NSTX

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Study of Error Field Physics in Tokamaks and Implications for ITER

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Non-axisymmetric error fields are dangerous to tokamaks

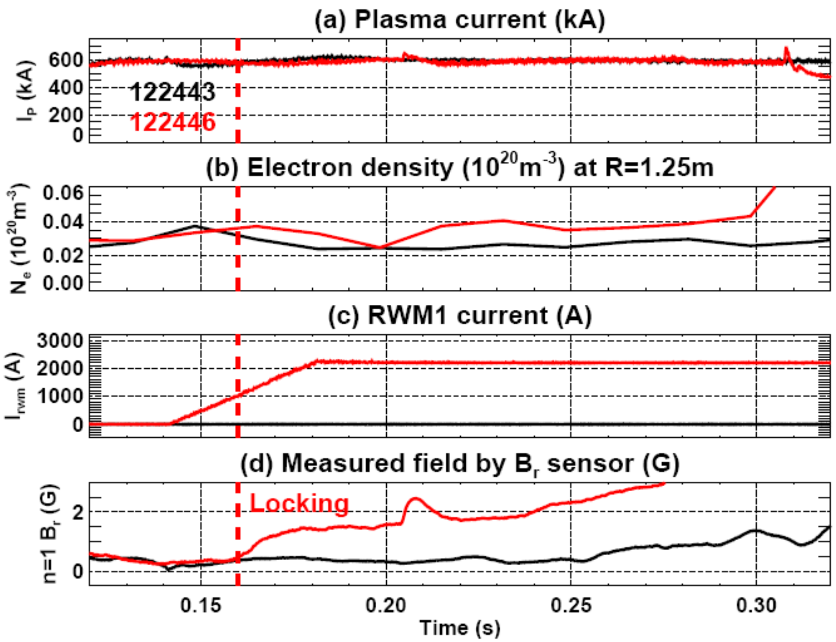
- Non-axisymmetric error field can
  - Destroy magnetic surfaces and produce magnetic islands
  - Deform magnetic surfaces and produce non-ambipolar transport

- Magnetic islands can
  - **Cause Locked Modes (LMs)**
  - **Cause Neoclassical Tearing Modes (NTMs)**
- Low toroidal harmonic (n=1) perturbations are typically related to LMs and NTMs

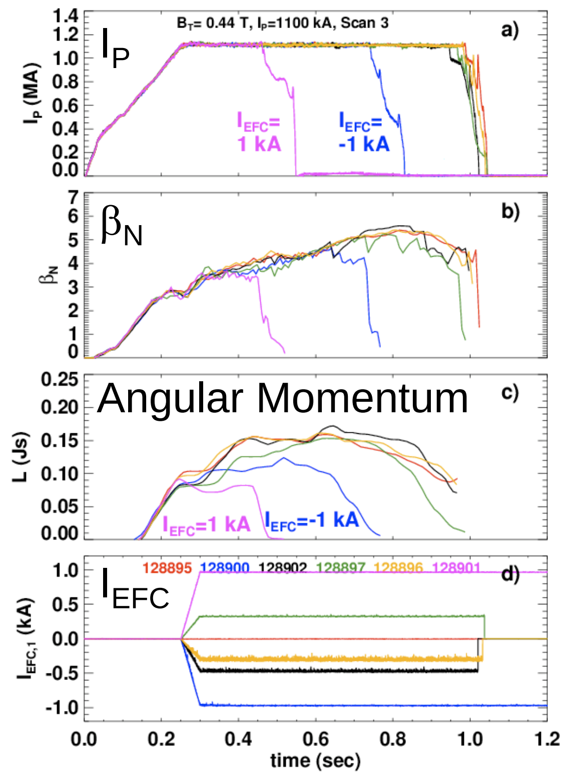
- Non-ambipolar transport can
  - **Cause Neoclassical Toroidal Viscosity (NTV) transport**
  - **Cause other transport?**
- Higher toroidal harmonics (n=3) perturbations are typically related to NTV transport

Plasma performance can be greatly changed by error fields

- Plasmas can be locked and disrupted by n=1 error fields in NSTX



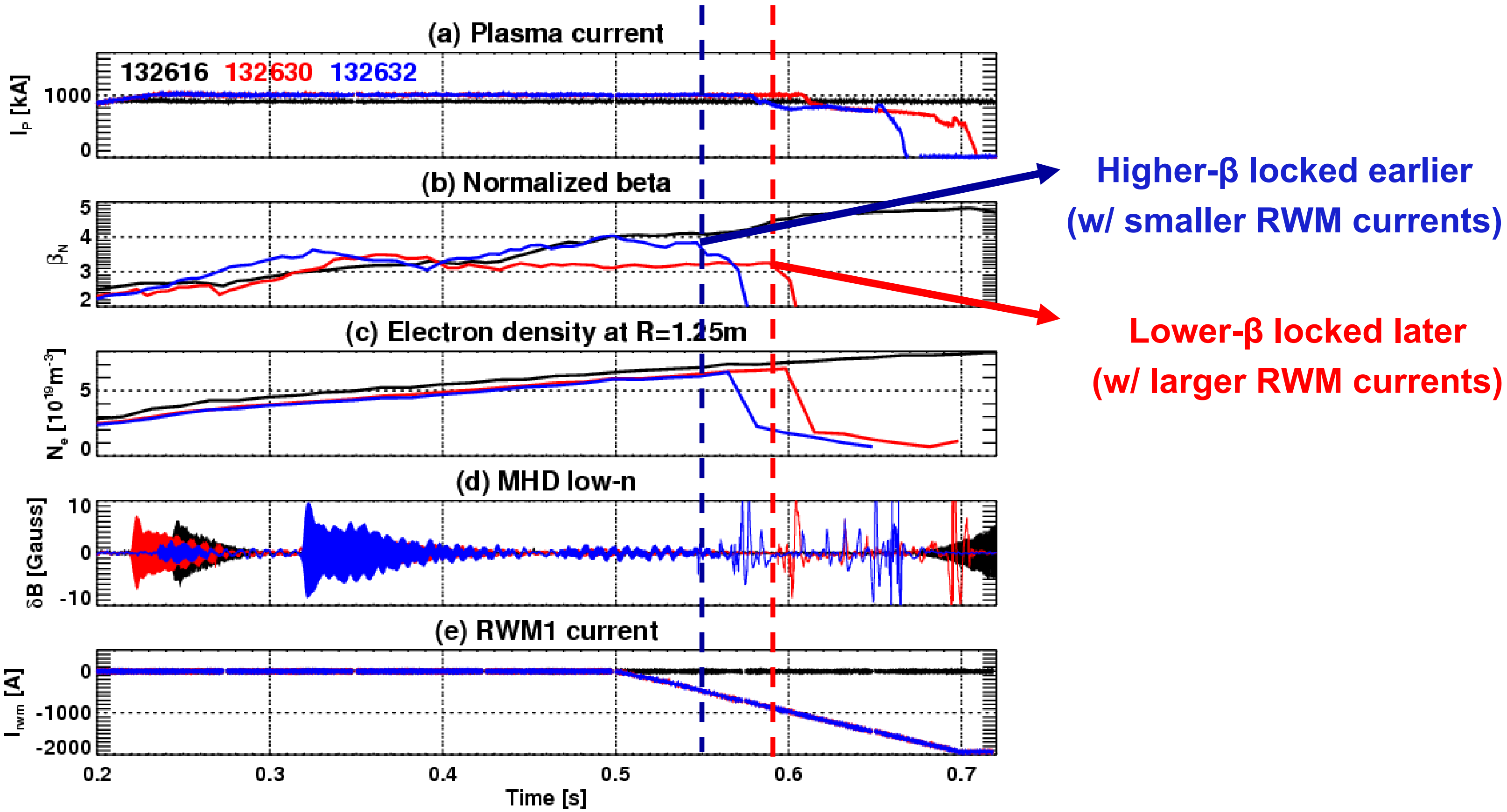
- Plasmas can be sustained longer by correcting n=3 error fields in NSTX and by suppressing NTV rotational damping



[See NSTX talk by S. P. Gerhardt]

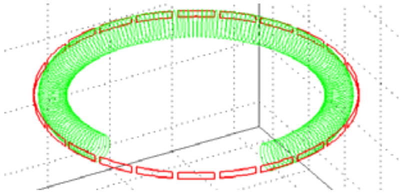
Plasma response is important to explain different sensitivity of plasmas to error field

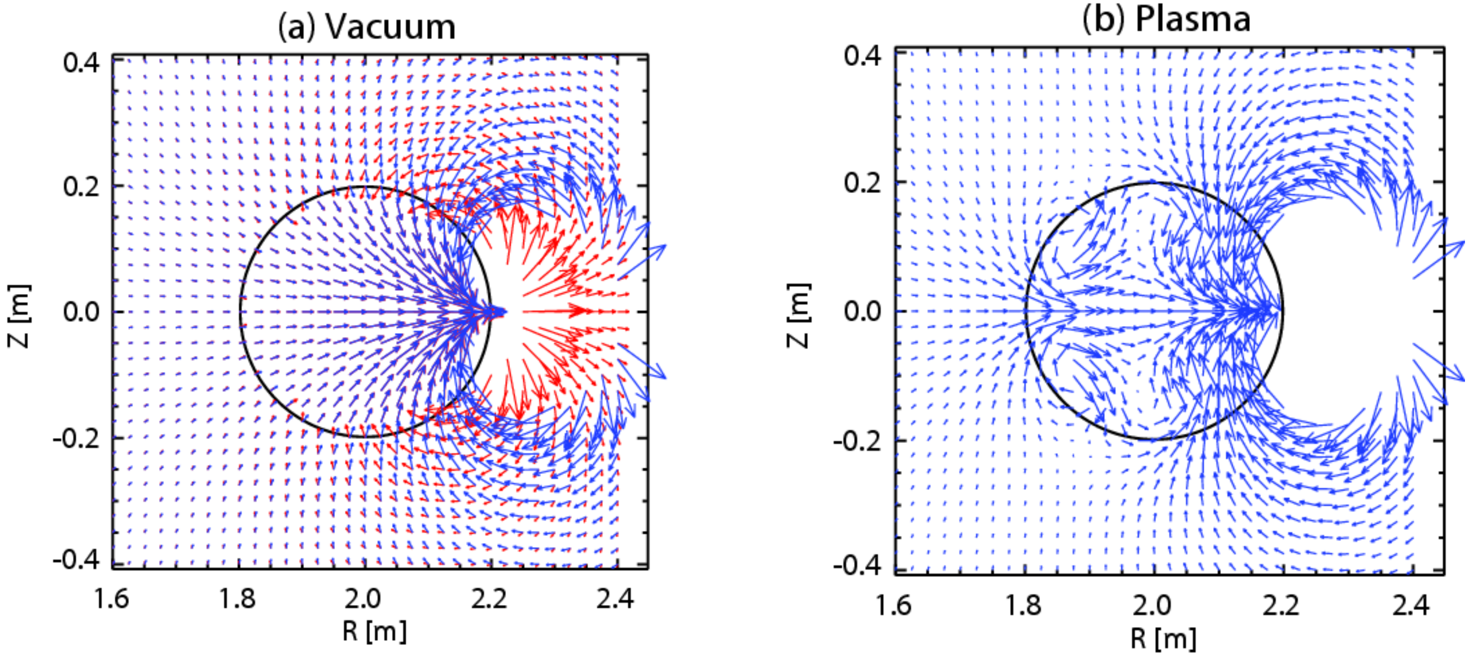
- Plasma response is important to explain the sensitivity of plasmas to external error fields



Ideal plasma response is fundamental, but important step

- Force-free cylindrical example :
  - Total Perturbed field (δB) = Plasma Field from perturbed plasma currents (δB^P) + External field from external currents (δB^X)





IPEC solves ideal plasma response with shielded islands

- Ideal Perturbed Equilibrium Code (IPEC) solves ideal perturbed tokamak equilibria with free boundary
  - Ideal force balance (since plasma is almost ideal in practice) :

$$\text{axisymmetric } \vec{\nabla} p_0 = \vec{j}_0 \times \vec{B}_0 \text{ and small (linear) perturbations}$$

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

$$\delta\vec{B} = \vec{\nabla} \times (\vec{\xi} \times \vec{B}_0), \;\; \delta\vec{j} = (\vec{\nabla} \times \delta\vec{B}) / \mu_0 \text{ and } \delta p = -\vec{\xi} \cdot \vec{\nabla} p_0 - \gamma p_0 (\vec{\nabla} \cdot \vec{\xi})$$

  - Internal boundary conditions suppressing islands :

$$\text{Resonant field } = 0 \text{ at the resonant surfaces}$$

$$\text{with currents shielding the total resonant field } \delta B_{mn}$$

Total resonant field can open islands and cause locking

  - External boundary conditions are given by external coils

IPEC solves free boundary equilibria in a unique way

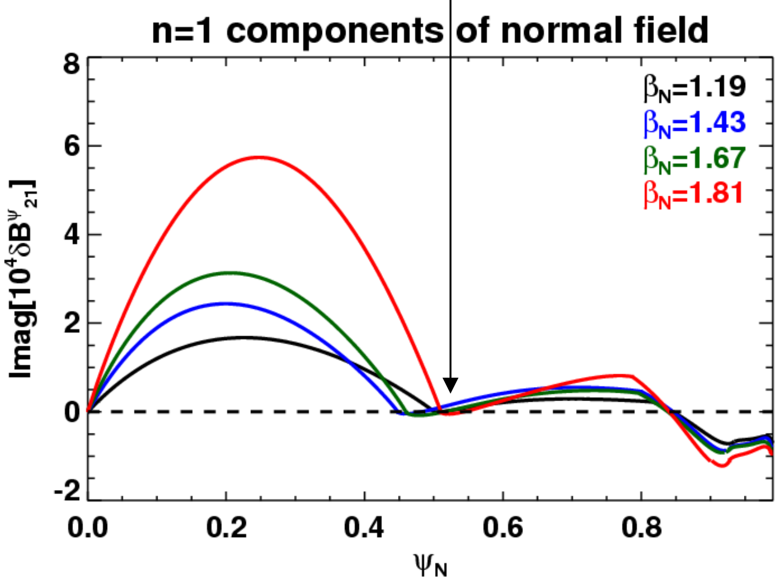
[*Park et al, Phys. Plasmas 14, 052110 (2007)*]

IPEC gives relevant physics for LMs and NTV

- Total resonant field at the rational surfaces is the field driving magnetic islands and LMs

$$\delta \vec{j}_{||} = \frac{i\Delta_{mn} e^{i(m\vartheta - n\varphi)}}{\mu_0 n \int B_0^2 / |\nabla\psi|^3 \, da} \delta(\psi - \psi_{mn}) \vec{B}_0$$

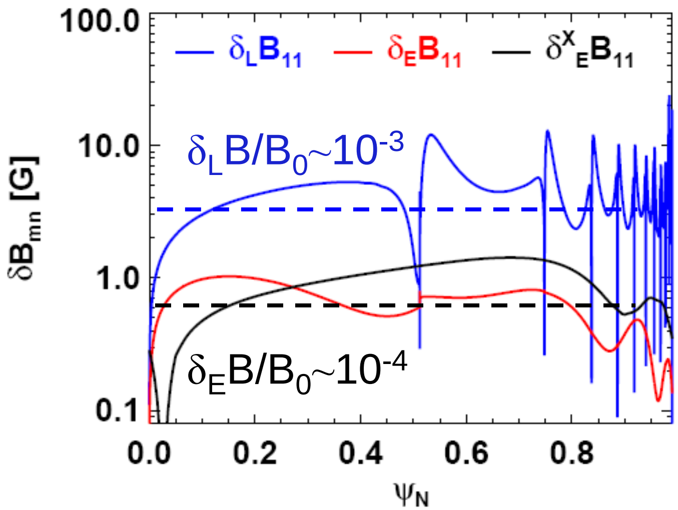
$$\text{with the jump } \Delta_{mn} = \left[\frac{\partial}{\partial\psi} \left(\frac{\delta\vec{B}\cdot\vec{\nabla}\psi}{\vec{B}_0\cdot\vec{\nabla}\vartheta} \right) \right]_{mn}$$



- Variation in the field strength along the perturbed field lines is driving non-ambipolar transport and NTV

$$\delta B_L \equiv \delta B_E + \vec{\xi} \cdot \vec{\nabla} B_0$$

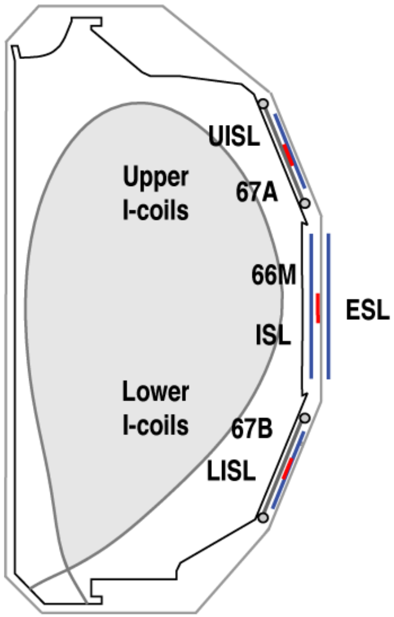
$$\text{with } \delta_E B \equiv \delta\vec{B} \cdot \hat{b}_0$$

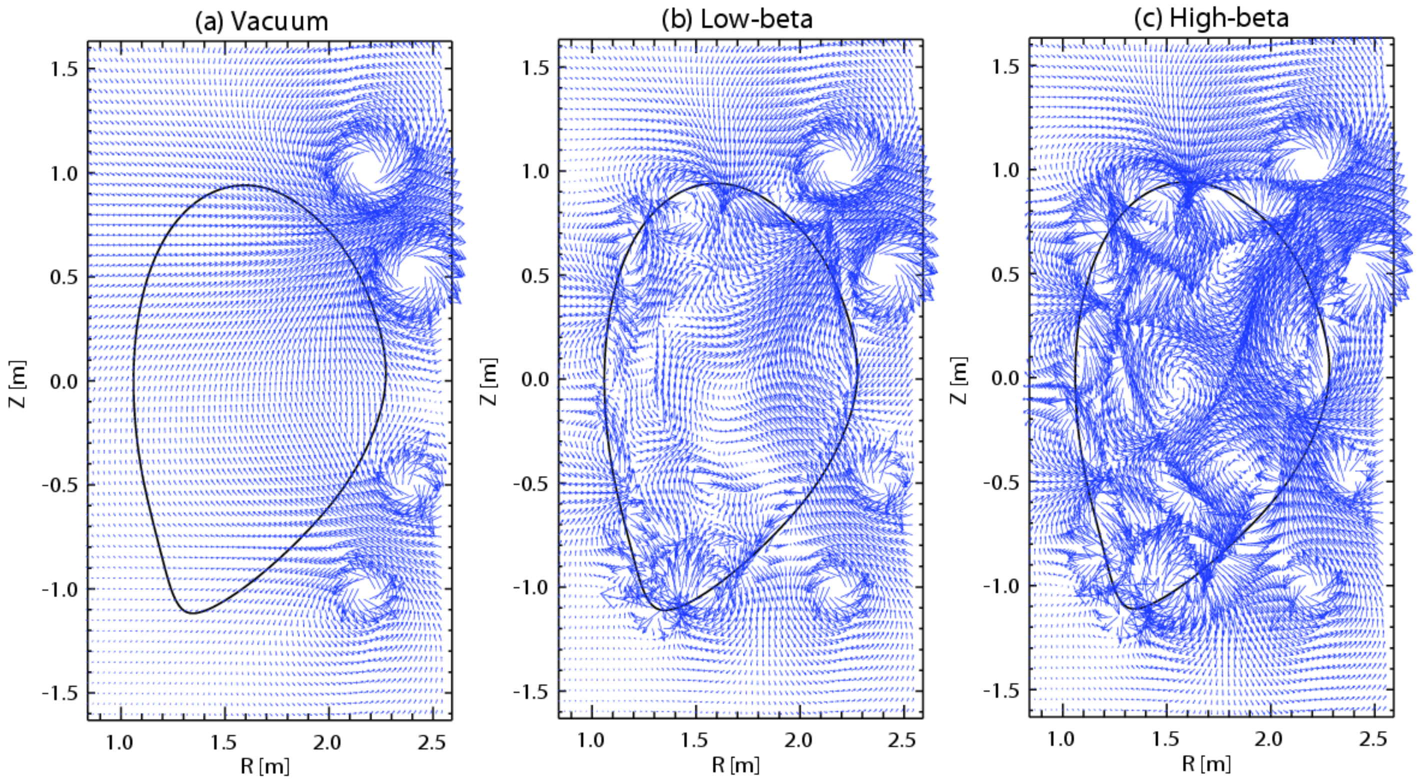


[*Park et al, Phys. Plasmas 16, 082512 (2009)*]

Magnetic sensor measurements can show importance of ideal plasma response

- IPEC can calculate the field (δB^P) by ideally perturbed plasma currents
- Plasma response at sensors can be estimated by integrating IPEC field and can be directly compared with RFA measurements





#135762, β_N=1.19 **#135765, β_N=1.81**

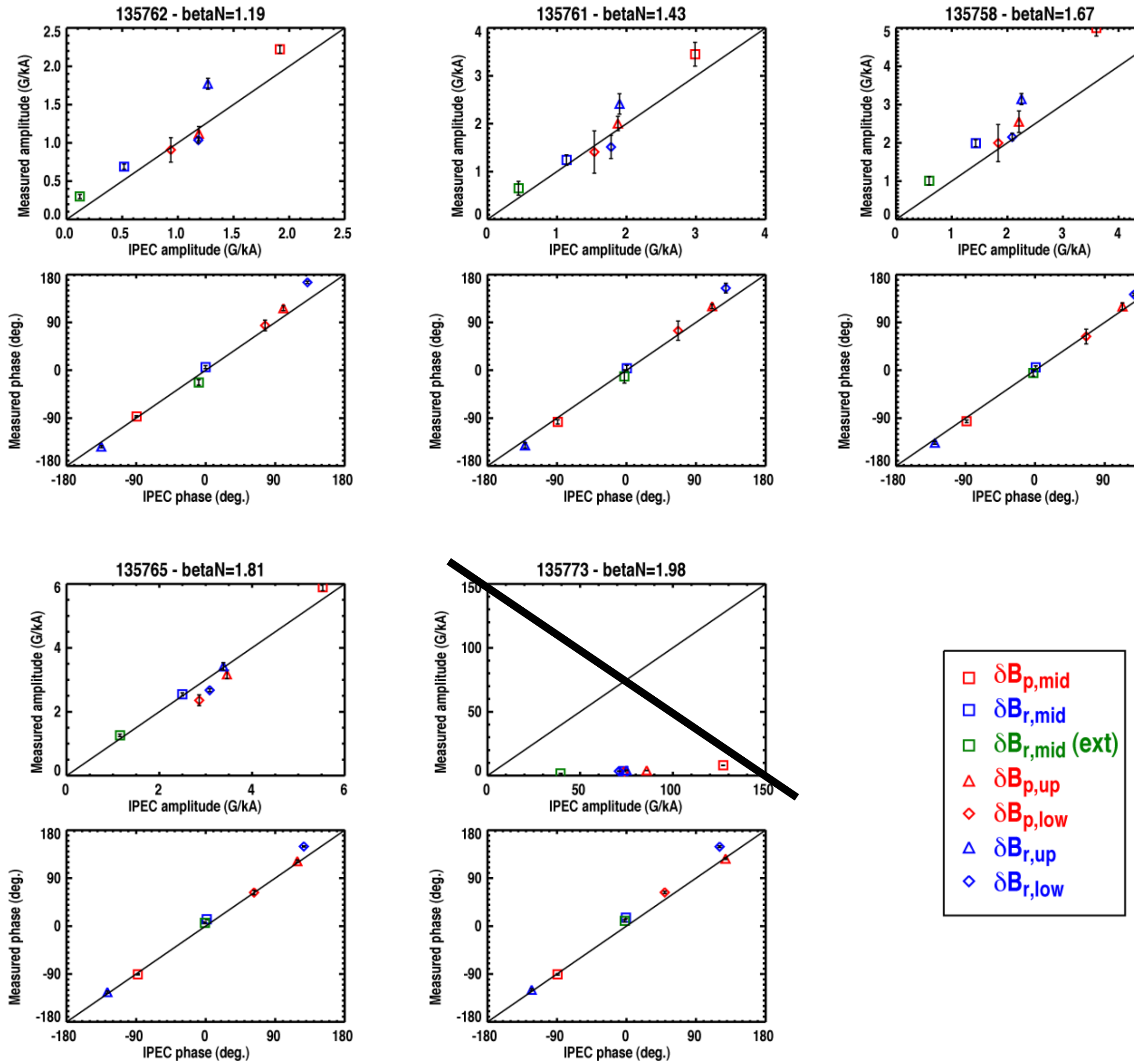
Comparison between IPEC and n=1 RFA DIII-D measurements showed good agreements except marginally stable case

- All the sensors give good agreements for amplitudes and toroidal phases, when plasma is below the no-wall limit

[See DIII-D poster by H. Reimerdes]

- RFA results are also successfully compared with MARS simulations

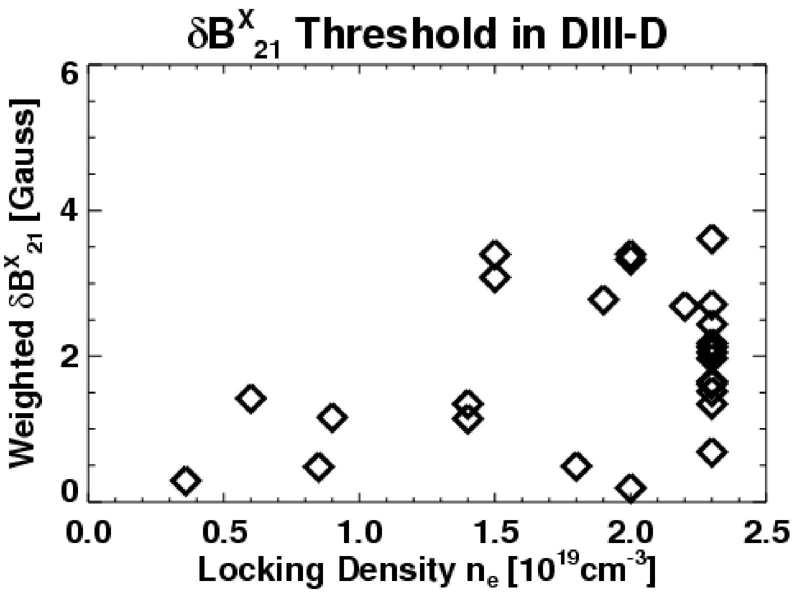
[See DIII-D talk by M. Lanctot]



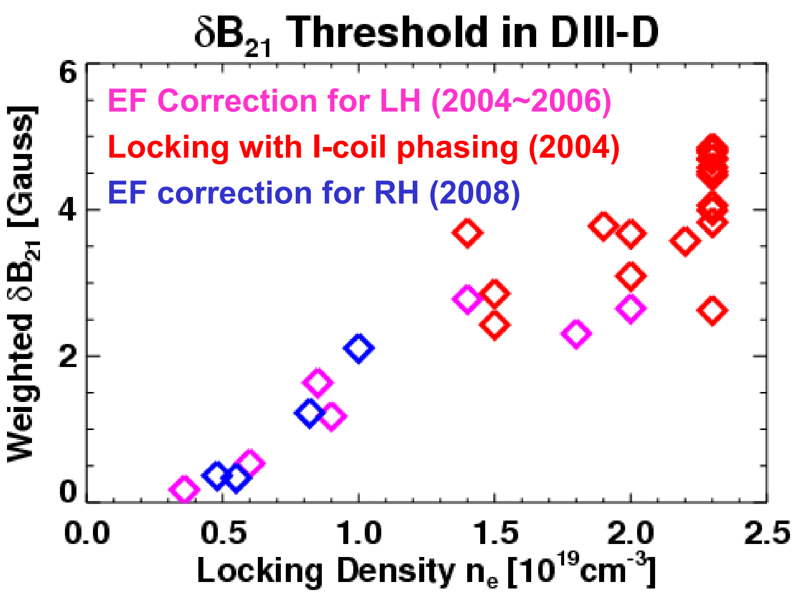
IPEC applications to LMs explained paradoxical error field correction results in tokamaks

- Error field corrections and locking experiments in NSTX and DIII-D could not be explained by standard density correlations, when various intrinsic error fields and corrections are combined

With external (vacuum) resonant field

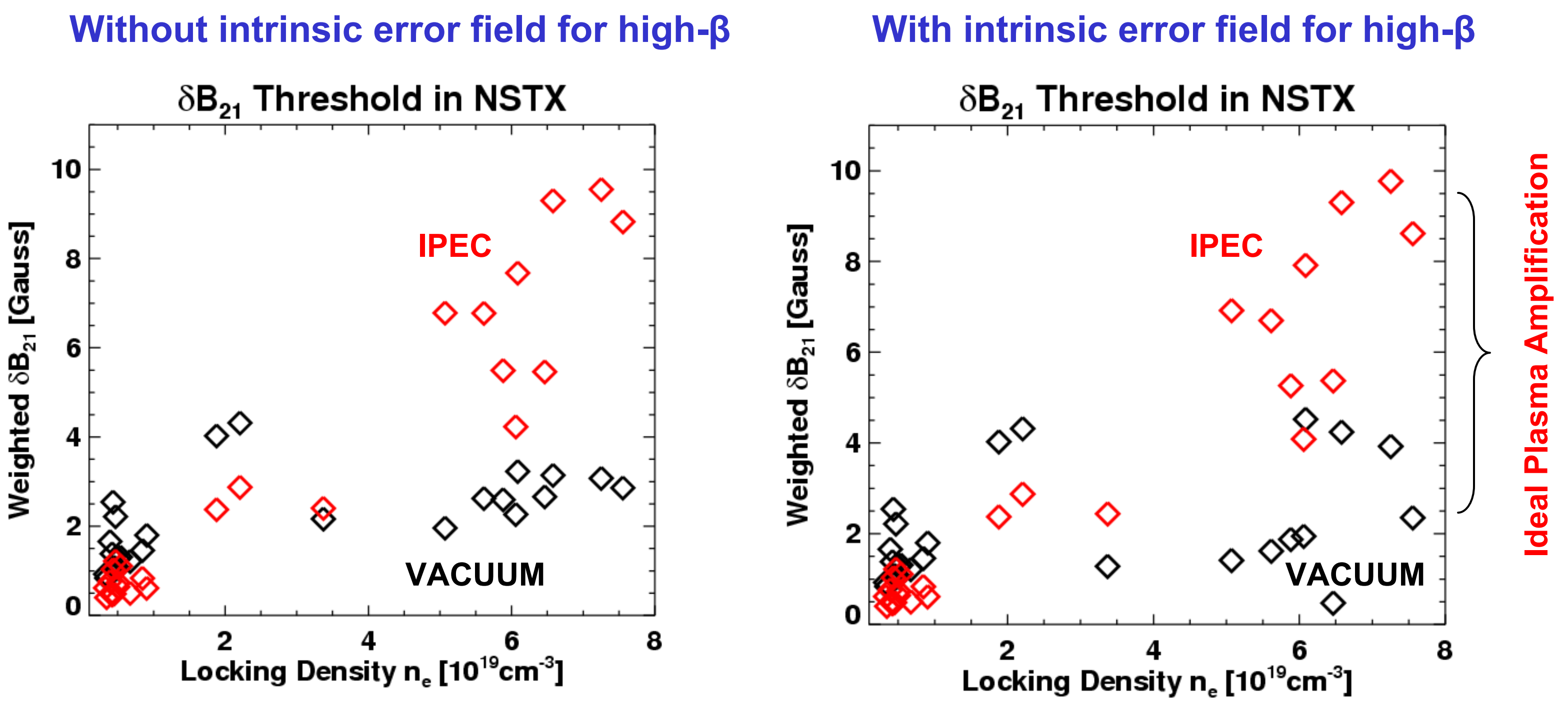


With total resonant field



IPEC applications to LMs explained greater sensitivity of plasmas to error fields at high-β

- IPEC resonant field restores linear density correlation across low-β and high-β plasmas
- Intrinsic error field effects are very weak for IPEC resonant field due to large shielding of the unfavorable field spectrum



[See NSTX talk by S. P. Gerhardt]

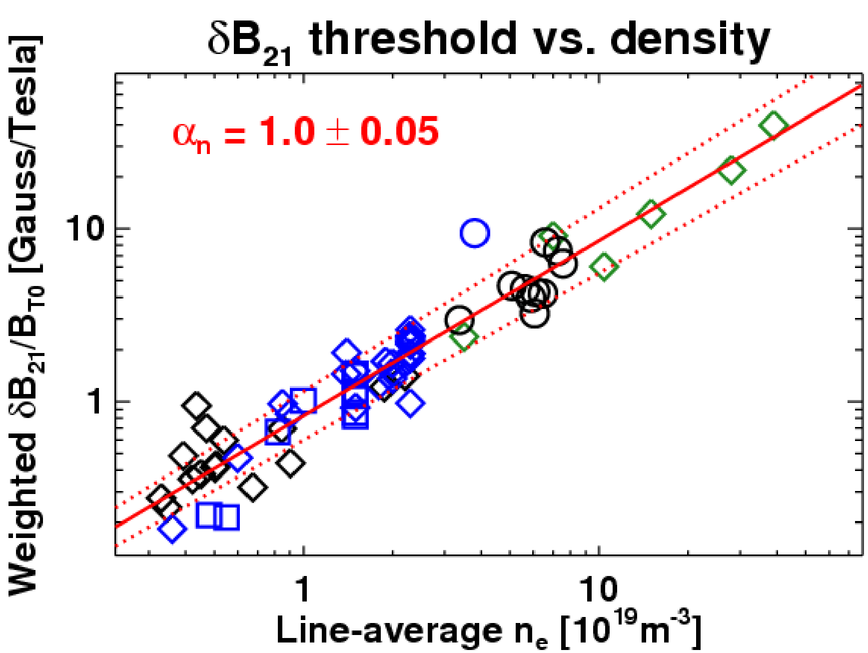
Total resonant field and density give good parametric scaling for LMs

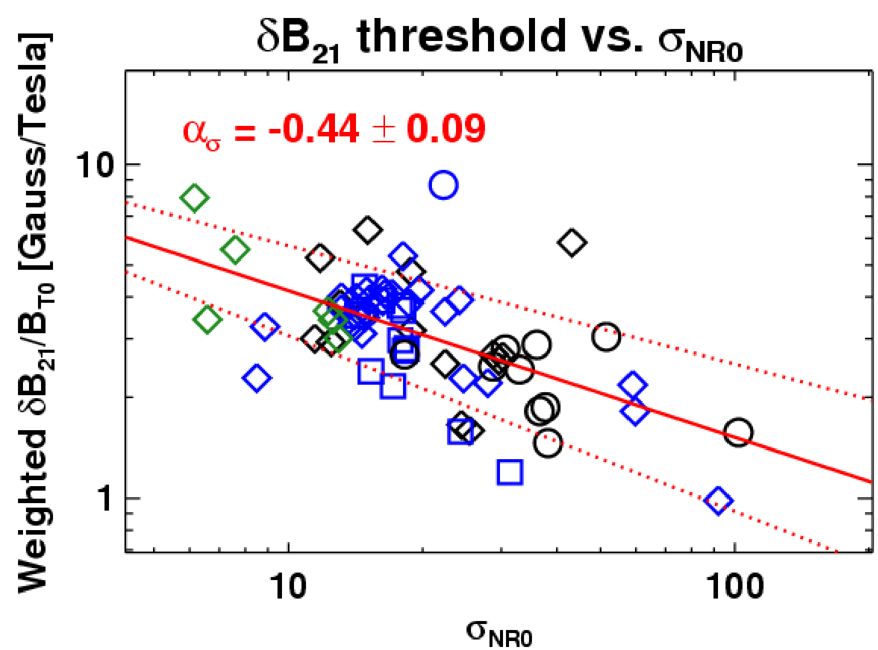
- The best four-parameter scaling with total resonant field:

$$\frac{\delta B_{21}}{B_{T0}} \leq 3.7\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.0}\left(B_{T0}[T]\right)^{-1.4}\left(R_0[m]\right)^{0.85}\sigma_{NR0}^{-0.44}$$

Where $\sigma_{NR0} = \left[\frac{\sum_{nmm'} n^2\delta^2_{nmm'}F^{-1/2}_{nm0}F^{-1/2}_{nm'0}}{\delta B^2_{21}}\right]^{1/2}$ *is the ratio of non-resonant field to resonant field*

◇ **Low-β NSTX** ◇ **Low-β DIII-D** ◇ **Low-β CMOD** □ **Low-β DIII-D with Right-handed config.**
○ **High-β NSTX** ○ **High-β DIII-D**





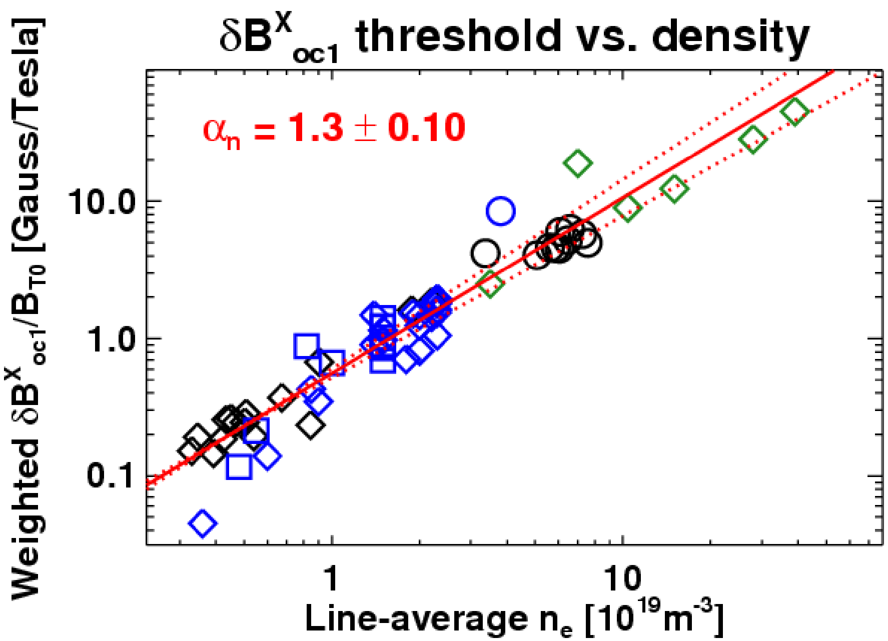
Overlapped external field and density give good parametric scaling for LMs

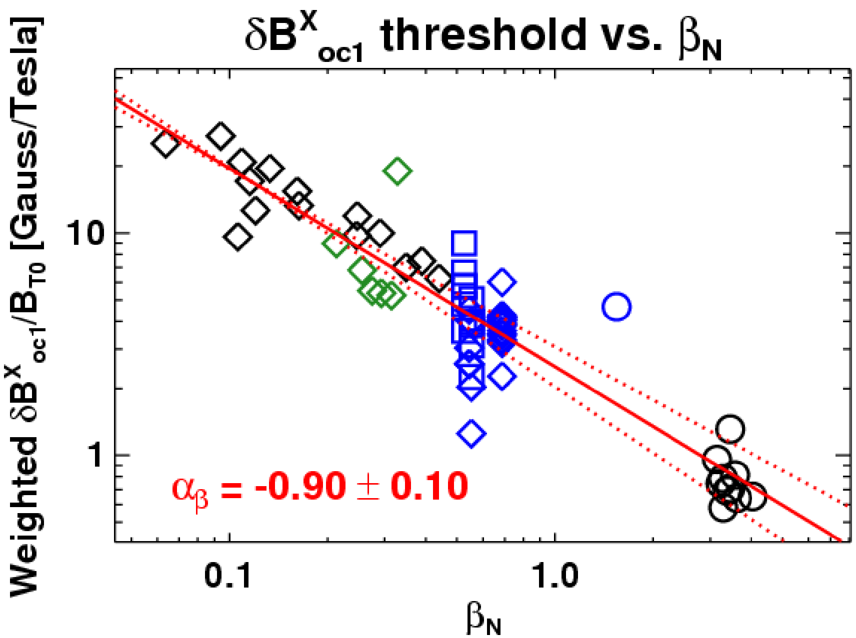
- The best four-parameter scaling with overlapped external field :

$$\frac{\delta B^{x}_{oc1}}{B_{T0}} \leq 0.5\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.3}\left(B_{T0}[T]\right)^{-1.8}\left(R_0[m]\right)^{1.3}\beta_N^{-0.90}$$

Where the overlapped external field is the convolution between applied field and the most sensitive external field that maximizes total resonant field for the core

◇ Low-β NSTX ◇ Low-β DIII-D ◇ Low-β CMOD □ Low-β DIII-D with Right-handed config.
○ High-β NSTX ○ High-β DIII-D



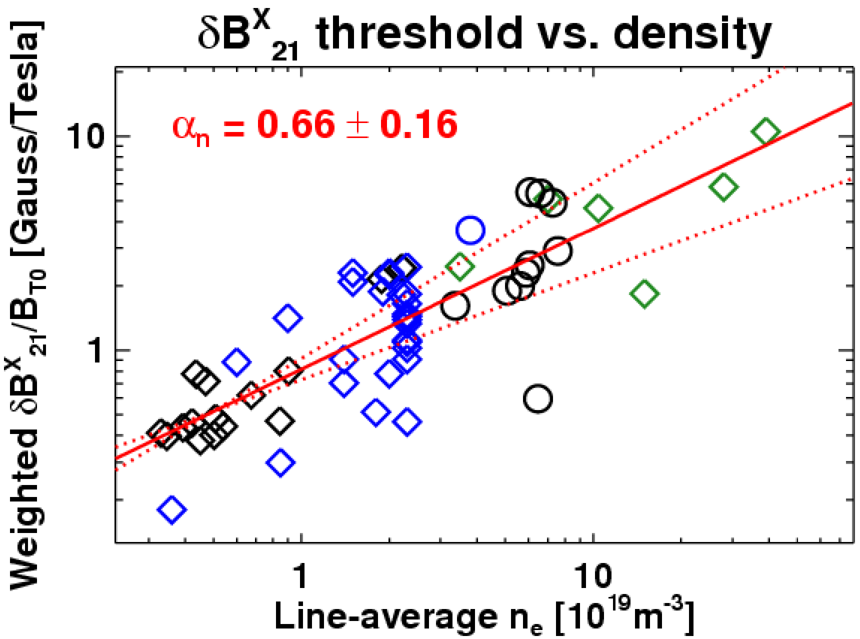


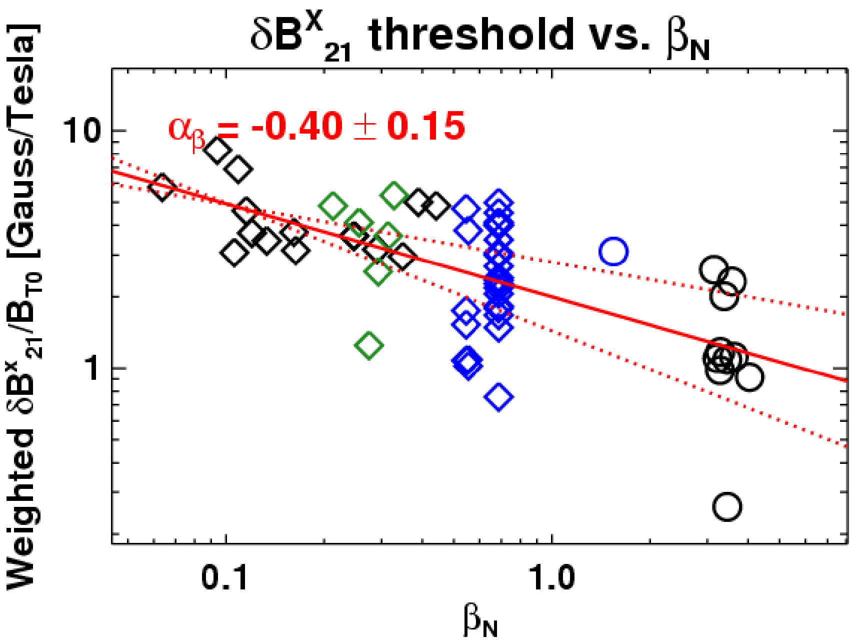
External resonant field gives poor correlation even with corrections by plasma amplifications

- Correlations can be found if amplification effects are included by normalized beta scaling, but are still very poor :

$$\frac{\delta B_{21}^{x}}{B_{T0}} \leq 1.1\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{0.66}\left(B_{T0}[T]\right)^{-1.0}\left(R_0[m]\right)^{0.02}\beta_N^{-0.40}$$

◇ Low-β NSTX ◇ Low-β DIII-D ◇ Low-β CMOD □ Low-β DIII-D with Right-handed config.
○ High-β NSTX ○ High-β DIII-D





Extrapolations to ITER

- Three parametric scaling :

$$\frac{\delta B_{21}}{B_{T0}} \le 3.7\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.0}\left(B_{T0}[T]\right)^{-1.4}\left(R_0[m]\right)^{0.85}\sigma_{NR0}^{-0.44}$$

$$\frac{\delta B_{oc1}^{x}}{B_{T0}} \le 0.5\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.3}\left(B_{T0}[T]\right)^{-1.8}\left(R_0[m]\right)^{1.3}\beta_N^{-0.90}$$

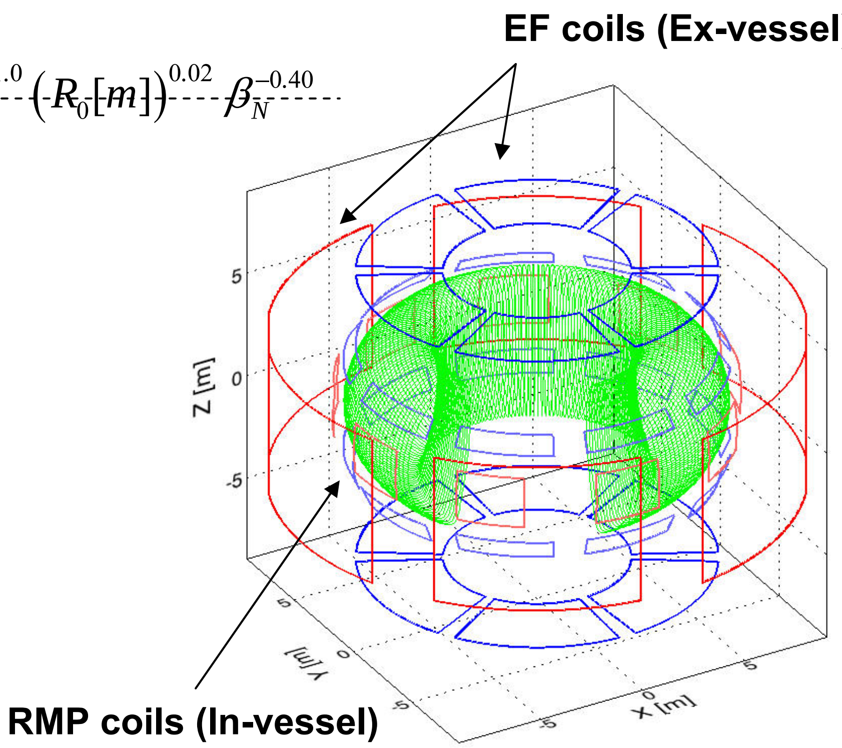
$$\frac{\delta B_{21}^{x}}{B_{T0}} \le 1.1\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{0.66}\left(B_{T0}[T]\right)^{-1.0}\left(R_0[m]\right)^{0.02}\beta_N^{-0.40}$$

- Extrapolations to ITER :

$$\frac{\delta B_{21}}{B_{T0}} \le 1.6\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.0}\sigma_{NR0}^{-0.44}$$

$$\frac{\delta B_{oc1}^{x}}{B_{T0}} \le 0.26\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.3}\beta_N^{-0.90}$$

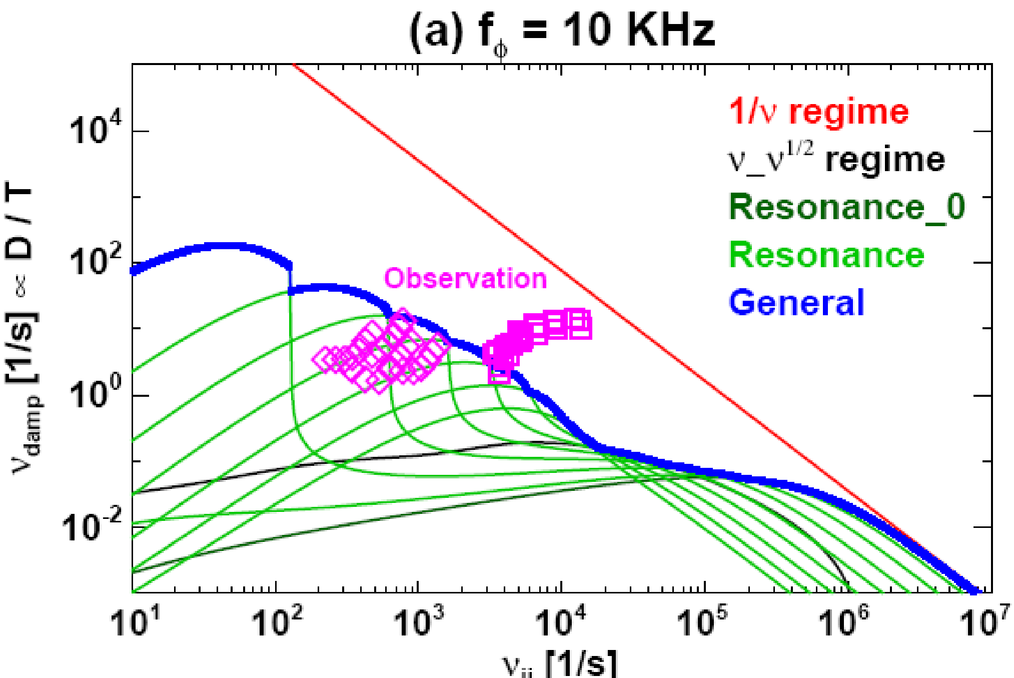
$$\frac{\delta B_{21}^{x}}{B_{T0}} \le 0.2\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{0.66}\beta_N^{-0.40}$$



NTV transport can be coupled with IPEC variation in the field strength

- IPEC gives variation in the field strength along the perturbed field lines
- IPEC information can be coupled to various NTV formula

$$\tau_{\varphi} \cong C\left[\delta B\right]^2 \frac{\nu(\omega_E - \omega_0)}{(\ell\omega_\ell - n\omega_E - n\omega_B)^2 + \nu^2}$$

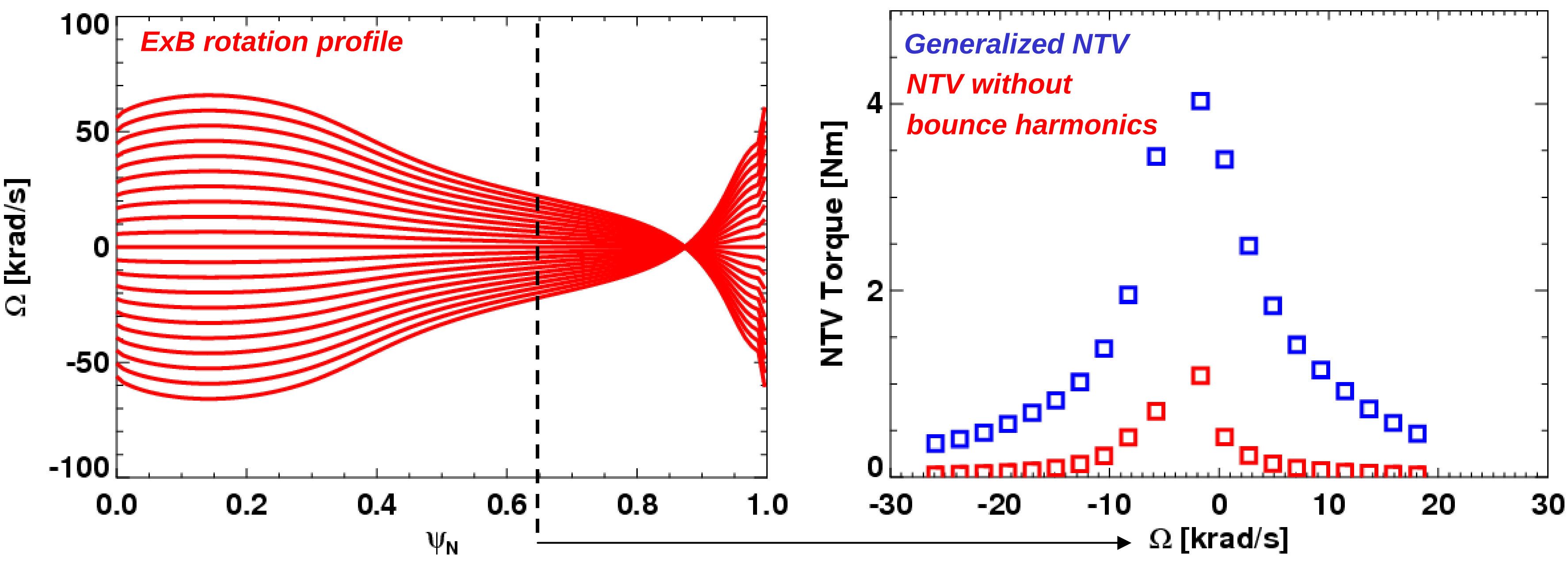


[Park et al, Phys. Rev. Lett. 102, 065002 (2009)]

Fundamental parametric dependency is under active study

- Parametric dependency is under study
- Lorentzian response has been reported from DIII-D

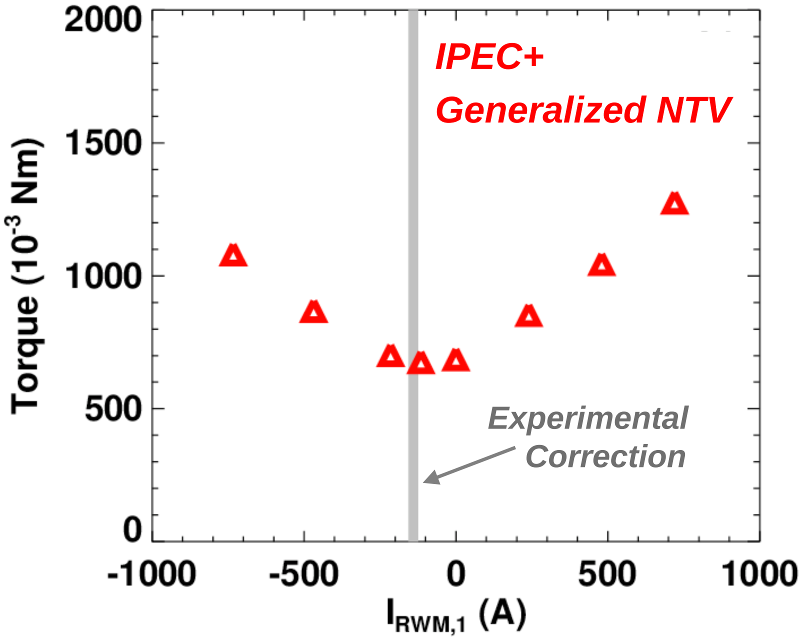
$$\tau_\varphi \propto \frac{\nu(\omega_E - \omega_0)}{(\ell\omega_\ell - n\omega_E)^2 + \nu^2}$$



[See DIII-D talk by W. M. Solomon]

NTV coupled with IPEC calculations can explain n=3 error field correction results in NSTX within order of magnitudes

- Generalized NTV coupled with IPEC calculations can explain n=3 error field correction results within order of magnitudes



[*See NSTX talk by S. P. Gerhardt*]

Summary and Future Work

- Ideal plasma response is the key to understanding of error field physics up to the no-wall limit
  - Plasma amplifications by IPEC can bridge low and high-β error field threshold
  - Error field threshold for n=1 is successfully established for ITER across low and high, and across NSTX, DIII-D, and CMOD
  - Error field corrections for n=3 can be also explained by NTV coupled with IPEC calculations

- IPEC and NTV will be used to establish more comprehensive error field database combining
  - Different toroidal harmonic perturbations
  - Rotation and magnetic braking
  - Onset of Neoclassical Tearing Modes (NTMs)

Back up