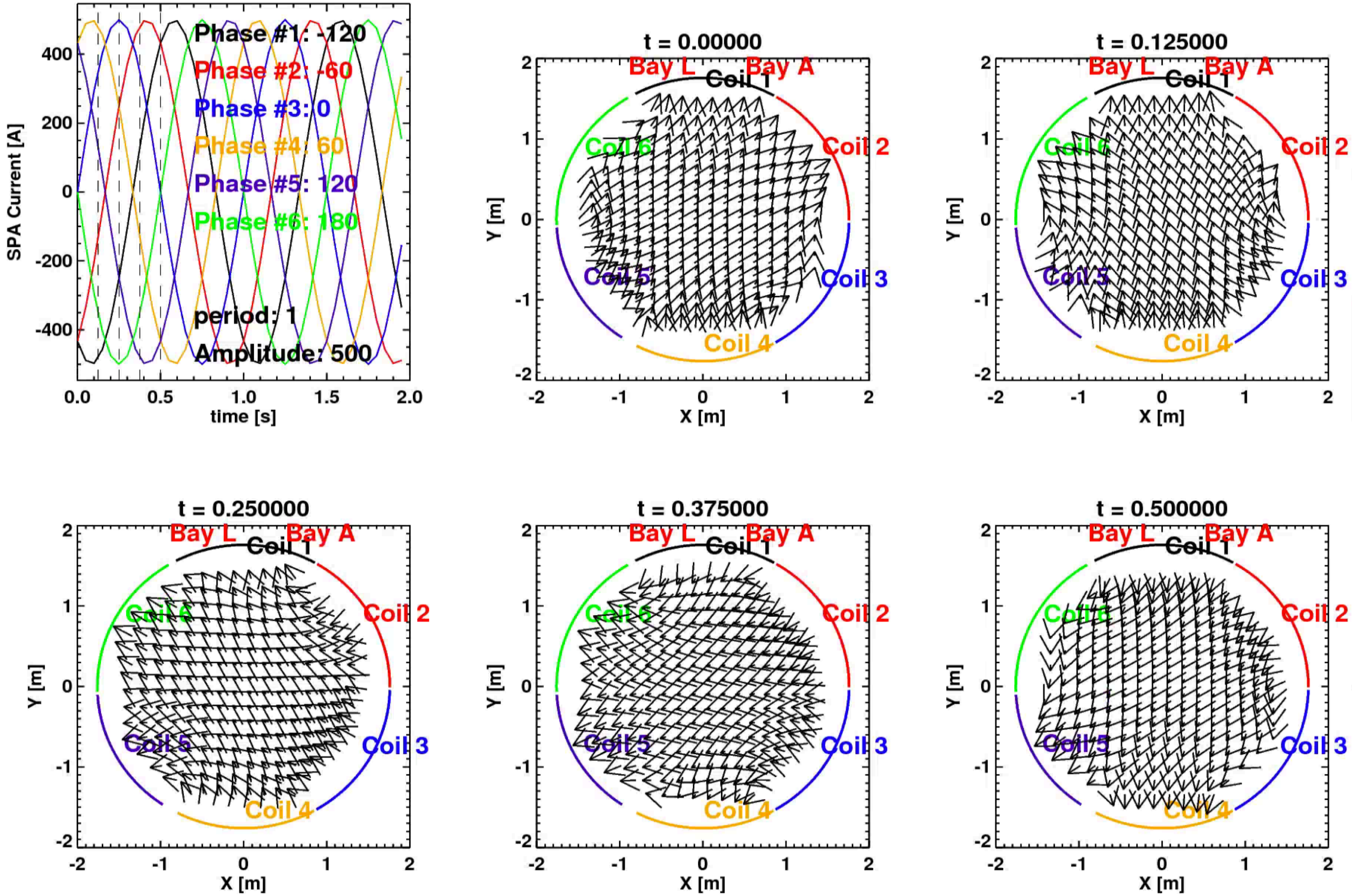
- The PCS requests are always supply current.
  - So a positive PCS request will make field pointing into the vessel for the associated coil.
  - This is a bit different than for the PF/TF coils, where the requests are the coil current.

- The SPA currents are recorded multiple ways.
  - \pc_spa_SUX_IY, X={1:6} & Y={1:2}, are the 2 DCCTs on the SPAs themselves. They have the polarity of the supply current.

  - The \IRWMX, X={1:6} are the subunit currents mapped to the coils and corrected for signs so that positive current corresponds to positive radial field.

  - The \RWMX_I, X={1:6}, are current measurements on the coil leads, but with the engineering convention.
    - Positive values correspond to clockwise currents and inward pointing field

Typical Application is to Make n=1 Traveling Waves



You Will Use the PCS Waveform Generator Function to Produce Traveling Waves

PCS Sine Wave Generator

Determined by Parameters

1: offset,

2: amp,

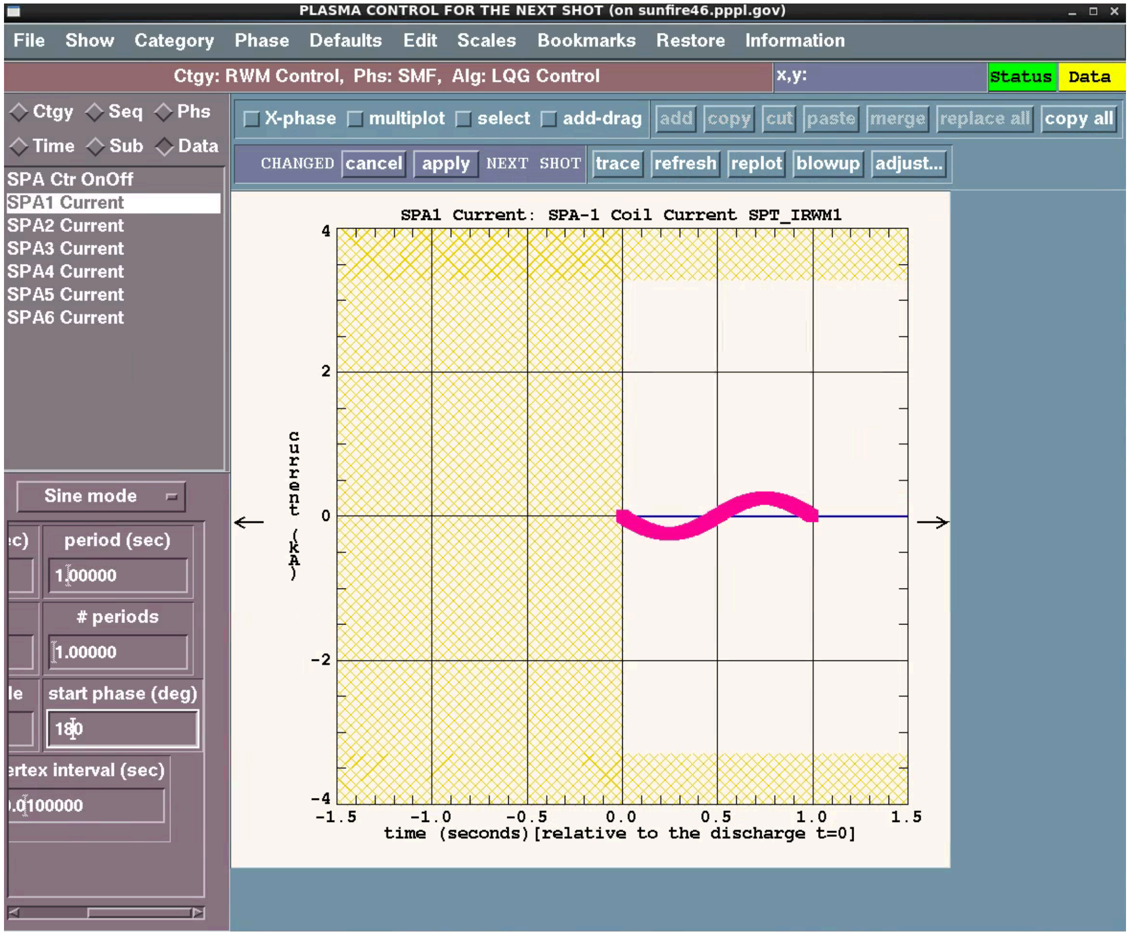
3: period [seconds],

4: # of periods,

5: start phase [degrees]}

Or

$[Y_{DC}, Y_{amp}, T_{cycle}, \text{\# of periods}, \phi_{start}]$



Ctgy: RWM Control, Phs: SMF, Alg: LQG Control

period (sec): 1.00000

periods: 1.00000

start phase (deg): 180

ertex interval (sec): .0100000

$$I_{SPA}=Y_{DC}+Y_{AMP}\sin(2\pi t/T_{cycle} + \pi\phi_{start}/180))$$

XP authors/forms should know exactly the parameters to get the correct traveling wave

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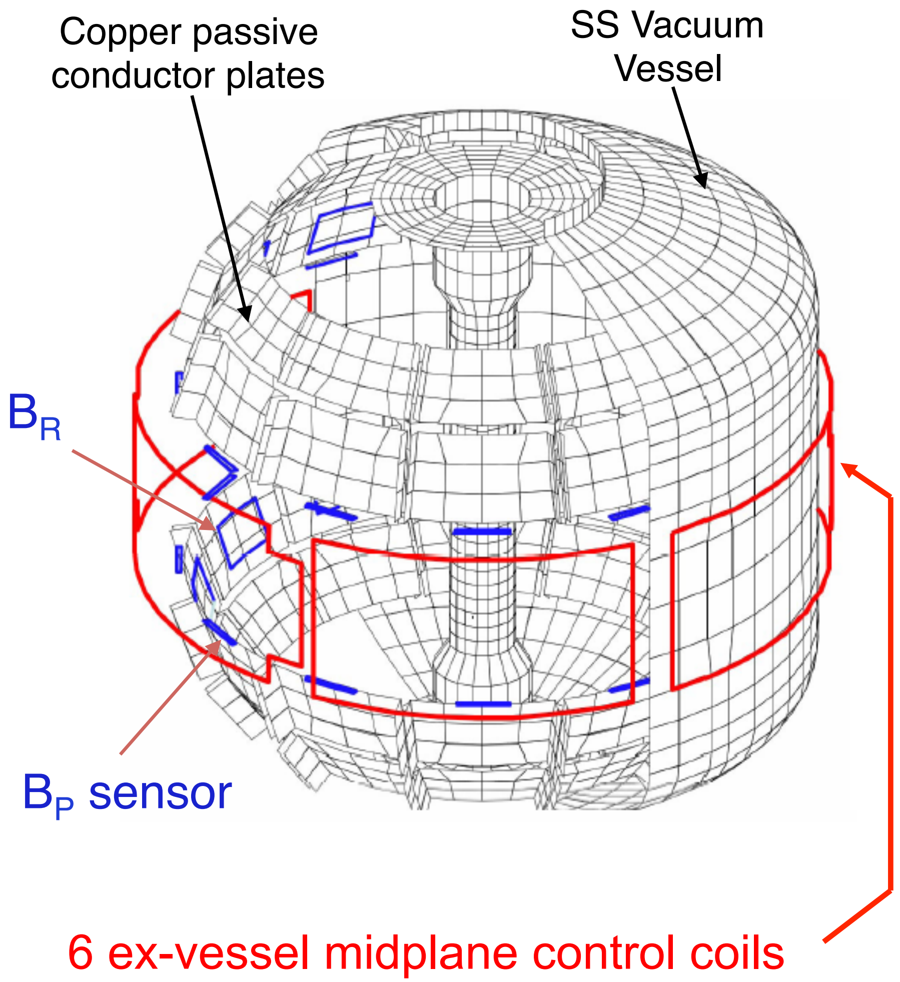
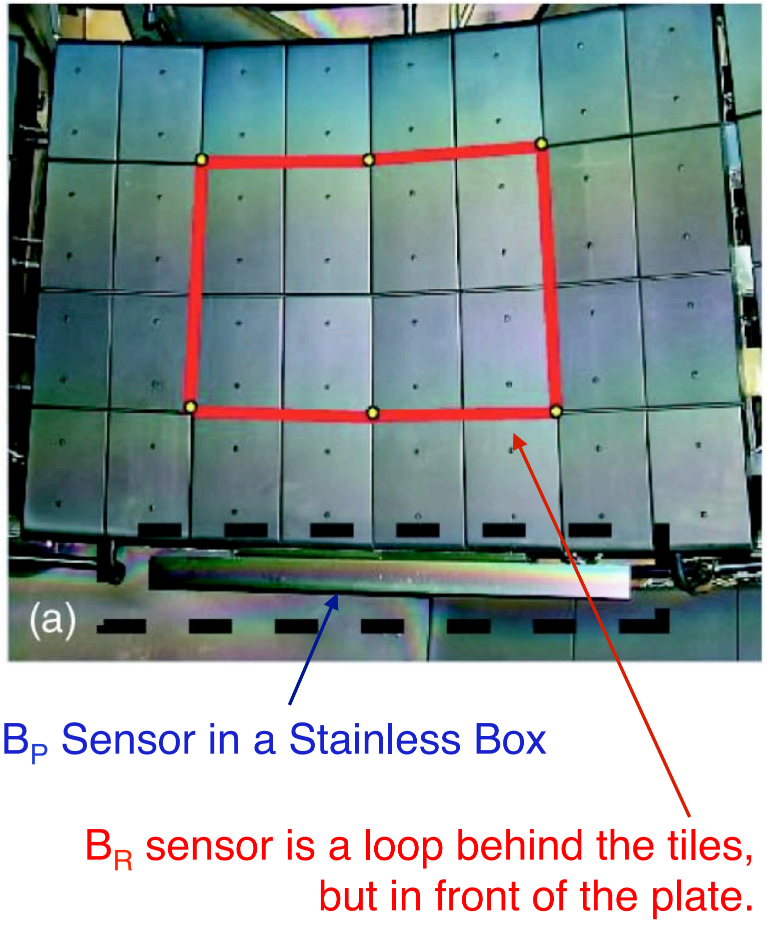
NSTX-U has Off-Midplane Internal 3D Field Sensors

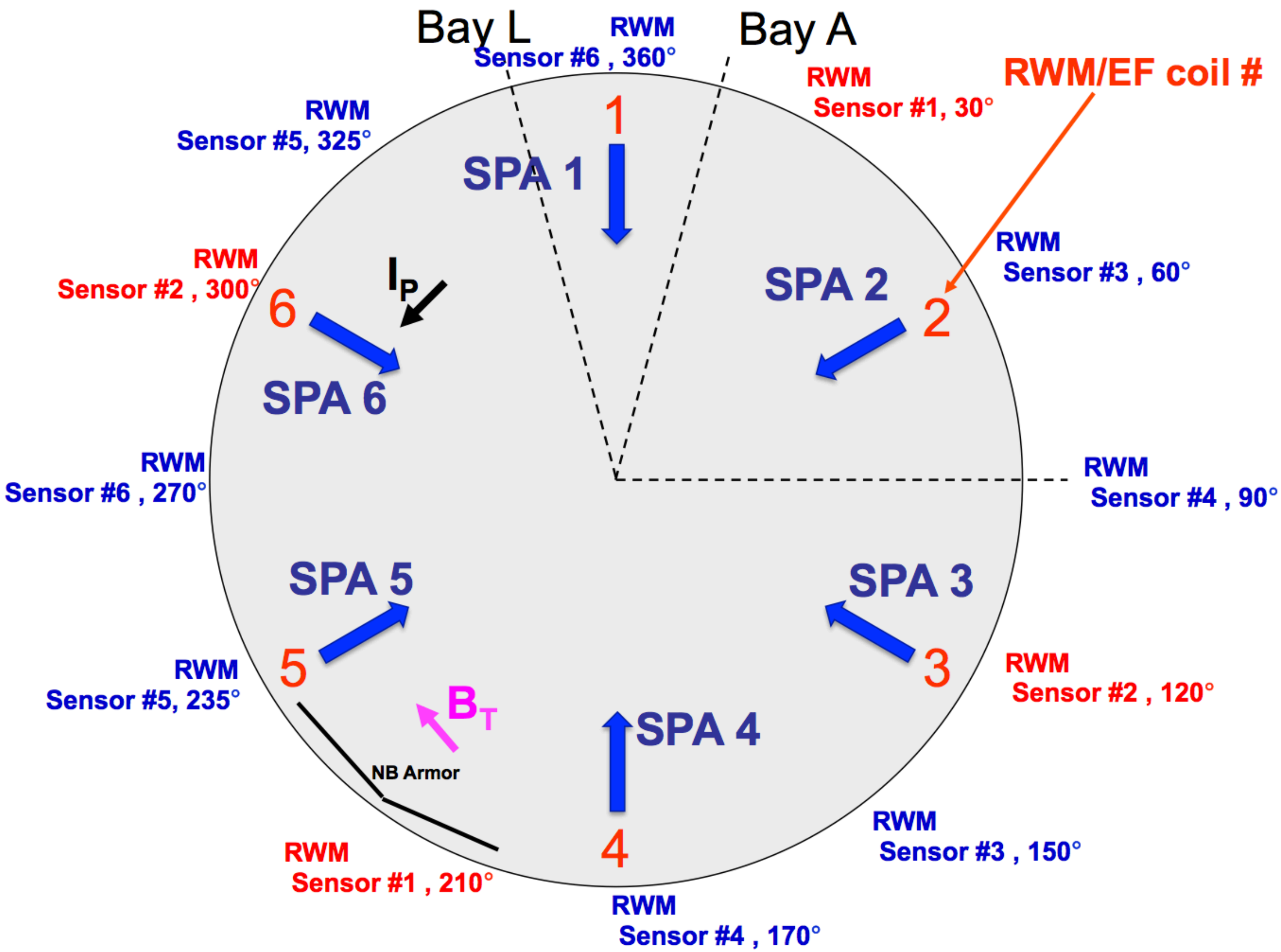


VALEN Model of NSTX (Columbia Univ.)

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



We Actually Integrate Sensor Sums and Differences



PCS Signal Compensation For RWM Coils

- Any given sensor detects the field from the plasma perturbation, plus other sources.
  - – "Other sources" include direct coil pickup, eddy currents.
- Subtract non-plasma pickup from each signal.
- Many coefficients involved, all in model tree.

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

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

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

In ACQ

In the modelID category

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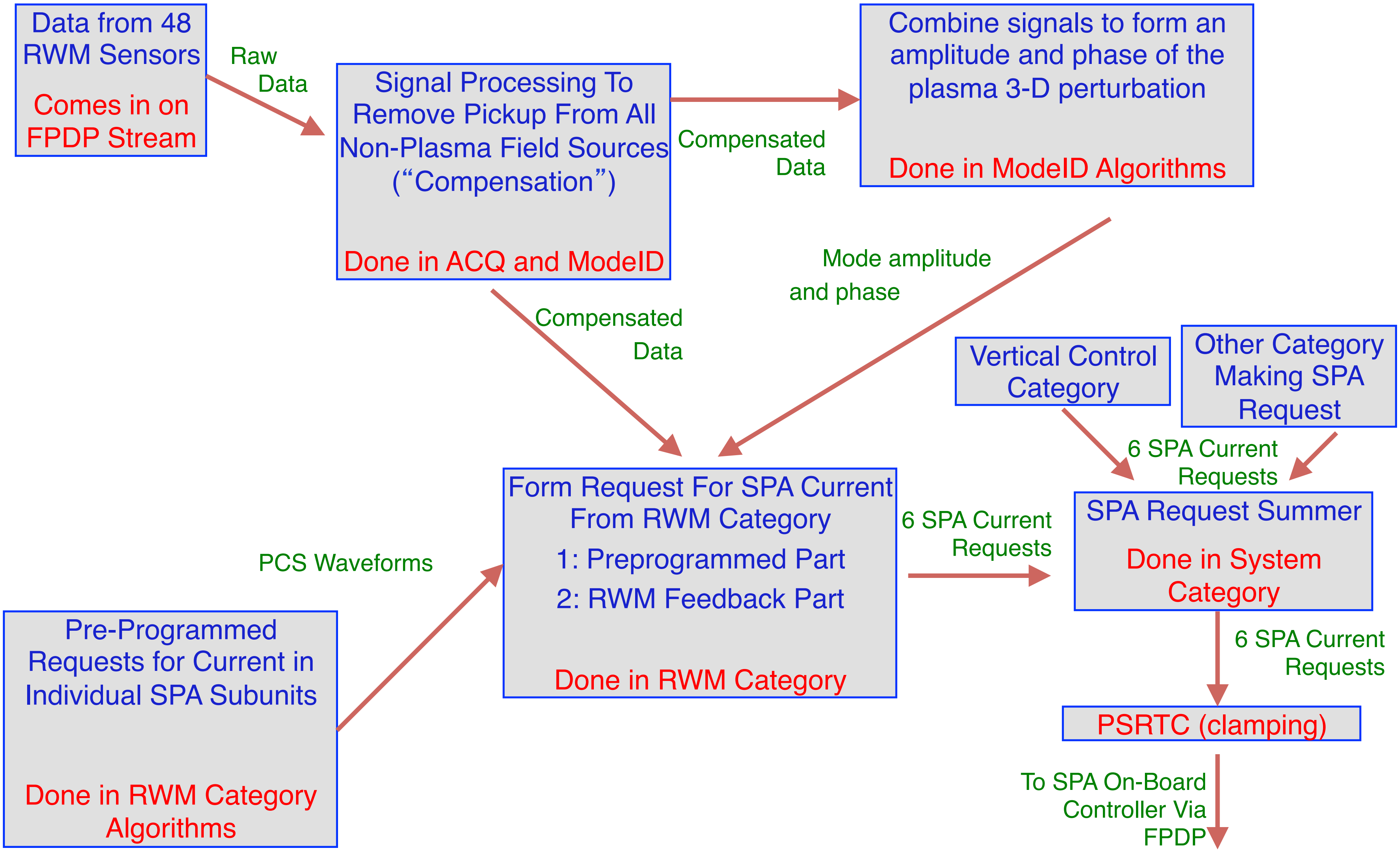
Overall Scheme for Control



Data from 48 RWM Sensors

Comes in on FPDP Stream

Raw Data

Signal Processing To Remove Pickup From All Non-Plasma Field Sources (“Compensation”)

Done in ACQ and ModelD

Compensated Data

Combine signals to form an amplitude and phase of the plasma 3-D perturbation

Done in ModeID Algorithms

Mode amplitude and phase

Compensated Data

Vertical Control Category

Other Category Making SPA Request

6 SPA Current Requests

PCS Waveforms

Form Request For SPA Current From RWM Category

1: Preprogrammed Part

2: RWM Feedback Part

Done in RWM Category

6 SPA Current Requests

SPA Request Summer

Done in System Category

6 SPA Current Requests

PSRTC (clamping)

To SPA On-Board Controller Via FPDP

Pre-Programmed Requests for Current in Individual SPA Subunits

Done in RWM Category Algorithms

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, CEM, or 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!

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

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

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

  - Matrix elements are a/the primary input to the algorithm.
- Many more details in reality, but this is the idea.
- Big gotcha: Sometimes sensors fail. The mode-ID matrix must use only the good sensors.
  - Beware reloading! Consult CEM and SPG if in doubt.

Algorithms for Mode Identification: mid

- mid=“Mode Identification” (modeid Category)
- Uses 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

- miu=“Mode Identification Upgrade” (modeid Category)
- Applies 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 "tmf" Algorithm

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
- Apply an n=1 field with:
  - Amplitude proportional to the detected 3-D field
  - Fixed phase shift from the detected 3-D field.

$$I^{RWM}_{SPA,BP}(t) = -1 \times G_{RWM,BP}(t) B_{BP1}(t) / L_{eff}$$

$$I^{RWM}_{SPA-1}(t) = \qquad I^{RWM}_{SPA-BP}(t)\cos(0° - \theta_{BP1}(t) + \delta_{BP}(t))$$

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Feedback Gain (PCS Waveform)

$$I^{RWM}_{SPA-1}(t) = \qquad I^{RWM}_{SPA-BP}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t))$$

Detected Mode Amplitude
(From Mode ID)

RWM/DEFC Feedback Methodology in the "tmf" Algorithm

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
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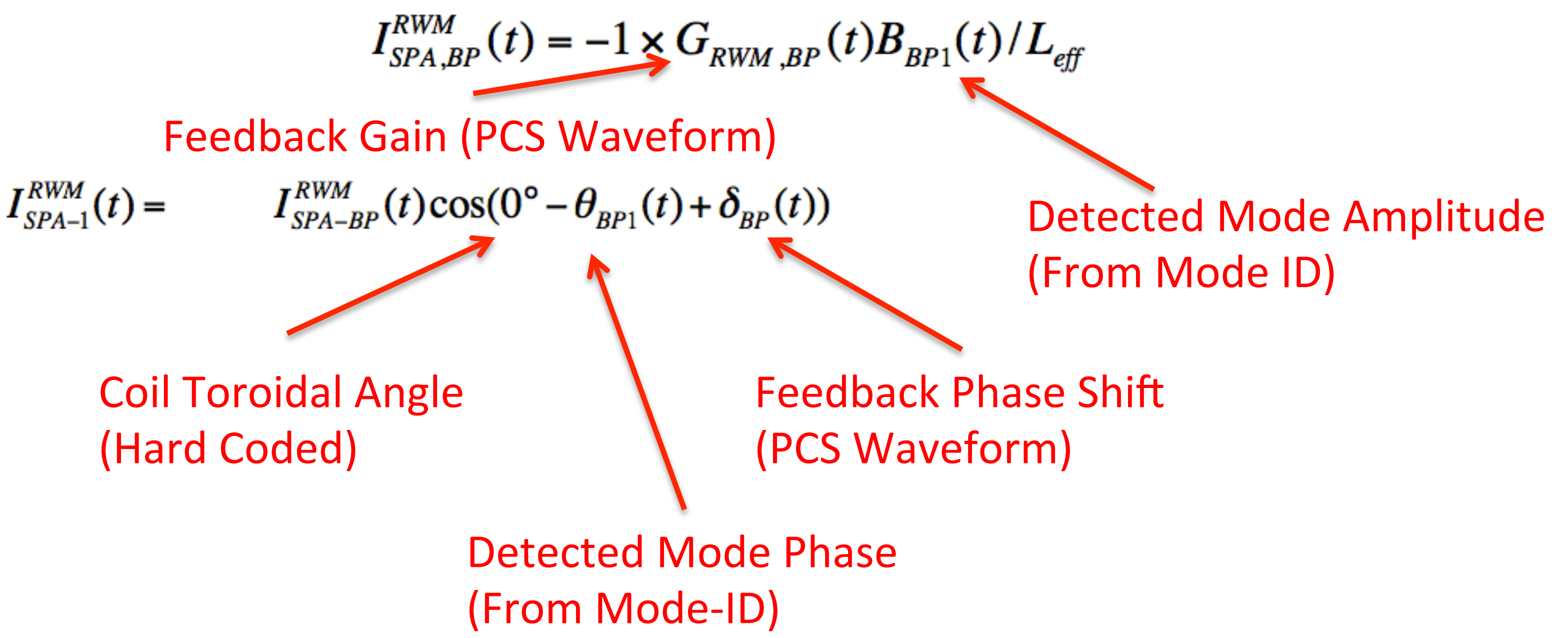

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(From Mode ID)

$$I^{RWM}_{SPA-1}(t) = \quad I^{RWM}_{SPA-BP}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t))$$

Coil Toroidal Angle
(Hard Coded)

Feedback Phase Shift
(PCS Waveform)

Detected Mode Phase
(From Mode-ID)

RWM/DEFC Feedback Methodology in the "tmf" Algorithm

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
- Apply an n=1 field with:
  - Amplitude proportional to the detected 3-D field
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$$I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM,BP}(t) B_{BP1}(t) / L_{eff}$$

$$I_{SPA-1}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t) \cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right)$$

RWM/DEFC Feedback Methodology in the "tmf" Algorithm

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
- Apply an n=1 field with:
  - Amplitude proportional to the detected 3-D field
  - Fixed phase shift from the detected 3-D field.

$$I^{RWM}_{SPA,BP}(t) = -1 \times G_{RWM,BP}(t) B_{BP1}(t) / L_{eff}$$
$$I^{RWM}_{SPA,BR}(t) = -1 \times G_{RWM,BR}(t) B_{BR1}(t) / L_{eff}$$

$$I^{RWM}_{SPA-1}(t) = LPF\left(I^{RWM}_{SPA-BP}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I^{RWM}_{SPA-BR}(t)\cos(0^\circ - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

RWM/DEFC Feedback Methodology in the "tmf" Algorithm

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
- Apply an n=1 field with:
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$$I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM,BP}(t) B_{BP1}(t) / L_{eff}$$

$$I_{SPA,BR}^{RWM}(t) = -1 \times G_{RWM,BR}(t) B_{BR1}(t) / L_{eff}$$

$$I_{SPA-1}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(0° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(0° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

$$I_{SPA-2}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(60° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(60° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

$$I_{SPA-3}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(120° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(120° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

$$I_{SPA-4}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(180° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(180° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

$$I_{SPA-5}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(240° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(240° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

$$I_{SPA-6}^{RWM}(t) = LPF\left(I_{SPA-BP}^{RWM}(t)\cos(300° - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}\right) + LPF\left(I_{SPA-BR}^{RWM}(t)\cos(300° - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR}\right)$$

There Are Other Algorithms in the RWM Category

- "ssp"="six subunit control"
  - Pre-programmed EFC coil currents only.
  - No real reason for you to use this.
- "LQG" = "Linear Quadratic Gaussian"
  - State-Space feedback
  - Next slide.
- Old defunct algorithms that have vanished
  - "spa": pre-programmed control of 3 sub-units
  - "fec": Field Error Correction
  - "imf"=Initial Mode Feedback
  - "smf"=Second Mode Feedback

Advanced RWM Controller

- Effort lead by Columbia University collaborators
- 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 simple 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,…
- Tested in 2010 run, will be used again in 2016 run.

About Reloading

- All plasma shots ever taken were in the 3 subunit configuration.
  - A few engineering test shots taken with 6 subunits.
- Therefore, you should never reload the entire RWM category from ShotNumber<200000.
  - OK to reload specific waveforms after consideration.
- Due to changes in the RWM sensor availability, you should never reload the ModelD category from ShotNumber<200000
  - Again, OK to reload specific waveforms after consideration.
- No use of these categories until they have been qualified by XMPs (Gerhardt, et al)

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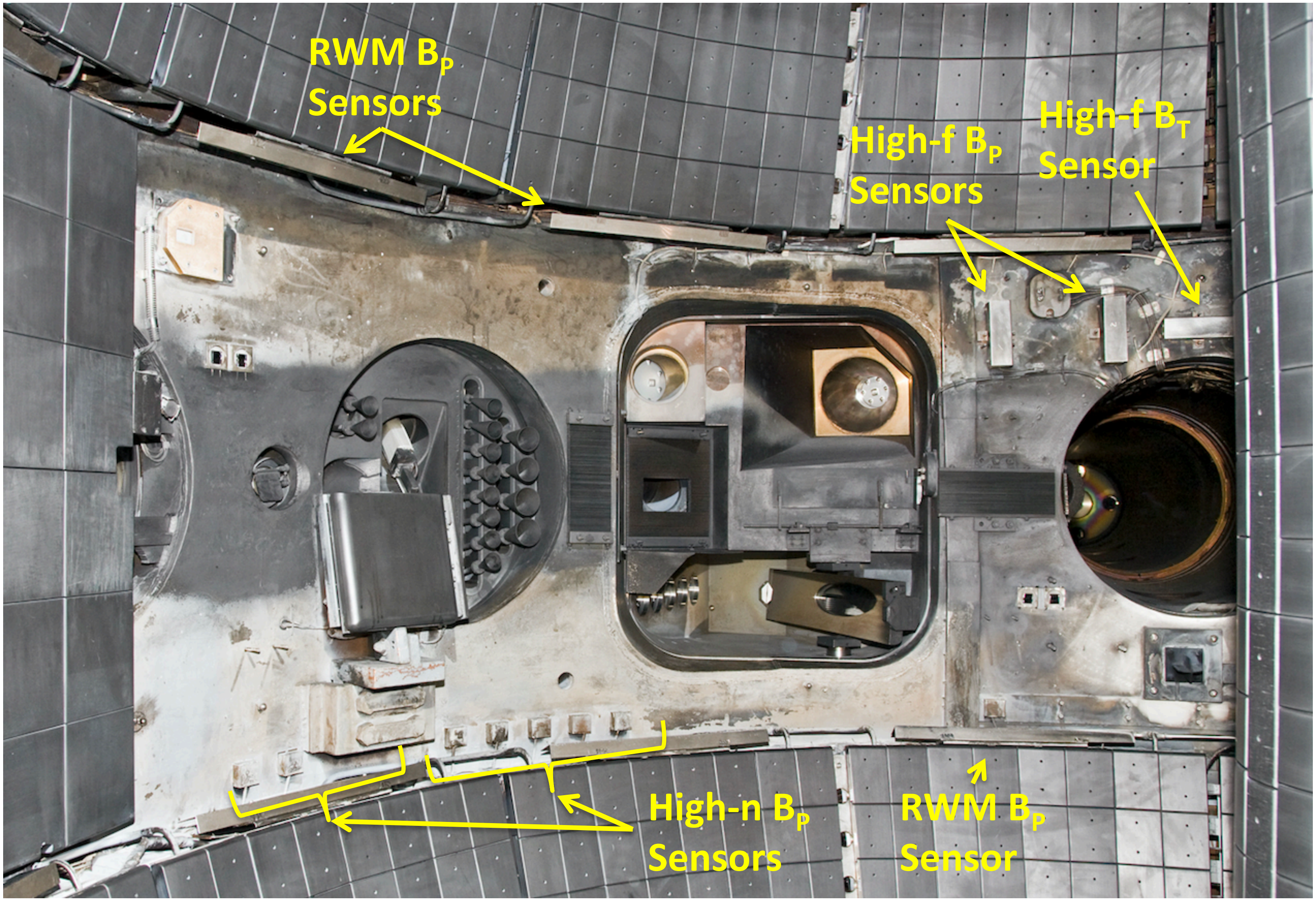
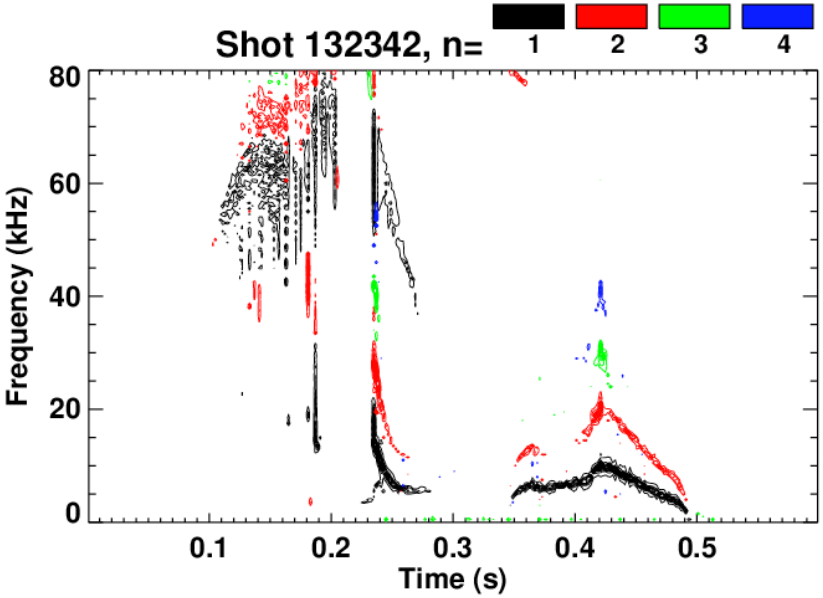
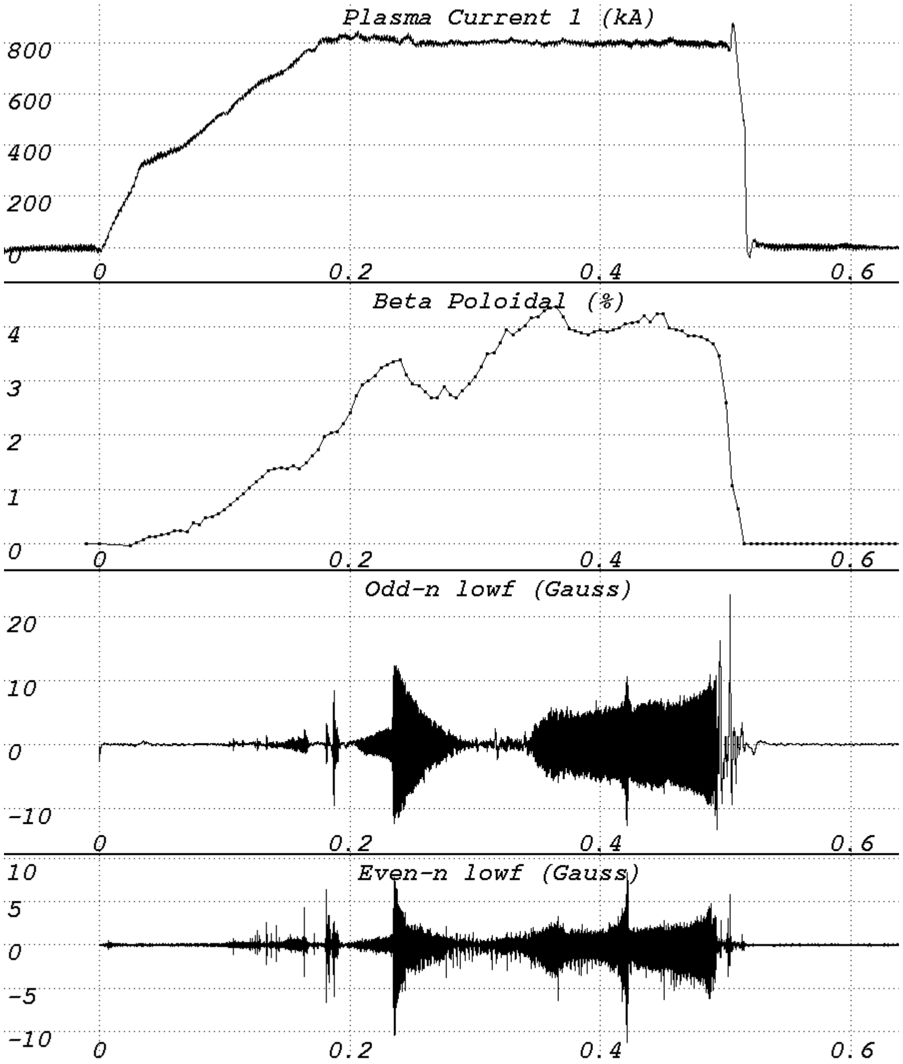
High-Frequency 3D Fields Detected by In-Vessel Sensors (NSTX, not NSTX-U, but Conceptually Identical)



Analysis Methods For High-Frequency Perturbations

- 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
- Or Eric Fredrickson has lots of routines.





Who's Who For 3D Fields

- SPAs: Weiguo Que, Bob Mozulay, Raki Ramakrishnan
- RWM Coils: George Labik, Steve Raftopoulos
- RWM Sensors: Stefan, Clayton
- Mode-ID Software: Stefan, Clayton
- RWM Control Codes: Stefan, Steve Sabbagh, Clayton
- High-n array: Eric Fredrickson and Stefan Gerhardt
- High-f array: Eric Fredrickson
- Magnetic Braking: S. Sabbagh, J.-K. Park