U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Error Field Correction Experiments in FY16

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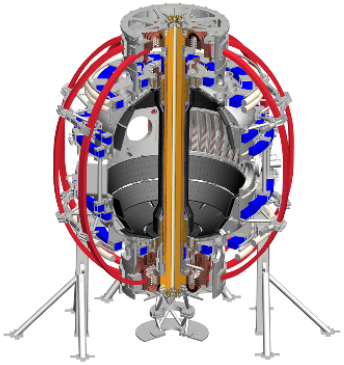
NSTX-U Results Review
September 21–22, 2016

PPPL



Candidate error field sources in NSTX-U

- Candidate error field sources:
  - The PF5 coils: known to be out-of-round, clamped differently than in NSTX
  - Induced vacuum vessel currents: new J/K cap, higher OH loop voltage
  - OH×TF interaction: time-dependent error field, major issue in NSTX
  - Tilted TF coil: center stack not perfectly aligned to the vertical
  - Tilted OH coil: center stack not perfectly aligned to the vertical
- Error field correction XPs and XMPs run in FY16:
  - XP-1506: Low-beta, low-density locked mode studies
  - XMP-106: Plasma-like vacuum shots
  - XMP-140: PF5-proportional EFC
  - XMP-141: Early-time EFC
  - XMP-146: Preliminary higher order EFC

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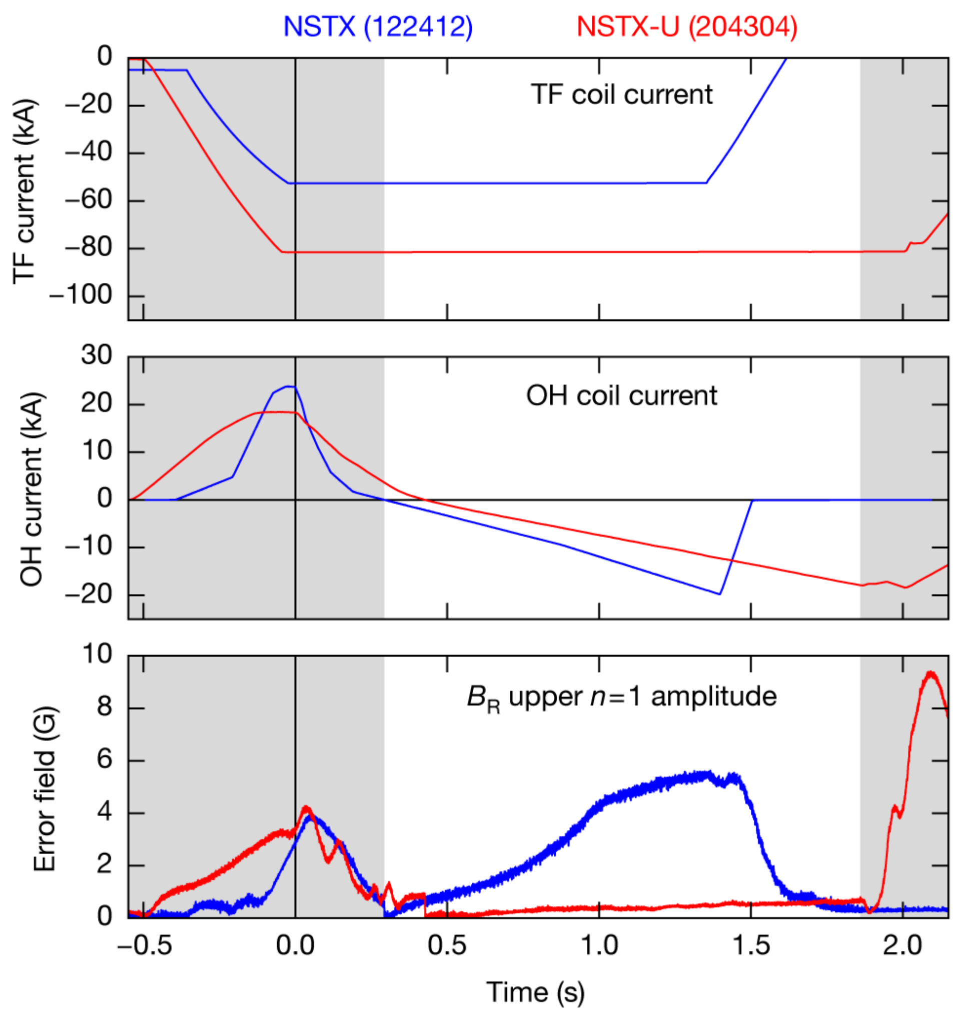
Four types of $n=1$ error field correction experiments

- Plasma-like vacuum shots (OH×TF):
  - 03 May 2016: Replicate 700 kA, 1 MW L-mode scenario (XMP-106)
- PF5-proportional $n=1$ EFC in ohmic plasmas
  - 25 Feb 2016: 700 kA ohmic – PF5-proportional EFC (XMP-140)
  - 01 Mar 2016: 900 kA ohmic – PF5-proportional EFC (XMP-140)
- Compass scans ($n=1$)
  - 03 Mar 2016: 700 kA ohmic – low density compass scan (XP-1506)
  - 01 Apr 2016: 650 kA 1 MW L-mode – low density compass scan (XP-1506)
  - 11 May 2016: 650 kA 1 MW L-mode – higher density compass scan (XP-1506)
  - 23 Jun 2016: 650 kA 1 MW L-mode – compass scan w/ 8 kA OH (XP-1506)
- Early-time $n=1$ EFC
  - 09 May 2016: 650 kA 1 MW L-mode – loop-voltage-proportional EFC (XMP-141)
  - 22 Jun 2016: 650 kA 1 MW L-mode – static early EFC w/ 20 kA OH (XMP-141)
  - 23 Jun 2016: 650 kA 1 MW L-mode – static early EFC w/ 20 kA OH (XMP-141)
  - 23 Jun 2016: 650 kA 1 MW L-mode – static early EFC w/ 8 kA OH (XMP-141)
  - 27 Jun 2016: 600 kA H-mode scenario – static early EFC (XMP-153)

The time-dependent OH×TF EF is absent in NSTX-U

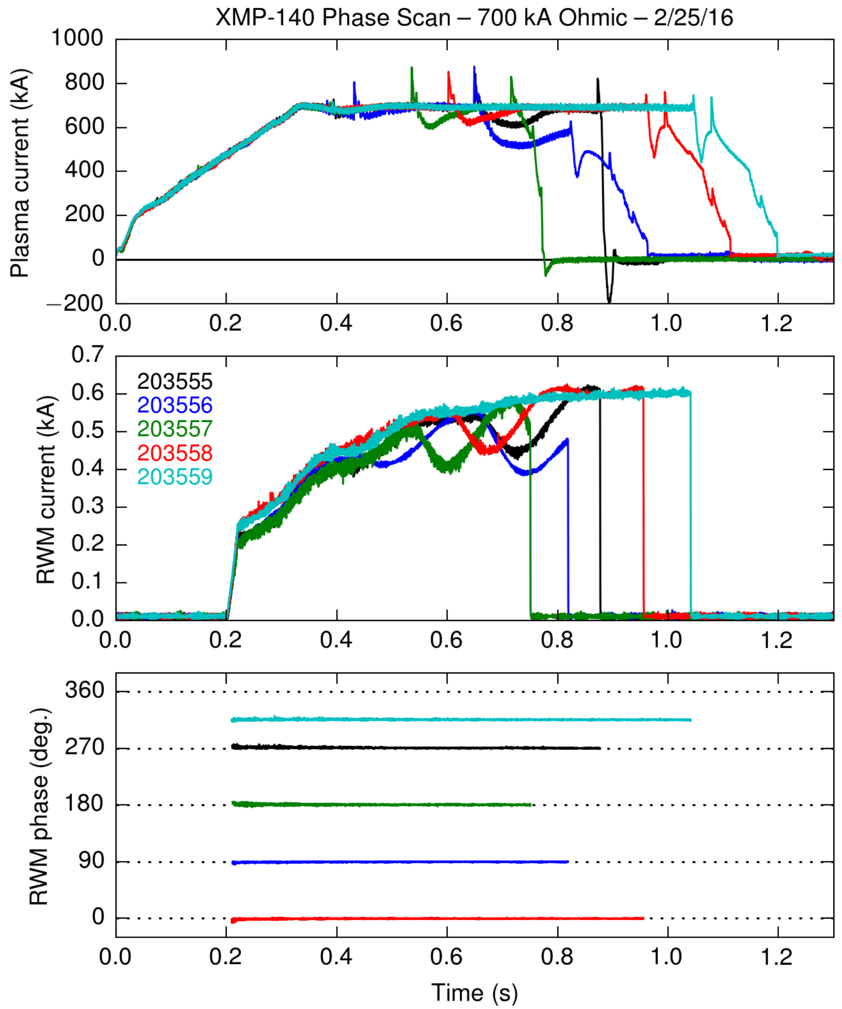
- NSTX had a time-dependent error field due to OH×TF interaction:
  - Dynamic EFC required to achieve high performance [Menard 2010]
  - Designed out of NSTX-U with a coaxial OH lead assembly [Menard 2012]
- No OH×TF error field in NSTX-U:
  - Compare plasma-like vacuum shots from NSTX and NSTX-U
  - Error field visible on the RWM/EF sensors in NSTX as the OH current swings to high negative values
  - No such large error field is measured for a comparable shot in NSTX-U



PF5-proportional scan shows preferred n=1 phase

XMP-140: PF5-proportional phase scan

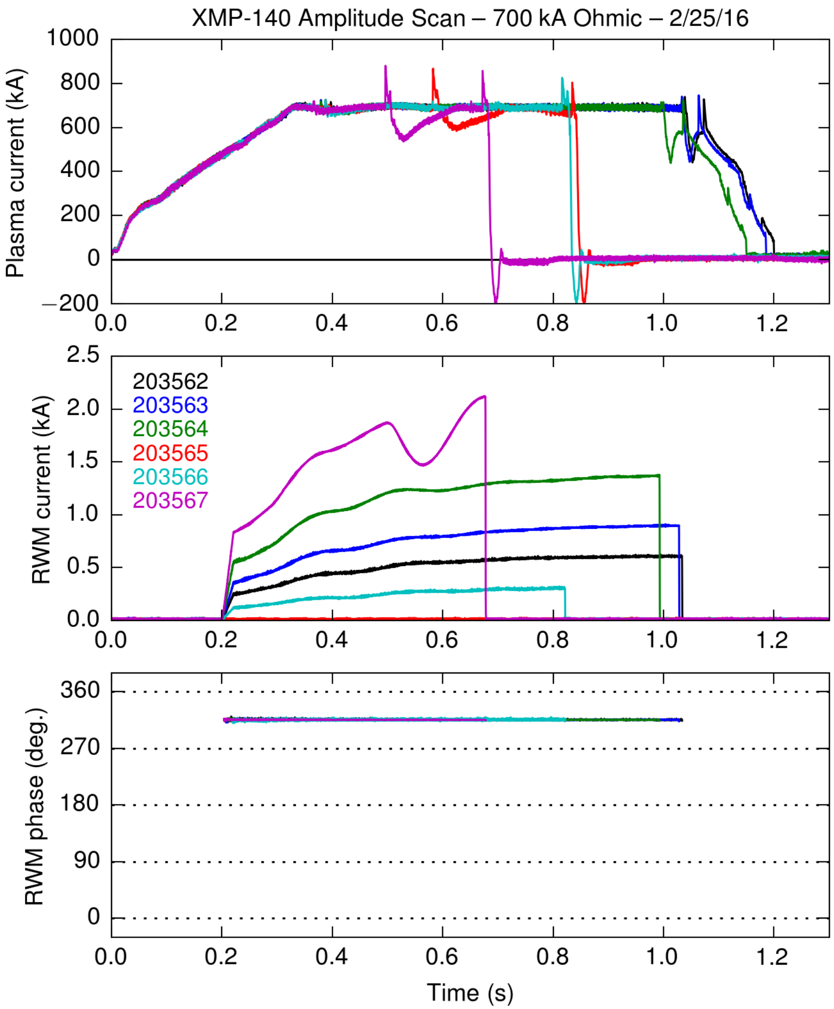
- 700 kA ohmic plasmas
- $n_e \sim 1.3\times10^{13}$ cm^{-3}
- Amplitude = 0.086 A/A
- Best phases:
  - 203559 = 315°
  - 203559 = 0°
- Conclusion: based on shot duration, there is a preferred n=1 phase



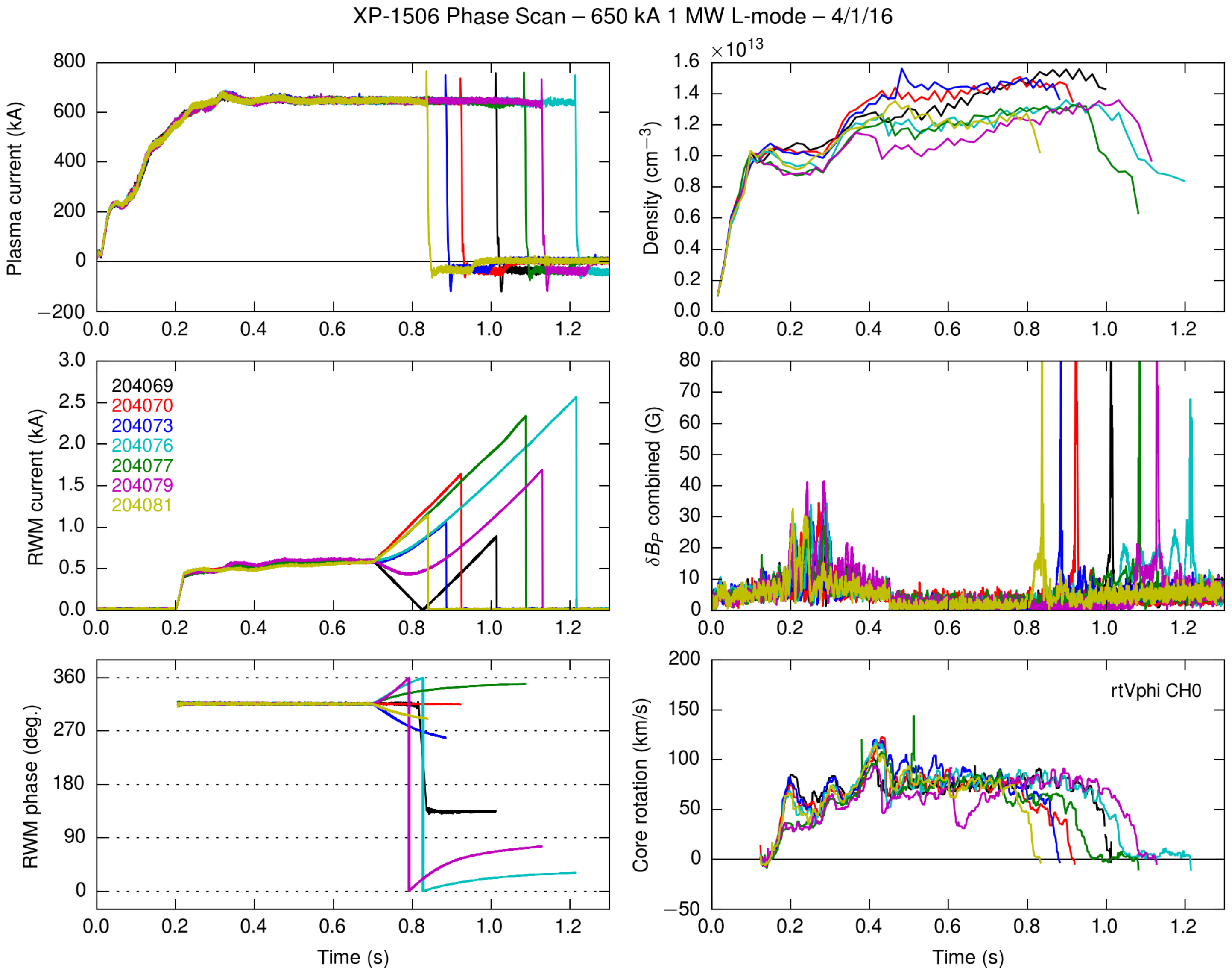
PF5-proportional scan shows preferred n=1 amplitude

XMP-140: PF5-proportional ampl. scan

- 700 kA ohmic plasmas
- $n_e \sim 1.3\times10^{13}$ cm^{-3}
- Phase = 315°
- Best amplitudes:
  - 203562 = 0.086 A/A
  - 203563 = 0.129 A/A
- Conclusion: based on shot duration, there is a preferred n=1 amplitude

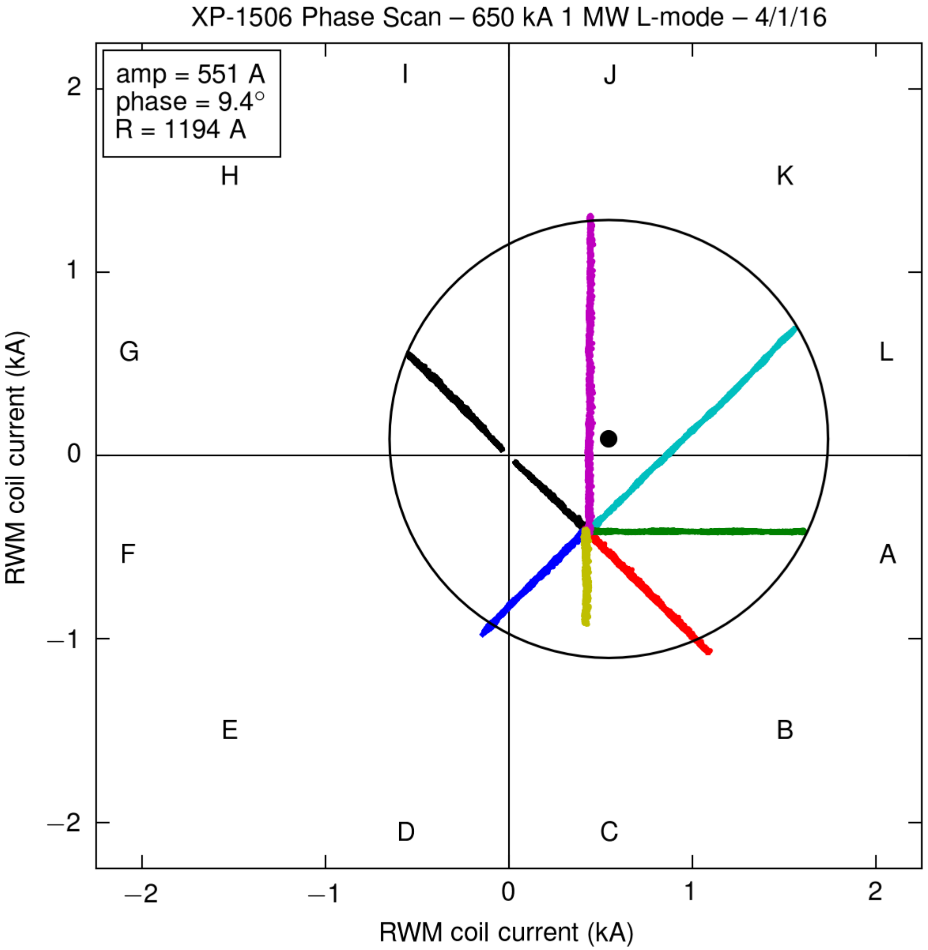


Initial compass scan locates the optimum L-mode EFC phase and amplitude in the flattop



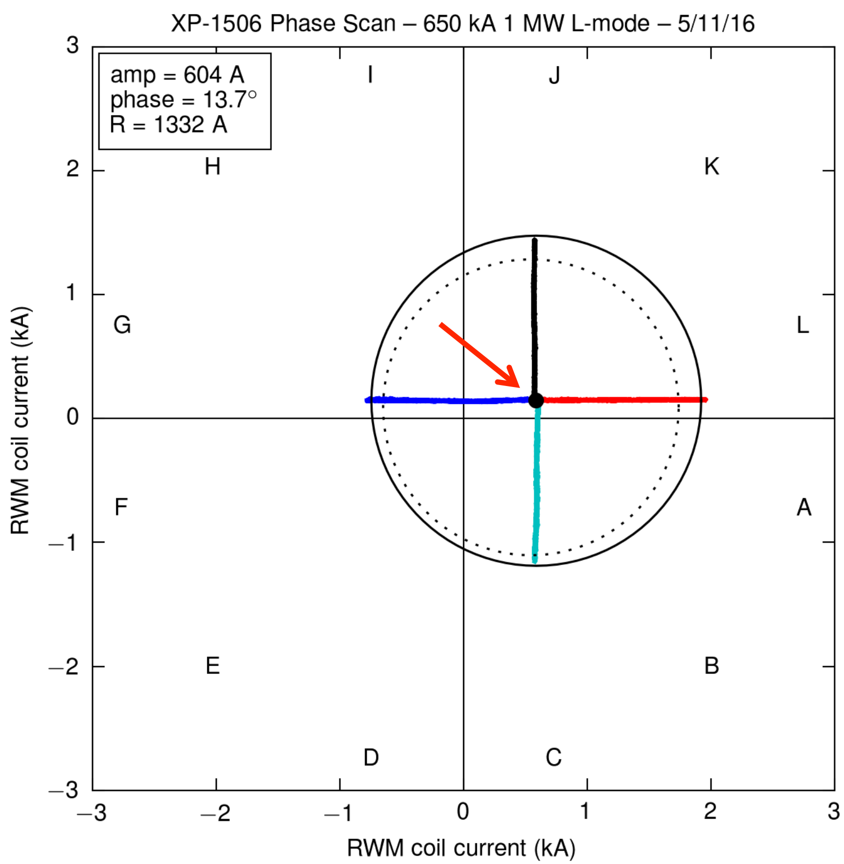
Initial compass scan locates the optimum L-mode EFC phase and amplitude in the flattop

- XMP-1506: $n = 1$ compass scan
  - Goal is to determine optimum n=1 EFC as maximum 'distance' from locking
  - Primary diagnostic = RWM sensors
- Results
  - Well-resolved circle with amplitude of I_{RWM} ~ 550 A and phase ~ 10°
  - Supports previous ohmic results
- Path forward
  - Use these results as the 'standard' prescription for PF5-proportional EFC
  - This prescription was in use for 204112 and 204118 (trophy NSTX-U H-modes)

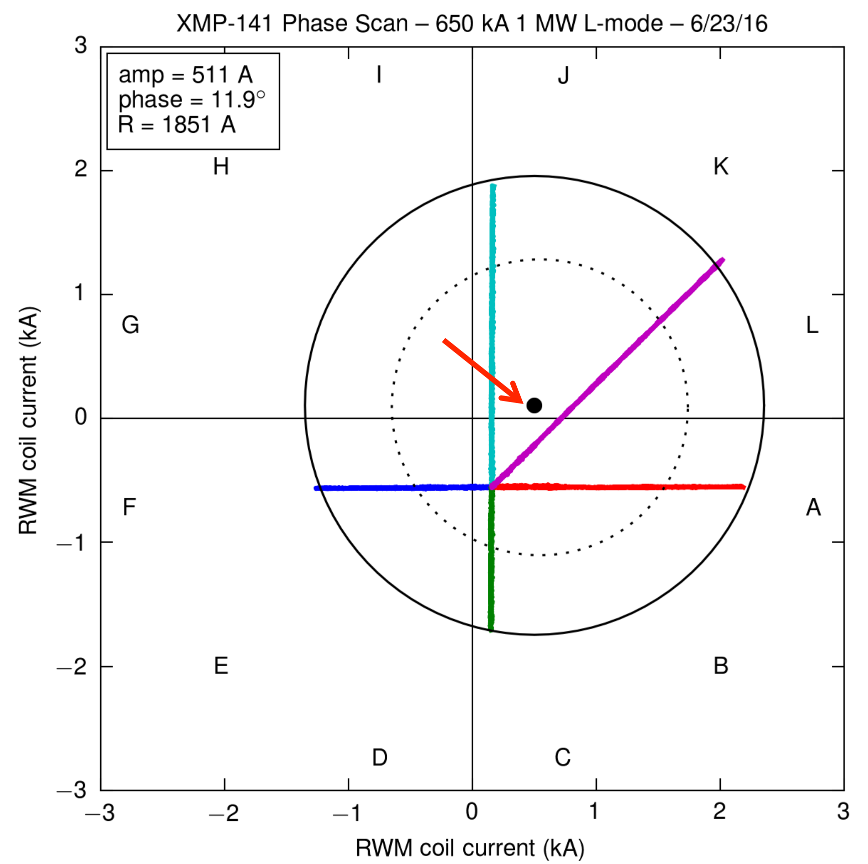


Two additional compass scans confirm the optimum L-mode EFC in the flattop

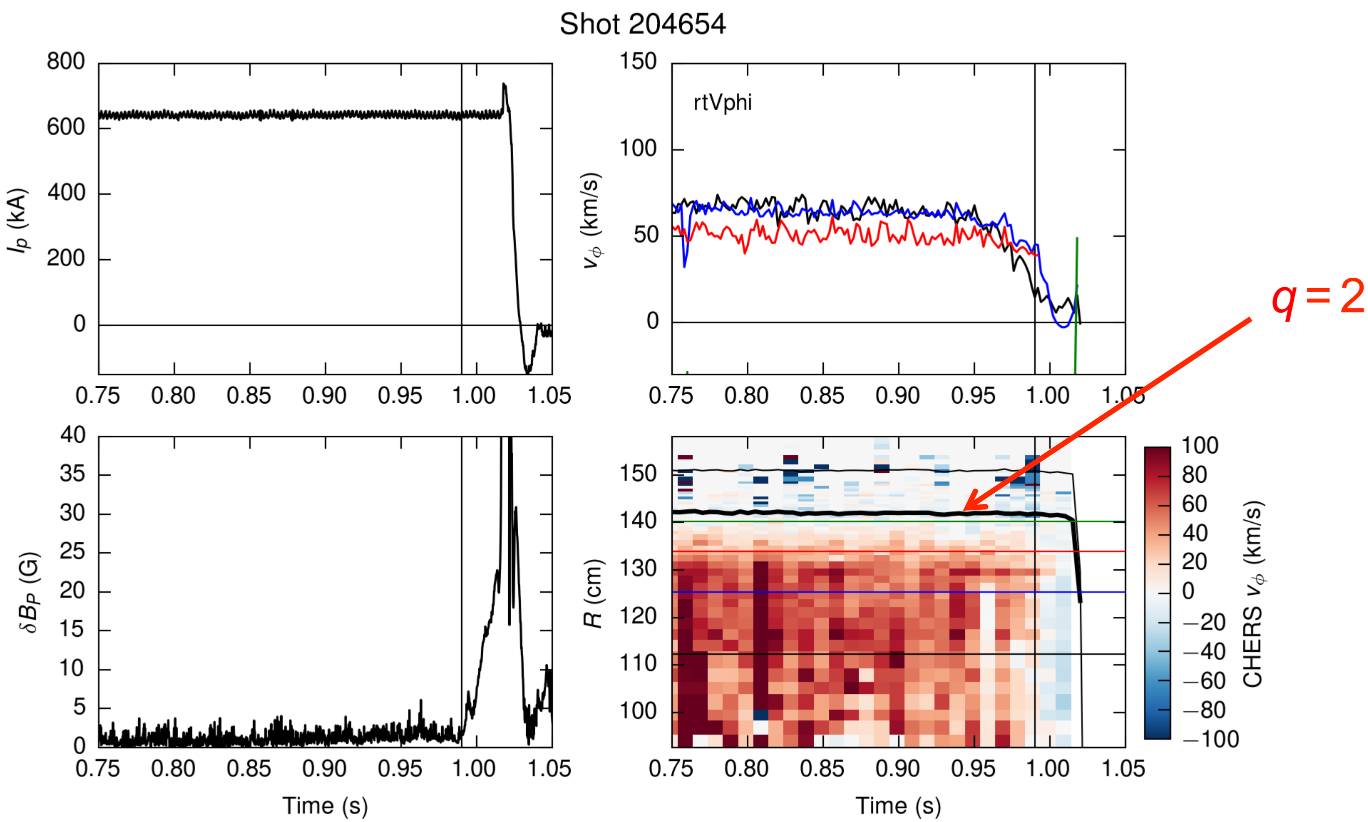
Higher density (2.9 vs. 1.4×10[13])



Higher density (2.9×10[13])
Lower OH pre-charge (8 kA vs. 20 kA)



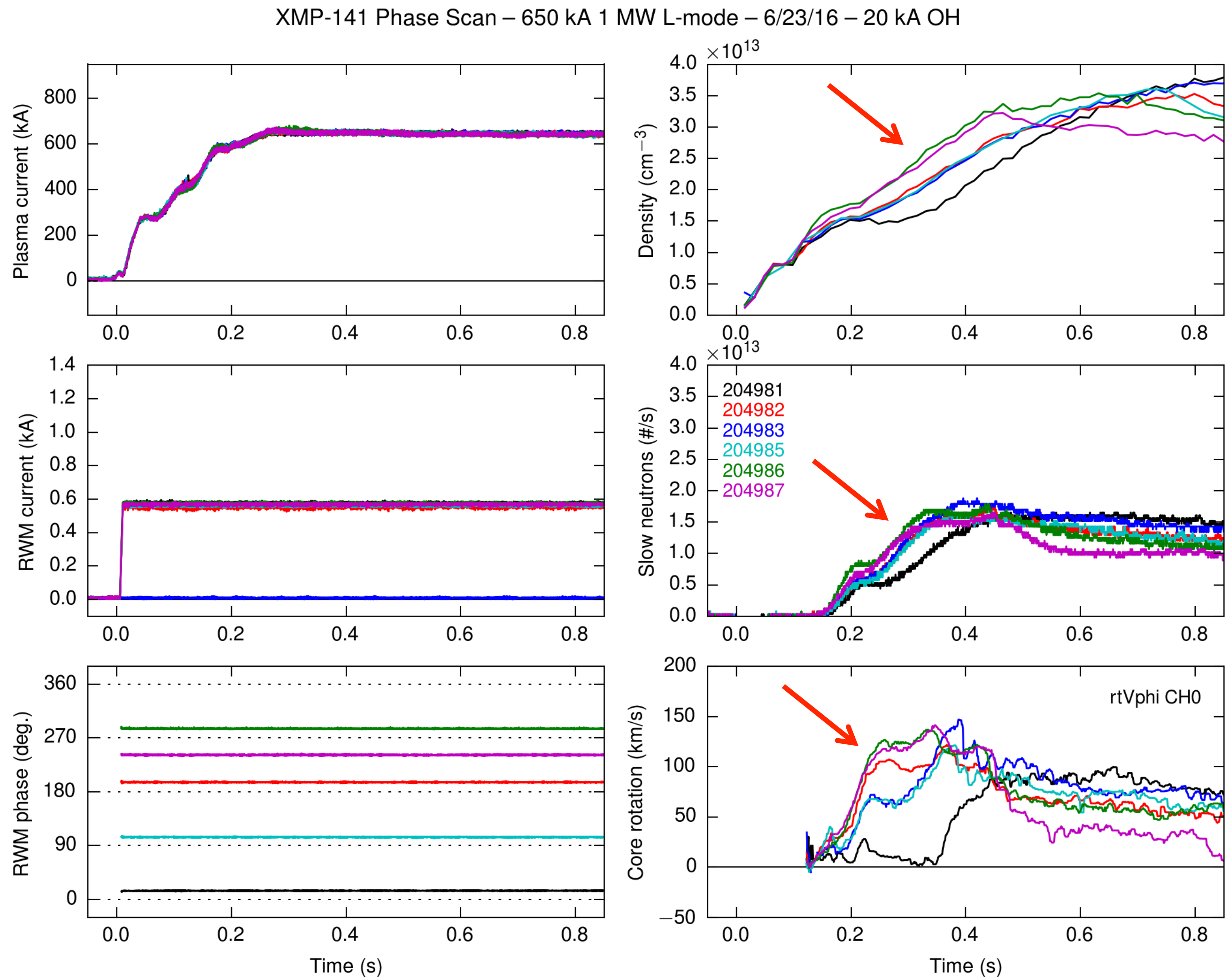
The region where $q > 2$ is always locked in L-mode



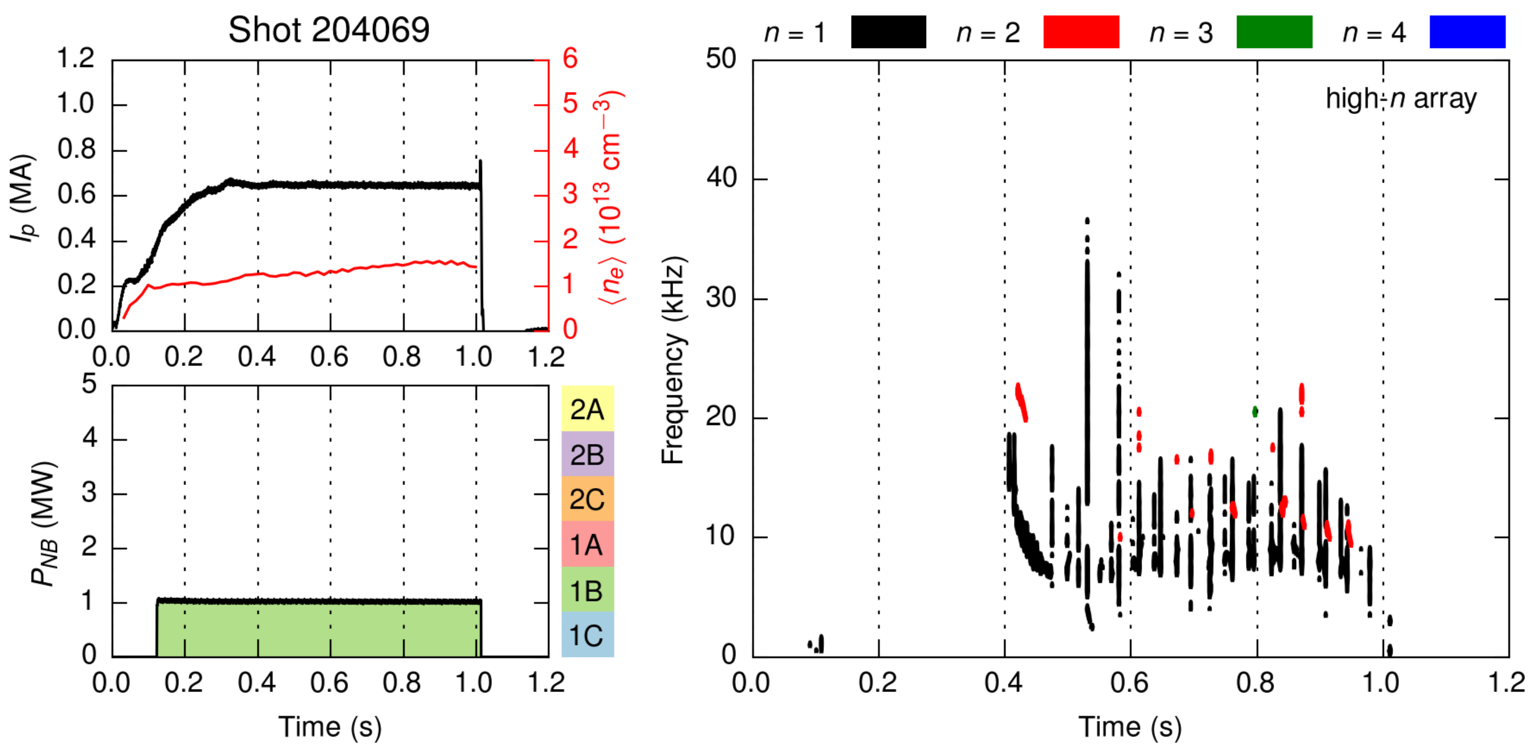
- The edge region where $q > 2$ is always locked in L-mode
- Mode locking experiments therefore lock the 1/1 core rather than the 2/1 edge

Static EFC scan early in time → different EFC phase

- Static EFC scan early in the discharge shows different optimum phase
- Flattop phase of 15° is *counter-productive* early on
- Phase asymmetry is visible in density, neutrons, and core rotation
- Search for the source of the time-evolving error field is ongoing



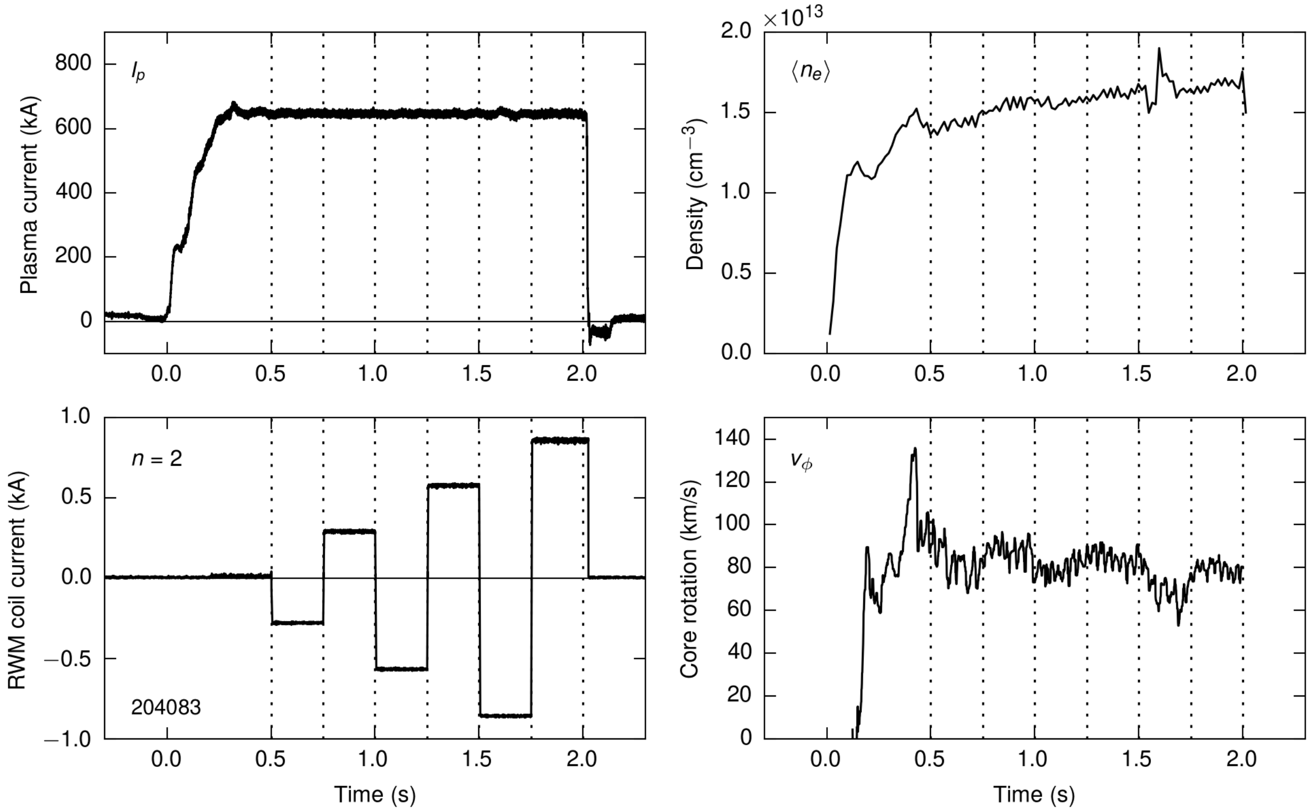
A 1/1 core mode appears around 400 ms



- The 400 ms mode onset time is repeatable in the 1 MW L-mode scenario
- Here, the core mode spins down before the onset of sawtoothing at 500 ms
- Spin-down could be a response of the $q \sim 1$ core to EF from tilted TF rod (?)

Initial $n=2$ experiments show asymmetric response

- Briefly tried modulating n=2,3 perturbations in XMP-146
- This n=2 shots shows an asymmetric response in core rotation, etc.
- PF5 coil shape measurements indicate that n=2 could be larger than in NSTX



Summary and future plans

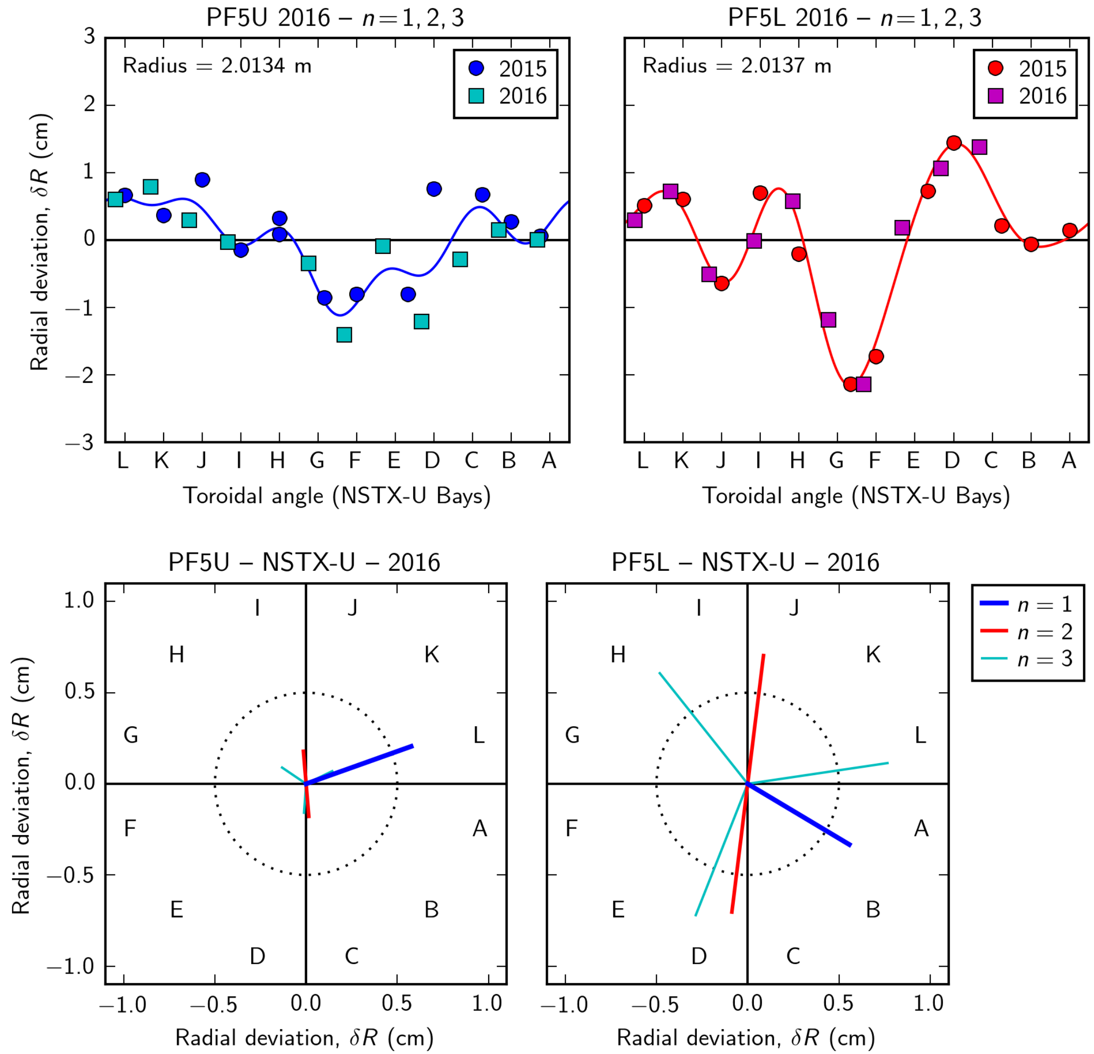
- Candidate error field sources:
  - The PF5 coils: known to be out-of-round, clamped differently than in NSTX
  - Induced vacuum vessel currents: new J/K cap, higher OH loop voltage
  - ~~OH×TF interaction: time-dependent error field, major issue in NSTX~~
  - Tilted TF coil: center stack not perfectly aligned to the vertical
  - ~~Tilted OH coil: center stack not perfectly aligned to the vertical~~

- The path forward:
  - New metrology of the vacuum vessel shape:
    - Complete the PF5 coil shape measurements
    - Feed into IPEC, M3D-C1 modeling efforts
  - Realign the OH/TF bundle within the CS casing:
    - The OH/TF bundle will be centered within the casing upon reinstallation
    - This is an ancillary benefit of removing the center stack
  - Additional analysis and modeling of the FY16 EFC experiments

Backup

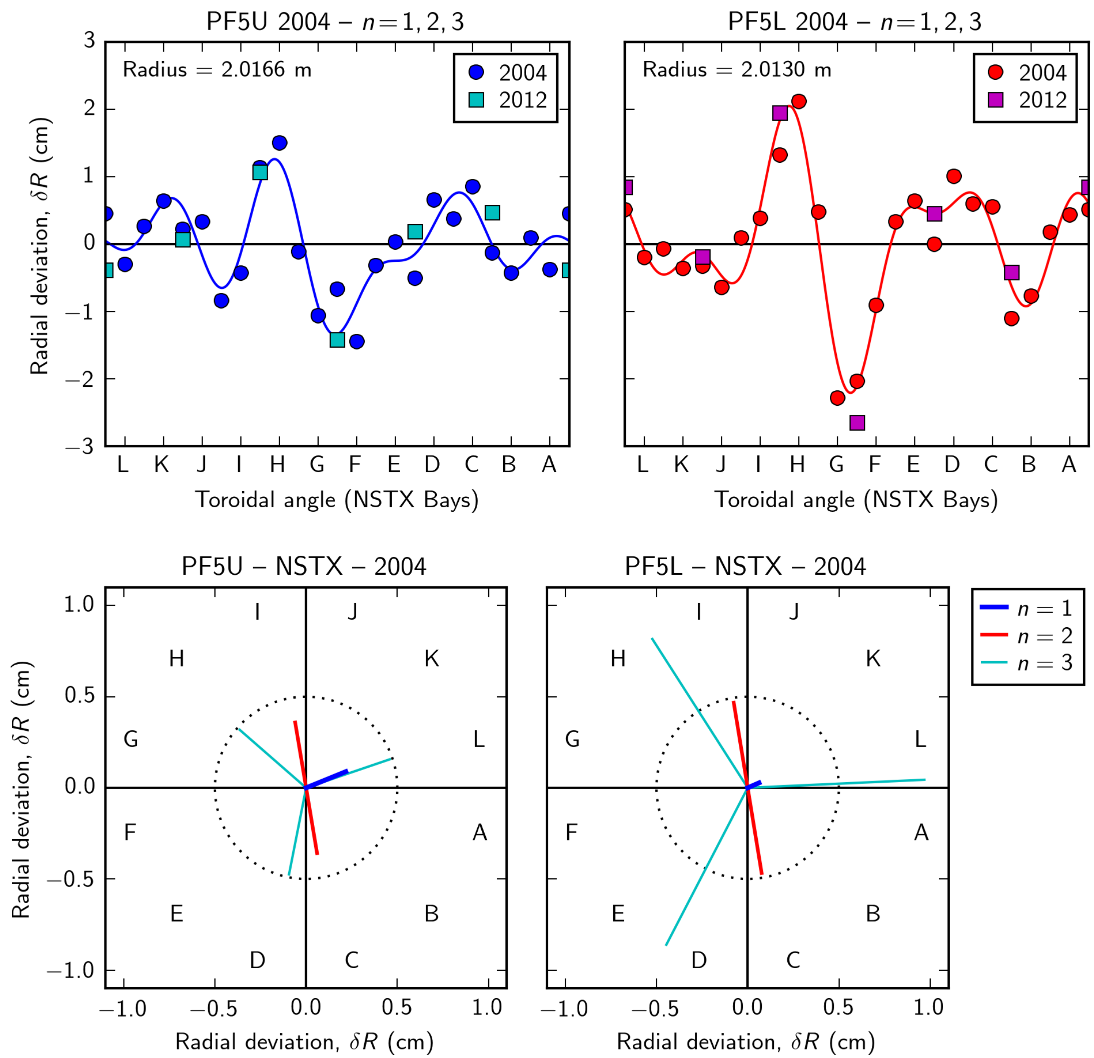
PF5 shape measurements (2016)

- Approach
  - Measurements from Nov. 2015 and Feb. 2016
  - Fit *n*=1-5 to each coil
  - Still looking for more consistent measurements of the upper coil
- Results
  - Substantial *n*=1 in both coils
  - Substantial *n*=2,3 in only the lower coil
  - It's interesting to note that the *n*=1 phases are 15° and 315°, respectively
  - These are the two PF5 proportional settings that we found → coincidence?



PF5 shape measurements (2004)

- Approach
  - Measurements from 2004 and 2012
  - Fit n=1-5 to each coil, only using 2004 measurements
- Results
  - Small n=1 in both coils
  - Comparable n=2 in both coils
  - Substantial n=3 in both coils, but esp. the lower coil



PF5 shape measurements (Upper-Lower δR)

- Approach
  - Compare PF5U-PF5L δR in 2004 and 2016
  - Fit *n*=1-5 to the difference
- Results
  - Significantly larger *n*=1 and *n*=2 displacements in 2016
  - Comparable *n*=3 amplitude with slight phase change
- Caveats
  - Shape measurements are not final (looking esp. for new PF5U measurements)
  - Midplane δR not the sole arbiter of the plasma response