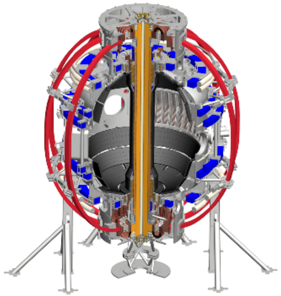
Initial error field correction studies in the National Spherical Torus Experiment Upgrade

Clayton E. Myers[1], S. P. Gerhardt[1], J. E. Menard[1], N. M. Ferraro[1], J.-K. Park[1], R. E. Bell[1], B. P. LeBlanc[1], M. Podestà[1], and S. A. Sabbagh[2]

[1]*Princeton Plasma Physics Laboratory*, [2]*Columbia University*

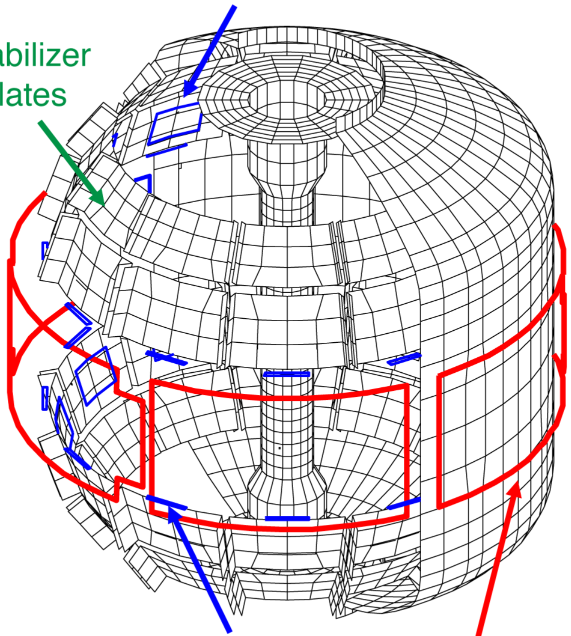
APS-DPP 2016
San Jose, California
November 1, 2016



Error field correction is key to achieving high performance

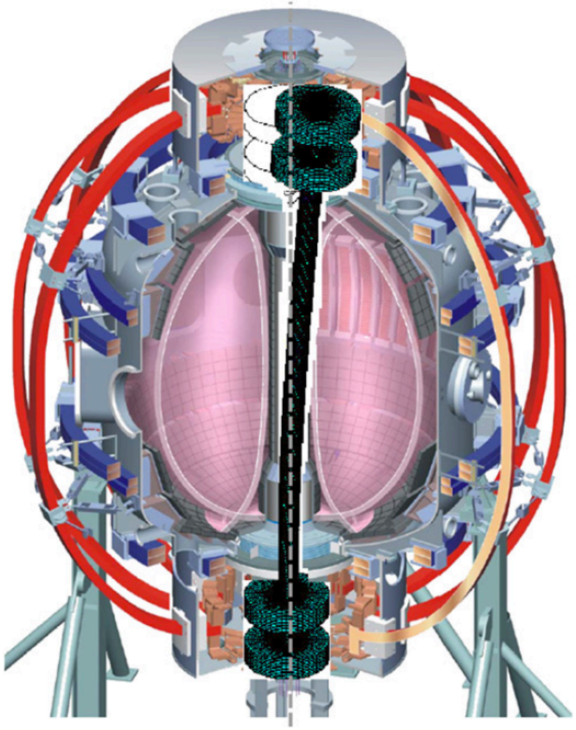
- Error field correction (EFC) objectives:
  - Probe the plasma response to applied 3D fields
  - Near-term empirical EFC prescription
  - Error field source identification

- EFC sensors and actuators in NSTX-U:
  - Four sets of 3D magnetic field sensors with 12 toroidal locations each (B_P/B_R, Upper/Lower)
  - Six midplane EFC coils to apply n=1,2,3 fields simultaneously ← new capability for NSTX-U



Candidate error field sources in NSTX-U

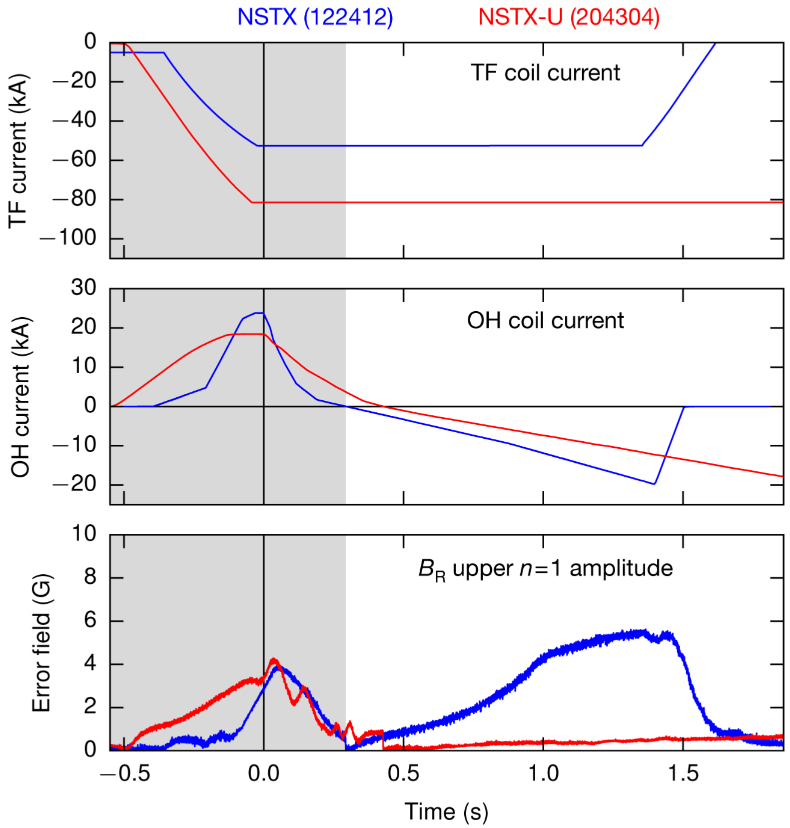
- Candidate error field sources:
  - Non-circularity of the main vertical field coil (PF5)
  - Non-axisymmetry of vessel eddy currents
  - Tilt of the TF coil from the vertical
  - Tilt of the OH coil from the vertical
  - Time-dependent OH×TF interaction [see right]
- Error field identification techniques:
  - Plasma-like vacuum shots
  - Feed-forward EFC coil currents
  - Compass scans ($n = 1$)



Menard et al. *Nucl. Fusion* 2010

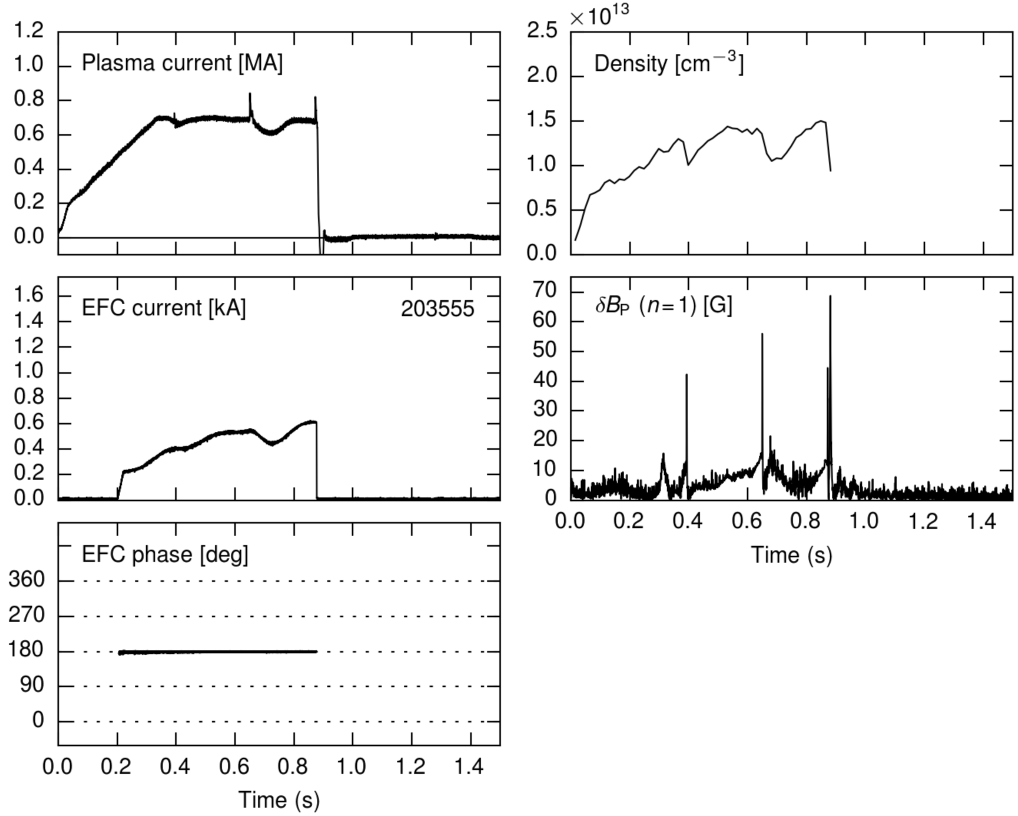
OH×TF interaction definitively ruled out

- In NSTX, time-dependent OH×TF error field due to OH lead geometry
- Designed out of NSTX-U with coaxial OH lead assembly [Menard NF 2012]
- Compare plasma-like vacuum shots:
  - In NSTX, OH×TF error field visible in δB_R as I_{OH} swings negative
  - In NSTX-U, no such OH×TF error field is measured



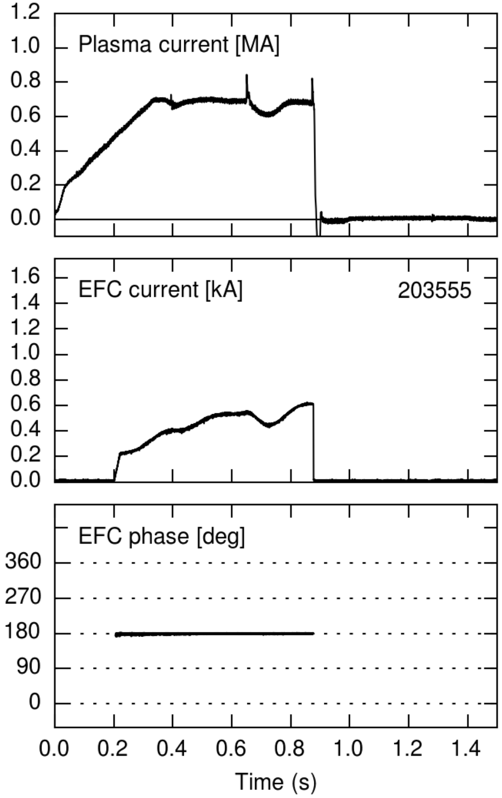
Seek initial $n=1$ EFC with PF5-proportional 3D fields

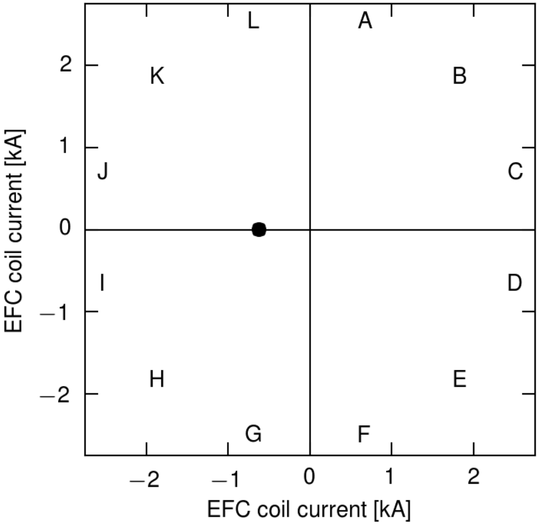
- Apply $n=1$ fields at fixed phase
- Set amplitude proportional to the main vertical field (PF5)
- Locking events visible in the density and in δB_P



Seek initial $n=1$ EFC with PF5-proportional 3D fields

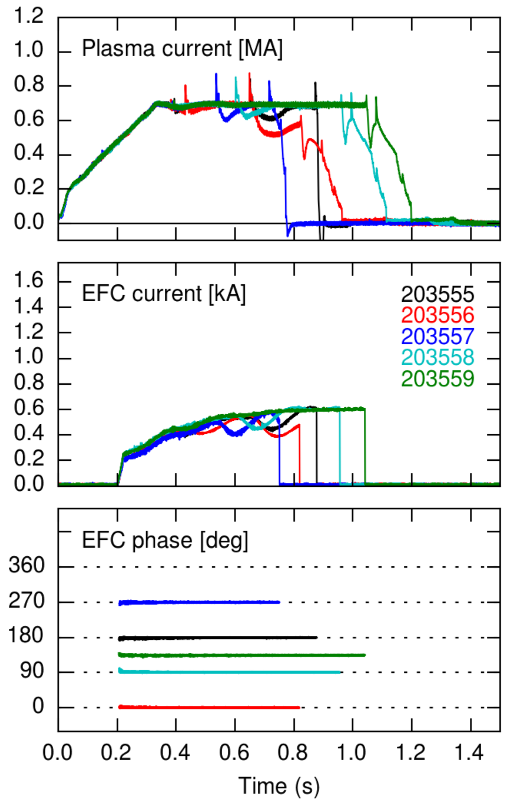
- Apply $n=1$ fields at fixed phase
- Set amplitude proportional to the main vertical field (PF5)
- Locking events visible in the density and in δB_P

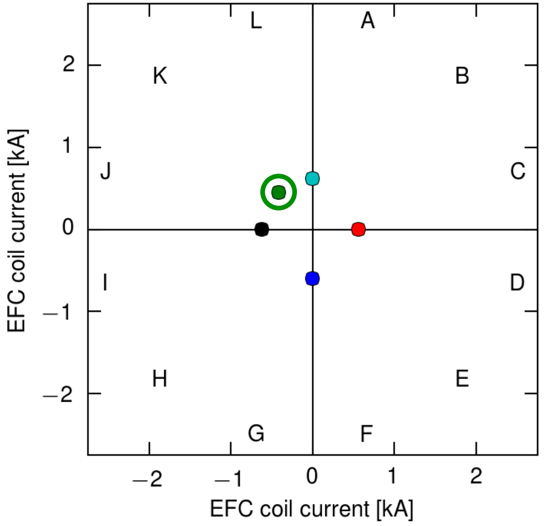




Feed-forward phase scan: $\phi = 135°$

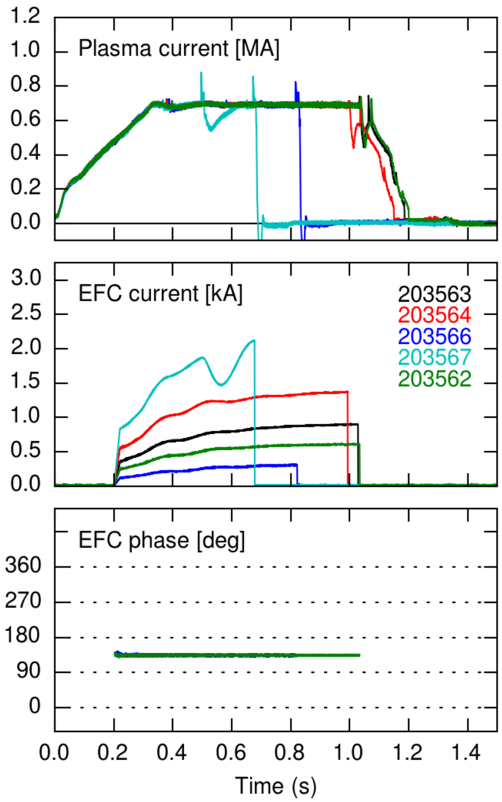
- Apply $n = 1$ fields at fixed phase
- Set amplitude proportional to the main vertical field (PF5)
- Locking events visible in the density and in δB_P
- Applied field phase scan:
  - Optimum phase = 135°

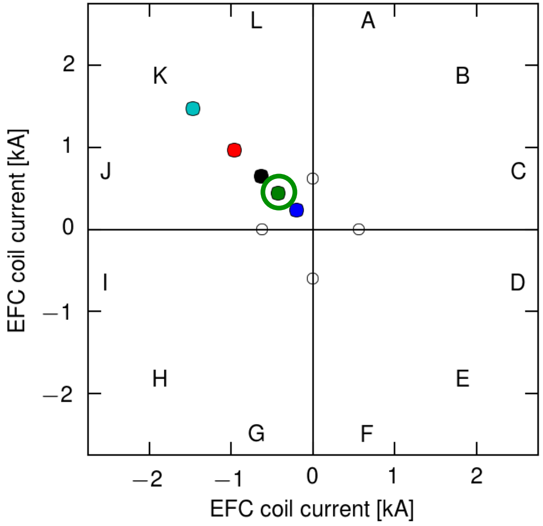




Feed-forward amplitude scan: $I_{EFC} = 600$ A

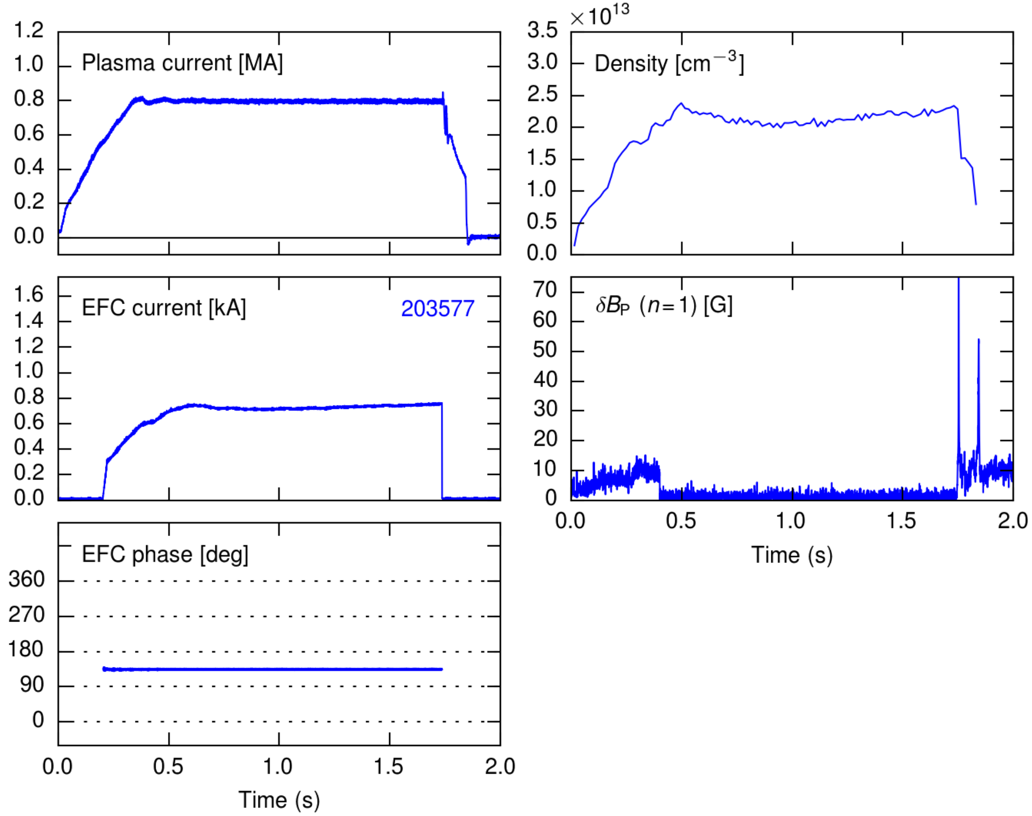
- Apply $n = 1$ fields at fixed phase
- Set amplitude proportional to the main vertical field (PF5)
- Locking events visible in the density and in δB_P
- Applied field phase scan:
  - Optimum phase = 135°
- Applied field amplitude scan:
  - Optimum amplitude = 600 A
  - Proportional to PF5





Long-pulse L-mode scenario established after implementing PF5-proportional EFC

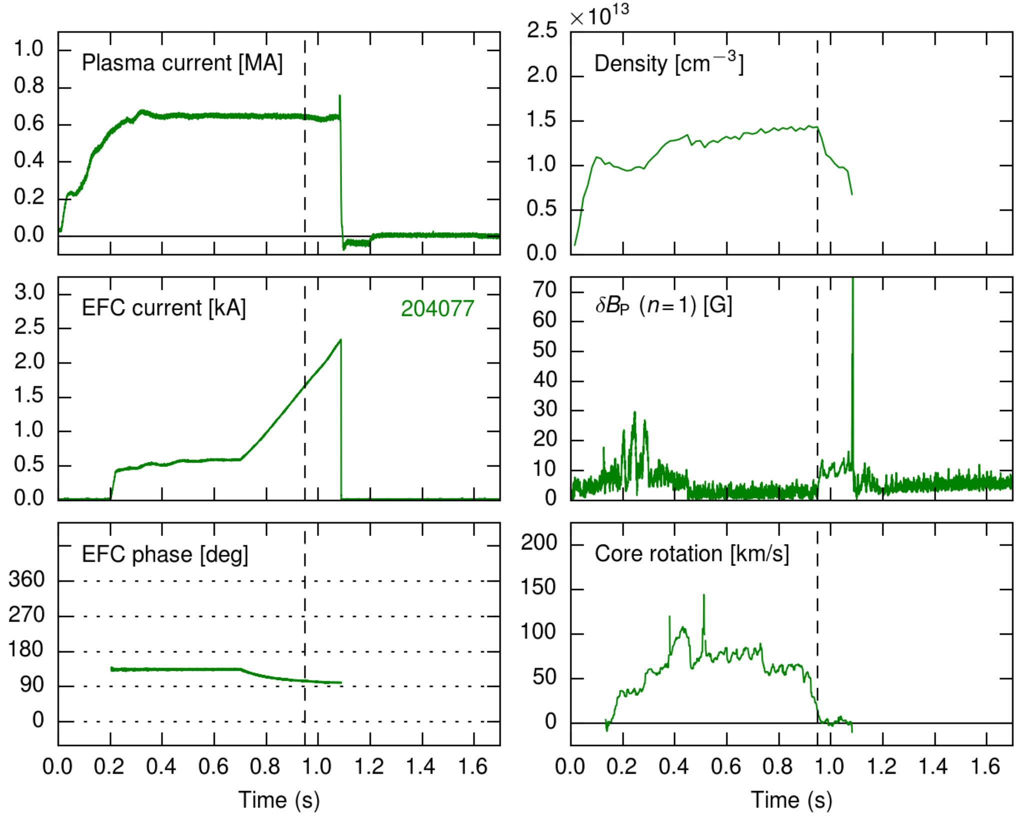
- Quickly established a robust 1 MW beam-heated L-mode scenario
- I_p = 800 kA with flat density evolution and quiescent δB_P
- The discharge terminates at ~1.7 sec due I_{OH} limit



Refine optimum EFC with an $n=1$ compass scan

Compass scan steps:

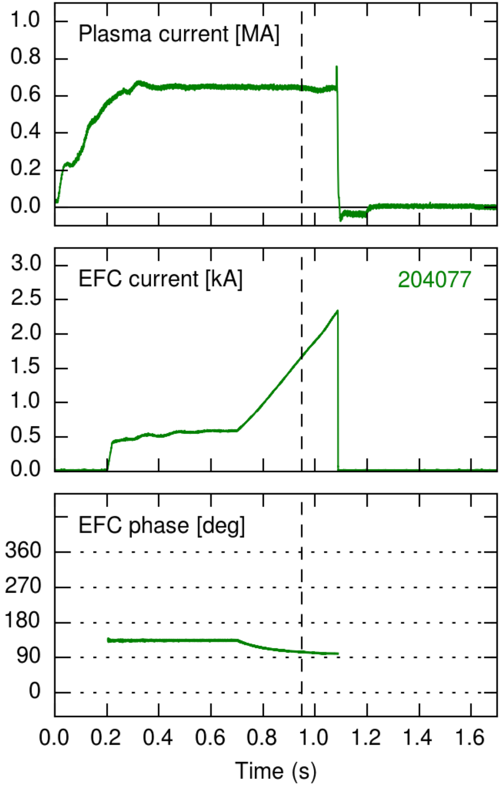
1. Select $n=1$ phase
2. Ramp $n=1$ amplitude until the discharge terminates

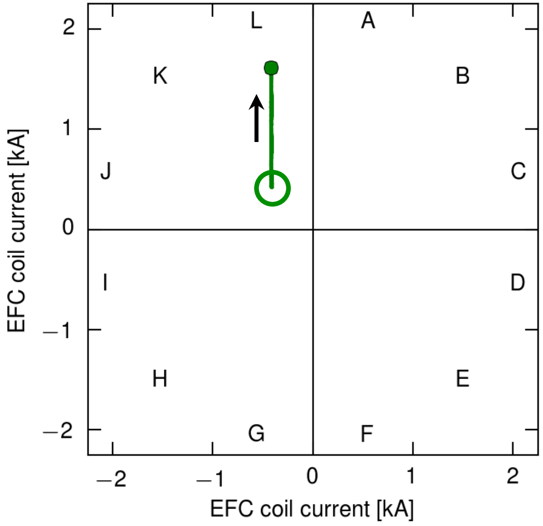


Refine optimum EFC with an $n=1$ compass scan

Compass scan steps:

1. Select $n=1$ phase
2. Ramp $n=1$ amplitude until the discharge terminates

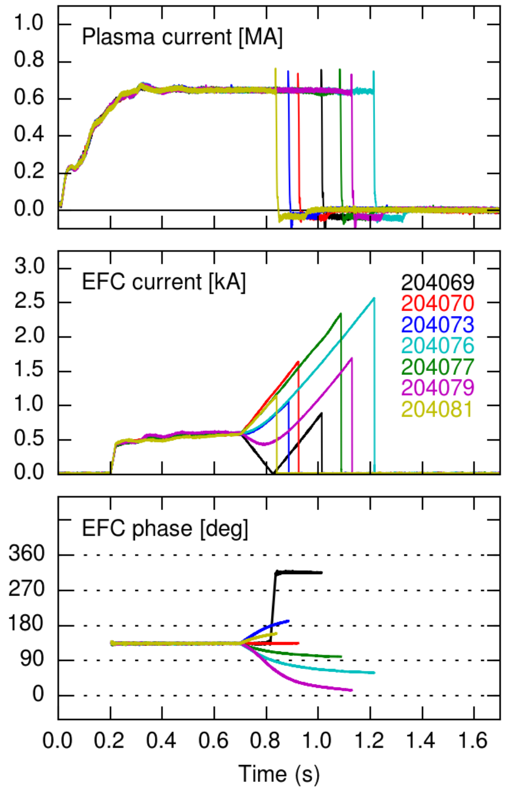


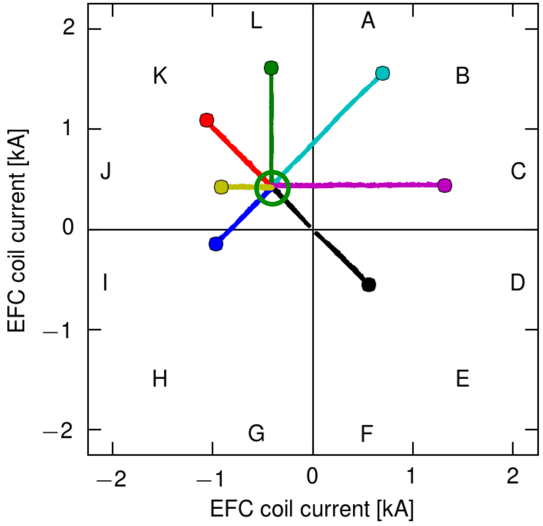


Refine optimum EFC with an $n = 1$ compass scan

Compass scan steps:

1. Select $n = 1$ phase
2. Ramp $n = 1$ amplitude until the discharge terminates
3. Repeat at multiple phases





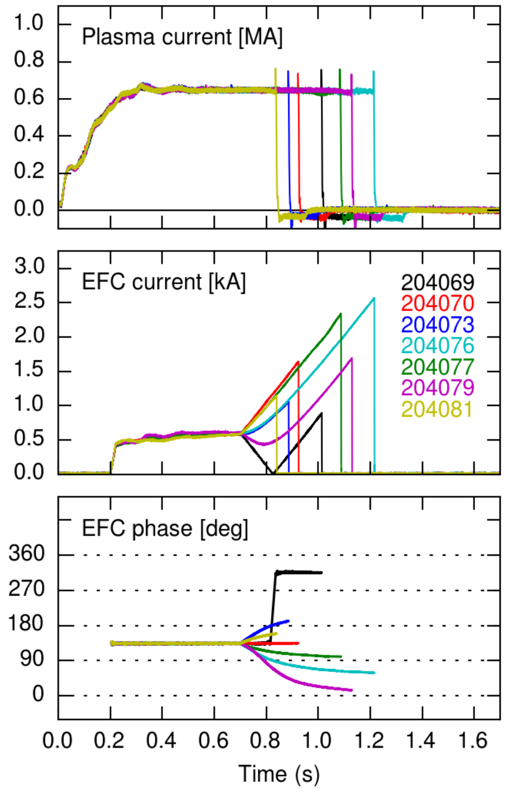
The optimum phase shifts from 135° to 80°

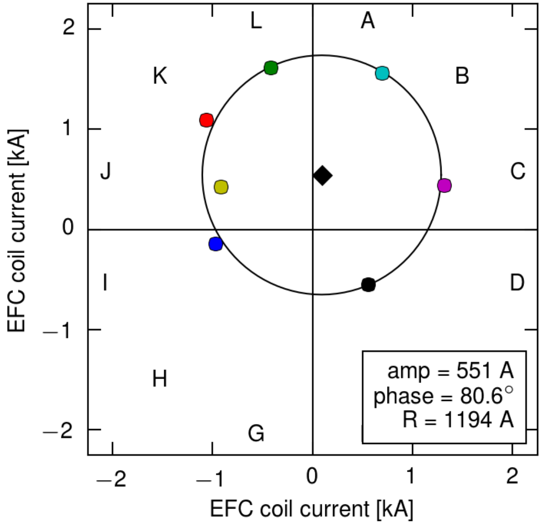
Compass scan steps:

1. Select $n = 1$ phase
2. Ramp $n = 1$ amplitude until the discharge terminates
3. Repeat at multiple phases
4. Fit circle to locking points
5. The optimum EFC is located at the center of the circle

Optimum EFC:

- ϕ = 80° (prev. 135°)
- I_{EFC} = 550 A (prev. 600 A)



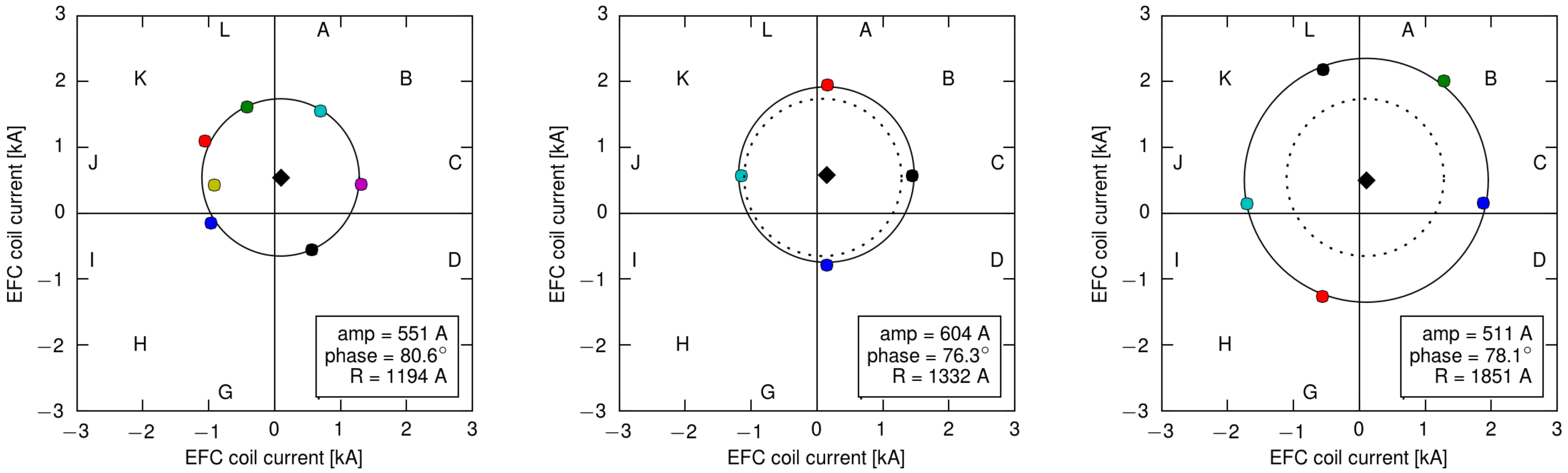


Additional compass scans confirm the optimum EFC

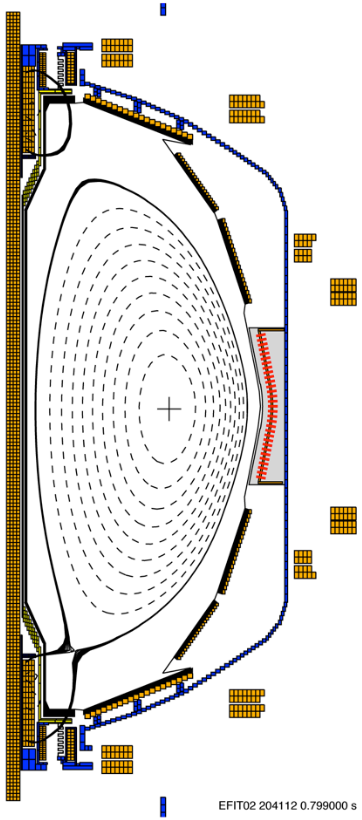
- Original compass scan
- Optimum amplitude: 550 A
- Optimum phase: 80°

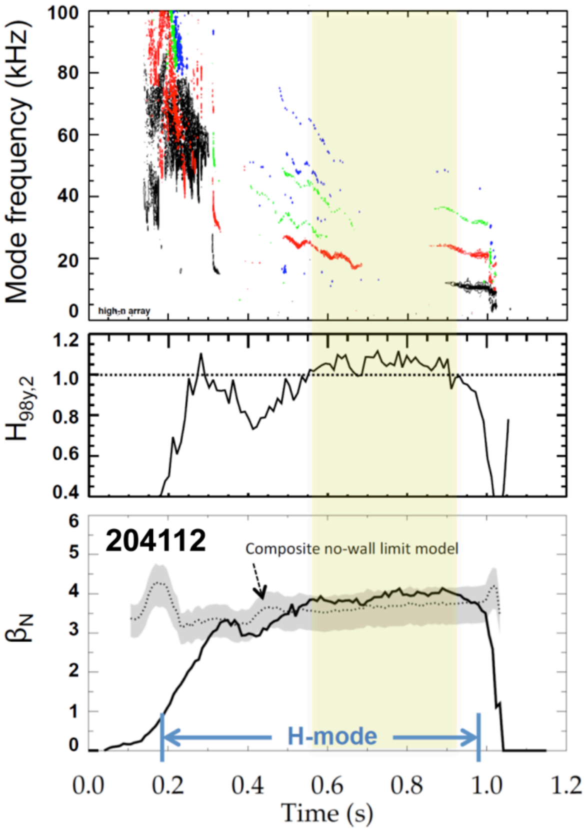
- Higher density
- Same optimum EFC
- Rotation dominates the density scaling?

- Different OH flux state
- Same optimum EFC
- Eliminates the OH as a major error field source



High performance H-modes achieved after implementing compass-scan-optimized EFC





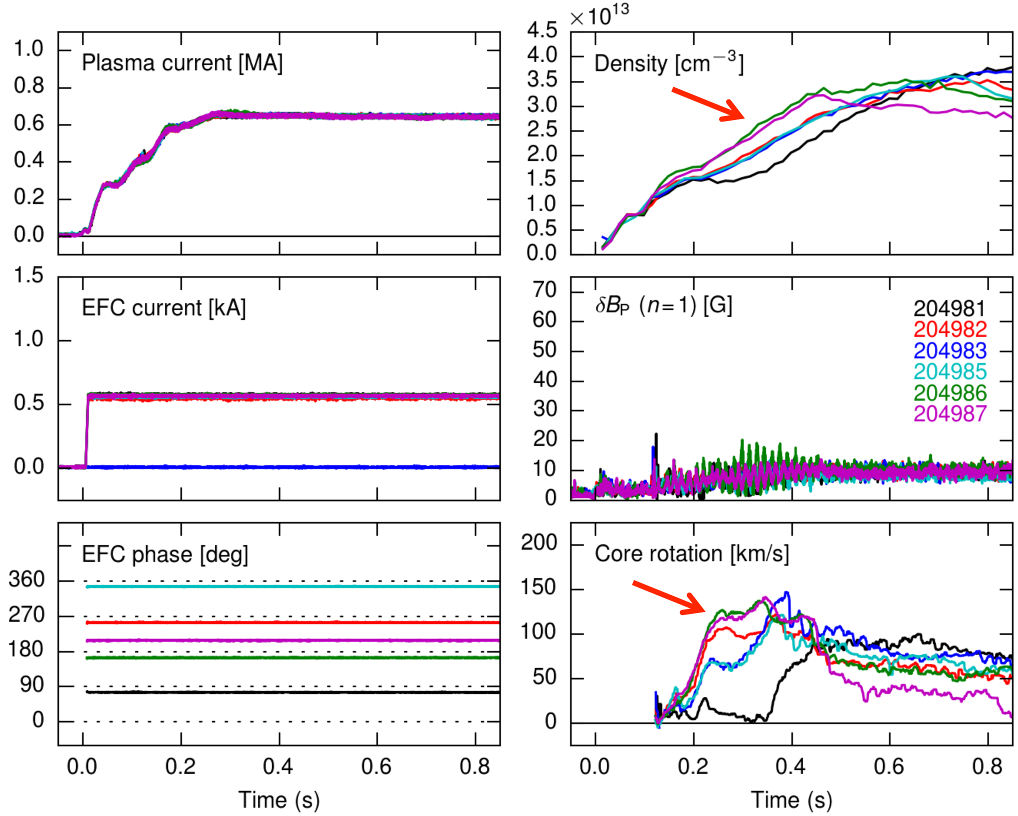
Minimal core MHD

$H_{98y,2} \geq 1$

$\beta_N/\beta_{no\text{-}wall} \geq 1$

A different EFC phase is required early in time

- A static applied $n = 1$ phase scan early in time shows a different optimum EFC phase
- The optimum flattop phase of 80° is *counter-productive* early
- The phase asymmetry is visible in the density and core rotation
- Continue to search for the time-evolving error field source



Optimized EFC enables long-pulse L-modes and high-performance H-modes in NSTX-U

- Summary:
  - Identified flattop EFC settings that enable long-pulse L-modes and high-performance H-modes
  - Eliminated two candidate error field sources:
    - OH×TF interaction
    - Tilt of the OH coil from the vertical
  - Identified an asymmetry in the optimum early time EFC with respect to the optimum flattop EFC

- More analysis and metrology are ongoing:
  - Multiple error field sources are in play (PF5 + ??)
  - Suspect a static tilt of the TF bundle is contributing
  - Time-dependent plasma response?