3D Fields: Detection and Application

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Phys. Ops. Course 2015
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 $\beta$.
  – 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.
  - \texttt{\textbackslash 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 \texttt{\textbackslash 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 \texttt{\textbackslash 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

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

\[ I_{SPA} = Y_{DC} + Y_{amp} \sin\left(2\pi t/T_{cycle} + \pi\phi_{start}/180\right) \]

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

Copper passive conductor plates

SS Vacuum Vessel

6 ex-vessel midplane control coils

VALEN Model of NSTX (Columbia Univ.)

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

B_R sensor is a loop behind the tiles, but in front of the plate.

B_P Sensor in a Stainless Box
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.
\( P_{ij} \) are mutual inductances

\[
C_{i,\text{static}} = \sum_{j=0}^{\text{NumCoils}-1} P_{i,j} I_j
\]

816 Coefficients

**AC Compensation For Fluctuating RWM Coil Currents**
Eddy currents driven by RWM coils make fields...subtract these out.

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

504 Coefficients

**Final Field For Plasma Mode Identification**

\[
B_{i,\text{plasma}} = B_i - C_{i,\text{static}} - C_{i,AC}
\]

In ACQ
In the modelID category

NSTX-U
2015 Phys. Ops. Course-3D Fields (Gerhardt)
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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 ModeID

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

Form Request For SPA Current From RWM Category
1: Preprogrammed Part
2: RWM Feedback Part
Done in RWM Category

Pre-Programmed Requests for Current in Individual SPA Subunits
Done in RWM Category Algorithms

PCS Waveforms

Vertical Control Category

Other Category Making SPA Request

6 SPA Current Requests

SPA Request Summer
Done in System Category

6 SPA Current Requests

PSRTC (clamping)
To SPA On-Board Controller Via FPDP

6 SPA Current Requests
Process for Mode Identification

• The actual magnetic perturbation has an amplitude \( A_{RWM} \) and phase \( \phi_{RWM} \)

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

  – How to determine \( A_{RWM} \) & \( \phi_{RWM} \)?

• 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 \([2 \times 24]\)
  – Multiply these together…resulting \([2 \times 1]\) array contains (essentially) \( A_{RWM} \) & \( \phi_{RWM} \)

• 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 \(A_{\text{RWM}}\) and phase \(\phi_{\text{RWM}}\)

\[B = A_{\text{RWM}} \cos(\phi - \phi_{\text{RWM}})\]

• At the \(i\)th sensor, the measured amplitude is:

\[B_i = A_{\text{RWM}} \cos(\phi_i - \phi_{\text{RWM}}) \Rightarrow\]

\[B_i = A_{\text{RWM}} \cos(\phi_{\text{RWM}}) \cos(\phi_i) + A_{\text{RWM}} \sin(\phi_{\text{RWM}}) \sin(\phi_i) \Rightarrow\]

\[B_i = C_{\text{RWM}} \cos(\phi_i) + S_{\text{RWM}} \sin(\phi_i)\]

• Many sensors…build a matrix and invert it!

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

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

\[
A_{\text{RWM}} = \sqrt{C_{\text{RWM}}^2 + S_{\text{RWM}}^2}
\]

\[
\phi_{\text{RWM}} = \tan^{-1}(S_{\text{RWM}} / C_{\text{RWM}})
\]

• 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 Iₚ 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 Bₚ sensors.
  - Amplitude and phase of mode as detected by Bₐ sensors.
  - Amplitude and phase of mode as detected by Bₐ + Bₚ 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”.

2015 Phys. Ops. Course-3D Fields (Gerhardt)
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.

\[ I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM,BP}(t)B_{BP1}(t)/L_{eff} \]

\[ I_{SPA-1}^{RWM}(t) = I_{SPA-BP}^{RWM}(t)\cos(\theta_{BP1}(t) + \delta_{BP}(t)) \]
RWM/DEFC Feedback Methodology in the “tmf” Algorithm

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\[ I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM,BP}(t)B_{BP1}(t)/L_{eff} \]

Feedback Gain (PCS Waveform)

\[ I_{SPA-1}^{RWM}(t) = I_{SPA-BP}^{RWM}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t)) \]

Detected Mode Amplitude (From Mode ID)
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.

\[
I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM,BP}(t)B_{BP1}(t)/L_{eff}
\]

\[
I_{SPA-1}^{RWM}(t) = I_{SPA-BP}^{RWM}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t))
\]
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.

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

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

\[
I_{SPA,BP}^{RWM}(t) = -1 \times G_{RWM, BP}(t)B_{BP1}(t)/L_{eff}
\]
\[
I_{SPA, BR}^{RWM}(t) = -1 \times G_{RWM, BR}(t)B_{BR1}(t)/L_{eff}
\]

\[
I_{SPA-1}^{RWM}(t) = LPF(I_{SPA-BP}^{RWM}(t) \cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t)); \tau_{BP}) + LPF(I_{SPA-BR}^{RWM}(t) \cos(0^\circ - \theta_{BR1}(t) + \delta_{BR}(t)); \tau_{BR})
\]
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.

\[
\begin{align*}
I_{SPA,BP}^{RWM}(t) &= -1 \times G_{RWM,BP}(t)B_{BP1}(t)/L_{eff} \\
I_{SPA,BR}^{RWM}(t) &= -1 \times G_{RWM,BR}(t)B_{BR1}(t)/L_{eff}
\end{align*}
\]

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

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

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

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

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

\[
I_{SPA-6}^{RWM}(t) = \text{LPF}\left(I_{SPA-BP}^{RWM}(t)\cos(300^\circ - \theta_{BP1}(t) + \delta_{BP}(t));\tau_{BP}\right) + \text{LPF}\left(I_{SPA-BR}^{RWM}(t)\cos(300^\circ - \theta_{BR1}(t) + \delta_{BR}(t));\tau_{BR}\right)
\]
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 ModelID 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 180° 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