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New Understanding of Tokamak Plasma Response to 3D Magnetic Fields (EX/5-3Rb)

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J.-K. Park,
J. E. Menard, A. H. Boozer,
M. J. Schaffer, R. J. Hawryluk, T. Evans, H. Reimerdes,
S. A. Sabbagh, S. P. Gerhardt,
the NSTX team and the DIII-D team

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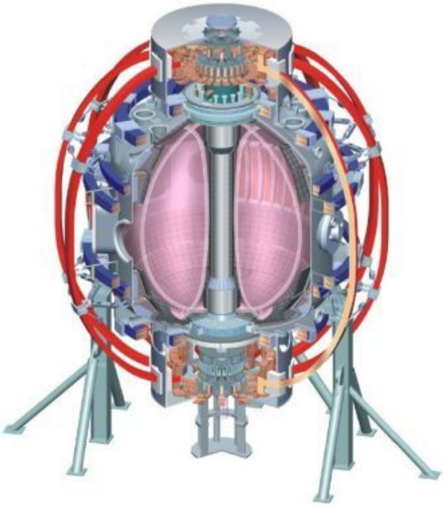

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Small non-axisymmetric (3D) perturbations can greatly change tokamak plasma performance

- **Degradations of performance :**
  - Tokamaks can
    - Never be built with required accuracy
      (A perturbation $\delta B^x/B \sim 10^{-4}$ can cause a disruption)
    - Not have practical coils that can remove the error field
  - Error field effects should be minimized
    - To avoid Locked Modes (LMs)
    - To reduce rotation damping

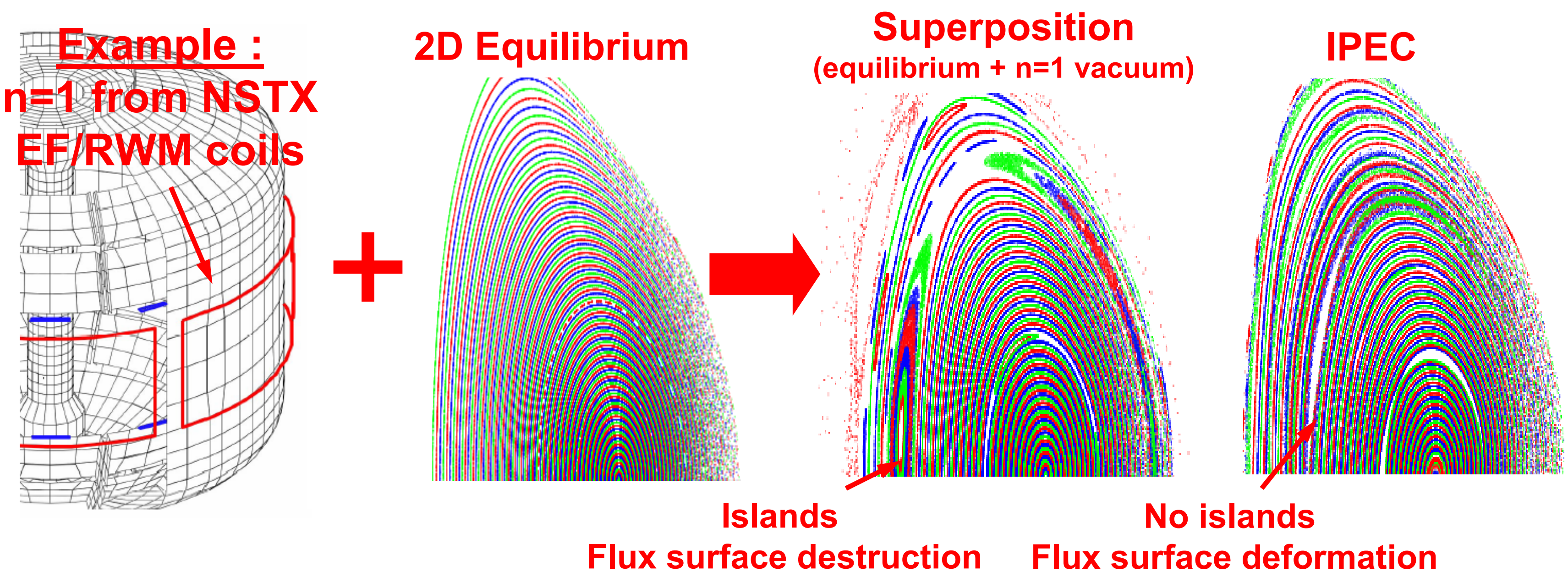
- **Benefits for performance :**
  - Static control of Edge Localized Modes (ELMs) by control of particle transport in pedestal
  - Dynamic control of Resistive Wall Modes (RWMs)

Ideal Perturbed Equilibrium Code (IPEC) solves 3D perturbed tokamak equilibria with shielded islands

- IPEC calculates free-boundary 3D tokamak equilibria while preserving p(ψ) and q(ψ) profiles

[IPEC is based on DCON and VACUUM stability codes] [Park et al, Phys. Plasmas (2007)]

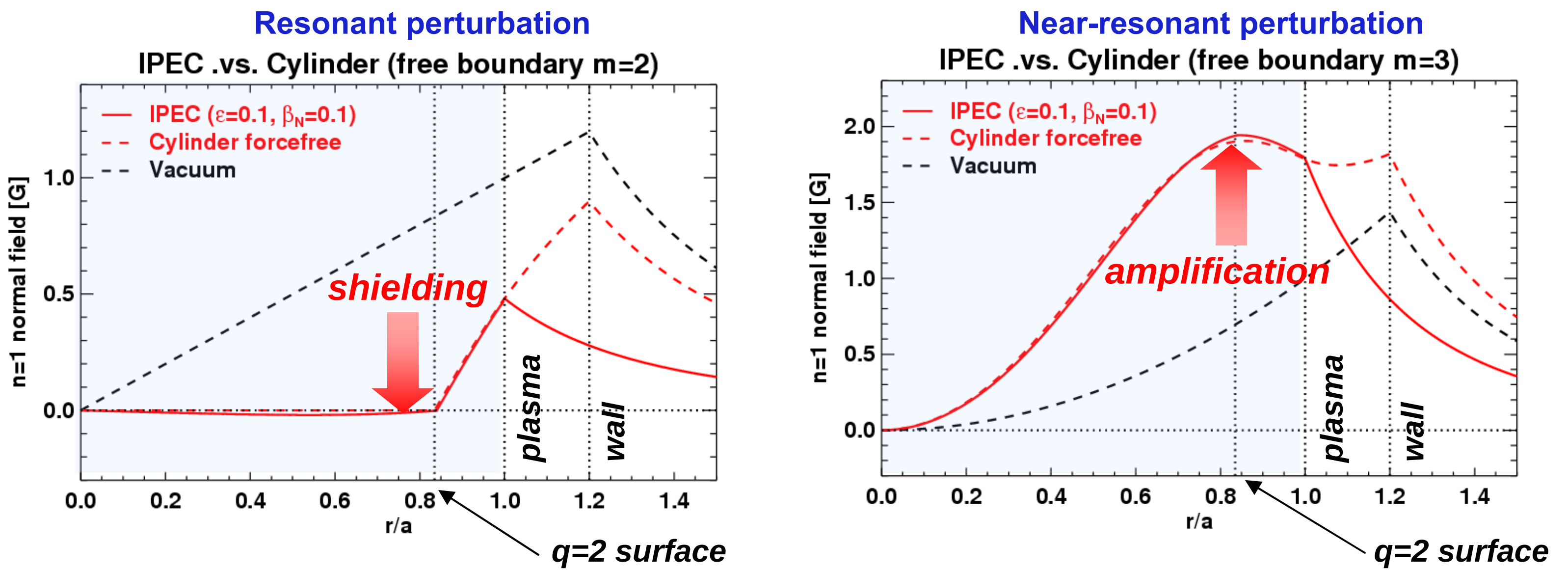
1) **Islands are shielded when q(ψ) is preserved (Empirically true before locking)**
   → Shielding currents at the rational surfaces give the total resonant field
2) **Magnetic surfaces are not destroyed, but deformed**
   → Important variation of the field strength is along the perturbed field lines



Ideal plasma response gives shielding, amplification, poloidal mode coupling of the field and deformed magnetic surfaces

- Ideal plasma response includes the effects of perturbed plasma currents
  - **Two sources of the 3D field** :
    - **External currents in the external coils : External field (Vacuum superposition) δB^{ext}**
    - **Perturbed currents in the plasma : Plasma field δB^{plas}**
    - **Total field $\delta B = \delta B^{ext} + \delta B^{plas}$**
  - **Ideal plasma response effects denote any difference from the vacuum superposition method - shielding, amplification, poloidal mode coupling of the field and deformed magnetic surfaces**

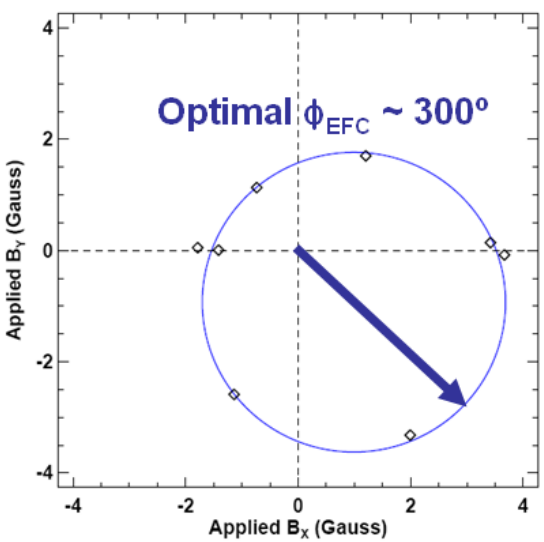
Near-cylindrical force-free example



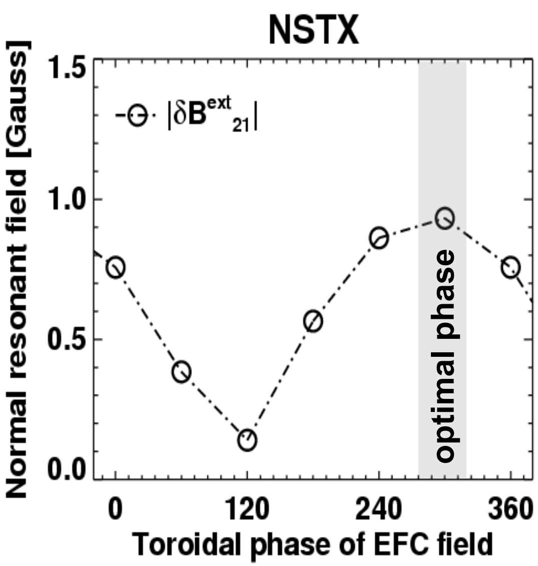
Plasma response is essential to explain paradoxical optimal toroidal phase of NSTX correction field

- The optimal toroidal phase of EFC correction field was found in NSTX
  - **Optimal phase of EFC field should minimize the combined resonant field (intrinsic error field + EFC correction field)**
- External resonant field (δB^{ext}) gave paradoxical result
- Total resonant field in IPEC ($\delta B = \delta B^{ext} + \delta B^{plas}$) resolved the issue

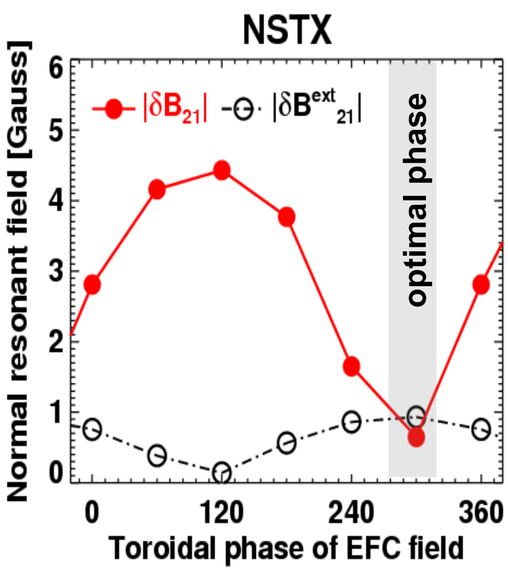
External resonant field by EFC correction



External resonant field by EFC (varying phase) + Intrinsic field



Total resonant field by EFC (varying phase) + Intrinsic field

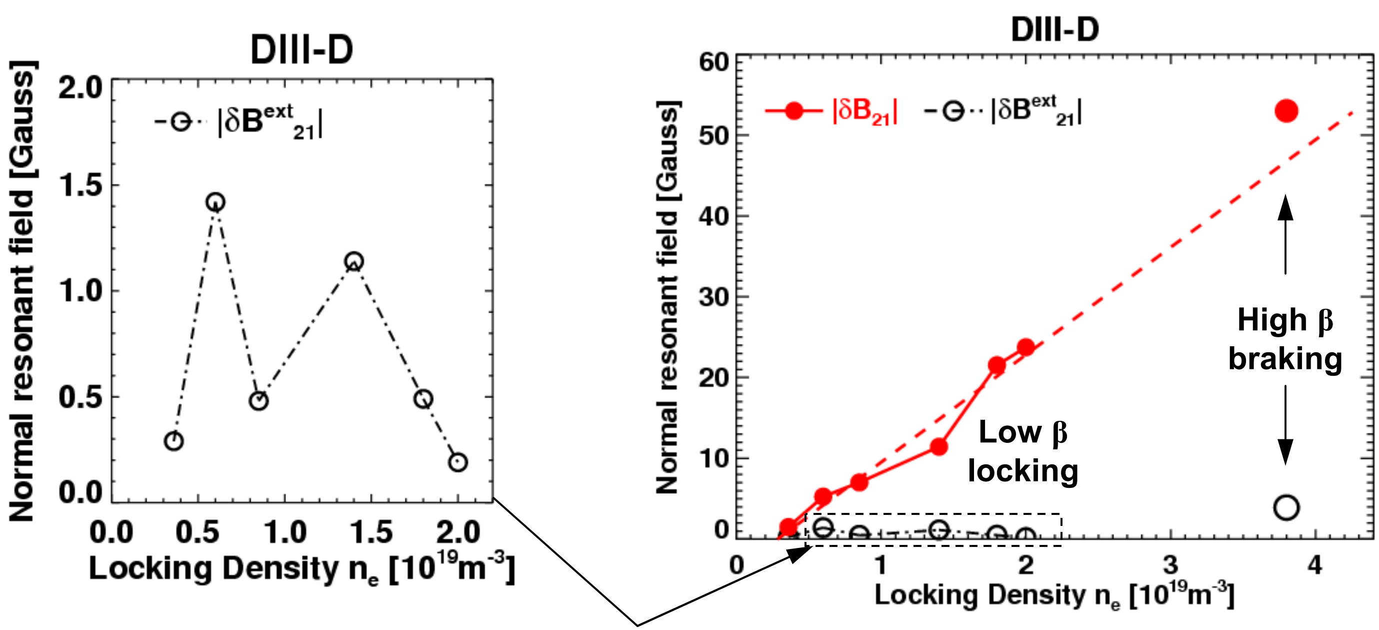


Plasma response is essential to explain paradoxical DIII-D locking data

- The detailed experiments in DIII-D did not show any correlation between the external resonant field and the locking density
  - **Approximately linear correlation must be seen as observed in many experiments (at least positive correlation expected in locking theory)**
- Total resonant field in IPEC restored the linear correlation

[Park et al, Phys. Rev. Lett. (2007)]

- IPEC is valid in high β, up to the marginally stable limit

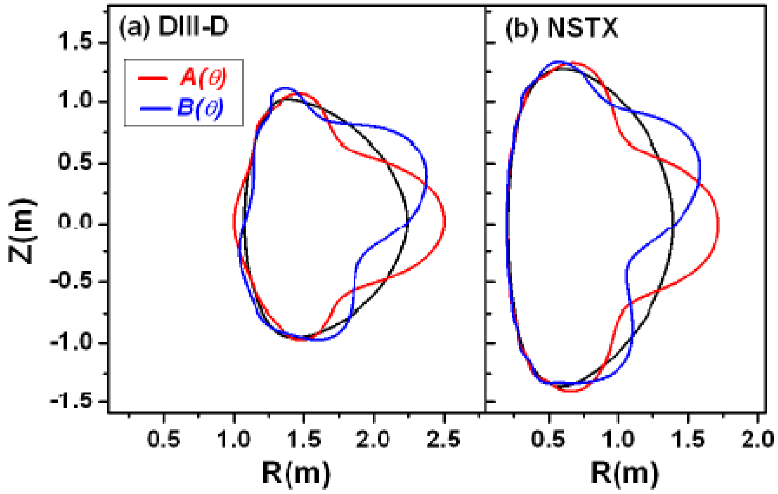


The external field to which plasma is most sensitive differs from external resonant field

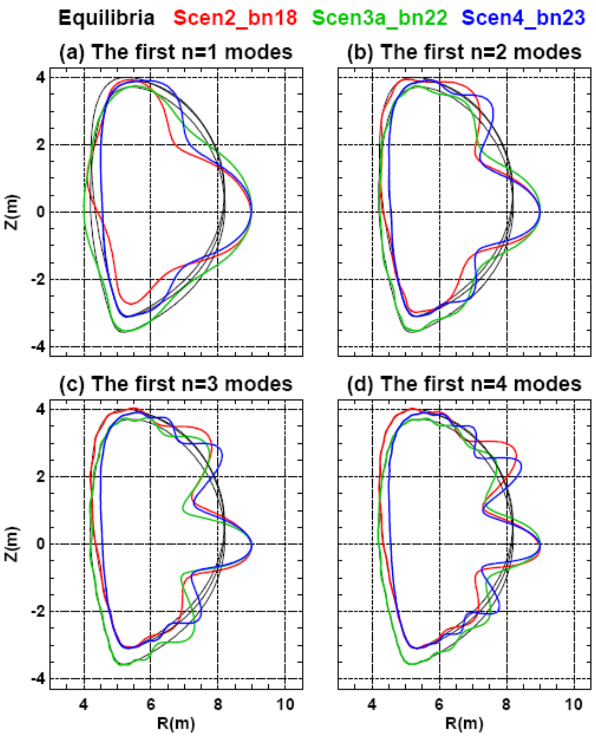
- The most sensitive external field is the external field that maximizes the damage to the plasma (maximizes the total resonant field)
- It has a kink-ballooning type distribution
- It is similar over a wide range of plasma parameters

The most sensitive external field at the plasma boundary

$$(\delta B^{ext})_b(\theta,\varphi)=A(\theta)\cos\varphi + B(\theta)\sin\varphi$$



For ITER three scenarios



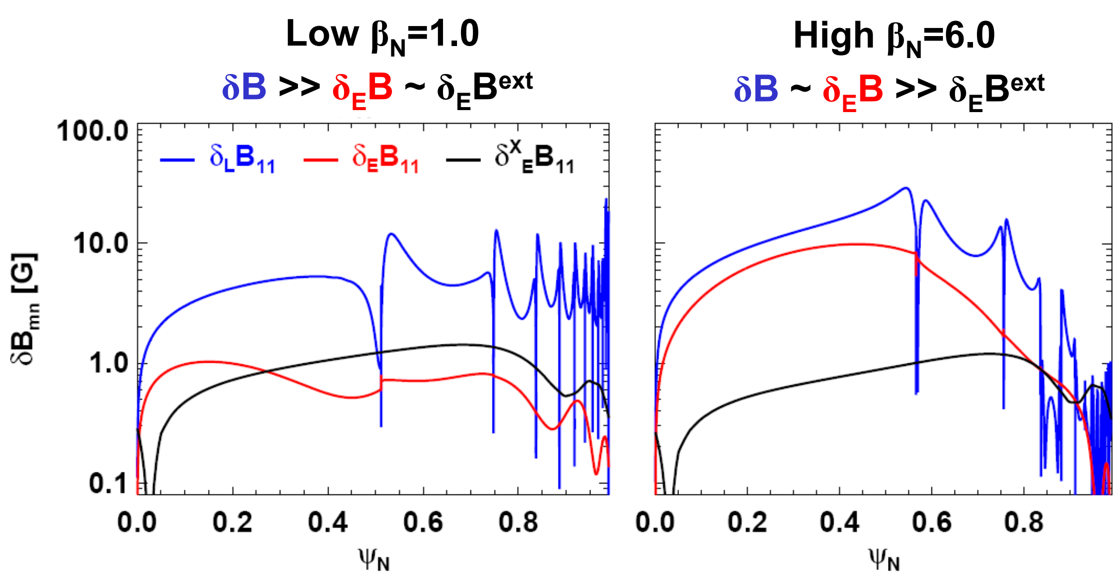
Variation of field strength along the magnetic field lines in IPEC is very different from vacuum superposition

- Non-axisymmetric variation of field strength produces non-ambipolar transport of particles (NTV transport) and toroidal torque (magnetic braking)
- Variation must be evaluated along the magnetic field lines
  - **Lagrangian $\delta B = \delta_E B + \xi \cdot \nabla B$ > Eulerian $\delta_E B$ > Vacuum superposition $\delta_E B^{ext}$**

(1) under "$+\xi \cdot \nabla B$ > Eulerian"; (2) under "$\delta_E B$ > Vacuum"

1) **Dominated by magnetic surface deformation**
2) **Enchanced by perturbed plasma currents**

ISOLVER NSTX Equilibrium + EFC coil currents n=1 600A →



Neoclassical Toroidal Viscosity (NTV) theory has been improved by a combined analytic treatment

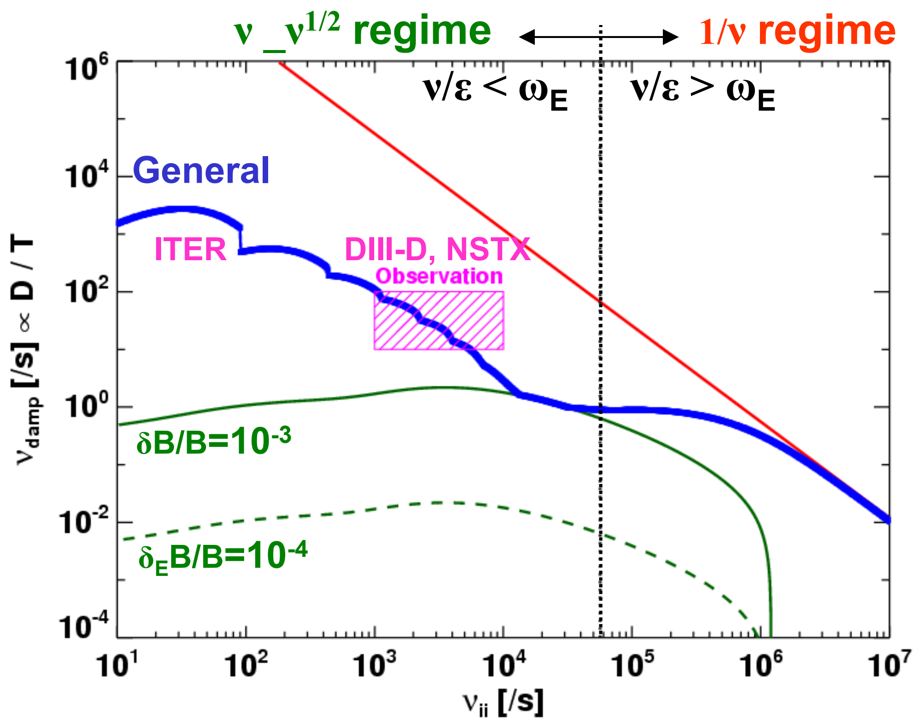
- Generalized treatment for NTV transport describes dynamics of bouncing (ω_b) trapped particles subjected to magnetic, electric toroidal precessions ($\omega_p = \omega_B + \omega_E$) and collisions ($\nu$) in a combined form

[See the supplementary slides on the right side for the analytic treatment]

$$\nu_{damp} \simeq \frac{F_{NTV}}{2\pi f_\varphi R_0 M n_e} \quad \text{and} \quad F_{NTV} \propto \frac{\nu_{eff}}{\left(\left(\ell\omega_b - n(\omega_B + \omega_E)\right)^2 + \nu_{eff}^2\right)} \left(\delta B / B\right)_w^2$$

Parameters

R_0=2m, fφ=10kHz,
n_e=5x10^{19}m^{-3}, q=2.2, ε=0.3,
T_e=0.01~100keV,
Gaussian n=3 field (-10<m<20)
with **δB/B = 10^{-3}**
(corresponds to $\delta B_E/B = 10^{-4}$)

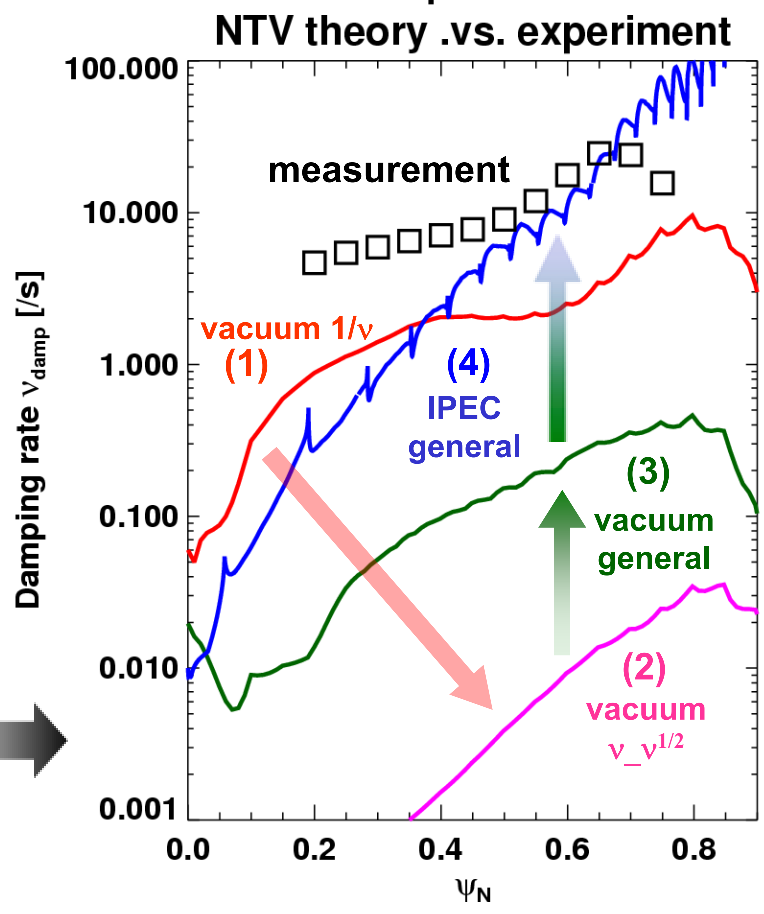


Generalized NTV theory with IPEC field is consistent with experimental magnetic braking in NSTX

- Important physics in NTV theory :
  a) Toroidal precession rates (ω_p), which are often faster than the collisional rates (ν)
  b) Trapped particle bounce rates (ω_b), which can resonate with the precession (ω_p)
  c) Variation of field strength along the perturbed magnetic field lines, which includes plasma response
     - Vacuum superposition model uses the field variation at fixed points in space

(1) (a), (b) and (c) are all ignored
(2) (a) is included
(3) (a) and (b) are included
(4) (a), (b) and (c) are all included
[See Becoulet, TH/2-1Rb]

NSTX
n=3 rotation braking experiment



Torque can change perturbed equilibria and plasma response

- IPEC can be inconsistent when the torque becomes large
  - **IPEC solves ∇p=j×B, but ∇p+∇·Π=j×B is required for consistency**
  - **A large NTV torque implies that ∇·Π can modify the perturbed equilibrium**
- Magnetic measurements can be used to determine if the currents associated to the toroidal torque is important in perturbed equilibria
- Maxwell equations imply

External (applied) field

Total field including plasma response

$$\frac{\vec{\Phi}^{\dagger}\cdot\overleftrightarrow{L}_p^{-1}\cdot\vec{\Phi}^{x}}{\vec{\Phi}^{\dagger}\cdot\overleftrightarrow{L}_p^{-1}\cdot\vec{\Phi}}=-s-i\alpha$$

Amplification and phase shift between the two fields in magnetic sensors give energy and torque

$$s=\frac{\delta W}{\delta W_v}=\frac{-\int d^3x\,\delta\vec{j}\cdot\delta\vec{A}}{\vec{\Phi}^{\dagger}\cdot\overleftrightarrow{L}_p^{-1}\cdot\vec{\Phi}}$$: Normalized perturbed energy in the plasma

$$\alpha=\frac{\tau_\varphi}{\delta W_v}=\frac{-\hat{z}\cdot\int d^3x\left\{\vec{x}\times\left(\delta\vec{j}\times\delta\vec{B}\right)\right\}}{\vec{\Phi}^{\dagger}\cdot\overleftrightarrow{L}_p^{-1}\cdot\vec{\Phi}}$$: Normalized toroidal torque in the plasma

$$\vec{\Phi}=\frac{1}{4\pi^2}\oint d\theta\oint d\varphi J\left(\delta\vec{B}\cdot\vec{\nabla}\psi\right)$$: Normal flux (field) on the plasma boundary

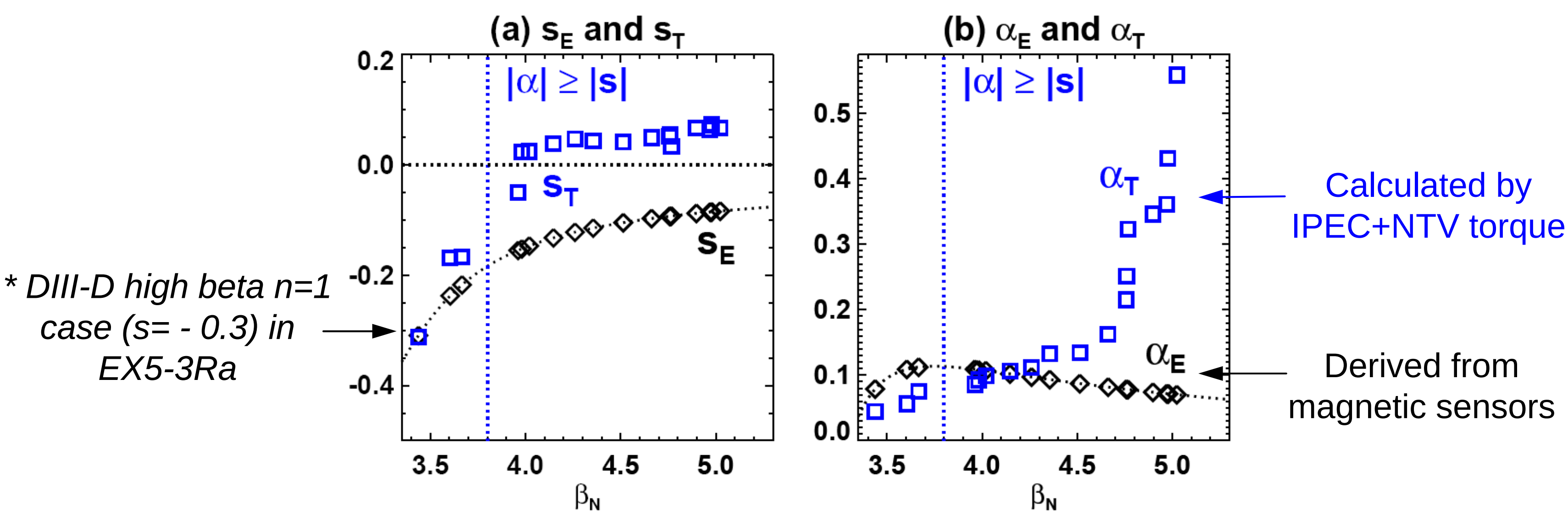
$\overleftrightarrow{L}_p$: Inductance of the plasma boundary

Tensor pressure (Torque) effects are important in high β plasma above the marginally stable limit

- Magnetic sensor measurements for NSTX n=1 rotating applied showed the inconsistency in high beta above the marginally stable limit
- $\nabla \cdot \Pi$ effect is negligible for most n>1 applications
- IPEC Extension including tensor pressure for perturbed equilibria is necessary to describe n=1 application to high beta plasma
  - **Important to optimize the feedback to suppress Resistive Wall Mode**

[Park et al, Phys. Rev. Lett., submitted (2008)]

NSTX n=1 Resonant Field Amplification (RFA) experiments

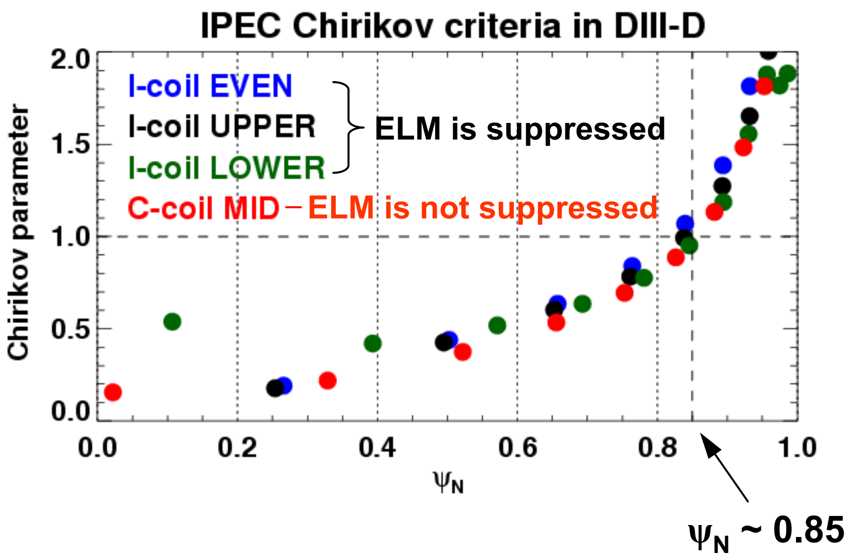


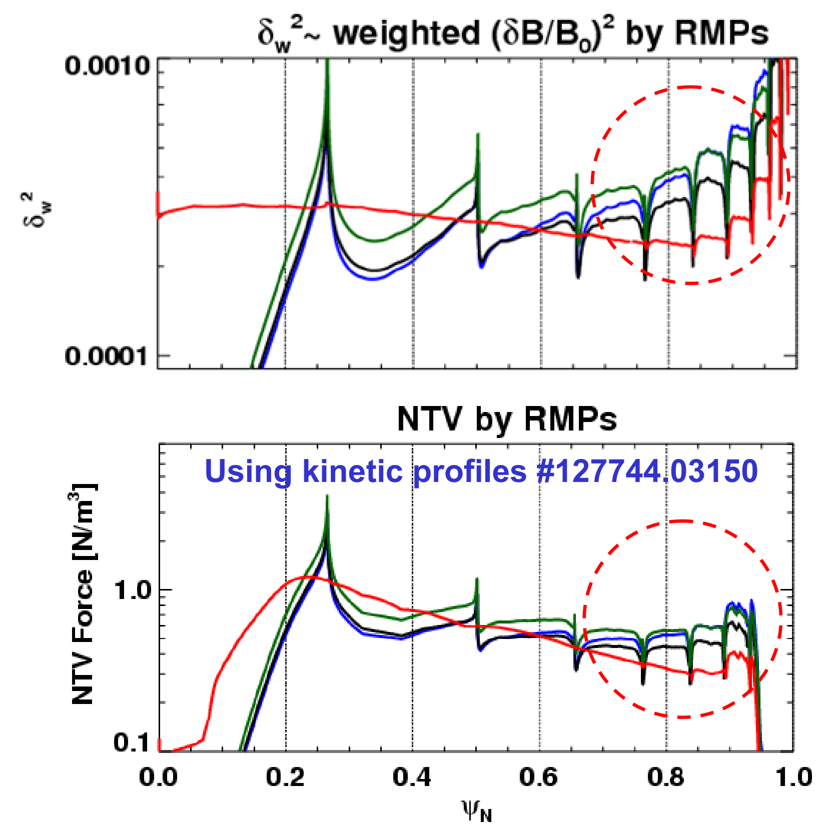
NTV transport can be a hidden variable in ELM suppression by Resonant Magnetic Perturbation (RMP)

- Chirikov ~ 1 at ψ_N=0.85 still holds as a necessary (not a sufficient) condition with IPEC evaluation as Vacuum evaluation

[See T. Evans EX4-1]

- NTV particle transport is clearly different when RMP suppressed ELM and not





RMP control of ELMs in ITER can be optimized using IPEC field and NTV calculation

- Three requirements for optimization :
  1) **Islands overlap for $\psi_N > 0.85$**
  2) **Minimize $\sum(dB_{mn})^2 / \sum(dB^{ext}_{mn})^2_{boundary}$ for $\psi_N < 0.8$**
  3) **Maximize $\sum(dB_{mn})^2 / \sum(dB^{ext}_{mn})^2_{boundary}$ for $\psi_N > 0.8$**

Optimized currents

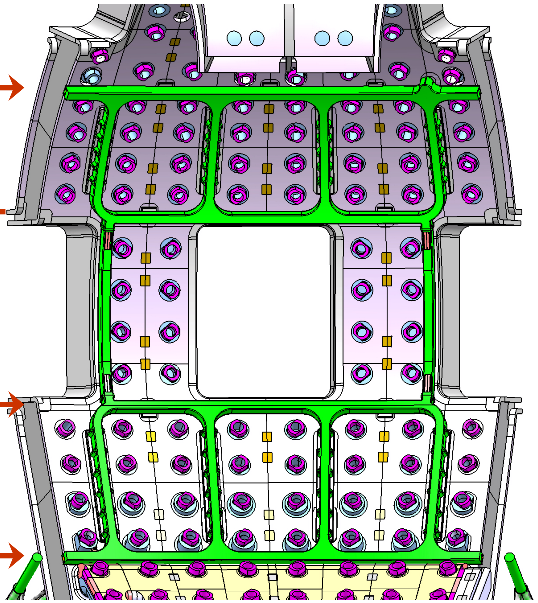
VAC02 Three-rows Coils

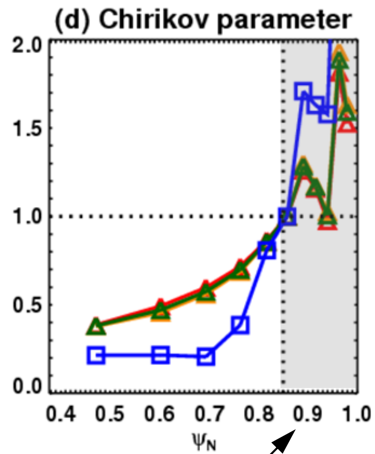
42kA →

85kA ←

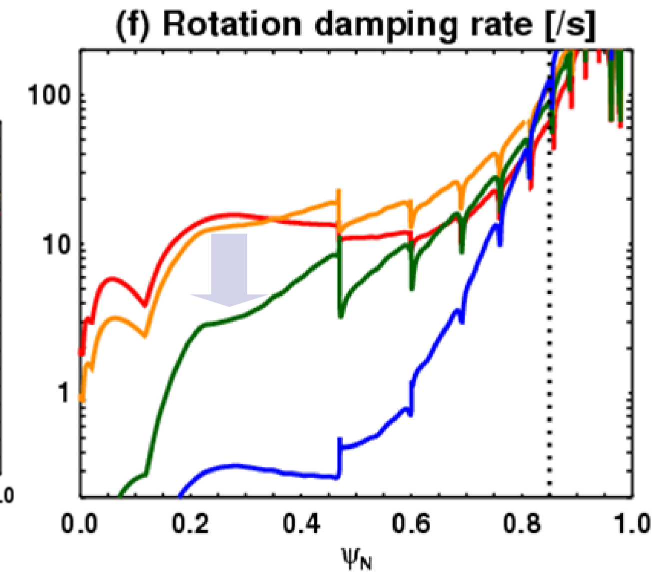
85kA →

42kA →





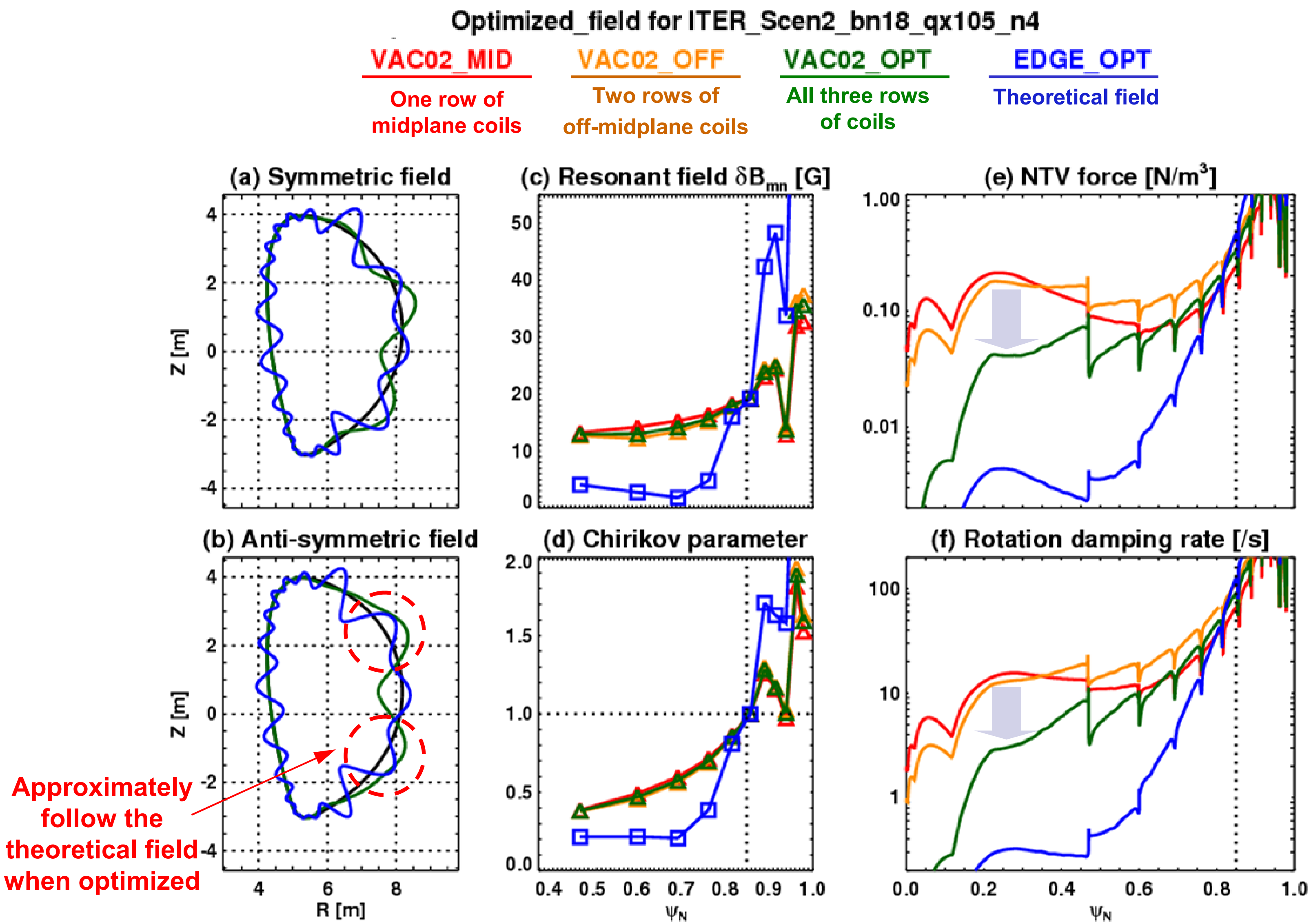
Islands overlap



n=4 RMP field In the ITER baseline inductive scenario

- **One row of the midplane coils** (red)
- **Two rows of the off-midplane coils** (orange)
- **Three rows of the coils** (green)
- **Theoretically best field** (blue)

RMP optimization can reduce core degradation using three-rows coils (VAC02) under consideration



Summary

- Ideal Perturbed Equilibrium Code (IPEC) solves free-boundary 3D tokamak equilibria with the fixed $p(\psi)$ and $q(\psi)$ profiles

- Total resonant field including ideal plasma response explained paradoxical error field problem and locking data in NSTX and DIII-D

- Important variation of field strength is along the magnetic field lines

- Generalized NTV includes resonances among ω_b, ω_B, and ω_E

- IPEC field with generalized NTV can resolve the inconsistency between theory and magnetic braking experiments

- The extension of IPEC to include tensor pressure is necessary above the ideal stability limit as seen in NSTX experiments

- IPEC and NTV theory can be used to optimize ITER RMP field, enhancing perturbations in the edge while reducing perturbations in the core

Back up

RMP optimization can give greater benefit if coils have more degrees of freedom