Modeling Error Fields in NSTX-U

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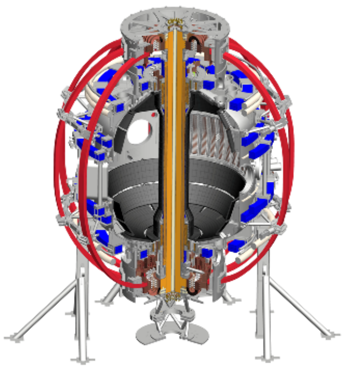
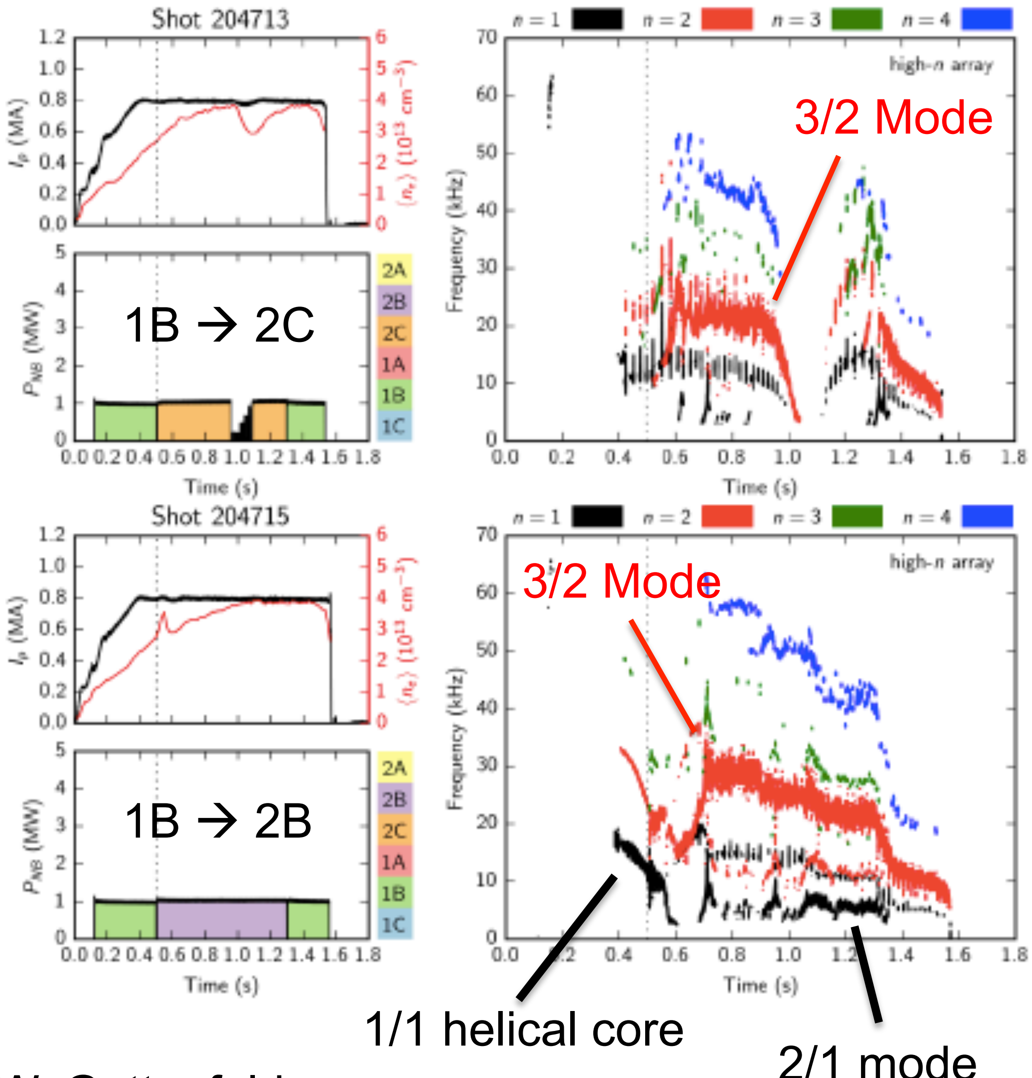
NSTX Results Review
PPPL
Sept 22, 2016



Strong MHD Activity Present in Most Shots



W. Guttenfelder

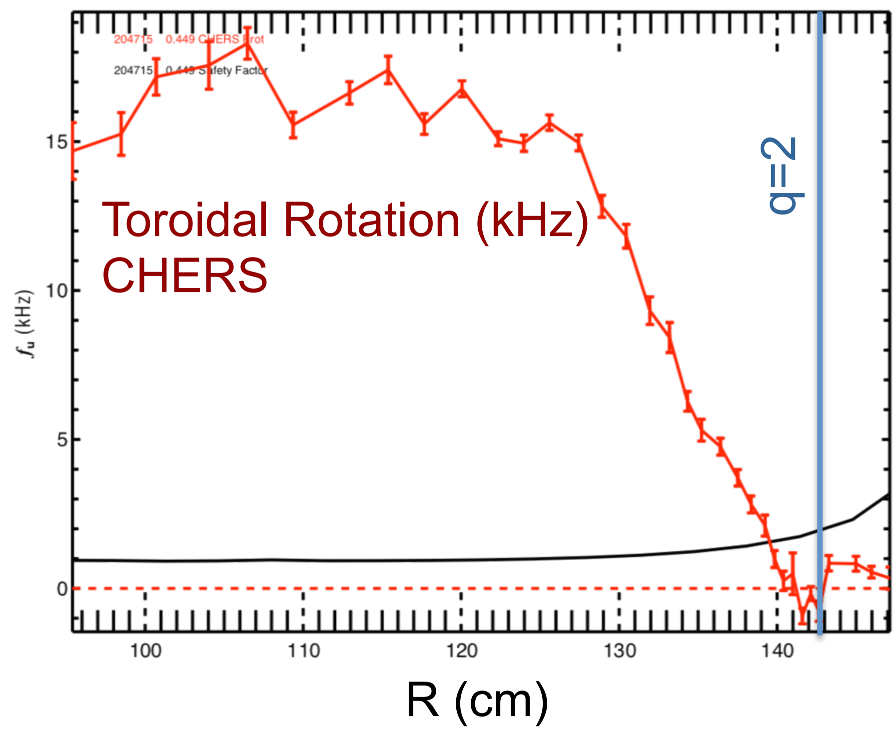
- 1/1 helical core modes often observed early
- Most shots are sawtoothing
- 3/2 modes are typically present in IP flattop
- MHD phenomenology strongly influenced by density and NB torque (Guttenfelder)

MHD Modeling Complicated by Ubiquitous Locking in L-Mode

- Early attempts to get profile data to model effect of rotation on stability found unexpected rotation profiles

- Subsequent investigation found that *nearly every L-mode discharge is locked from q=2 out*
  - A few shots with NBI from source 2B are possible exceptions
  - Profiles often show flattening at q=3/2 surface

- This complicates our understanding of all L-mode experiments



NSTX-U 204715 *t*=450 ms

Deeper Investigation Into Error Field Correction Revealed Further Mysteries

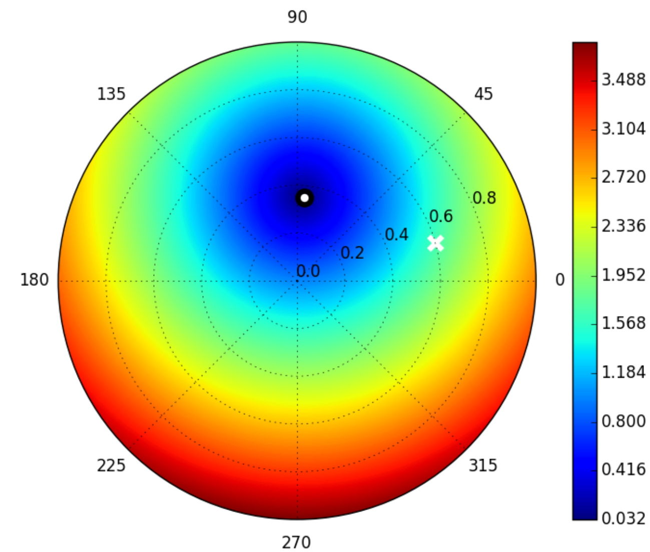
- EFC, at any phase or amplitude, failed to unlock edge (Myers)
  - Compass scans caused locking of core plasma
- Early EFC was not successful in preventing mode-locking (Myers)
- Optimal EFC phase was different for early EFC than for IP flattop EFC (Myers)
  - Time dependent source of error fields?
  - Time dependent plasma response?
- Several potential sources of EFC have been identified and evaluated

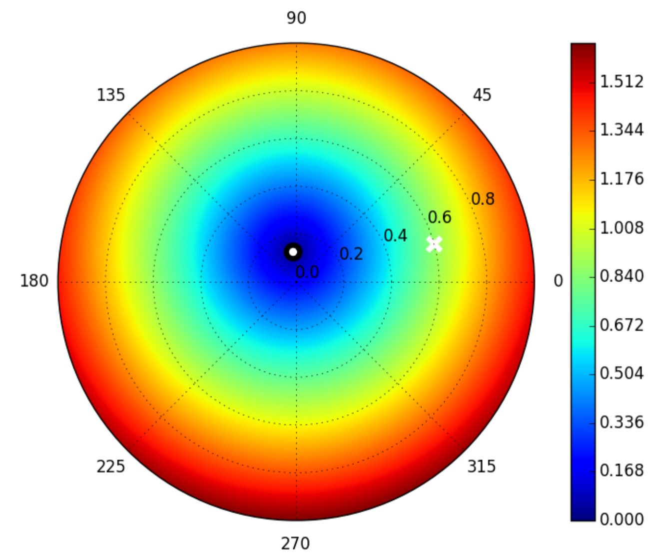
Suspect #1: PF5 Coils

- It is known that the PF5 coils are non-circular, and contribute to th n=1 error field

- IPEC modeling (J.-K. Park) finds that the optimal EFC to correct PF5 error differs significantly from empirical optimum

- Is PF5 model still accurate? Need metrology.





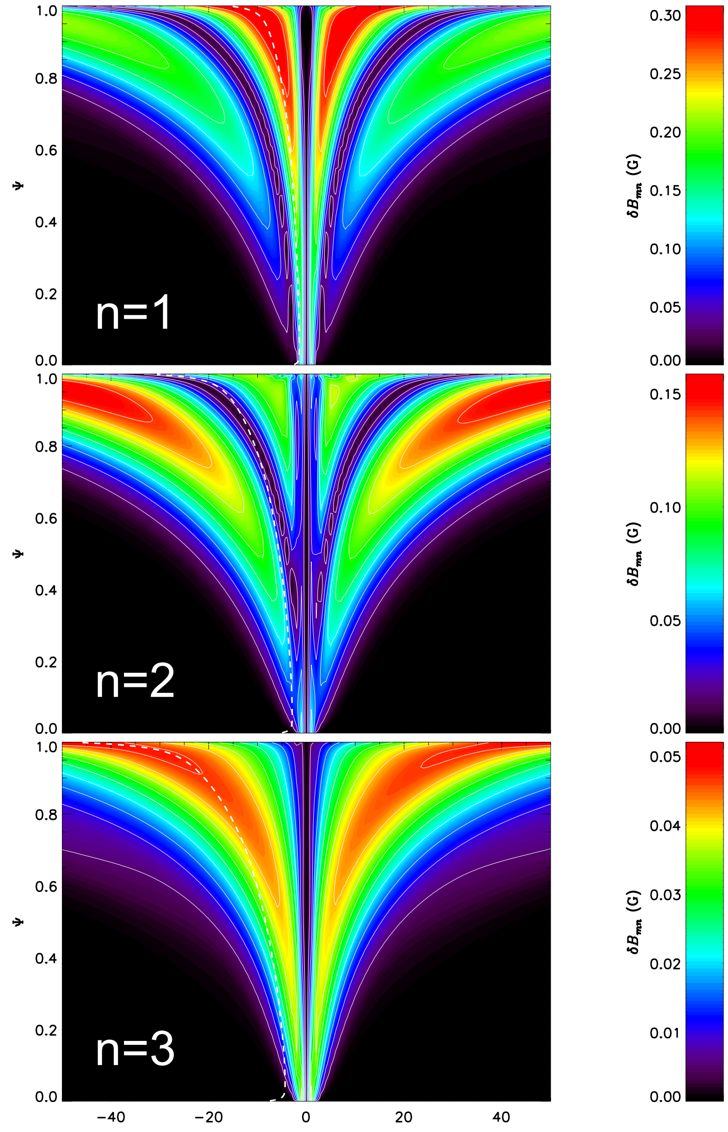
Suspect #2: Eddy Currents

- Vacuum vessel and other conducting structures have significant non-asymmetries
  - Loop voltage can lead to non-axisymmetric structures

- VL changes during discharge → could explain time-dependent EFC

- Eddy currents expected during IP ramp were calculated using VALEN (Bialek)

- Fields from eddy currents seem too small to explain locking
  - Caveat #1: some non-axisymmetric conductors are not included in VALEN model
  - Caveat #2: new revelations about copper cooling pipes make modeling very challenging



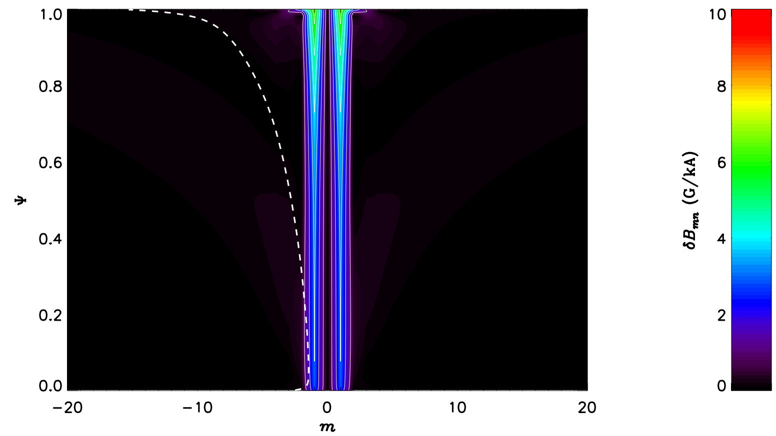
Suspect #3: Tilted OH

- If OH coil were tilted / shifted, this would create a time-dependent error field (Menard)
- Experiments found EFC was not dependent on OH pre-charge (Myers)
- Time-dependent TF tilt present on NSTX is not present on NSTX-U (Myers)

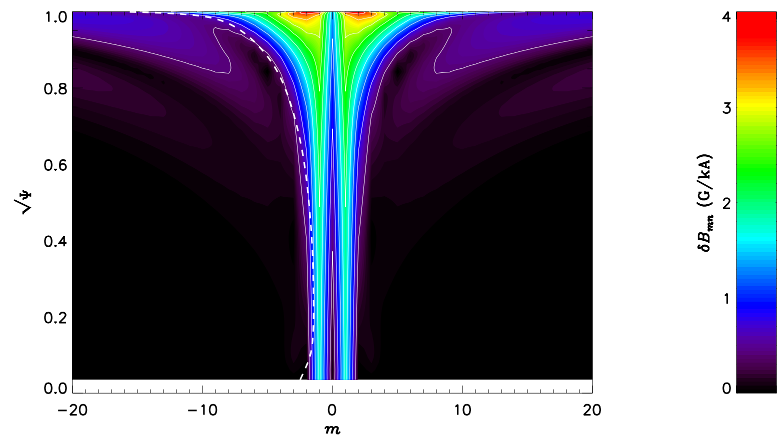
Suspect #4: Tilted TF

- TF shift or tilt would lead to strong 1/1 EFs
  - Plasma is not resonant with 1/1
  - 1/1 just represents “tilt” of coordinate system
- In tilted coordinate system, PFs now create m>1 n=1 EFs
  - In STs, B_p is a larger fraction of B than in conventional tokamaks
- Capability implemented in M3D-C1 to calculate response to shift / tilt in PF coils

B_n from tilting TF



B_n shifting & tilting all PFs



M3D-C1

It Is Easily Shown that Shifted & Tilted Coils Produce n=1 Error Fields

- Coil coordinates (r, ϕ, z) are shifted by δ in the φ_s direction and tilted α radians about the φ_t axis relative to the lab coordinates (R, φ, Z)

$$\begin{aligned} r &\approx R - \delta\cos(\varphi - \varphi_s) + Z\alpha\sin(\varphi - \varphi_t) \\ \phi &\approx \varphi - \frac{\delta}{R}\sin(\varphi - \varphi_s) + \frac{Z\alpha}{R}\cos(\varphi - \varphi_t) \\ z &\approx Z - R\alpha\sin(\varphi - \varphi_t) \end{aligned}$$

- To first order in α and δ/R, the field in lab coordinates is related to that in the coil coordinates by

$$\begin{aligned} \vec{B}(\vec{R}) = \vec{B}(\vec{r}) + \delta\, e^{-i\varphi_s} &\left\{ \begin{array}{c} \left[-\partial_r B_r + i\frac{1}{R}B_\phi\right]\hat{R} \\ -\left[\partial_r B_\phi + i\frac{1}{R}B_r\right]\hat{\varphi} \\ -\partial_r B_z \hat{Z} \end{array} \right\} \\ + \alpha\, e^{-i\varphi_t} &\left\{ \begin{array}{c} -\left[\frac{Z}{R}B_\phi + i(Z\,\partial_r B_r - R\,\partial_z B_z)\right]\hat{R} \\ +\left[\left(\frac{Z}{R}B_r - B_z\right) - iR\,\partial_z B_\phi\right]\hat{\varphi} \\ +\left[B_\phi - i\,(B_r + Z\,\partial_r B_z - R\,\partial_z B_z)\right]\hat{Z} \end{array} \right\} \end{aligned}$$

- For toroidal field coils, this yields

$$\vec{B}^{TF}(R,Z) = \frac{\mu_0 I}{2\pi R}\hat{\phi} + \frac{\mu_0 I}{2\pi R} \left\{ \begin{array}{c} \left[i\frac{\delta}{R}e^{-i\varphi_s} - \alpha\frac{Z}{R}e^{-i\varphi_t}\right]\hat{R} \\ +\left[\frac{\delta}{R}e^{-i\varphi_s} + i\alpha\frac{Z}{R}e^{-\varphi_t}\right]\hat{\varphi} \\ +\alpha e^{-i\varphi_t}\hat{Z} \end{array} \right\}$$

- For poloidal field coils, this yields

$$\begin{aligned} \tilde{B}(R,Z) = \tilde{B}(r,z) + \delta e^{-i\varphi_s} &\left[-\partial_r B_r \hat{R} - i\frac{1}{R}B_r\hat{\varphi} - \partial_r B_z \hat{Z}\right] \\ + \alpha e^{-i\varphi_t} &\left\{ \begin{array}{c} i\,(B_z + R\,\partial_z B_r - Z\,\partial_r B_r)\,\hat{R} \\ +\left(\frac{Z}{R}B_r - B_z\right)\hat{\varphi} \\ i\,(-B_r + R\,\partial_z B_z - Z\,\partial_r B_z)\,\hat{Z} \end{array} \right\} \end{aligned}$$

$$\vec{B}^{PF}(R,Z) = \frac{\mu_0 I}{2\pi\sqrt{(r-R_c)^2 + (z-Z_c)^2}} \left\{ \begin{array}{c} \frac{z-Z_c}{2R}\left(2K(-k^2) - \frac{2+k^2}{1+k^2}E(-k^2)\right)\hat{R} \\ +\left[\frac{1}{1+k^2}\left(1 + \frac{k^2(r-R_c)}{2R}\right)E(-k^2) - K(-k^2)\right]\hat{Z} \end{array} \right\}$$

$$k^2 = \frac{4RR_c}{(R-R_c)^2 + (Z-Z_c)^2}$$

Suspect #5: Plasma Instability

- MARS calculations show 3/1 & 4/1 TMs are unstable in some NSTX-U equilibria (Z. Wang)
  - Maybe these grow and lock to wall
- If this were the case, we would expect to see a mode born rotating and then spin down
  - Spectrograms & CHERS indicate that mode is born locked
- Might explain why unlocking is so difficult

Summary

- The locked edge is a dominant feature of most existing NSTX-U data
  - MHD and transport analysis should consider that the equilibrium is non-axisymmetric
- Dominant source of EFs is not known, but TF tilt and unanticipated eddy current paths are likely candidates
  - These will likely change when CS is re-installed
- New capabilities for modeling EFs have been developed to help diagnose sources and evaluate solutions (e.g. trim coils)
  - Interface between VALEN and M3D-C1
  - Model for fields from shifted / tilted PF coils
- Solutions developed for specific EF problems in NSTX-U can be applied broadly to EF issues that affect all tokamaks