Robust Correction of 3D Error Fields in Tokamaks including ITER

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Overview

- Dominant external field for tokamaks
- Validation through a highly localized error field - TBM
  - TBM mock-up experiments in DIII-D
  - Reduction of resonant components by corrections – IPEC analysis
  - Effects of non-resonant components – NTV analysis

- Overlap external field for tokamak error field thresholds
- Locking scaling in tokamaks and ITER
  - Error field corrections in various tokamaks
  - Optimization of corrections in ITER

- Summary and Future Work

Can we say : dominant external field is almost only field distribution driving locking?

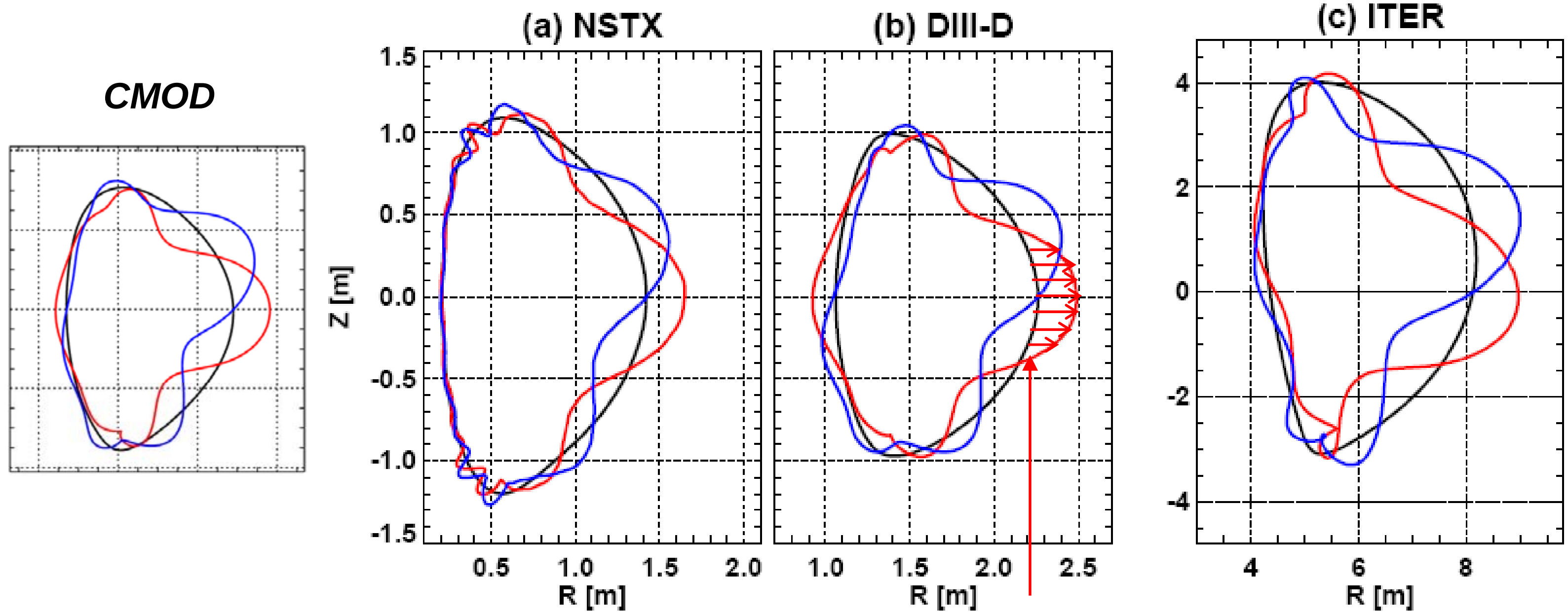
- Dominant external field for core : External normal field on the boundary maximizing the sum of the total resonant field for the core

[*Park et al, Nucl. Fusion 48 045006 (2008)*]

Shape of the dominant external field

<Cosine part (red) and Sine part (blue)> on the plasma boundary

$$\delta\vec{B}^{x}\cdot\hat{n}_{b}=A(\theta)\cos(n\phi)+B(\theta)\sin(n\phi)$$

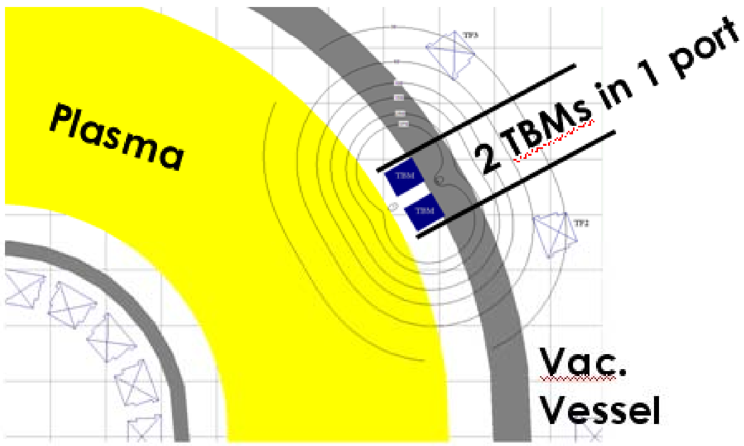


This is the shape of the external field to be minimized (can be quantified by overlap integral), and other distributions of the external field are less important roughly by an order of magnitude

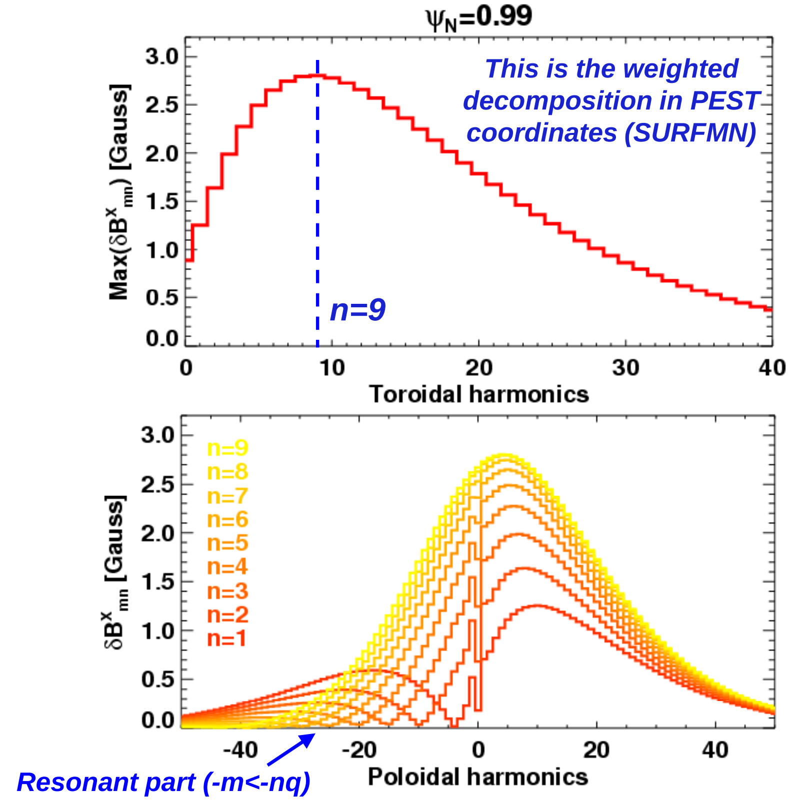
TBMs give an extreme example of 3D error fields due to their highly localized distribution

- TBMs have broad toroidal harmonic spectra
  - n=9 is the peak for the maximum amplitude of poloidal modes
- TBMs have broad poloidal harmonic spectra
  - Resonant for n=1~3
  - Non-resonant for n>4

ITER (schematic)



TBM (Mock-up) field

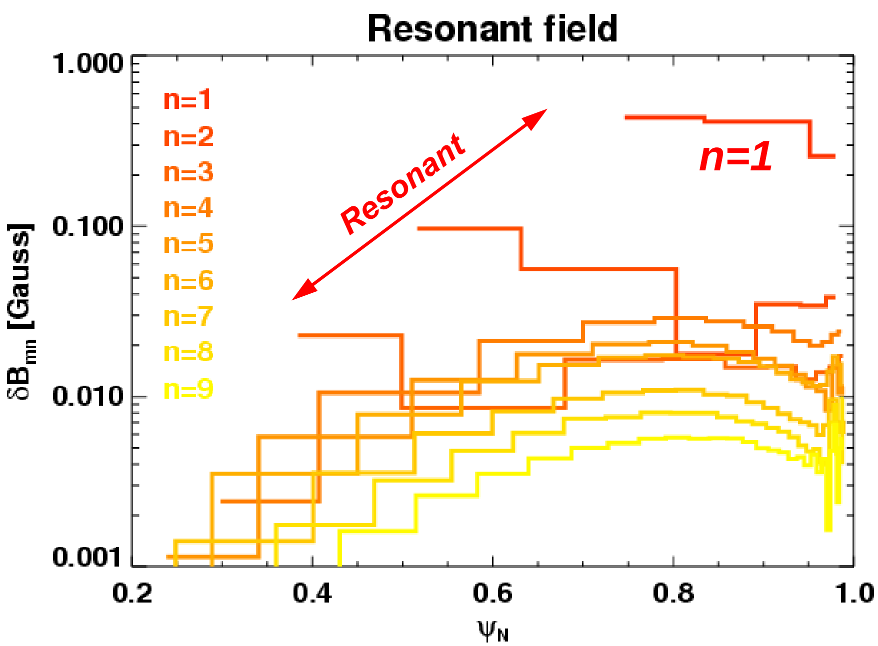


[*Park, PRL99, 195003*]

IPEC predicted n=1 by TBMs can induce locking

- IPEC calculations show
  - DIII-D has n=1 intrinsic error fields δB_{21}=1.6G
  - TBMs produce δB_{21}=0.43G/kA (Racetrack: 0.71G/kA, Solenoid: 1.1G/kA)
  - TBM error fields are ~30% of the intrinsic error fields
  - This implies the critical locking density would be ~30% higher with TBM 1kA

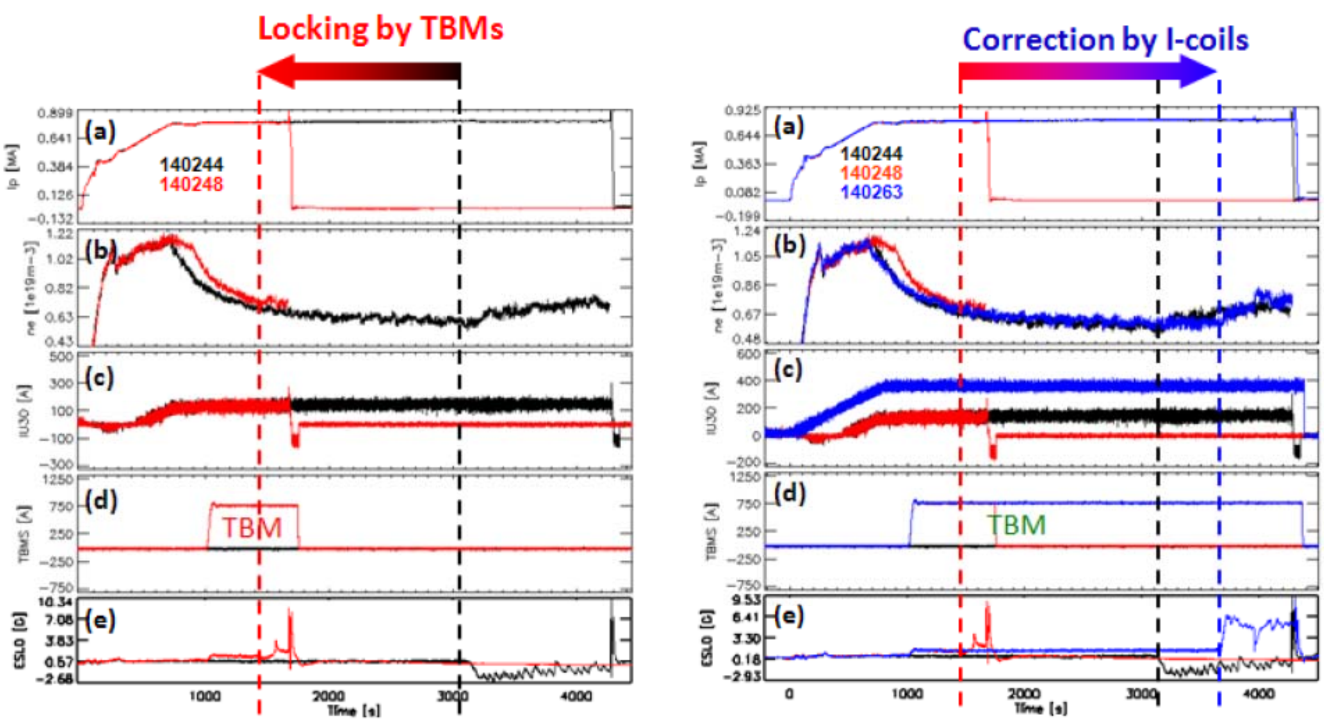
Ohmic model #124995.02502



- δB_{21} is the largest
- n=1~3 has resonant characteristics due to the resonant coupling between high m's to plasma
- n=4~9 has non-resonant charactersitics

IPEC predicted I-coil can correct TBM effects

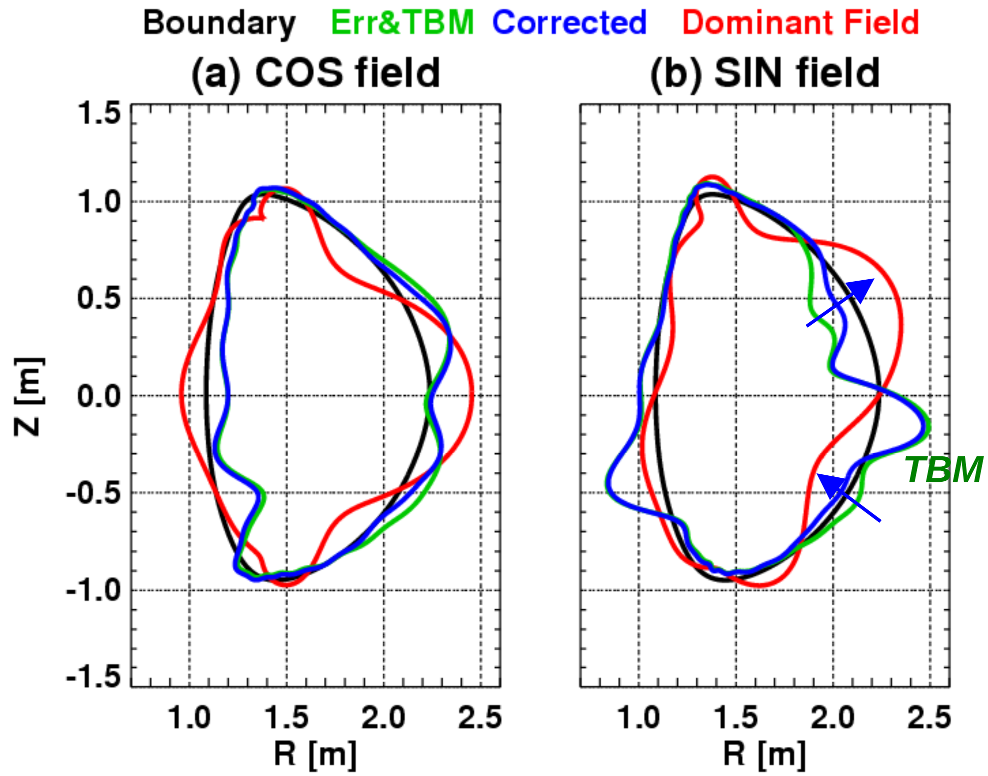
- IPEC predicted
  - TBMs will make a locking by n=1 components
  - If the locking is due to n=1 components, then I-coil n=1 correction can correct it
  - Experiments validated these predictions



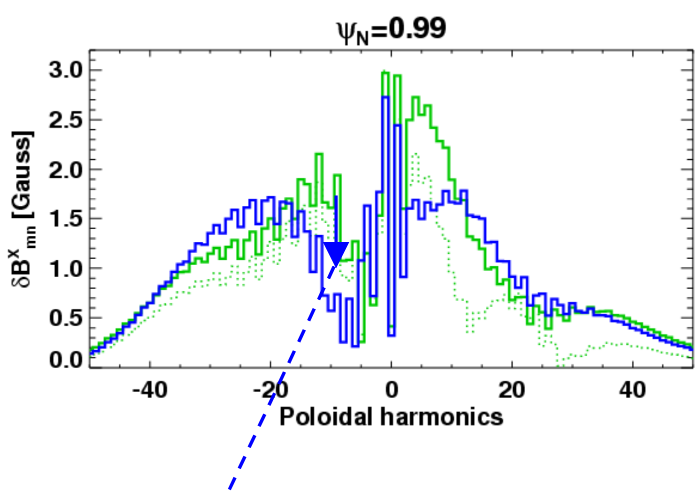
I-coil correction cannot change TBM fields, but can change dominant external field

- I-coils can not change TBM fields, but can mitigate TBM effects by decreasing (+) sine field and compensating (-) cosine field
- Remaining non-resonant components are irrelevant for a locking

Real space



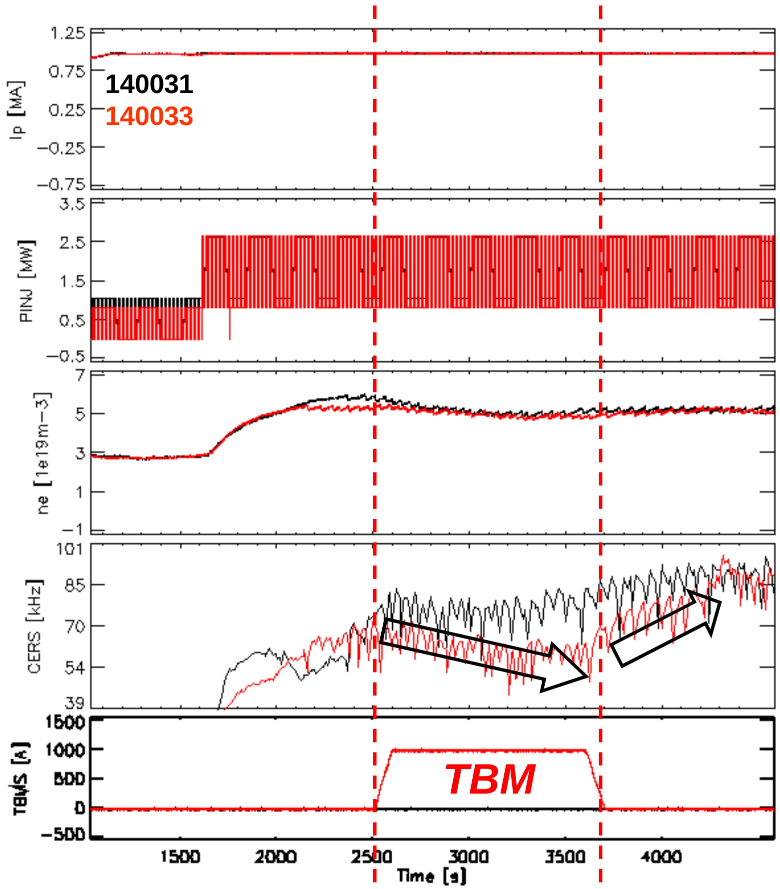
Fourier space

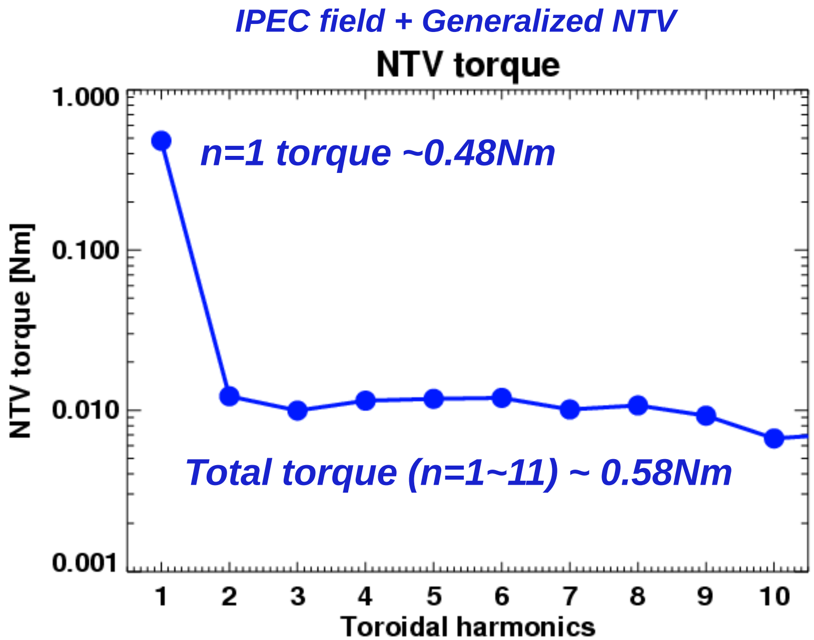


Reduction of resonant (-m<-nq) components by correction

TBMs also produce magnetic braking, and IPEC+NTV predicted n=1 may be most important

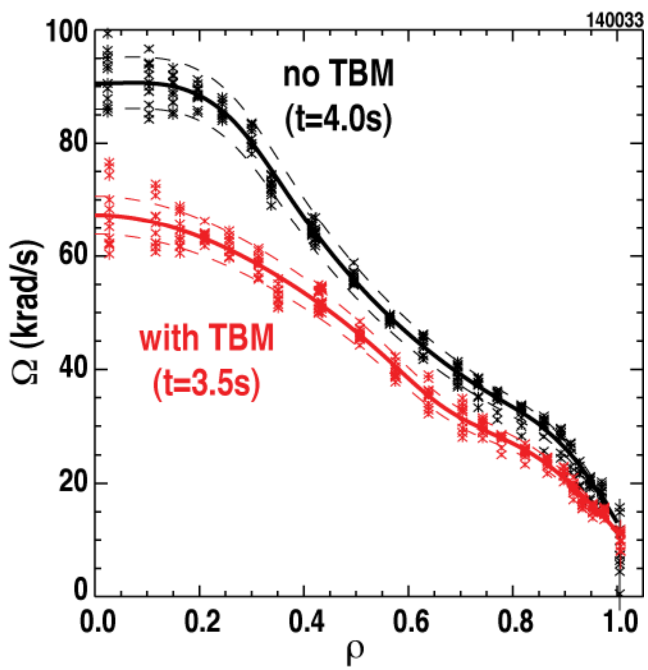
- TBMs give rotational damping by NTV
- Generalized NTV with IPEC Lagrangian field shows n=1 is most important (Theoretical torque ~ 0.58Nm and empirical torque ~ 0.2Nm)





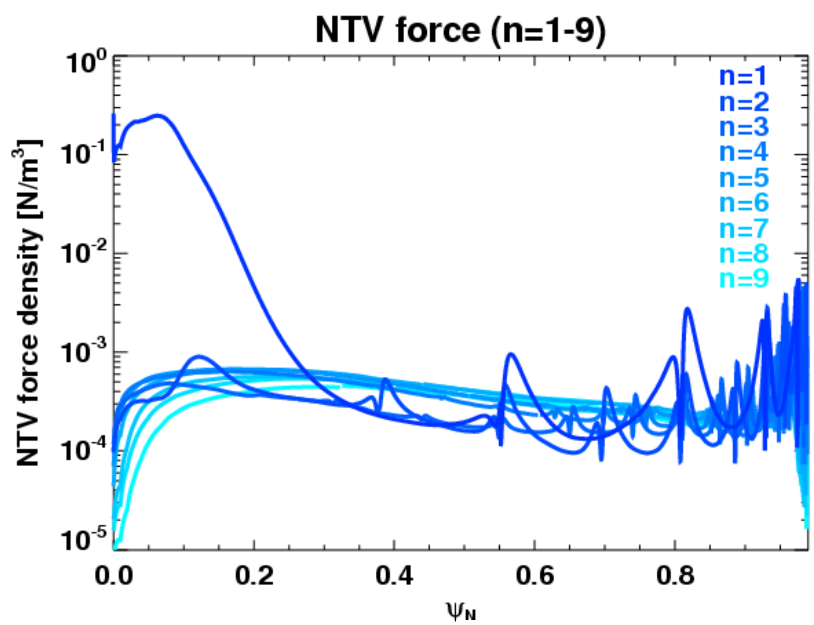
The n=1 gives core braking, and n=1~9 gives accumulatively edge braking

- n=1 braking is large at the core
- n=1~9 braking is concentrated at the edge, and may be not negligible for edge braking when accumulated
- Q: Damping due to n=1? or accumulated high n effects?



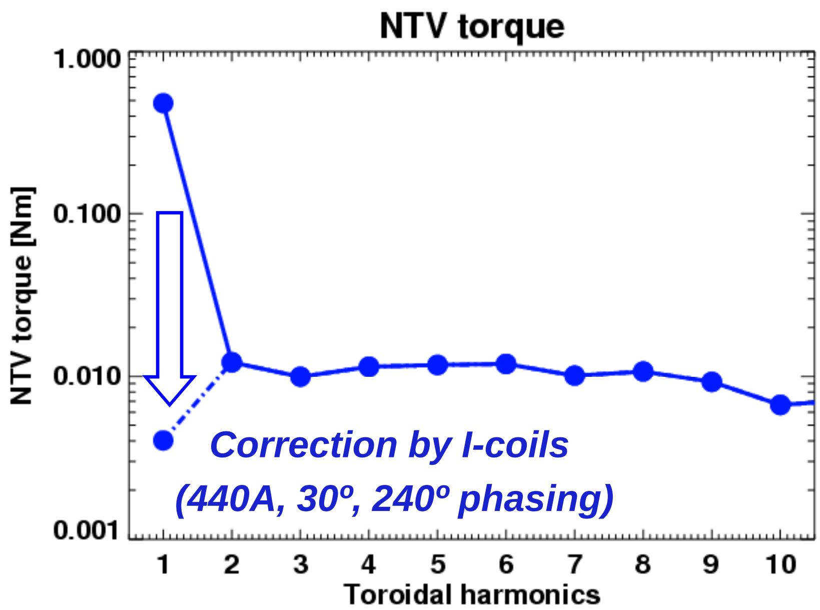
[*Reimerdes*]

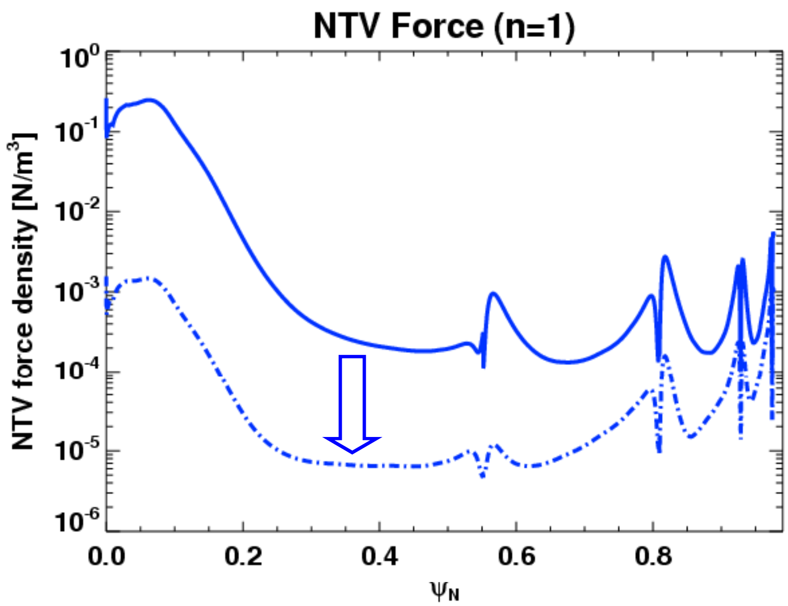
IPEC field + Generalized NTV



The n=1 correction for TBMs may be important for locking and also NTV!

- IPEC prediction gives n=1 is most important in TBM fields for both locking and NTV (or resonant and non-resonant braking)
- n=1 correction for TBM fields in H-mode would be a very important experiment





Overlap between a 3D external field and dominant external field determines the island drive

- You can assume the <u>dominant external field</u> for the core is the only one distribution to drive total resonant fields (other modes are less important by an order of magnitude)

- You can use <u>overlap external field</u> to measure the similarity of a given external field to the dominant external field by the number of Gauss

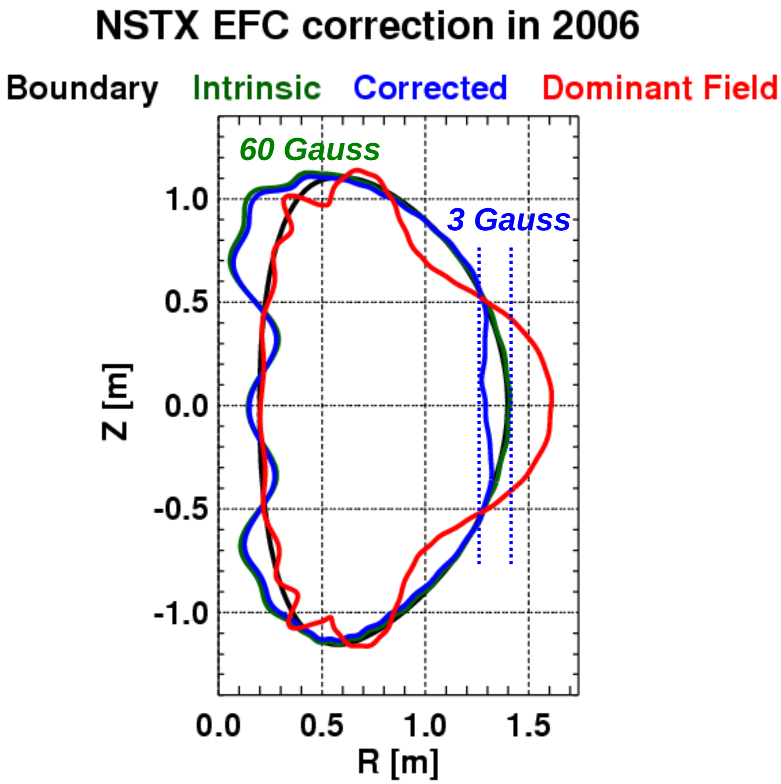
$$\delta B_{ocn} \equiv \frac{\int d\varphi' \int da\left(\delta B^{x}(\vartheta,\varphi)\right)\left(\delta B^{x}_{dcn}(\vartheta,\varphi'-\varphi)\right)}{\sqrt{\int da\left(\delta B^{x}_{dcn}(\vartheta,\varphi)\right)^{2}}} \text{ where } da = Jd\vartheta d\varphi$$

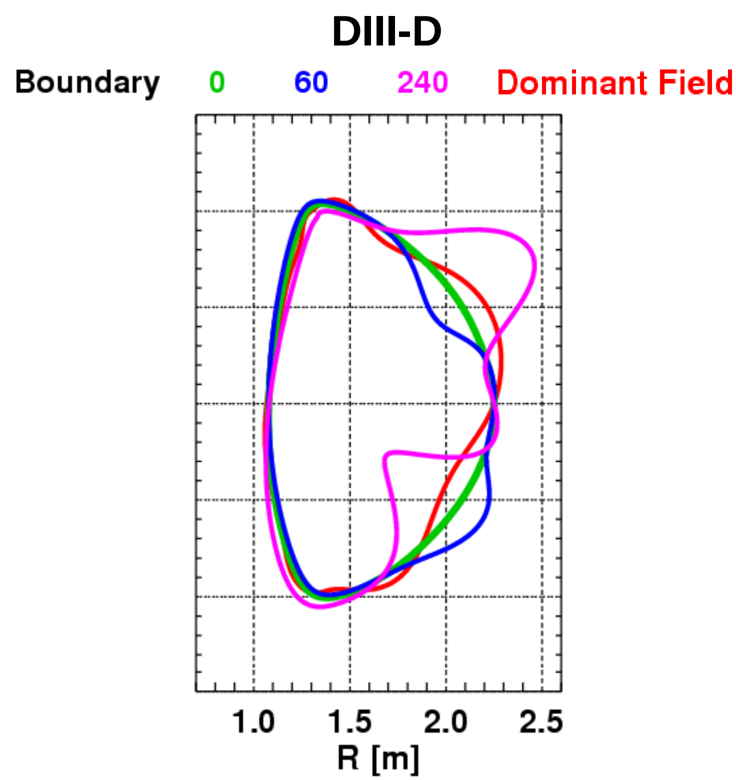
- You can use the <u>overlap</u> to measure the similarity of a given external field to the dominant external field up to unity (0~1)

$$C_{on} \equiv \frac{\int d\varphi' \int da\left(\delta B^{x}(\vartheta,\varphi)\right)\left(\delta B^{x}_{dcn}(\vartheta,\varphi'-\varphi)\right)}{\sqrt{\int da\left(\delta B^{x}(\vartheta,\varphi)\right)^{2} \int da\left(\delta B^{x}_{dcn}(\vartheta,\varphi)\right)^{2}}} \text{ where } da = Jd\vartheta d\varphi$$

NSTX and DIII-D error field correction can be understood by dominant external field and overlap

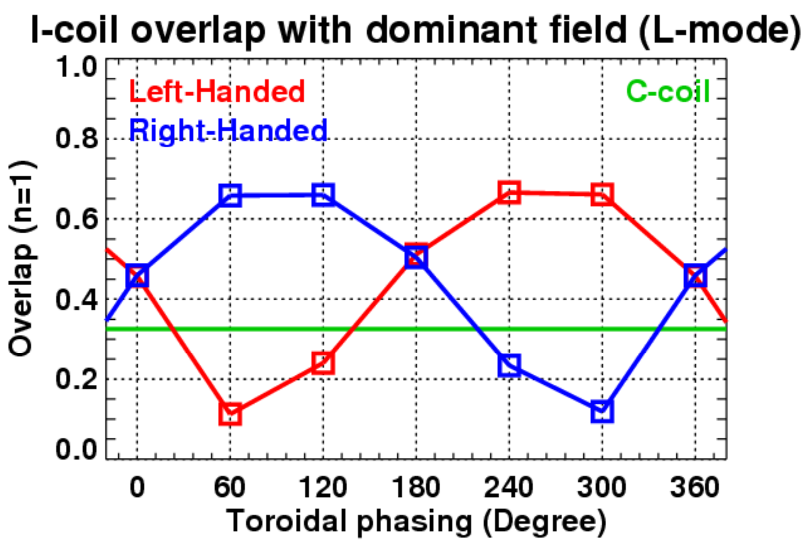
- NSTX : Large intrinsic error field (~60 Gauss) at the inboard can be compensated by small correction field (~3 Gauss) at the outboard
- DIII-D : The optimal phasing between upper and lower I-coils is ~240º, since then applied field is best coupled to dominant field

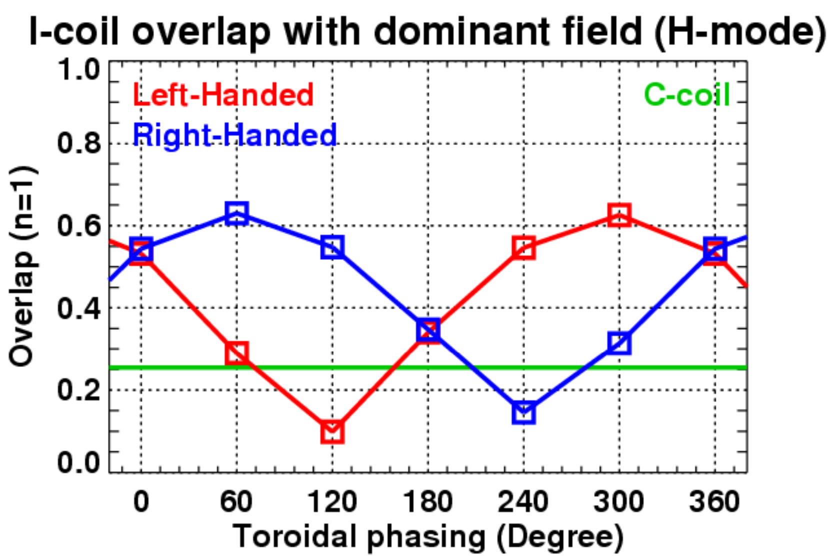




Overlap is highly consistent with empirical observations for the best phasing in DIII-D

- The overlap can explain the optimal phasing of I-coils and overall performance of I-coils and C-coils in DIII-D error field corrections
  - I-coil with optimal phasing is more efficient by 2.5 times than C-coil
  - I+C-coil can increase overlap by 0.7~0.8

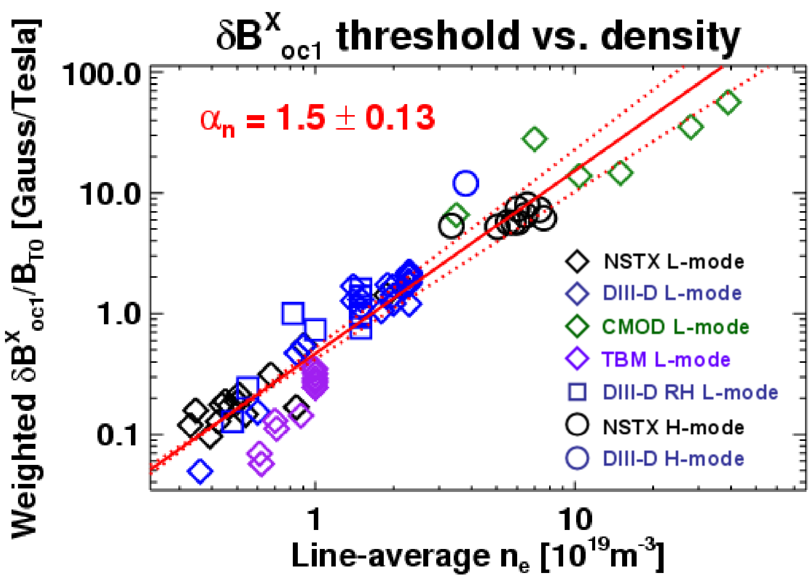


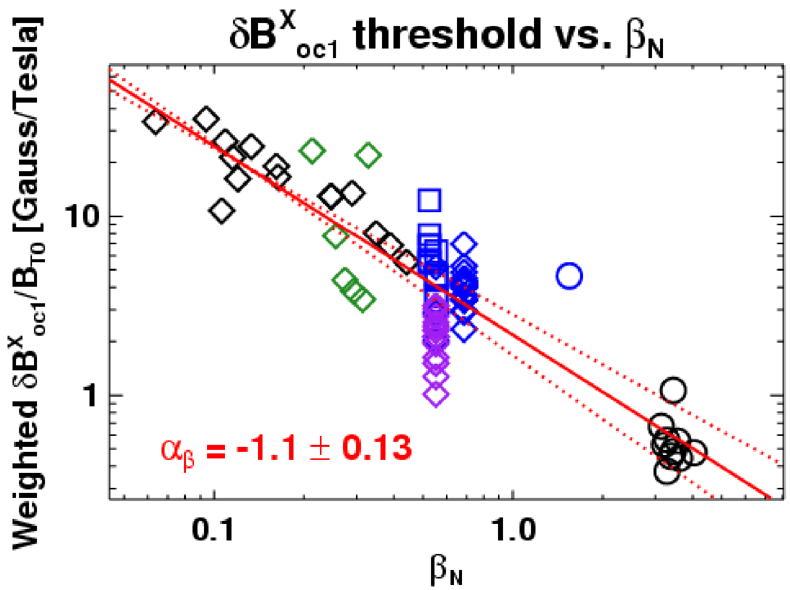


Error field corrections can be more robust with overlap external field and scaling

- The best four-parameter scaling with n=1 overlap external field:

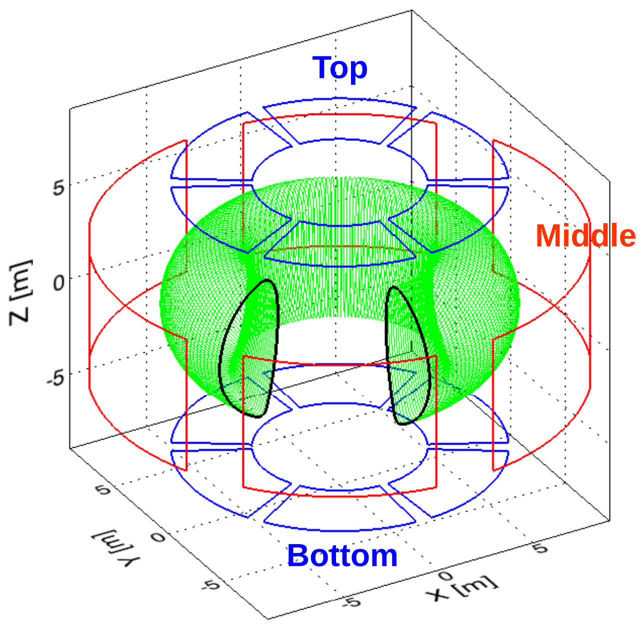
$$\frac{\delta B^{x}_{oc1}}{B_{T0}} \leq 0.4\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.5}\left(B_{T0}[T]\right)^{-1.9}\left(R_0[m]\right)^{1.2}\beta_N^{-1.1}$$

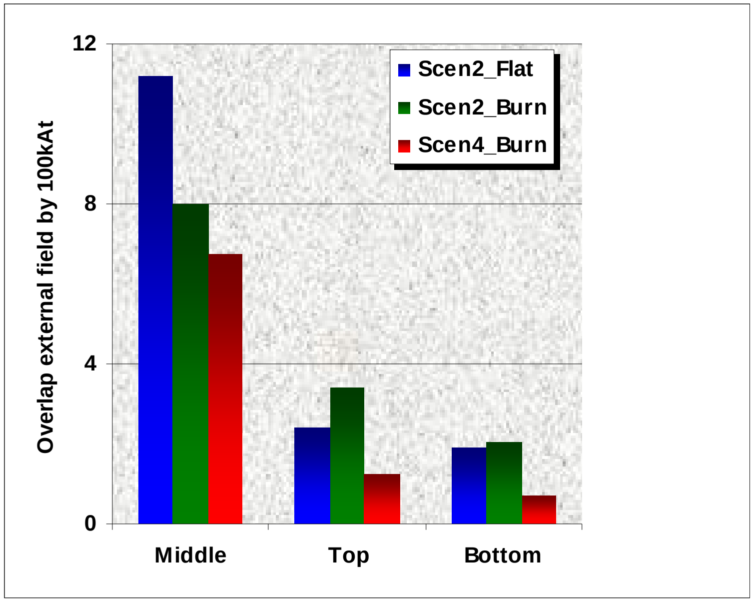




ITER EFCC is being revised with the new method

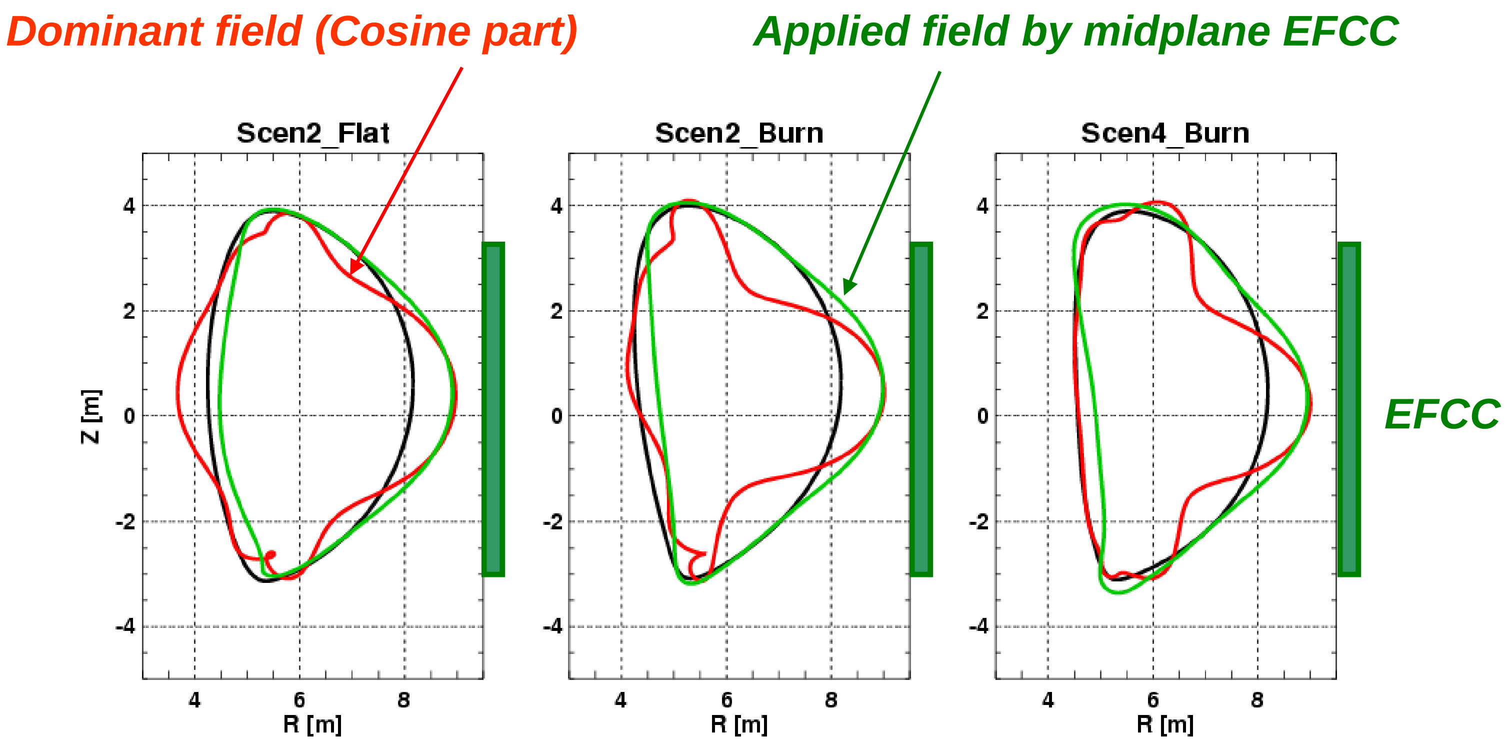
- The efficiency of each EFCC is being revised by the new method
  - Top and bottom EFCC produce only 10~20% overlap external field of midplane EFCC
  - Midplane EFCC can become ineffective for Scenario 4





ITER correction coils can be modified to best matching dominant external field

- The coils should be designed to couple to the patterns of the dominant external field, and thus to maximize the overlap



$C_{o1} = 0.46$ $C_{o1} = 0.29$ $C_{o1} = 0.23$

Summary and Future Work

- DIII-D TBM mock-up experiments demonstrate the importance of dominant external field
- The control of dominant external fields in TBMs can mitigate locking and even may largely reduce NTV damping
- Overlap external fields and dominant external fields give a robust way of 3D field control, with consistent scaling through many tokamaks
- ITER error field coils are under investigation based on the development
- JET locking data for Ohmic plasmas, and NSTX, DIII-D locking data for H-mode plasmas will be included in scaling