# Response of Tokamaks to Non-axisymmetric Magnetic Perturbations

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**J.-K. Park[1],**
**J. E. Menard[1], A. H. Boozer[2],**
**M. S. Chance[1], S. P. Gerhardt[1], R. J. Hawryluk[1], S. R. Hudson[1], H. E. Mynick[1], H. Reimerdes[2], M. Lanctot[2], S. A. Sabbagh[2], J. M. Bialek[2], M. J. Schaffer[3], A. M. Garofalo[3], R. J. Buttery[3], T. Evans[3], A. H. Glasser[4], J.-W. Ahn[5], J. M. Canik[5], R. Maingi[5], A. Cole[6], S. M. Wolfe[7], C. Nuehrenberg[8],**
**NSTX and DIII-D research team**

*1 Princeton Plasma Physics Laboratory, USA*
*2 Columbia University, USA*
*3 General Atomics, USA*
*4 University of Washington, USA*
*5 Oak Ridge National Laboratory, USA*
*6 University of Wisconsin-Madison, USA*
*7 Plasma Science Fusion Center, MIT, USA*
*8 IPP-Euratom Association, Germany*



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# Motivation

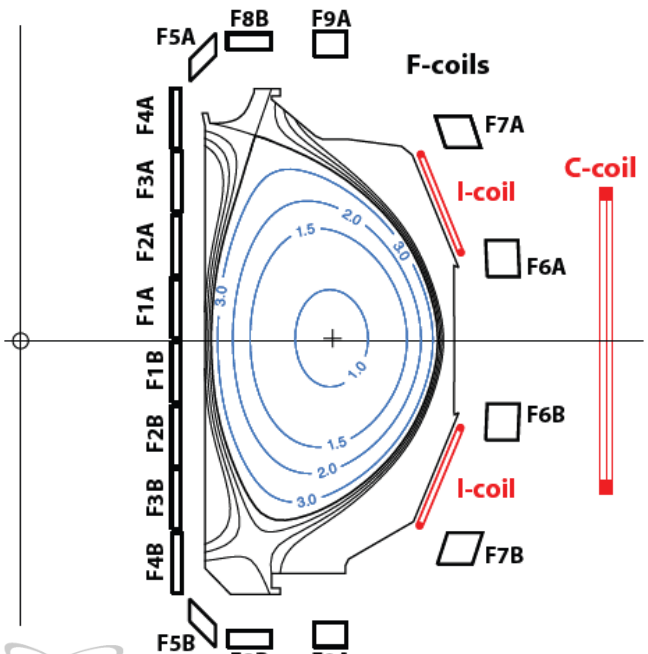
- Tokamaks are not in perfect axisymmetry
  - Small non-axisymmetric (3D) fields are unavoidable in tokamaks
  - Non-axisymmetric fields are typically bad (Locking, tearing, braking), but also can be good if controlled (RMP ELM suppression)

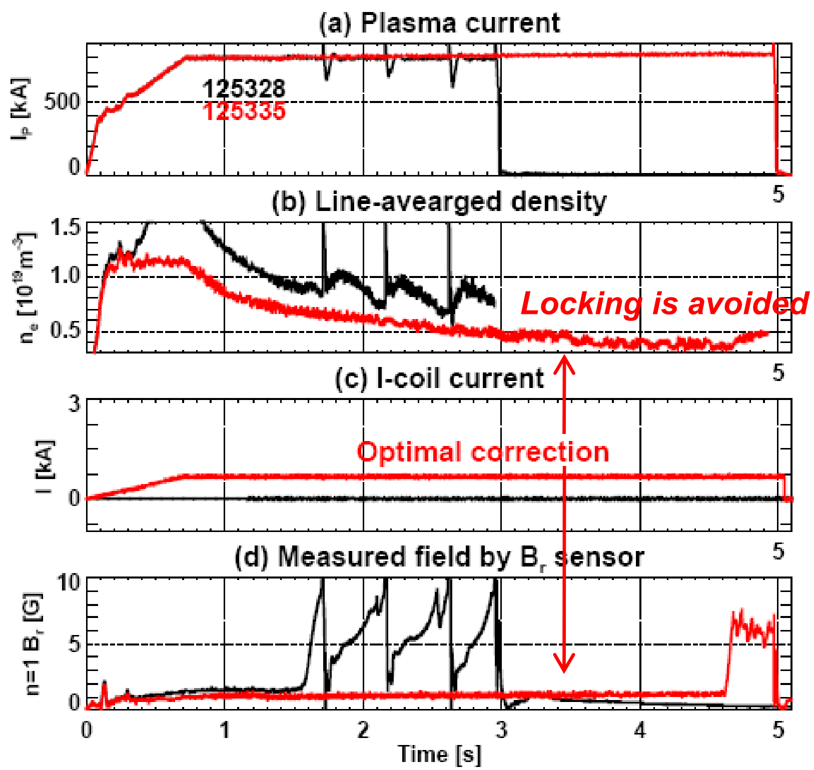
- Theoretical understanding for 3D equilibria is required
  - Non-ideal 3D codes (M3D, NIMROD,…) : Not free boundary yet…
  - Ideal 3D codes (VMEC,…) : Slow and not optimal to tokamaks
  - Vacuum 3D codes (Vacuum superposition) : Not in force-balance

- So, we use ideal perturbed equilibria :
  - Pros: Free-boundary, precise at rational surfaces, in force-balance
  - Cons: Ideal evolution, No inner-layer dynamics, etc

# DIII-D example of plasma responses to non-axisymmetric magnetic perturbations

- DIII-D has n=1 intrinsic error fields
  - Error fields can cause locking (opening of islands)
  - C-coil and I-coil can mitigate locking effects



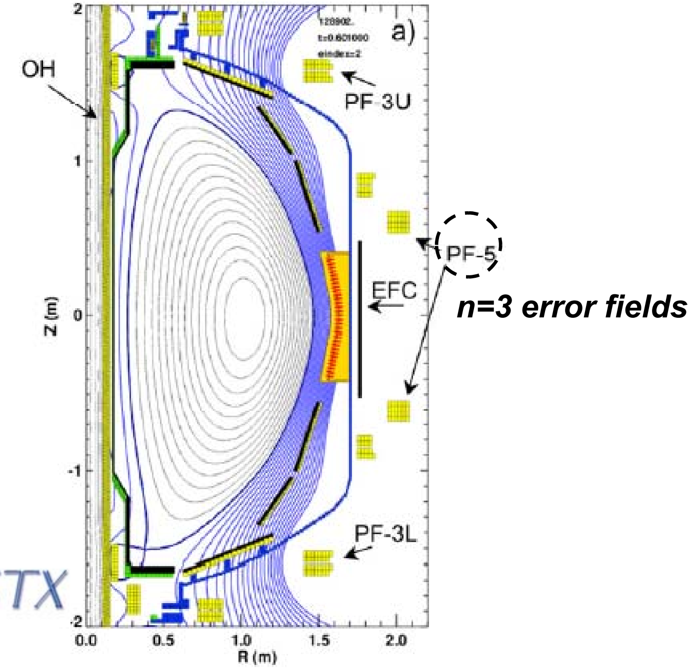



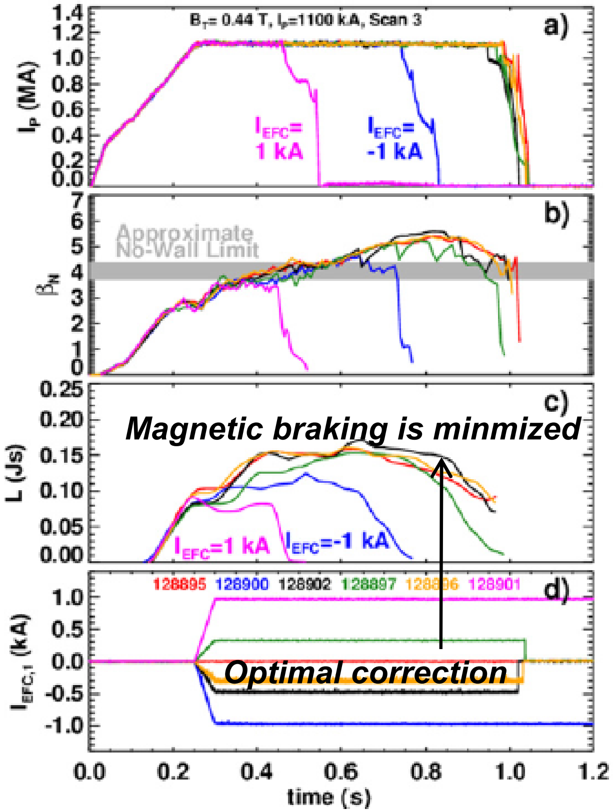

*[Park, PRL 99, 195003 (2007)]* *[Park, submitted to POP (2010)]*

# NSTX example of plasma responses to non-axisymmetric magnetic perturbations

- NSTX has n=1 and n=3 intrinsic error fields
  - n=3 error fields can cause magnetic braking (rotation damping)
  - EFC correction can mitigate both effects

[*Menard, NF 50, 045008 (2010)*]
[*Gerhardt, PPCF 52, 104003 (2010)*]



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- Development of Ideal Perturbed Equilibrium Code (IPEC)
- IPEC applications to tokamaks
  - Plasma responses to applied perturbations
  - Error field corrections and plasma locking
  - Non-ambipolar transport and magnetic braking
- Control of non-axisymmetric perturbations
  - Dominant external field distribution and overlap field
  - **ITER error field study**
- Summary and Future Work

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# IPEC solves ideal free-boundary perturbed equilibria

- Given an axisymmetric equilibrium, $\vec{\nabla} p_0 = \vec{j}_0 \times \vec{B}_0$ , and given an non-axisymmetric field, $\delta \vec{B}^x(\vec{x})$ , IPEC solves

[*Park, POP 14, 052110 (2007)*]

$$\vec{F}[\vec{\xi}] = \vec{0} = \delta\vec{j} \times \vec{B}_0 + \vec{j}_0 \times \delta\vec{B} - \vec{\nabla}\delta p$$

$$\delta\vec{B} = \vec{\nabla} \times (\vec{\xi} \times \vec{B}_0) \text{ and } \delta\vec{j} = (\vec{\nabla} \times \delta\vec{B}) / \mu_0$$

$$\delta p = -\vec{\xi} \cdot \vec{\nabla} p_0 - \gamma p_0 (\vec{\nabla} \cdot \vec{\xi})$$

$$p_0(\psi) \text{ and } q_0(\psi) \text{ profiles are preserved (ideal constraints)}$$

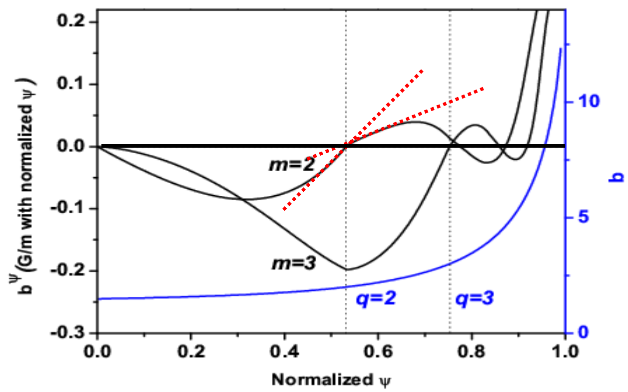
  - External field is given, and the total field is determined by virtual surface currents (external boundary condition)
    - External (vacuum) field : $\delta\vec{B}^x$
    - Total (External + Plasma) field : $\delta\vec{B} = \delta\vec{B}^x + \delta\vec{B}^p$
  - Then, DCON stability code solves ideal fixed-boundary perturbed equilibria without islands (internal boundary condition)

# Ideal constraints give total resonant fields driving islands

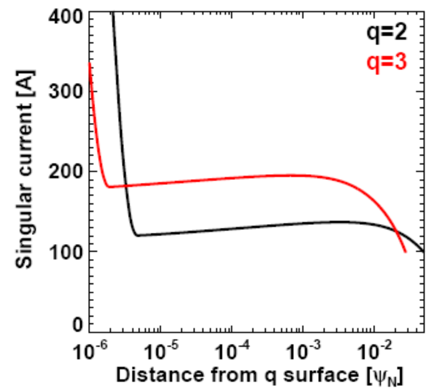
- Ideal constraints (no islands) give shielding current by the jump in the tangential field at the rational surface :

$$\delta \vec{j}_{||} = \frac{i\Delta_{mn} e^{i(m\vartheta - n\varphi)}}{\mu_0 n \int B_0^2 / |\nabla\psi|^3 \, da}\,\delta(\psi-\psi_{mn})\vec{B}_0 \quad \text{with the jump } \Delta_{mn} = \left[\frac{\partial}{\partial\psi}\left(\frac{\delta\vec{B}\cdot\vec{\nabla}\psi}{\vec{B}_0\cdot\vec{\nabla}\vartheta}\right)\right]_{mn}$$

NSTX




*at rational surfaces*

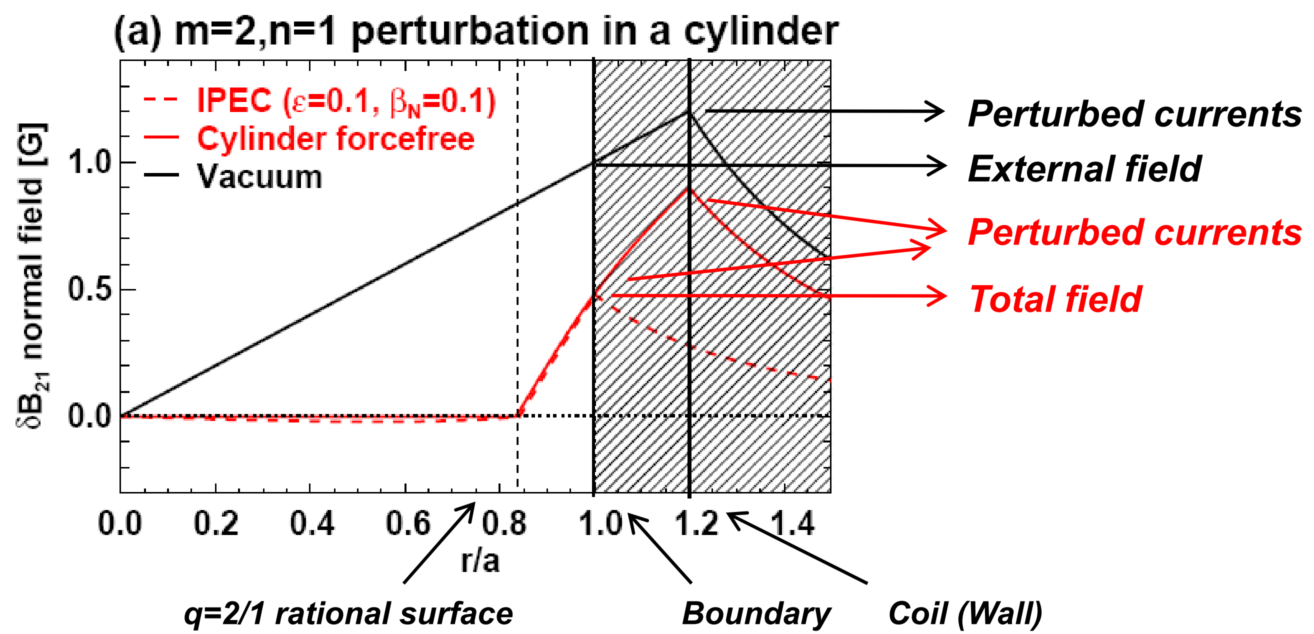



- The field suppressed by the shielding current : $\vec{\nabla}\times\delta\vec{B} = \mu_0 \delta\vec{j}_{||}$
- The total resonant field would drive islands without shielding currents :

$$\delta B_{mn} \equiv \frac{\int \delta\vec{B}\cdot d\vec{a}\; e^{-i(m\vartheta - n\varphi)}}{\int da}$$

# IPEC free-boundary solutions have been benchmarked in simple limits

- IPEC solutions are verified in a cylinder




**[*Park, POP 16, 056115 (2009)*]**

  - IPEC free boundary equilibria are benchmarked with cylindrical force-free solutions (and also with CAS3D in simple limits)
  - IPEC and vacuum solutions are very different even in simple limits

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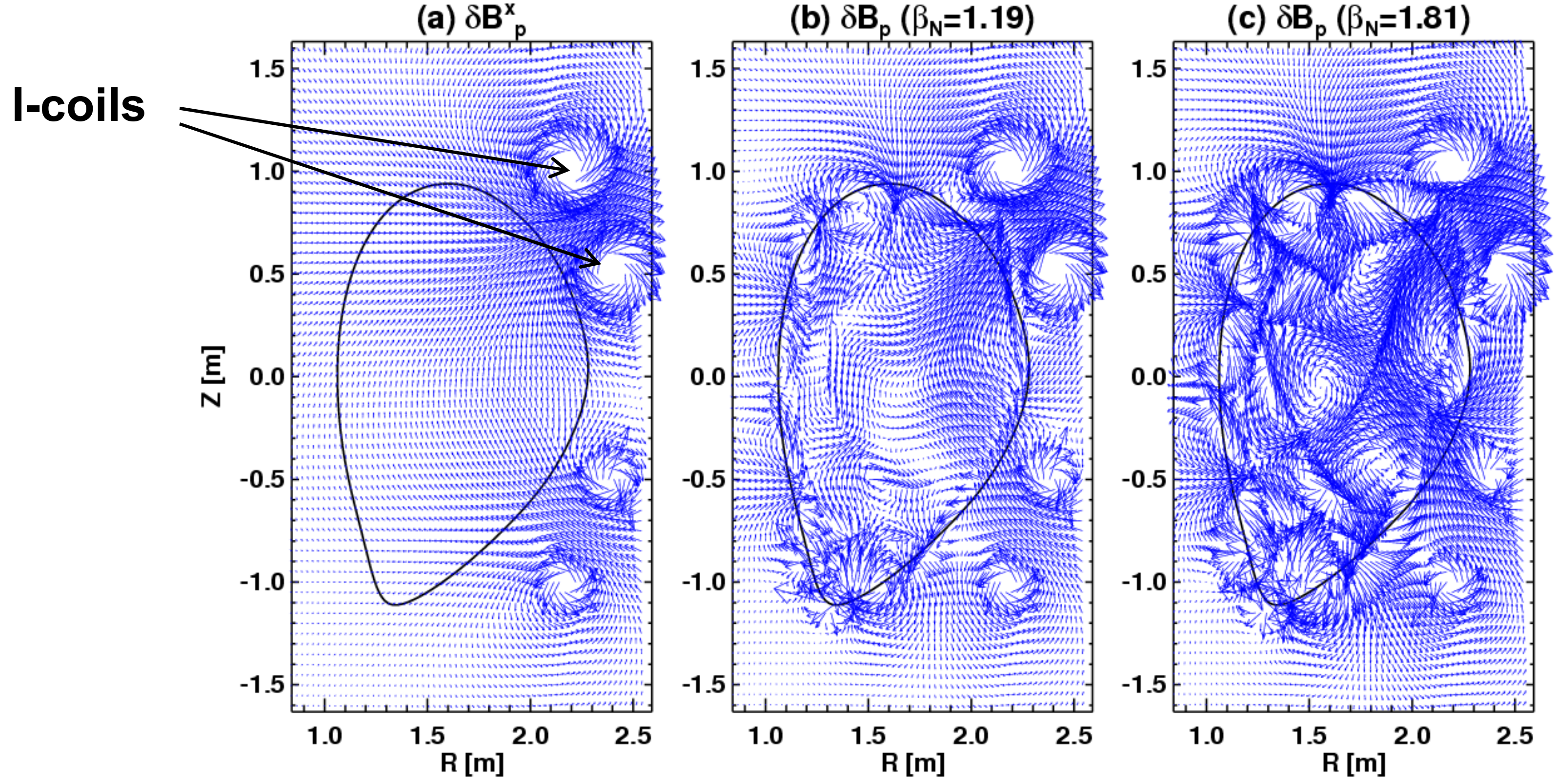
# Tokamak responses can be very strong by poloidal coupling, amplification or shielding

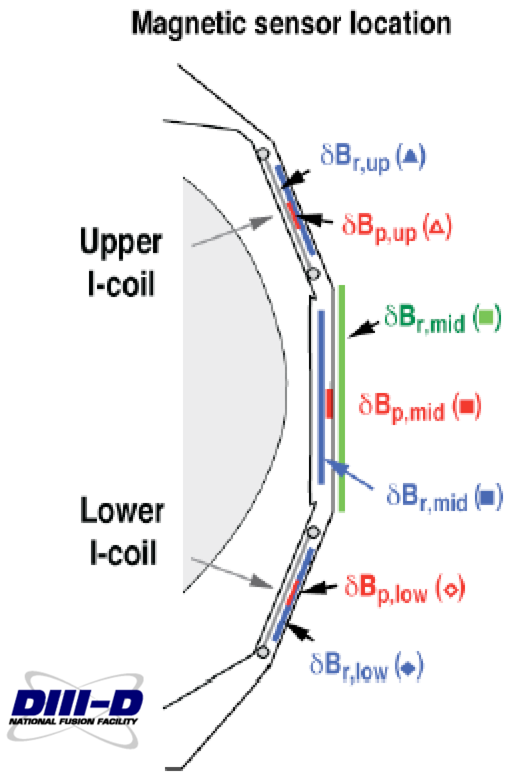
- Ideally perturbed plasma currents can strongly modify vacuum field in tokamaks and give strong plasma responses

**n=1 RFA** [*Lanctot, Reimerdes, Park*]

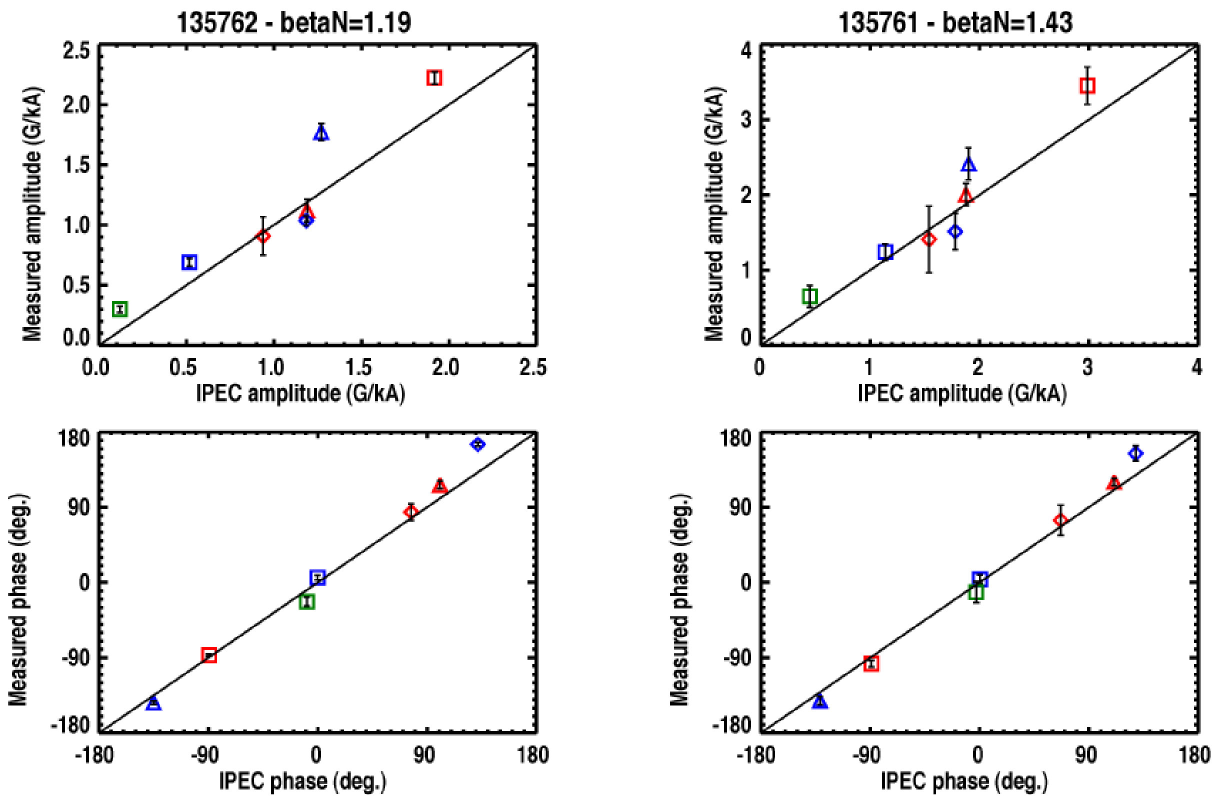


# Ideal predictions are validated by plasma response measurements when plasma is stable

- IPEC, MARS-F codes and DIII-D plasma response measurements show good agreements when plasma is stable




**n=1 RFA**




*[Lanctot, Reimerdes, Park]*

*[For MARS-F applications, see BI3.00002 by Lanctot ]*

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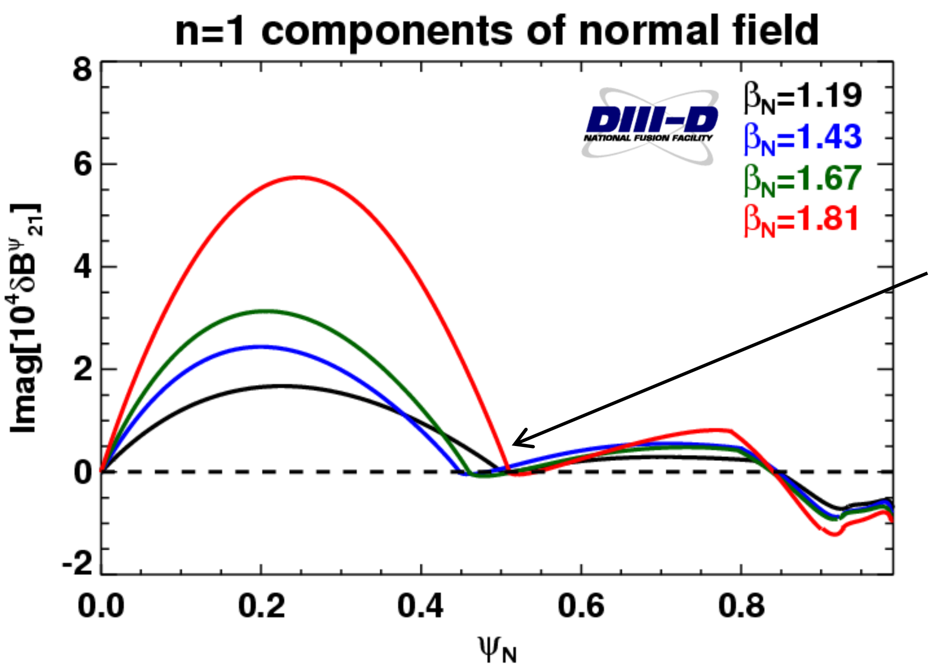
# IPEC total resonant fields give the drive of magnetic islands and locking

- IPEC total resonant fields are self-consistent in ideal limit and give the drive of magnetic islands and locking
- This is valid before the onset of locking

[*Lanctot, Reimerdes, Park*]

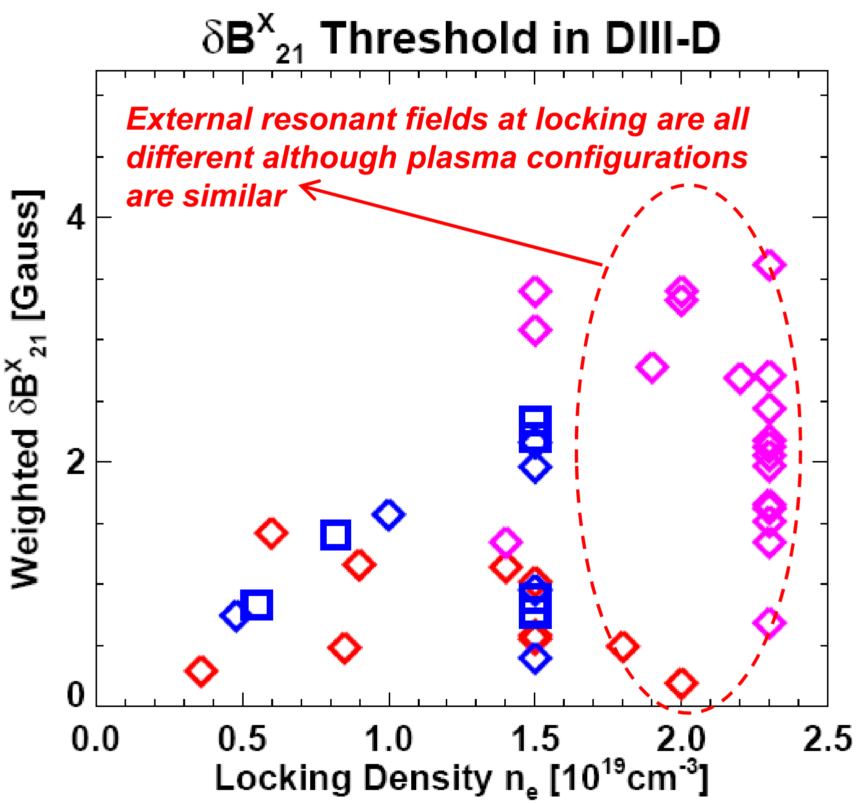


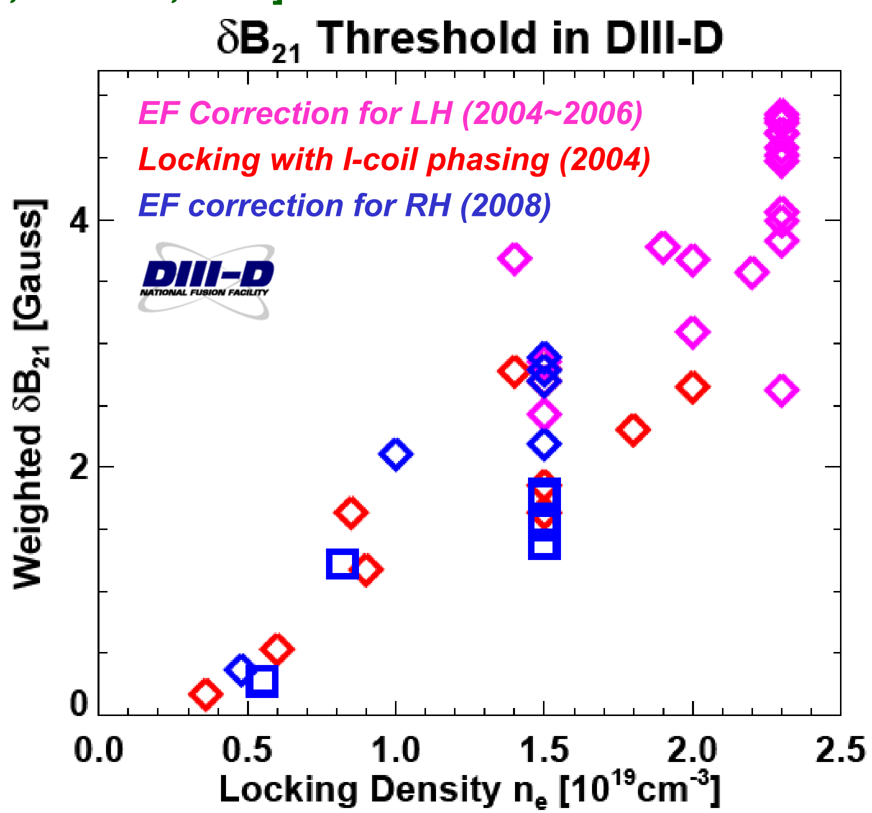

***Total resonant fields are suppressed, but become larger when plasma has higher pressure. Required shielding currents also become larger, and islands can open if plasma can not maintain shielding currents***

# Total resonant fields explain much better error field correction results than vacuum methods

- External resonant field (based on standard vacuum superposition, $\delta B^P=0$) showed often paradoxical results
- IPEC resonant field restored good parametric correlation as expected

[*Schaffer, LaHaye, Scoville, Park*]



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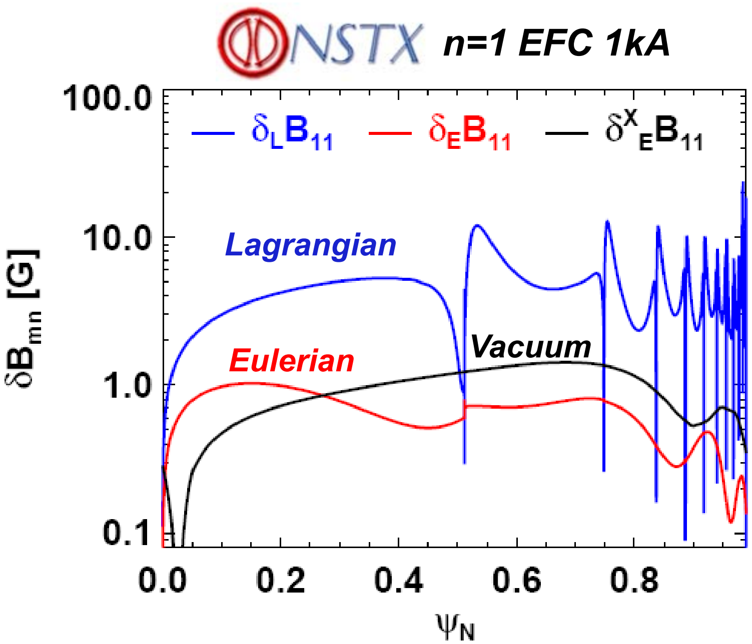
# Non-axisymmetric variation in |B| produces non-ambipolar transport

- Action is dependent on toroidal location in the presence of the non-axisymmetric variation in the field strength
- Action must be conserved, so a particle must have an additional radial non-ambipolar transport (Called NTV transport in tokamaks)
- Important variation occurs by the variation in the field strength along the perturbed field lines, not along unperturbed field lines : Need perturbed equilibrium calculations

***Lagrangian*** $\delta_L B \equiv \delta_E B + \vec{\xi} \cdot \vec{\nabla} B_0$

***Eulerian*** $\delta_E B \equiv \delta \vec{B} \cdot \hat{b}_0$

***Vacuum*** $\delta_E B^x \equiv \delta \vec{B}^x \cdot \hat{b}_0$




[Boozer, POP 13, 044501 (2009)]

[Park, POP 16, 056115 (2009)]

# NTV formula across different regimes has been derived with additional approximations

- New NTV formula has been derived with effective Krook collisional operators to combine different regimes **[Park, PRL 102, 065002 (2009)]**
  - NTV has the form of

$$\tau_\varphi \cong C[\delta B]^2 \frac{\nu_{eff}}{(\ell\omega_{\ell bounce} - n\omega_{E\times B} - n\omega_{\nabla B})^2 + \nu_{eff}^2}(\omega_{rot} - \omega_{neo})$$

  - NTV formula gives the toroidal torque density as

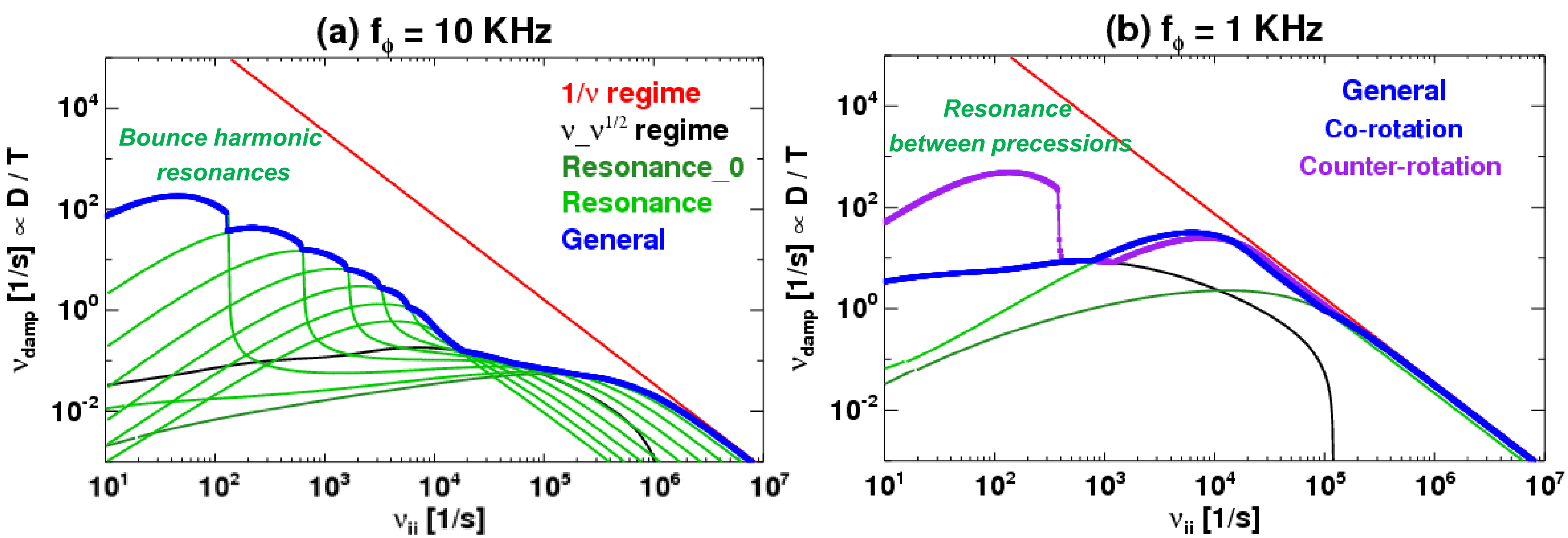
$$\langle \hat{\phi} \cdot \vec{\nabla} \cdot \overleftrightarrow{\Pi}_a \rangle_\ell = \underbrace{\frac{\epsilon^{-1/2} p_a}{\sqrt{2}\pi^{3/2} R_0}}_{C} \int_0^1 \underbrace{d\kappa^2 \delta_{w,\ell}^2}_{\delta B^2} \int_0^\infty \underbrace{dx \mathcal{R}_{a1\ell}}_{\text{Resonance}} \underbrace{\left[ u^\varphi + 2.0\sigma \left| \frac{1}{e}\frac{dT_a}{d\chi} \right| \right]}_{\omega_{rot}\text{-}\omega_{neo}}$$

$$\delta_{w,\ell}^2 = \sum_{nmm'} \delta_{nmm'}^2 \frac{F_{nm\ell}^{-1/2} F_{nm'\ell}^{-1/2}}{4K(\kappa)}, \quad F_{nm\ell}^y \equiv \int_{-\vartheta_t}^{\vartheta_t} d\vartheta (\kappa^2 - \sin^2(\vartheta/2))^y \cos(m - nq - \sigma\ell)\vartheta$$

$$\mathcal{R}_{ay\ell} = \frac{1}{2} \frac{n^2 (1 + (\frac{\ell}{2})^2) \frac{\nu_a}{2\epsilon} x (x - \frac{5}{2})^y e^{-x}}{\left[\ell \frac{\pi\sqrt{\epsilon}}{4\sqrt{2}} \omega_{ta}\sqrt{x} - n\omega_E - n\sigma \frac{q^3}{4\epsilon}(\omega_{ta}^2/\omega_{ga})x\right]^2 + \left[(1 + (\frac{\ell}{2})^2)\frac{\nu_a}{2\epsilon}\right]^2 x^{-3}}.$$

# Combined NTV gives right order of magnitudes as observations

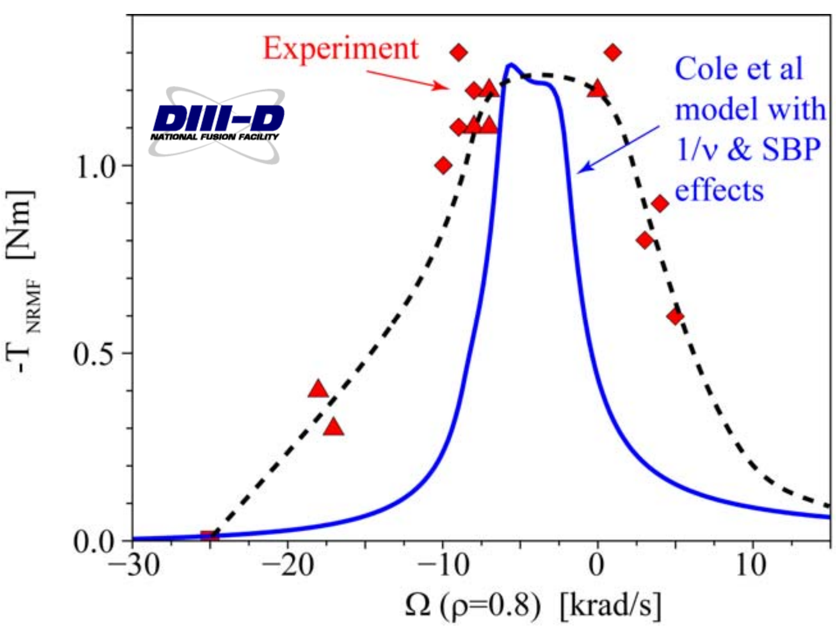
- Combined formula gives 10~100 $s^{-1}$ damping rates as observed in relevant parametric spaces of tokamak magnetic braking experiments
- Various predictions can be made :
  - NTV can be stronger in lower $\nu$, due to bounce-harmonic resonances
  - NTV can be stronger by counter-rotation in lower $\nu$ and lower rotations, due to resonances between electric and magnetic precessions



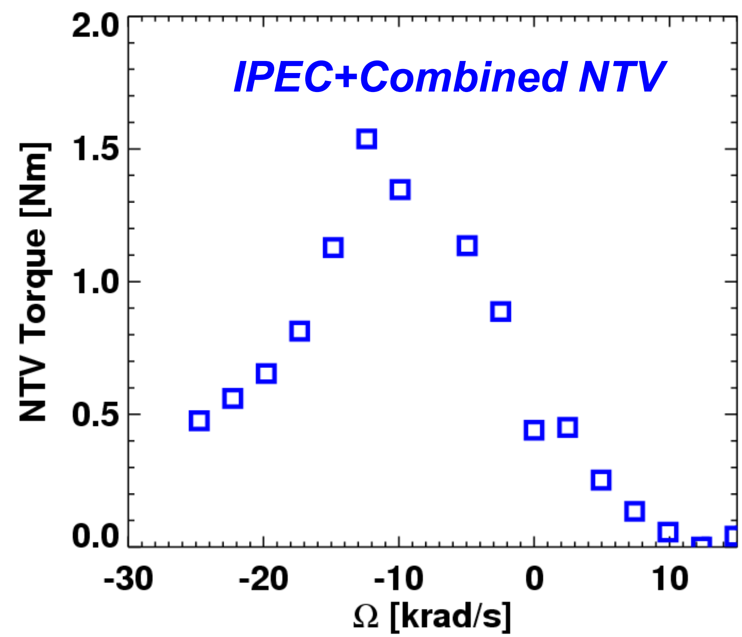
# Combined NTV theory with IPEC field is being compared with magnetic braking experiments

- DIII-D magnetic braking experiments have shown resonant behaviors in NTV when rotations are low
- SuperBanana Plateau (SBP) theory predicts the resonances
- IPEC field + combined NTV theory also gives good predictions using actual fields and all profiles in experiments

**[*See PI2.00005 by Cole* ]**




**[ *J.-K. Park, A. M. Garofalo, W. Solomon*]**



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# Non-axisymmetric external perturbations can be decomposed by their importance for physics

- A physically important quantity, such as total resonant field, can be represented by a matrix coupled to external representation

**Total resonant field at rational surfaces** **External field on the boundary**

$$\delta B_{rmn} \equiv \frac{\int \delta \vec{B} \cdot d\vec{a}_r \; e^{-i(m\vartheta - n\varphi)}}{\int da_r} \quad \xleftarrow{\textbf{IPEC}} \quad \delta B^x_{bmn} = \frac{\int \delta \vec{B}^x \cdot d\vec{a}_b^{1/2} e^{-i(m\vartheta - n\varphi)}}{\sqrt{\int da_b}}$$

$$\downarrow \qquad\qquad \downarrow$$

$$\vec{B}_r[R] = \overleftrightarrow{C}[R \times M] \cdot \vec{\Phi}^x_b[M]$$

- SVD analysis gives new decomposition of external field based on its importance on the physical quantity

$$\overleftrightarrow{C} = \left( \vec{U}^x_{b1} s_1 \vec{V}^{x\dagger}_{b1}, \cdots, \vec{U}^x_{bR} s_R \vec{V}^{x\dagger}_{bR} \right) \qquad \left| \vec{V}^x_{bi} \right| = 1$$

- The first mode is defined the "dominant external field", since the first mode is more important often by an order of magnitude than others

# Dominant external field is highly robust across different tokamak configurations

- Dominant external field is highly robust across various tokamak configurations and plasma parameters **[*Park, NF 48 045006 (2008)*]**

***Shape of the dominant external field***

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

$$\vec{V}_{b1}^{x} \rightarrow \delta\vec{B}^{x} \cdot \hat{n}_{b} = A(\theta)\cos(n\phi) + B(\theta)\sin(n\phi)$$

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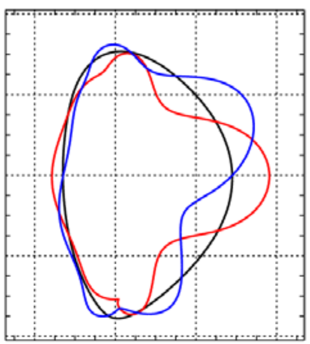
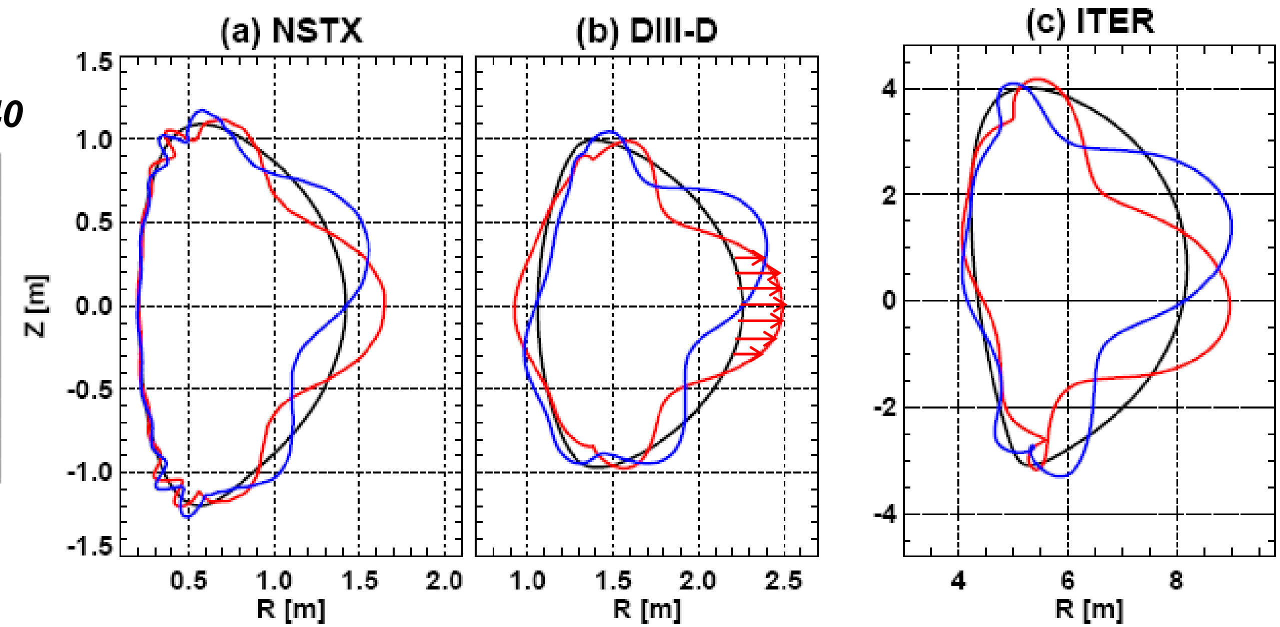




# Error field effects can be understood based on overlap with the dominant external field

- Given error field can be decomposed

$$\vec{\Phi}_b^{xerr} = \left(\vec{\Phi}_b^{xerr} \cdot \vec{V}_{b1}^{x}\right)\vec{V}_{b1}^{x} + \cdots$$

- If the dominant external field is almost only important distribution,

$$s_1 >> s_i\,,\ \overleftrightarrow{C} \cdot \vec{V}_{bi}^{x}\left(i \geq 2\right) \cong 0$$

- Then the total resonant field is

$$\left|\vec{B}_r\right| = \left|\left(\overleftrightarrow{C} \cdot \vec{V}_{b1}^{x}\right)\left(\vec{\Phi}_b^{xerr} \cdot \vec{V}_{b1}^{x}\right)\right| = s_1\left|\left(\vec{\Phi}_b^{xerr} \cdot \vec{V}_{b1}^{x}\right)\right|$$

- Overlap field is defined as

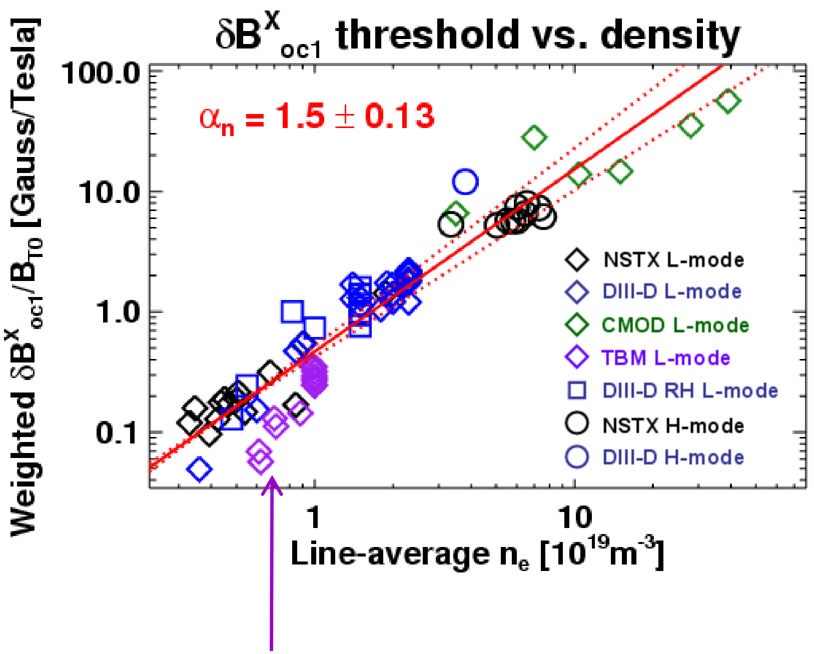
$$\delta B_o^x \equiv \left(\vec{\Phi}_b^{xerr} \cdot \vec{V}_{b1}^{x}\right)$$

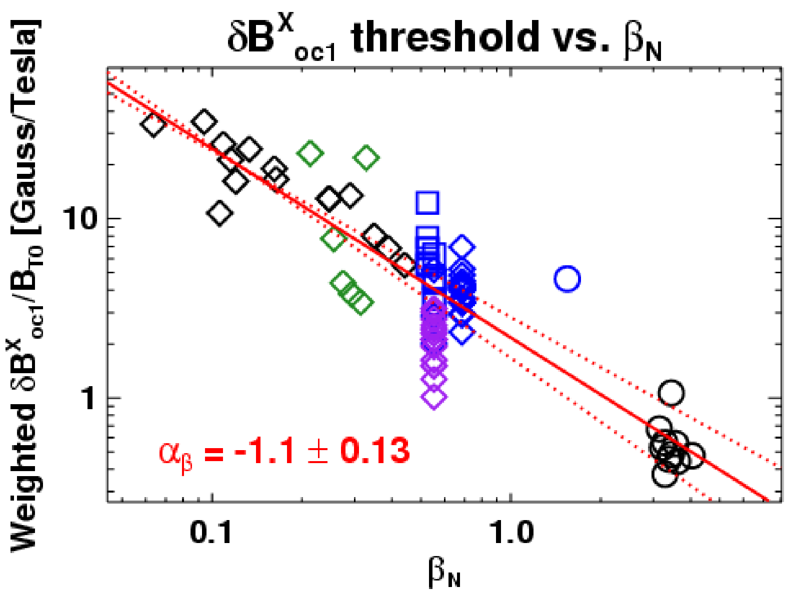
- Overlap field is the external representation of the total resonant field

# Scaling for locking drive becomes more reliable with overlap field

- Tokamak locking scaling based on overlap field :

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




*[For TBM cases, see BI3.00001 by Schaffer, and also see XO4.00003 on Friday ]*

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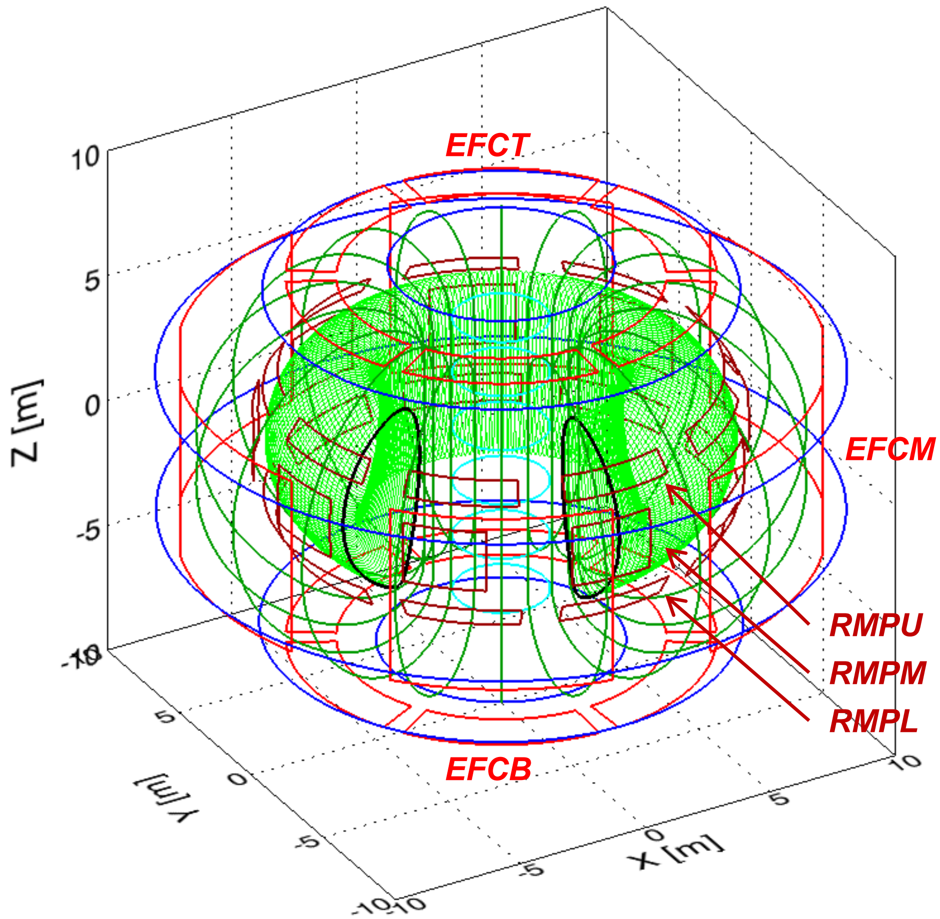
# ITER error field correction coil capability has been revisited with new methods

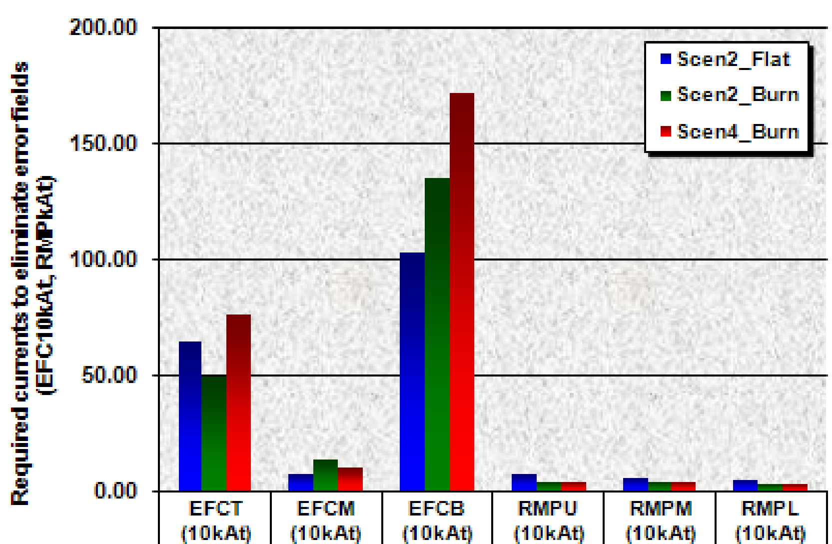
- Potentially ITER may have 3x6 Error Field Correction Coils (EFCC) and 3x9 Resonant Magnetic Perturbation Coils (RMPC)
- EFCC (or RMPC) must have capability to compensate error fields due to primary magnet (CS/PF/TF) coil distortions
- Coil capability has been revisited in order to include ideal plasma response effects



# Worst error fields and required corrections were estimated based on overlap field

- Overlap field of each component shows
  - **Worst error fields come from PF3~4 tilt**
  - **Correction capability of each correction : RMPU,M,L > EFCM >> EFCT,B**

**Required currents to eliminate the worst overlap fields**




| | EFCT (10kAt) | EFCM (10kAt) | EFCB (10kAt) | RMPU (10kAt) | RMPM (10kAt) | RMPL (10kAt) |
|---|---|---|---|---|---|---|
| Scen2_Flat | 64.13 | 7.71 | 102.60 | 6.84 | 5.40 | 4.89 |
| Scen2_Burn | 49.23 | 13.21 | 135.38 | 3.38 | 3.38 | 2.93 |
| Scen4_Burn | 76.44 | 10.12 | 172.00 | 4.05 | 3.82 | 2.87 |

# One conclusion : EFCT and EFCB coils are very inefficient for resonant field correction

- EFCT and EFCB coils are less efficient than EFCM by an order of magnitude for the resonant fields
- Are EFCT and EFCB coils still useful in terms of other physics?
- Even if so, can RMP coils do much better?
- Now we like to compare (EFCM+EFCT+EFCB) and (EFCM+RMPU+RMPL) with (EFCM only)

# Other physics? : NTV is the best known physics element for non-resonant fields

- Neoclassical Toroidal Viscosity (NTV) causes plasma rotation damping and destabilizes various MHD
- NTV estimation presently requires perturbed equilibrium calculations for the Lagrangian variation in the field strength with various bounce harmonic integrations

$$\tau_{\varphi} \cong C\left[\delta B\right]^{2} \frac{\nu_{eff}}{(\ell\omega_{\ell bounce} - n\omega_{E\times B} - n\omega_{\nabla B})^{2} + \nu_{eff}^{2}} (\omega_{rot} - \omega_{neo})$$

- That is, NTV is not easy to optimize
- So, we use overlap approximation : Correction should simultaneously
  - **Remove the overlap field (remove the resonant components)**
  - **Maximize the overlap (minimize the non-resonant components)**

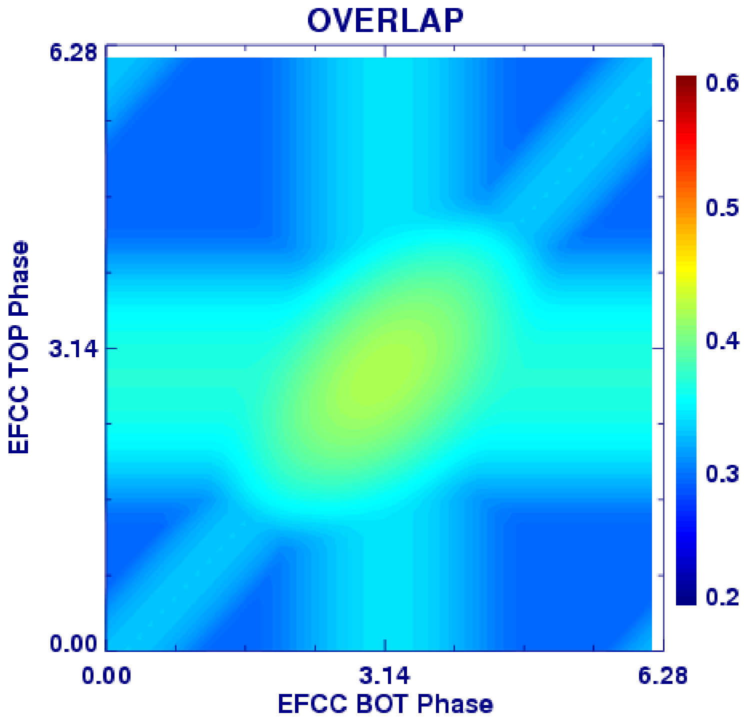
$$C_{o} \equiv \frac{\left(\vec{\Phi}_{b}^{xerr} \cdot \vec{\Phi}_{b1}^{x}\right)}{\left|\vec{\Phi}_{b}^{xerr}\right|\left|\vec{\Phi}_{b1}^{x}\right|}$$

***Overlap (0-1)=*** $\dfrac{\textit{Overlap field}}{\textit{RMS surface average of the field}} \approx \dfrac{\textit{Resonant component}}{\textit{Sum of non-resonant component}}$

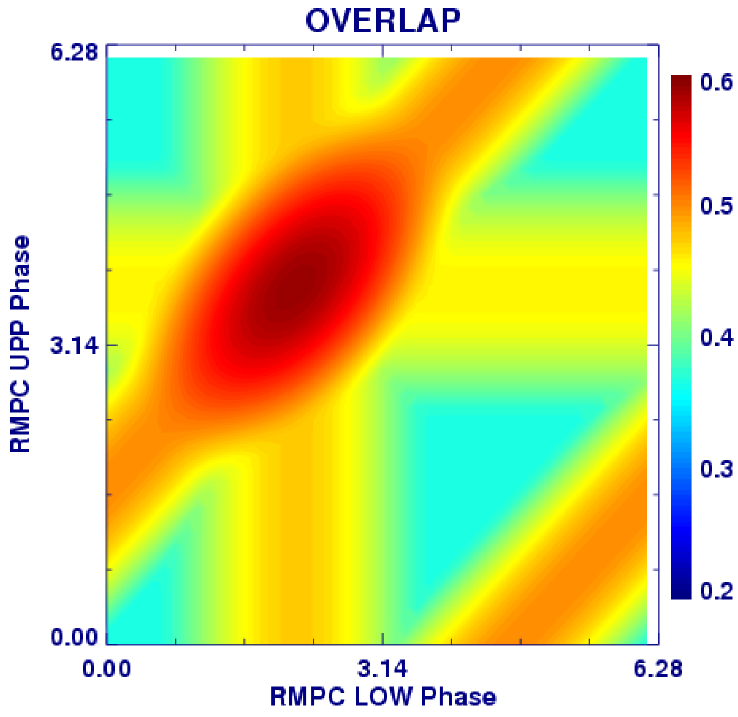
# Corrections were optimized based on overlap

- EFCT (RMPU) and EFCB (RMPL) amplitudes and phases (relatively to a fixed EFCM amplitude and phase) were optimized to maximize overlap

***(EFCM+EFCT+EFCB)***



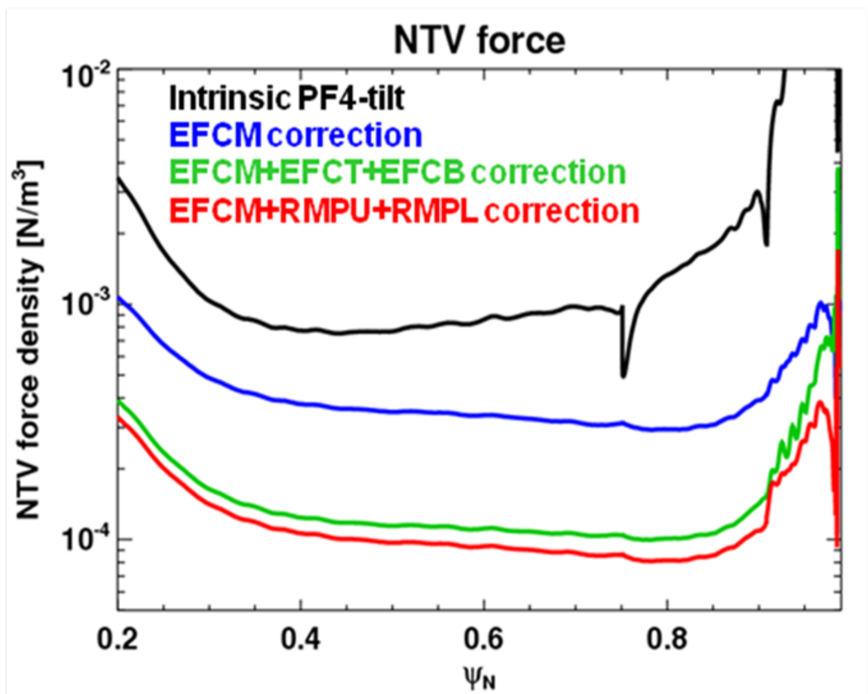

***(EFCM+RMPU+RMPL)***



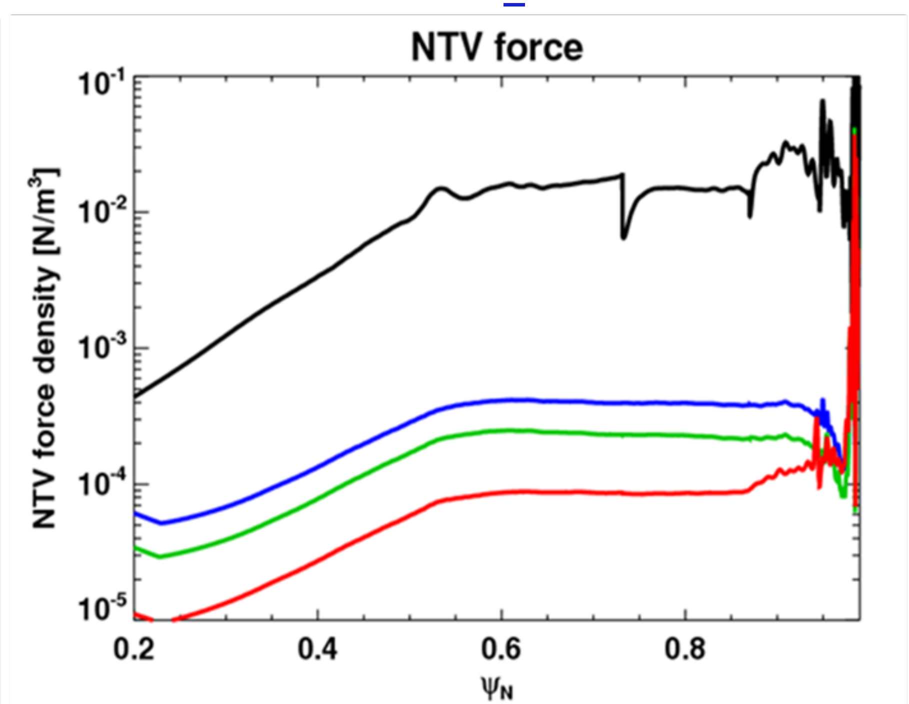
# Optimized corrections give the best capability for both resonant and non-resonant components

- EFCM gives NTV reduction by 1~2 orders of magnitude
  - **This indicates reduction of resonant components is also very important for NTV**
- Further NTV reduction by a factor of 1~3 is possible by optimization
- However, required currents are **EFCM+EFCT+EFCB (95+164+257kAt) >> EFCM only (132kAt) > EFCM+RMPU+RMPL (71+23+23kAt)**

*Scen2_Burn*




*Scen4_Burn*



# Overview

- Development of Ideal Perturbed Equilibrium Code (IPEC)

- IPEC applications to tokamaks
  - Plasma responses to applied perturbations
  - Error field corrections and plasma locking
  - Non-ambipolar transport and magnetic braking

- Control of non-axisymmetric perturbations
  - Dominant external field distribution and overlap field
  - **ITER error field study**

- Summary and Future Work

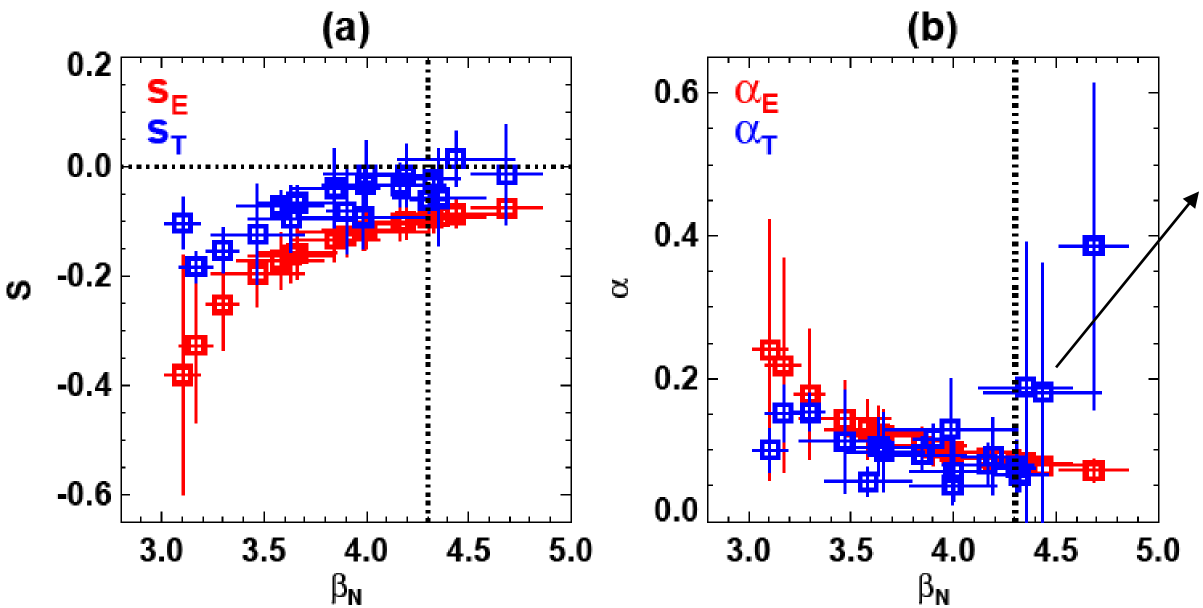
# High-β plasmas require perturbed equilibrium calculations consistently with non-ideal forces

- Locking and NTV give a toroidal torque, which is not included in IPEC, and so IPEC is not consistent when the torque is large

$$\vec{\nabla} p_0 = \vec{j}_0 \times \vec{B}_0 - \left( \vec{\nabla} \delta p - \delta \vec{j} \times \vec{B}_0 - \vec{j}_0 \times \delta \vec{B} + \delta \vec{f} \right) \text{ where } \delta \vec{f} = \vec{\nabla} \cdot \vec{\Pi} + \cdots$$

- Importance of the torque (non-ideal force) can be estimated as

$$s \equiv -\frac{\delta W}{\delta W_V} \quad \text{and} \quad \alpha \equiv -\frac{T_\phi}{2\delta W_V}$$




***In high beta plasmas,***
***The torque becomes too large, indicating the importance of the currents associated with the torque in perturbed equilibria :***
***Importance of tensor pressure perturbed equilibria***

**[*Park , POP 16, 082512 (2009)*]**

# Summary and Future Work

- IPEC solves free-boundary ideal perturbed equilibria
- IPEC applications showed that plasma response to non-axisymmetric fields are important in tokamaks
  - Vacuum superposition approximation is generally not valid
- Combined NTV with ideal perturbed equilibria give reasonable explanations and predictions for non-ambipolar transport in tokamaks
- Dominant external field and overlap give useful tools to understand control of non-axisymmetric magnetic perturbations
  - Revision of ITER error field study has shown (EFCM+RMPU+RMPL) is the best configuration for both resonant and non-resonant components
- Perturbed equilibria should include torques to be more self-consistent