NSTX-U

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Non-axisymmetry at the center of NSTX – Lessons to optimize 3D tokamaks

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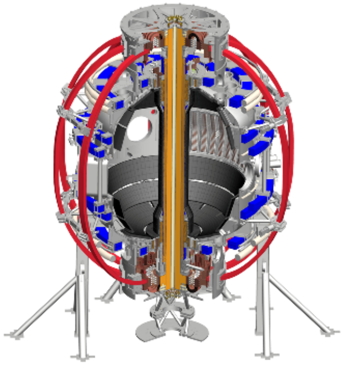
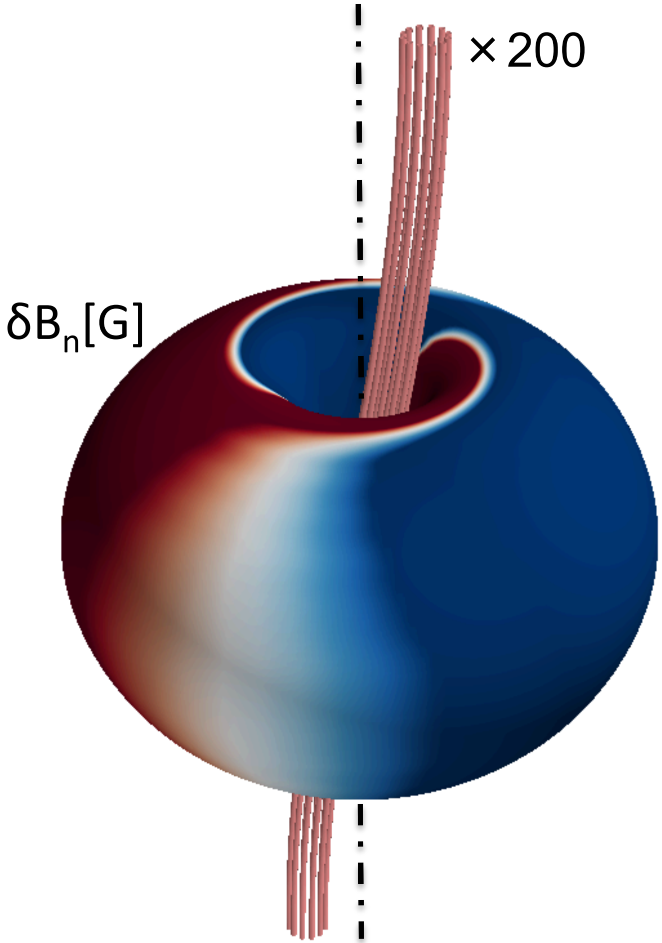
PPPL



Non-axisymmetry at the center of NSTX presents a challenge and opportunity to 3D tokamak physics

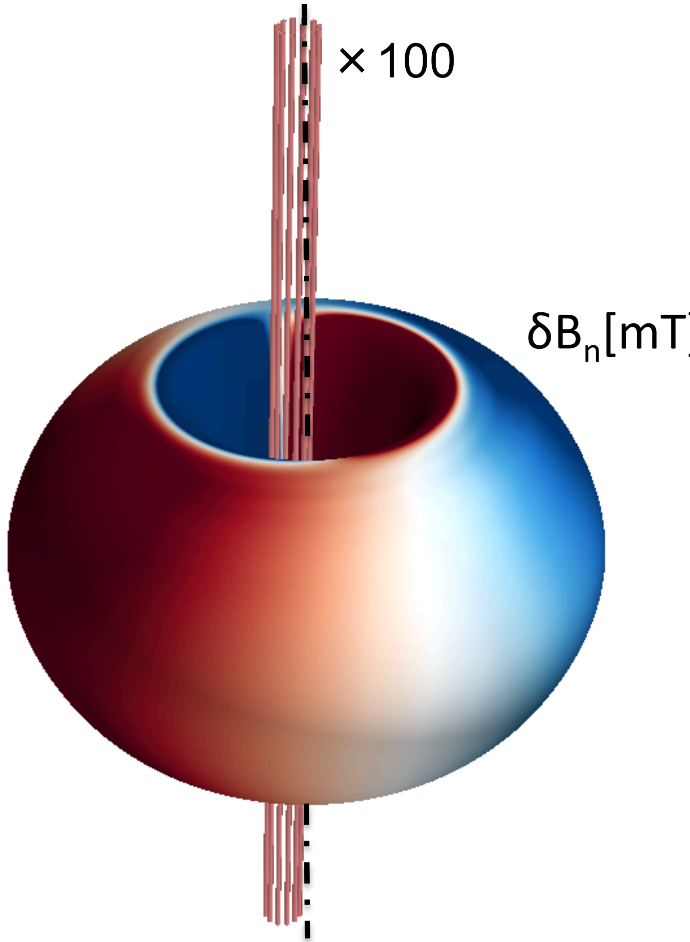
NSTX EF

Dynamic twist in OH-TF center-stack



NSTX-U EF

Static rigid misalignment of TF bundle



Overview

- Recap for NSTX OH-TF EF/C
- Metrology, phenomenology, experiments in NSTX-U TF EF/C
- Resonance, non-resonance, and plasma response modeling
- Special feature of HFS EF – NSTX-U and COMPASS
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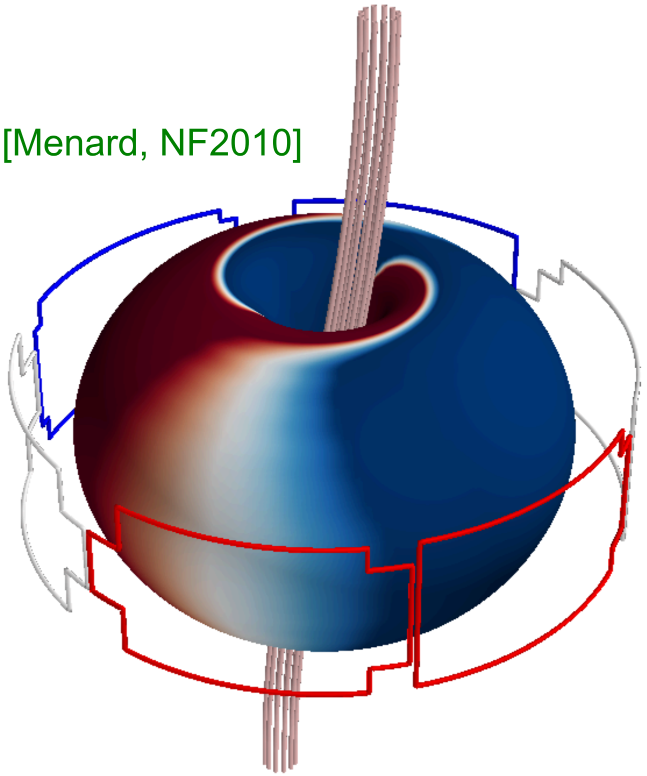
NSTX EFC studies addressed importance of poloidal mode coupling to core resonant modes for the first time

- Poloidal coupling is very strong in ST
- $dB_{m=2,n=1}$ driving 2/1 island locking is controlled by $dB^{x}_{m>10,n=1}$ in boundary
  - * 2/1 locking is the most disruptive event by non-axisymmetric error fields

[Menard, NF2010]



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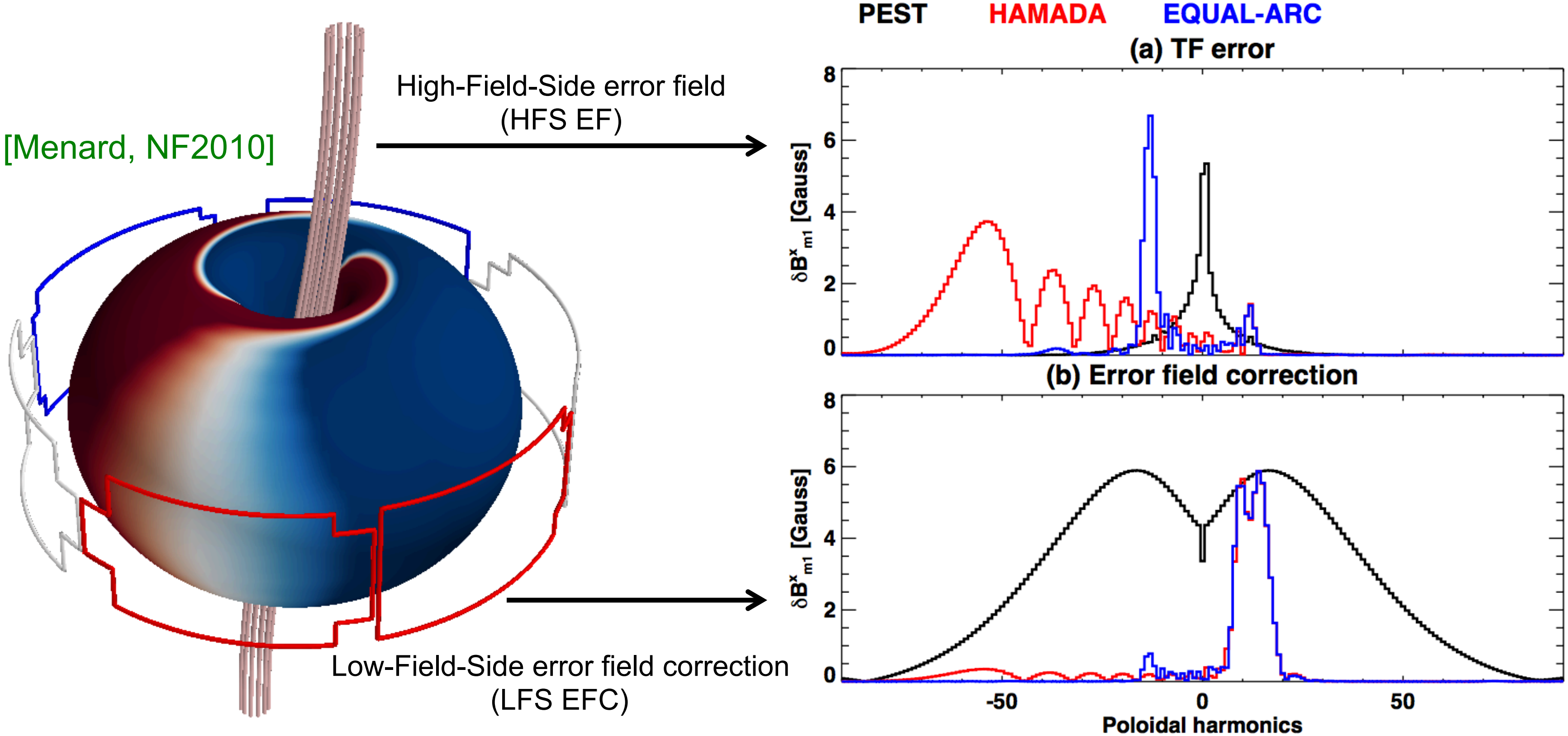

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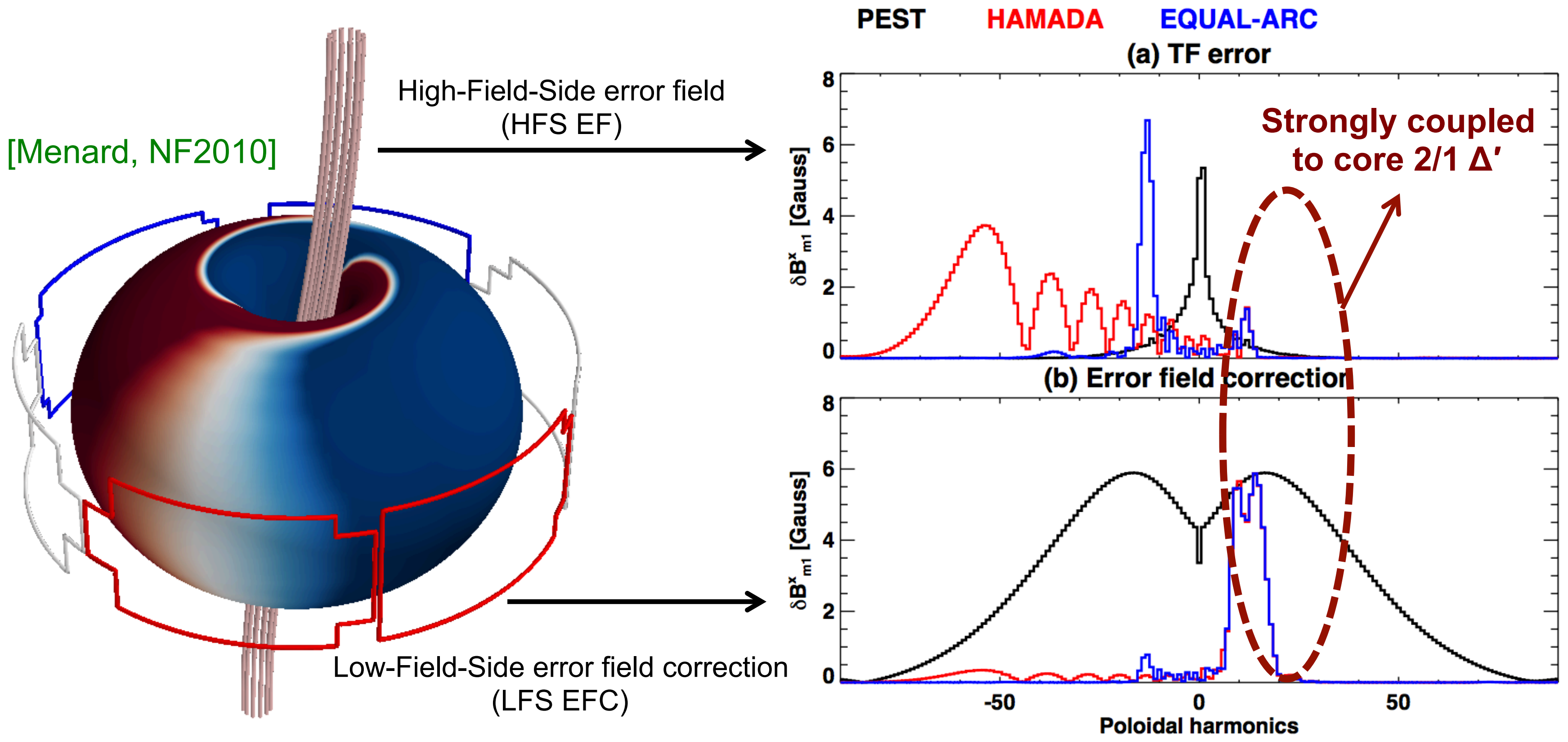
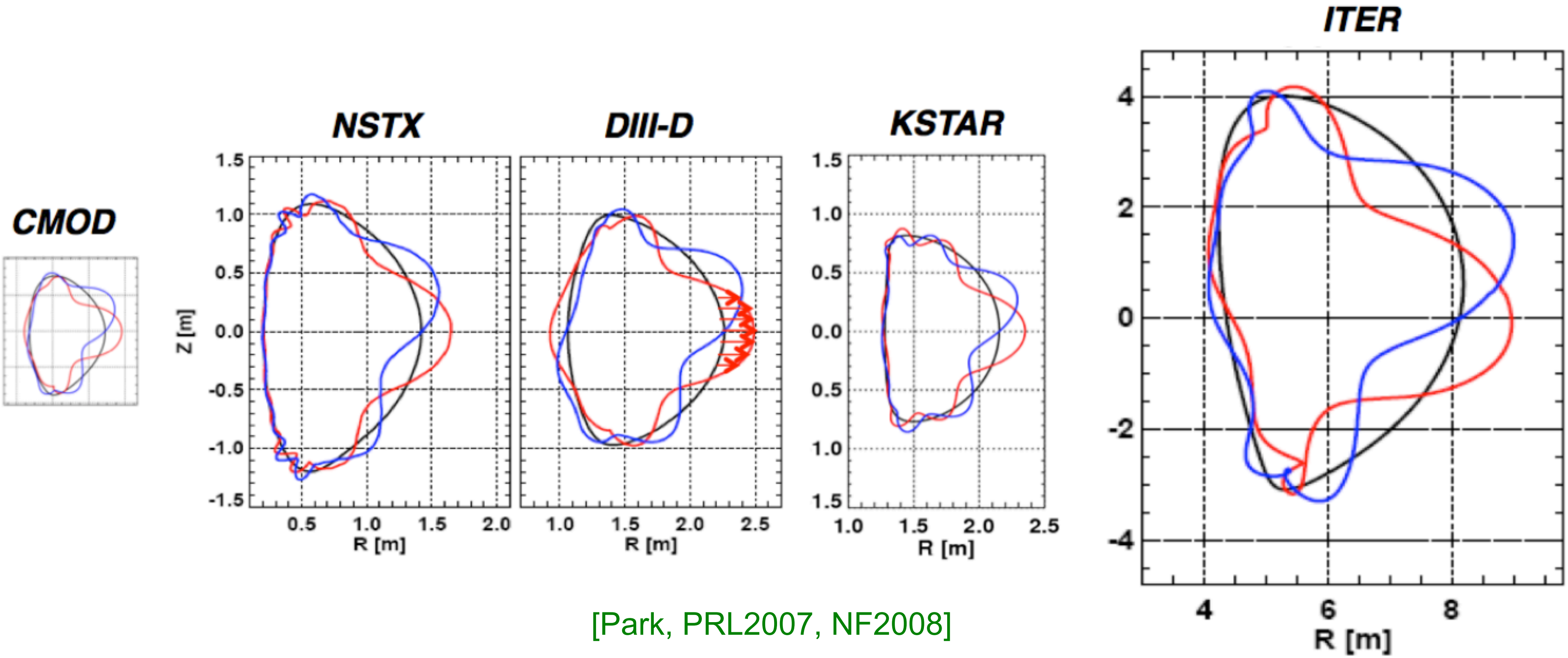


EFC studies since NSTX revealed robust dominant mode structure, enabling single-mode EFC strategy

- Dominant mode for core resonance (e.g. 2/1) is a combination of many ‘m’s
- It is similar to Kink, robustly favorable to LFS EFC

Shape of dominant mode structure at the plasma boundary



[Park, PRL2007, NF2008]

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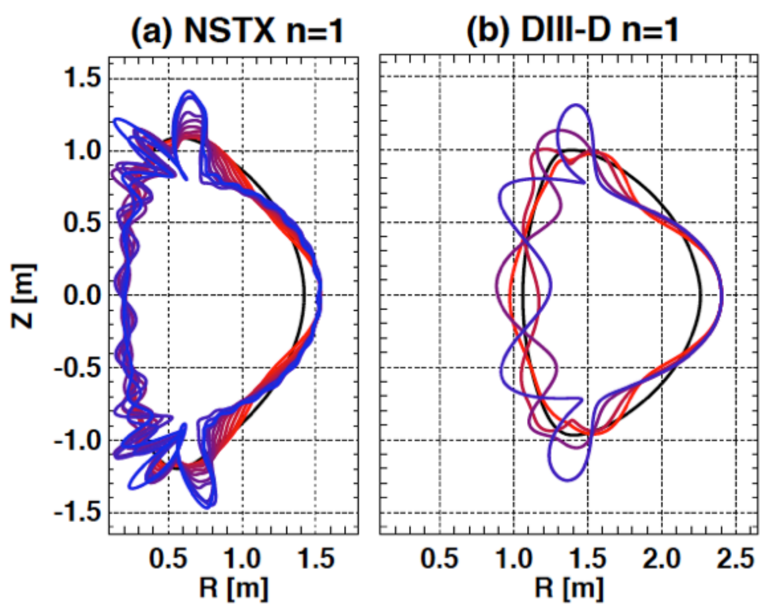
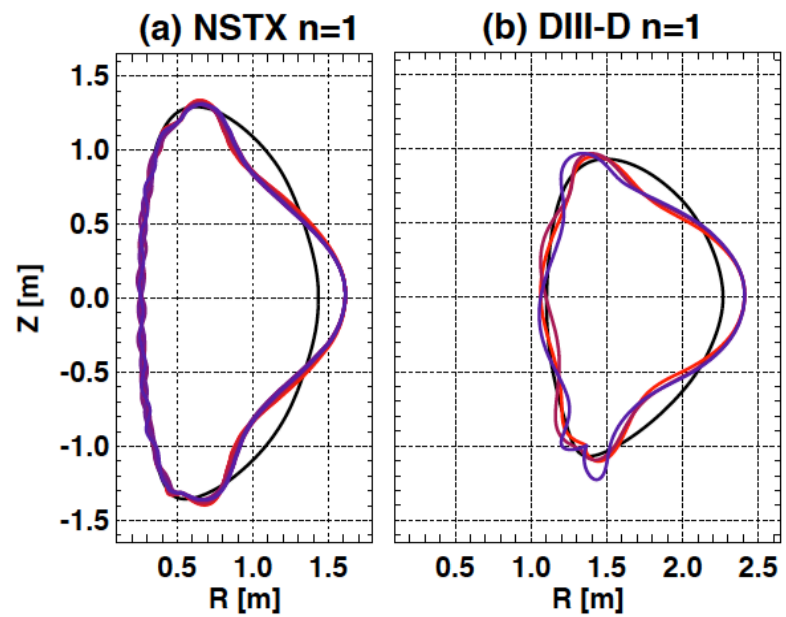
Dominant mode structure for **“each”** resonant field driving magnetic islands

Low β



High β



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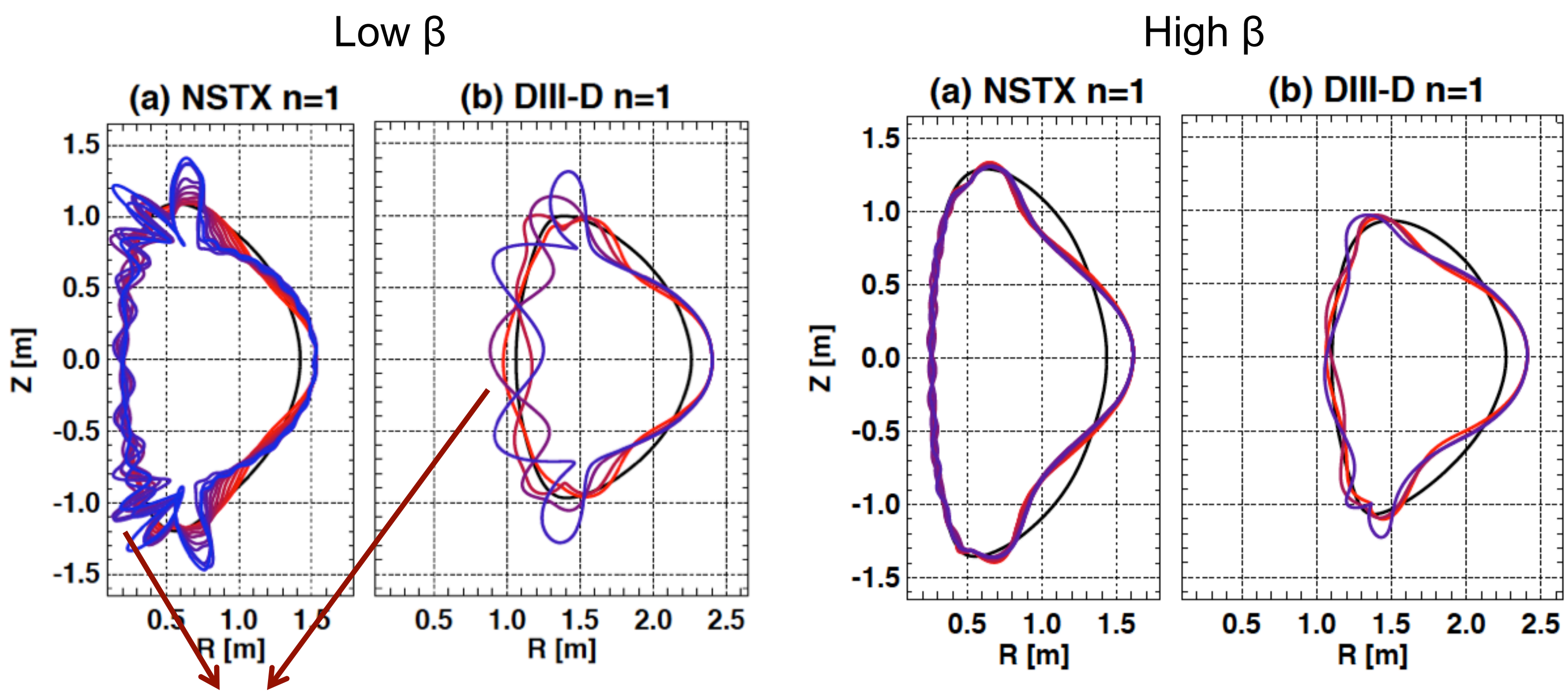

Maybe different for each, target-dependent, complex in phase, if HFS EF is large

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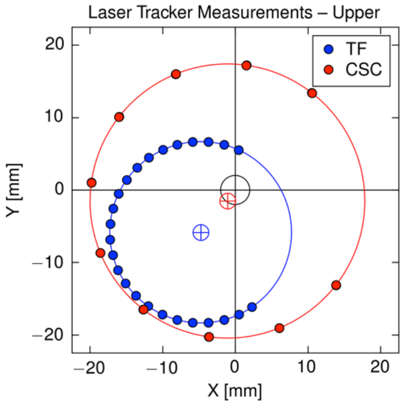
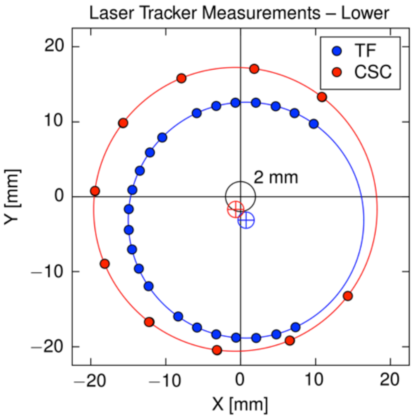
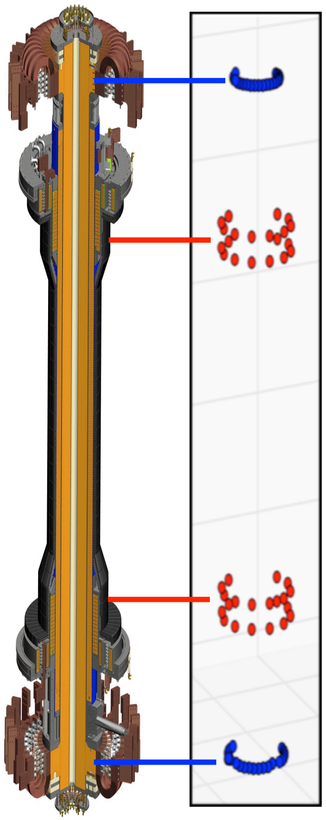
NSTX-U has identified 2 error field sources by advanced metrology

- TF bundle has 4.9mm shift and 1.2mrad tilt from the center (n=1)

This is 5 times larger than NSTX EF!







[On the courtesy of C. Myers]

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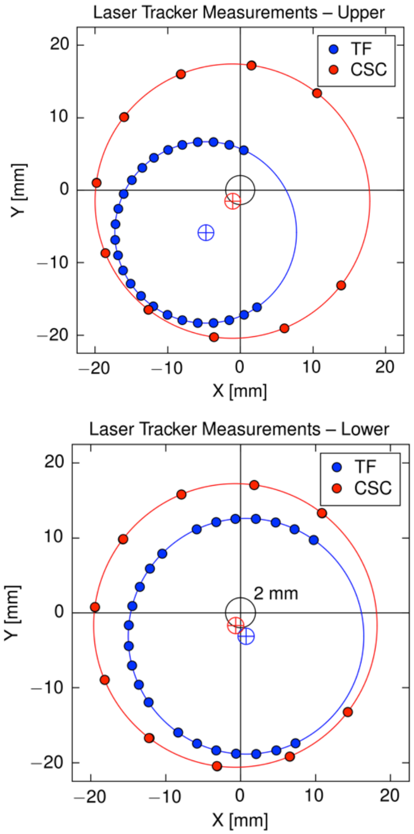
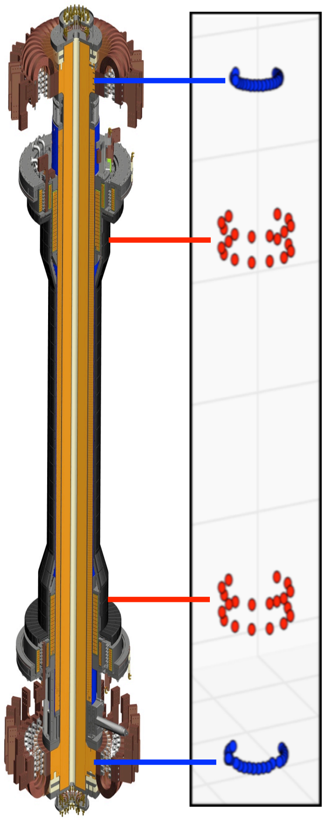
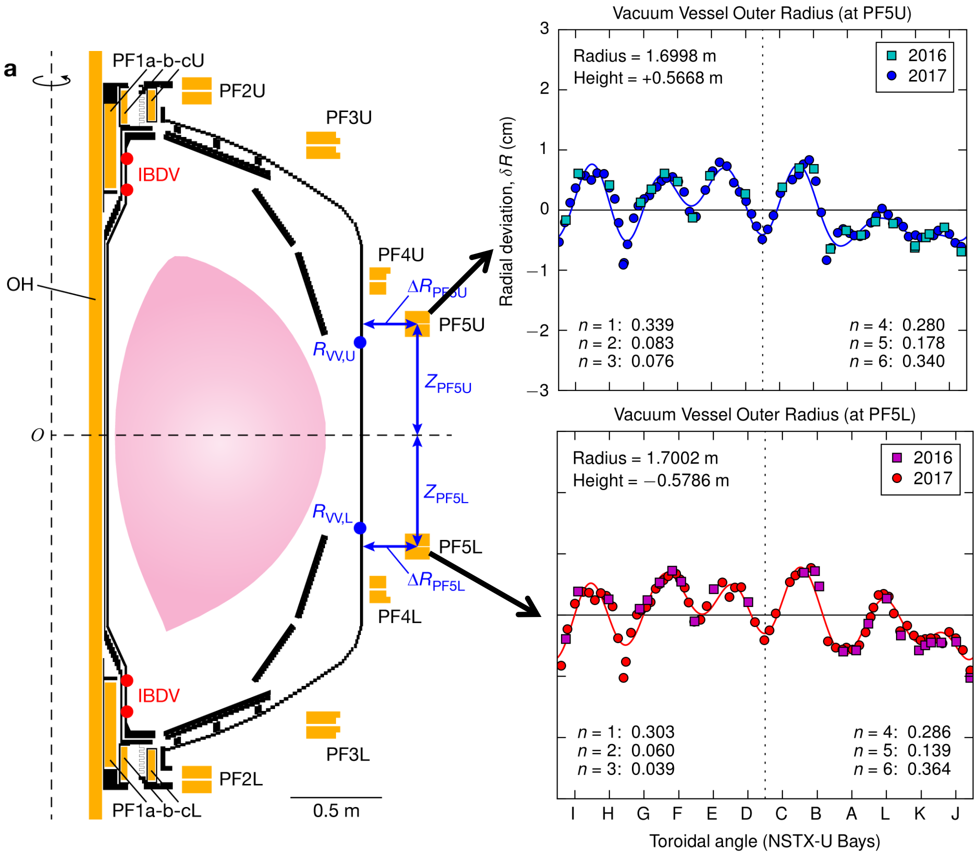
- PF5 U/L EF is subdominant but also larger than NSTX (can't be ignored in modeling and for n>1)



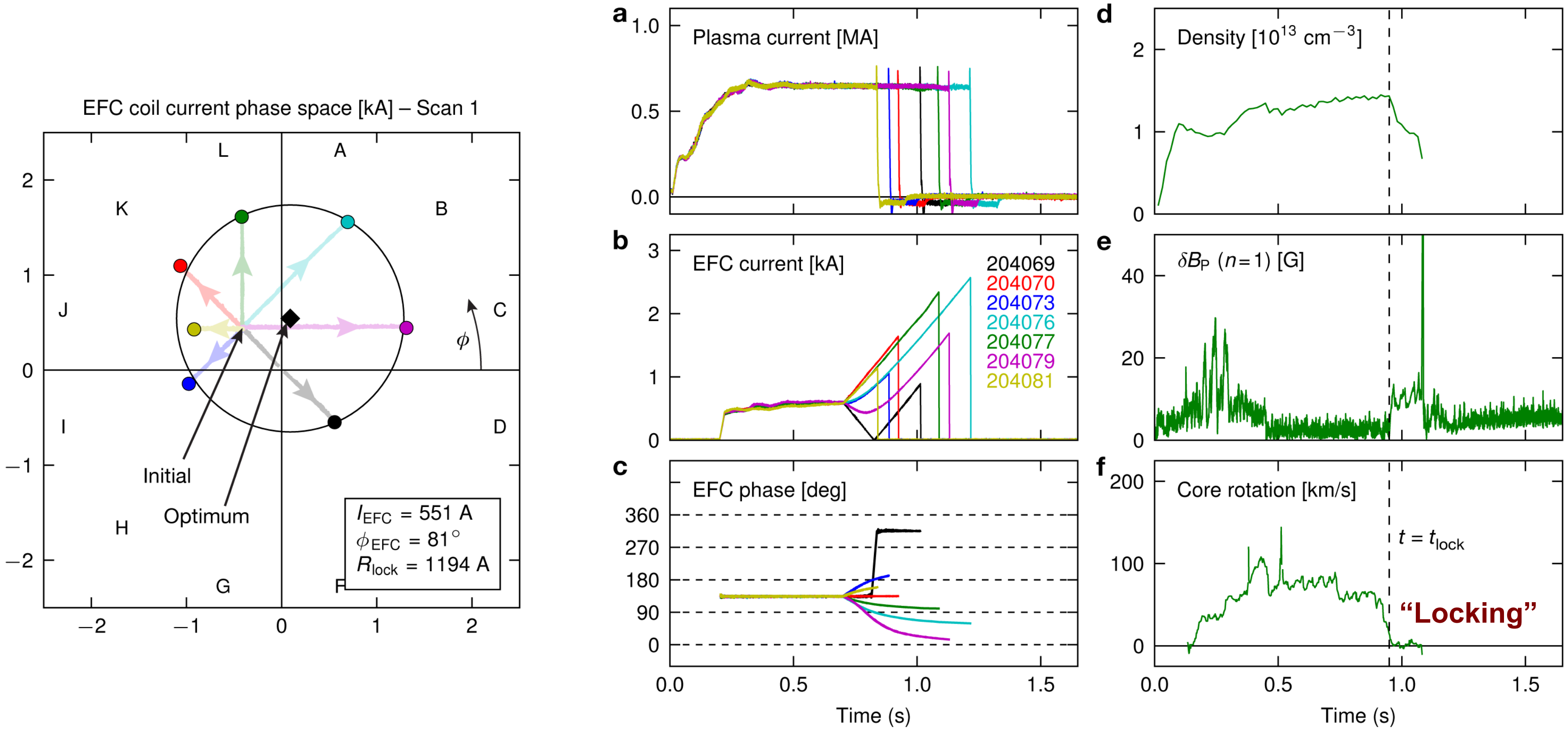




[On the courtesy of C. Myers]

Standard compass scans using LFS mid-EFC consistently found an optimal correction point in 1MW L-mode plasmas

- “Compass scan” is a standard method find EF and an optimal EFC
- Measure non-axisymmetric plasma response, typically disruptive locking



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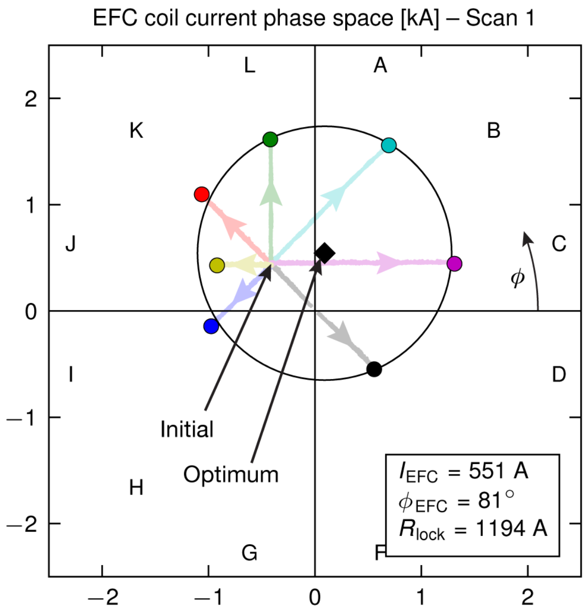
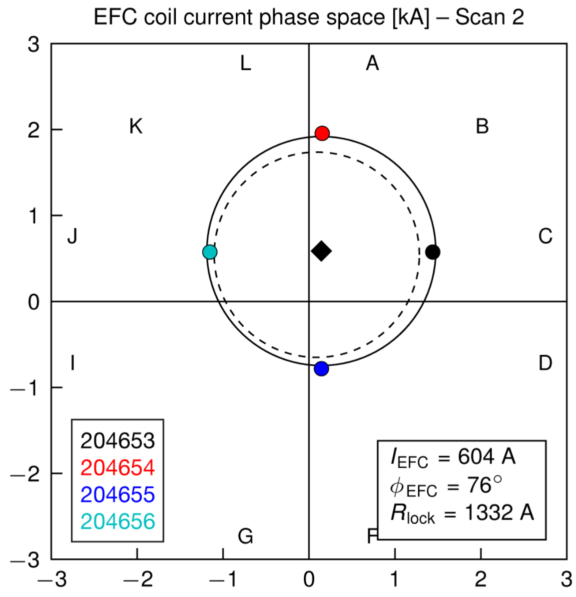
Standard compass scans using LFS mid-EFC consistently found an optimal correction point in 1MW L-mode plasmas

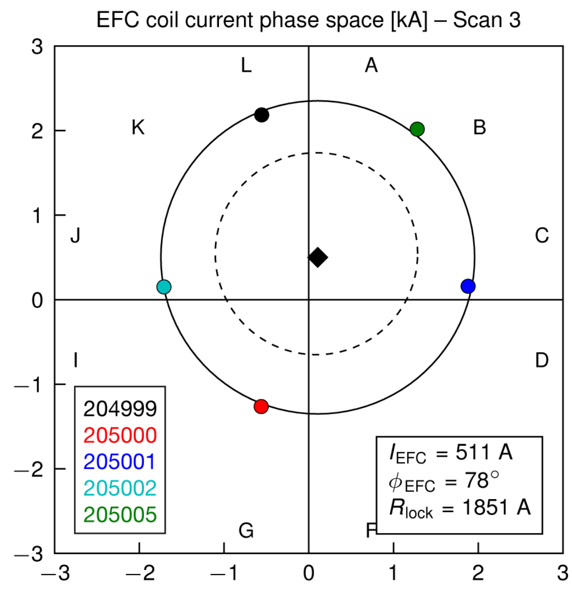
- “Compass scan” is a standard method find EF and an optimal EFC
- Measure non-axisymmetric plasma response, typically disruptive locking
- Optimal correction point shown to be consistent for 1MW L-mode plasmas



n_e=1.5×$10^{19}$$m^{-3}$
NB source: N1B



n_e=3.2×$10^{19}$$m^{-3}$
NB source: N1C

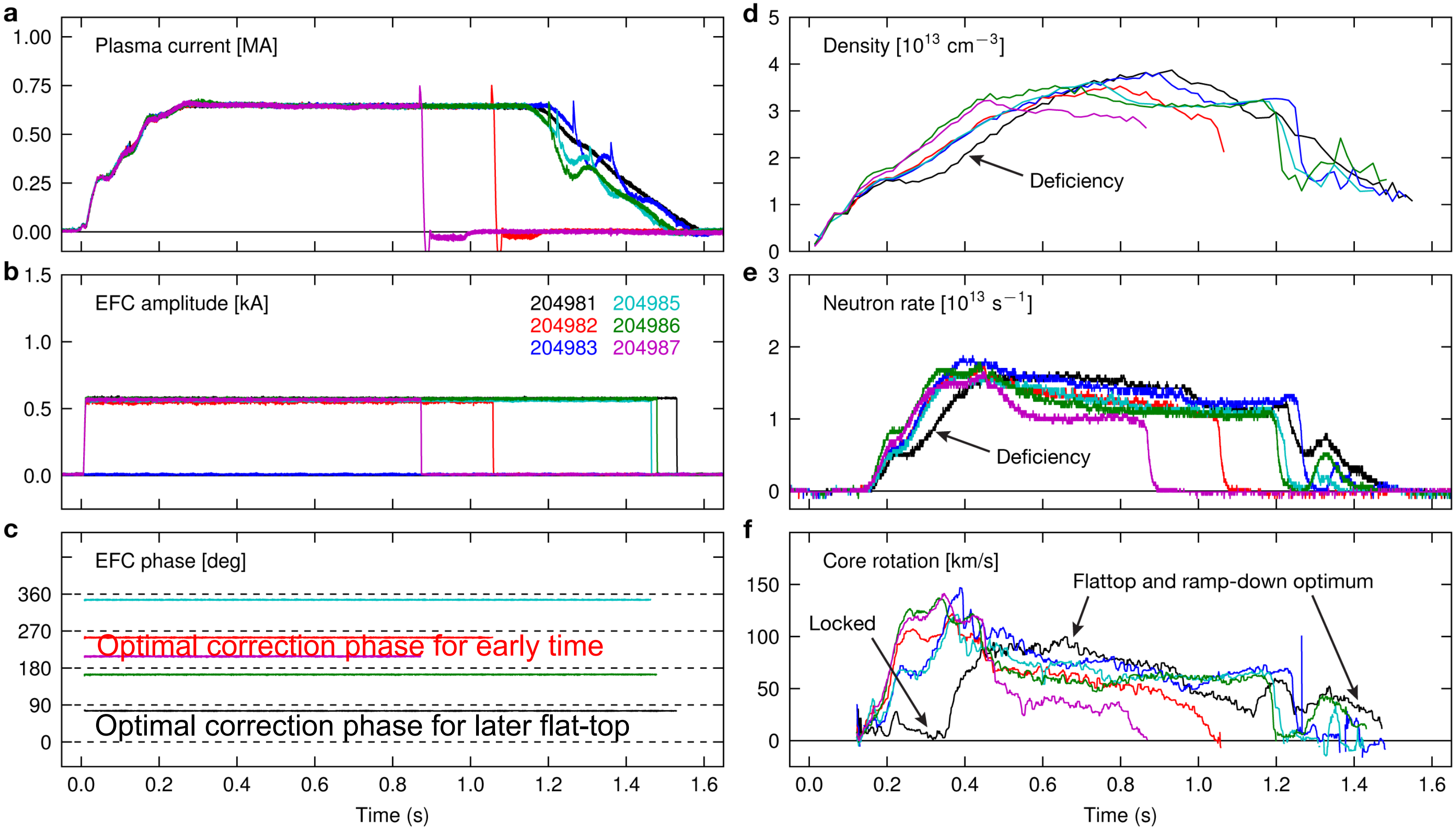


n_e=2.9×$10^{19}$$m^{-3}$
NB source: N1B

[On the courtesy of C. Myers]

However, optimal EFC is different in early phase of discharges and almost flips the sign

- Optimal correction in flat-top made performance worst in early time
- Optimal correction in early phase became worst in later flat-top



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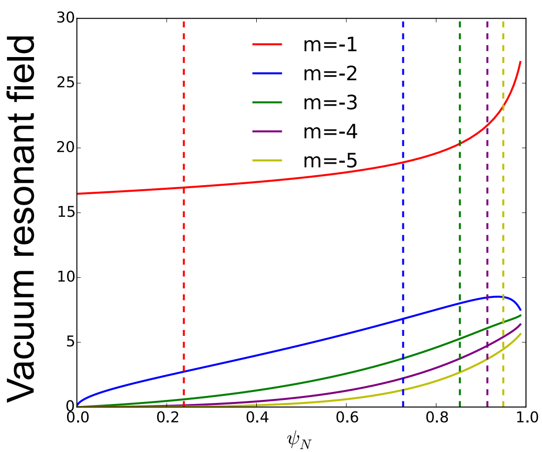
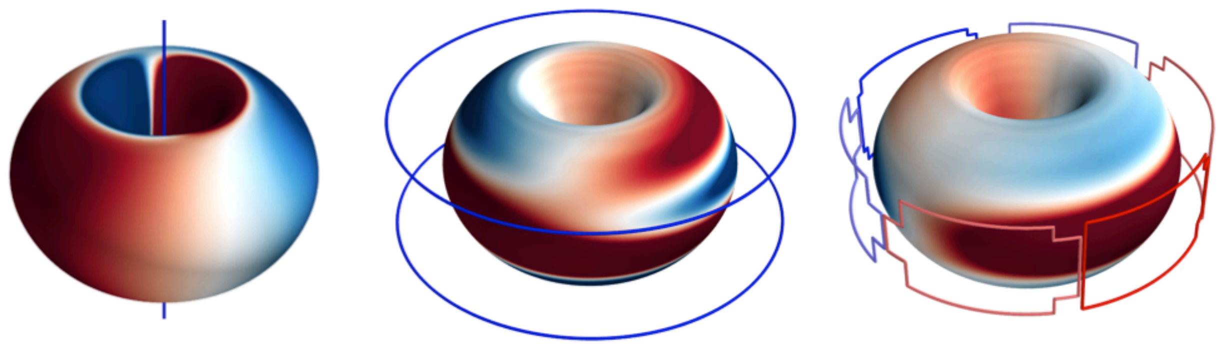
IPEC and M3D-C1 linear simulations confirm significant strong coupling and plasma shielding for resonant field

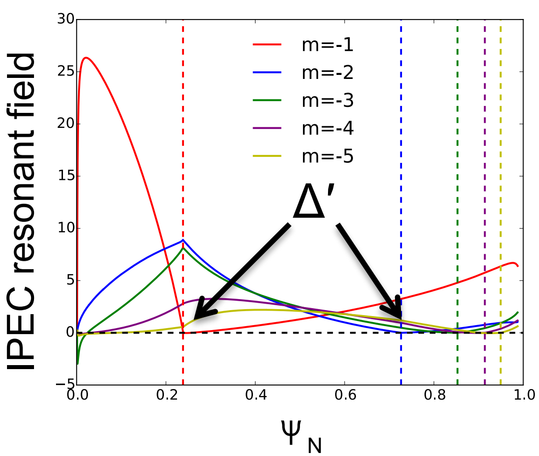
- Plasma amplifies Kink, but shields other modes (reluctance)
- Metric for resonant field driving locking : $\Delta'_{21} \propto dB_{21} \propto dB^{x}_{ovc}$

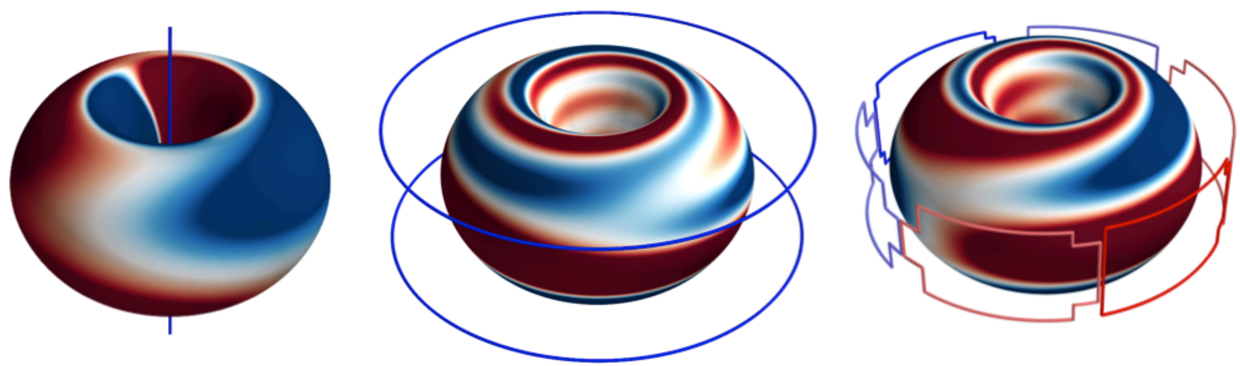




Vacuum

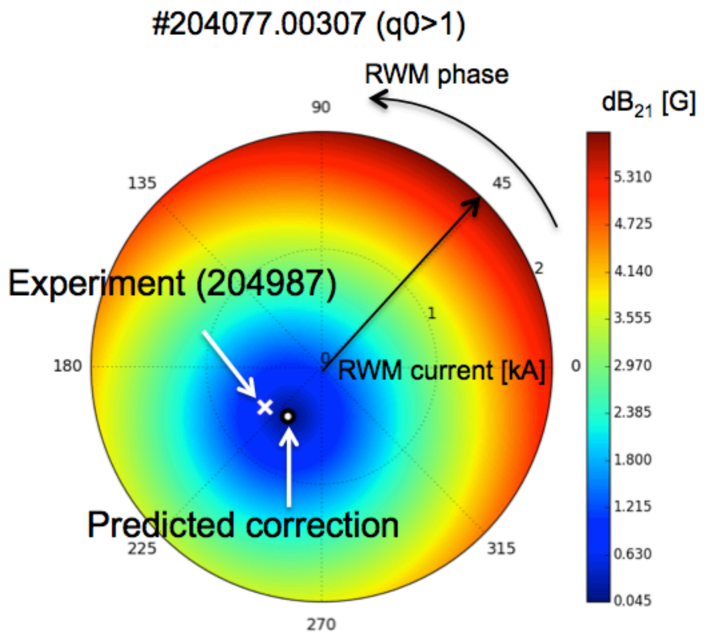
Plasma

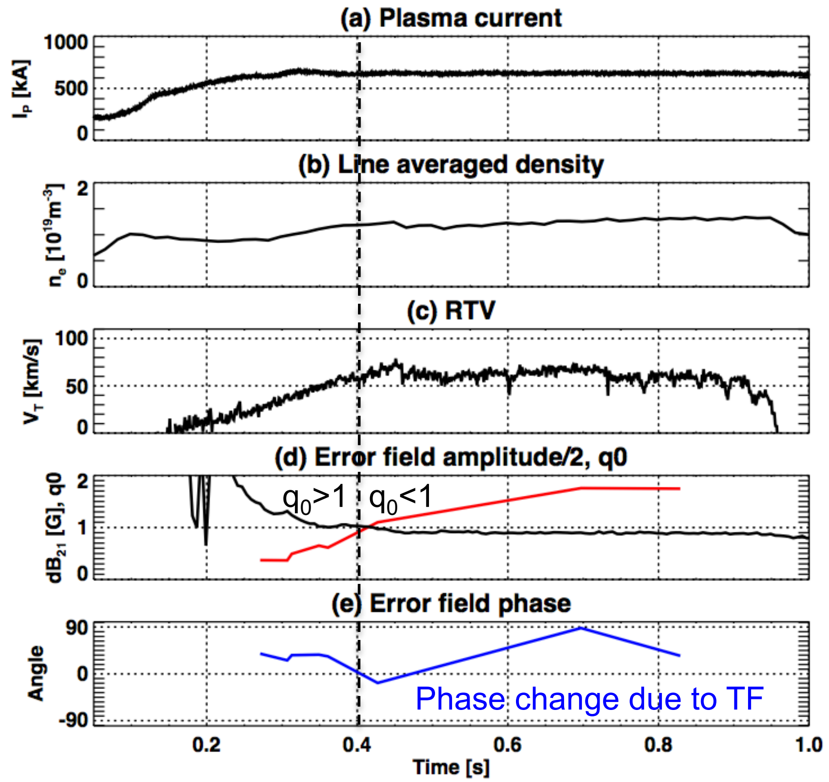




Linear plasma response explains optimal correction "only" for early time phase in 1MW L-mode cases

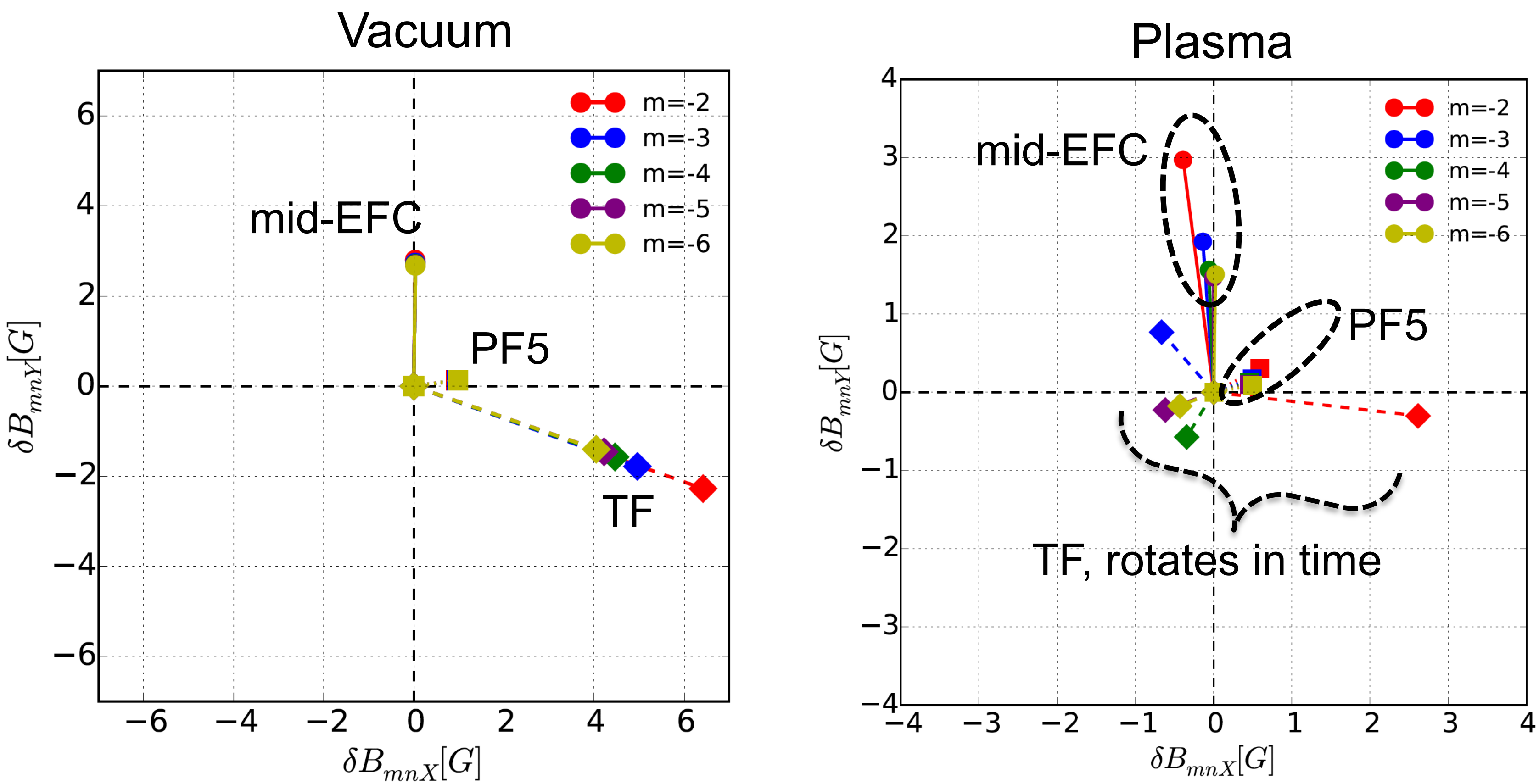
- Linear response is valid before the onset of islands (or q=1 enters)
- Shows dB_{21} is indeed minimized by optimal correction in early time
- Shows TF EF phase changes in time and equilibrium evolution, but can't match the sign flip observed in experiments





TF EF resonant coupling is complex in phase

- Toroidal phase of resonant field varies from core to the plasma edge, and rotates in time depending on equilibrium
- Correction for 2/1 at a time can make it worse for the others and in evolution



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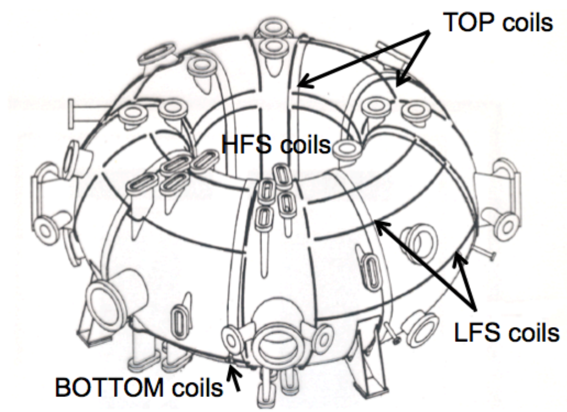
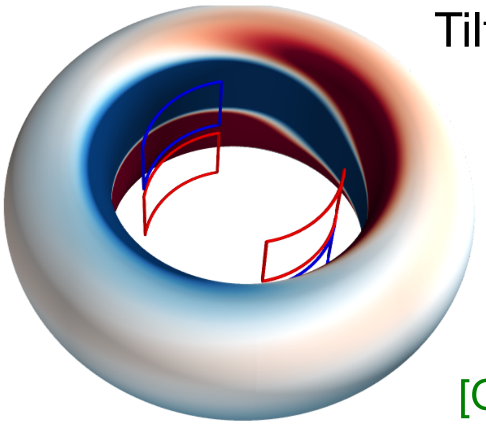
COMPASS can uniquely control HFS EF and confirms different resonant response between core and edge

- COMPASS is unique in controlling HFS EF
  - Performing high-impact experiments with IO
- IPEC and experiments show tilt EF >> shift EF (while shift EF >> tilt EF in NSTX-U)

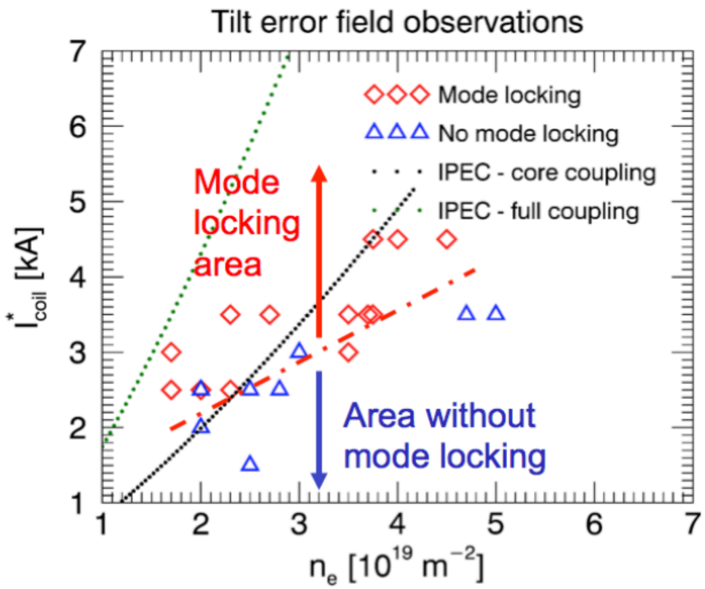




- LFS EF: Almost no difference in core, edge, full resonant coupling
- HFS EF: Large difference, and core resonance is only relevant as confirmed by initial COMPASS exps.

IPEC ITER EFC criterion

$$\delta B^{x}_{core,full} \leq 0.71\times10^{-4}\left(n_e[10^{19}m^{-3}]\right)^{1.3}\left(B_{T0}[T]\right)^{-2.0}\left(R[m]\right)^{0.93}\beta_N^{-0.69}\cdot B_{T0}$$

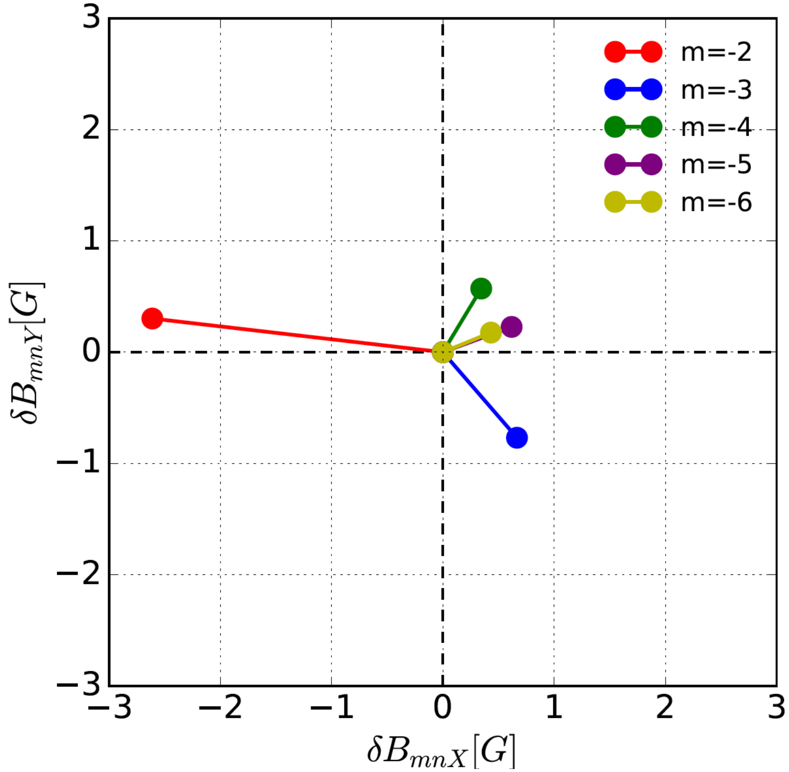


[On the courtesy of T. Markovic & M. Peterka]

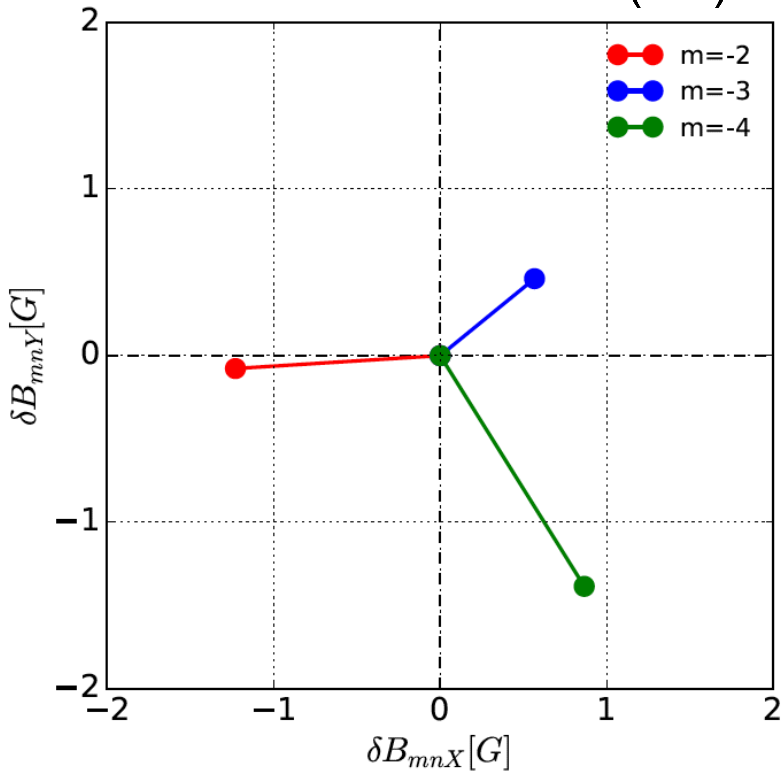
HFS EF is characterized by decoupling of each resonance, possibly giving an opportunity for edge resonance control

- Decoupling of each resonance is uniquely found only in HFS EF
- LFS correction for HFS EF core resonance will leave significant edge resonance – <u>This is the goal of RMP optimization for ELM control</u>

NSTX-U HFS TF



COMPASS HFS EF (Tilt)



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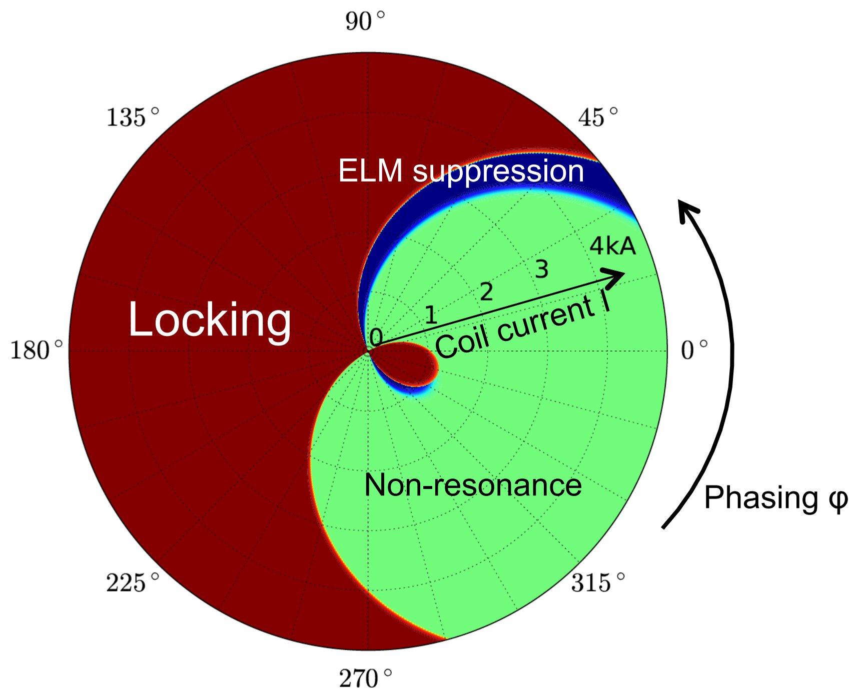
KSTAR shows importance of edge resonance decoupling in RMP ELM control

- Edge resonance ↑ and core resonance ↓ is the key to RMP optimization
- KSTAR 3 rows of in-vessel coils enables a distinct window and unique n=1 ELM suppression

KSTAR 3D stability diagram (I,φ)



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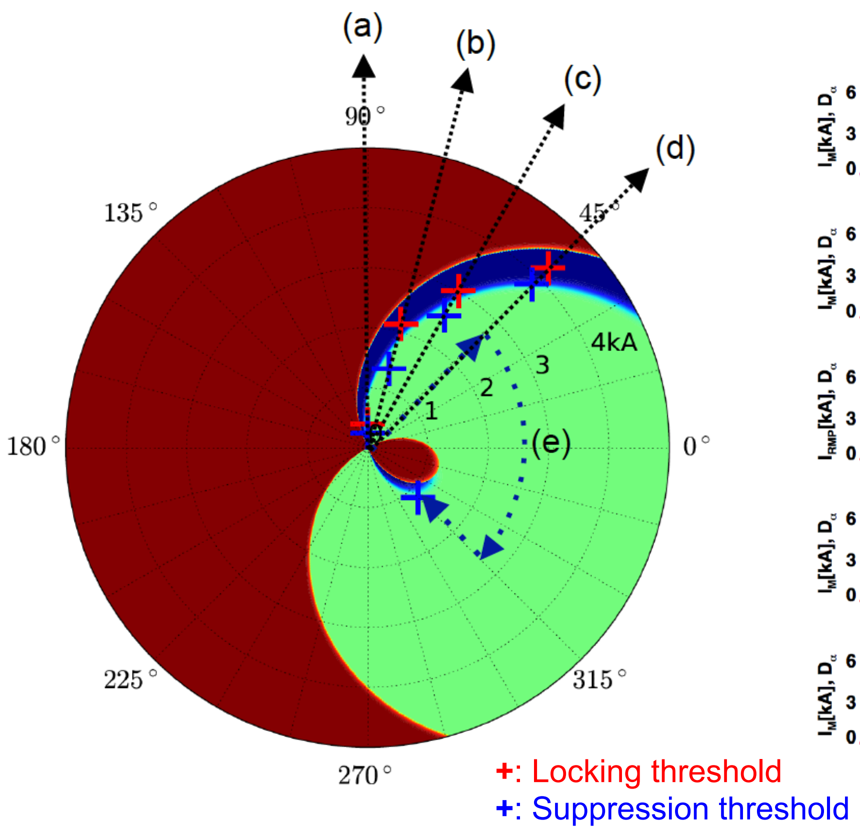
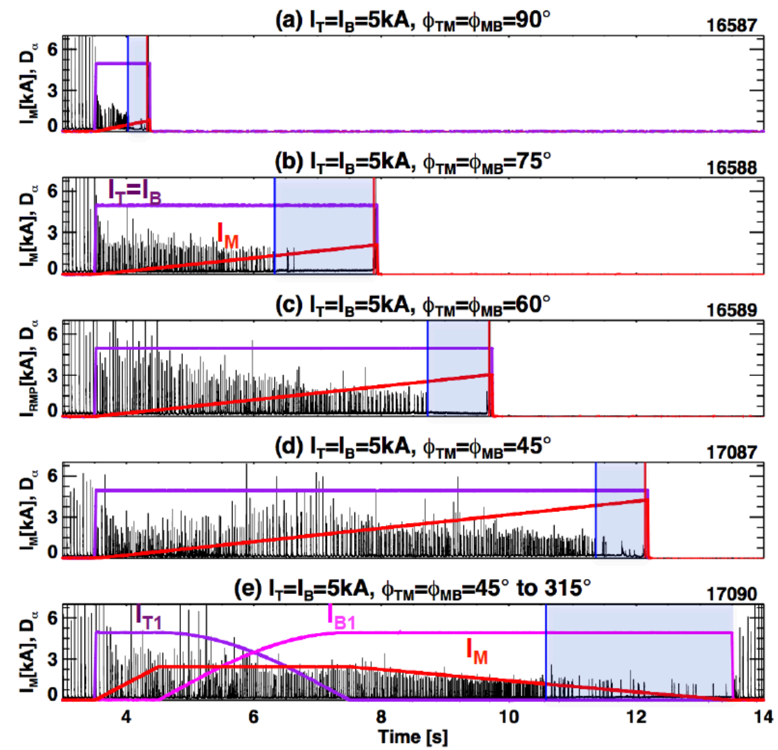
- KSTAR 3 rows of in-vessel coils enables a distinct window and unique n=1 ELM suppression – as demonstrated by experiments
- More coils will be better and HFS coils might do even better





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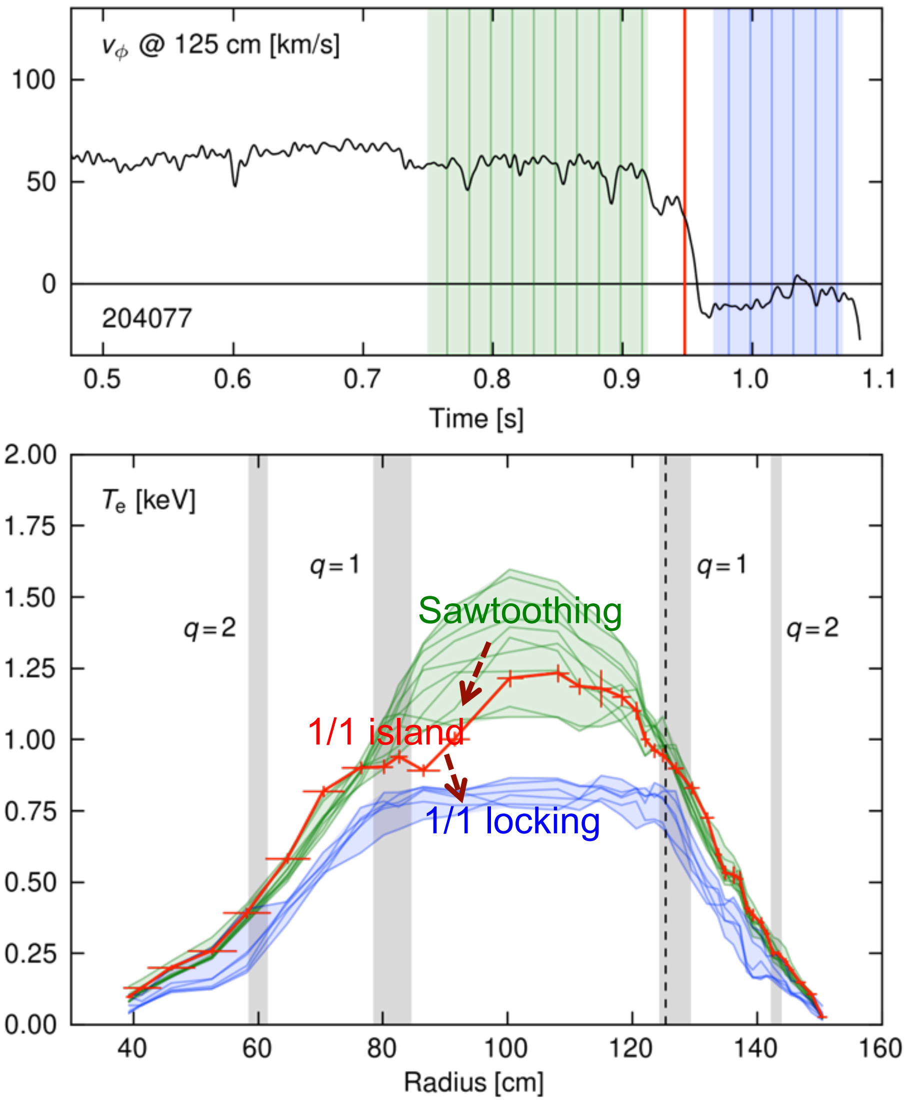
EFC sign flip in the later L-mode flat-top is possibly related to a direct 1/1 locking after 2/1 locking

[On the courtesy of C. Myers]



- TS and fast CHERS show a direct 1/1 locking from HFS due to large m=1 in TF error, for the first time in a tokamak:
- Early-time EFC can fail easily in evolution due to complex phase rotation of 2/1
- 2/1 may be initially locked but slowly rotates with plasma due to the injection torque
- Increased error field due to overcompensating EFC in addition to existing TF error may lead to a 1/1 direct locking, starting from HFS, and collapse

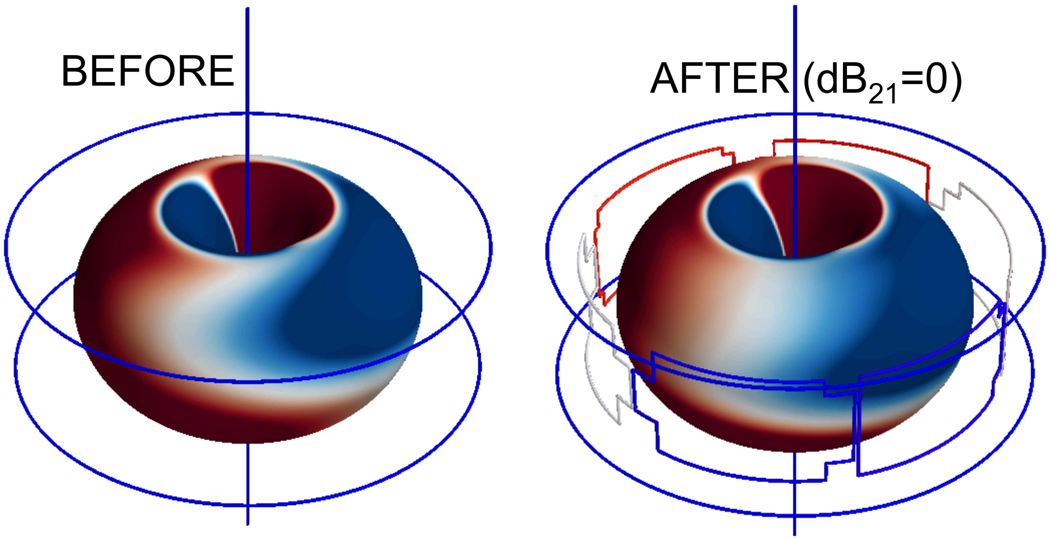
Summary

- Dynamic EF from moving centerstack in NSTX motivated major progress on EFC and 3D physics including dominant mode
- New EF identified from TF-bundle in NSTX-U presented again a challenge to standard single dominant mode method
- Response modeling indicated that HFS EF resonant response is complex in phase
- Decoupling of edge and core resonance by HFS EF implies innovative 3D coils for ELM control are still left for discovery
- NSTX-U EF also motivates non-linear study for a direct 1/1 locking – ITER must correct 2/1 but also 1/1 from HFS

Back up

TF EF can also induce uncorrectable and significant non-resonant degradation

- Correction of TF 2/1 leaves significant the others, including non-resonant fields as well as resonant fields
- NSTX-U TF EF is so large to drive significant NTV effects in high performance discharges, and is not correctable by LFS
- It is recommended to make a mechanical adjustment at least by a factor 3, (a factor of 3^2 expected for NTV) rather than LFS mid-EFC



NTV torque
(12MW I_P=2MA case)