Effect of resonant and non-resonant magnetic braking on error field tolerance in high beta plasmas

Holger Reimerdes

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Columbia University

New understanding of tokamak plasma response to 3D magnetic field

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NSTX

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Non-axisymmetric magnetic fields can stop the plasma rotation, drive locked modes and cause disruptions

1. **Plasma response to external non-axisymmetric perturbations is key in understanding the *n*=1 error field tolerance:**
    a) **In high β, H-mode plasmas**
    b) **In low β, L-mode plasmas**

2. **Magnetic braking of the plasma rotation is caused by two effects:**
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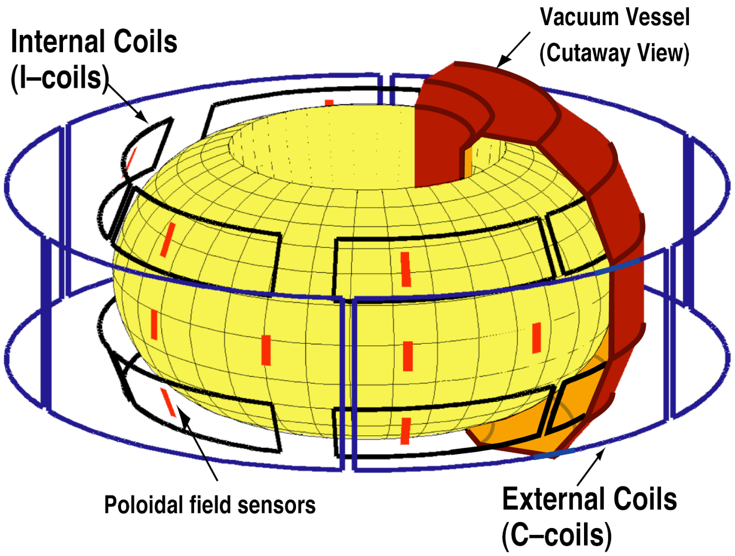
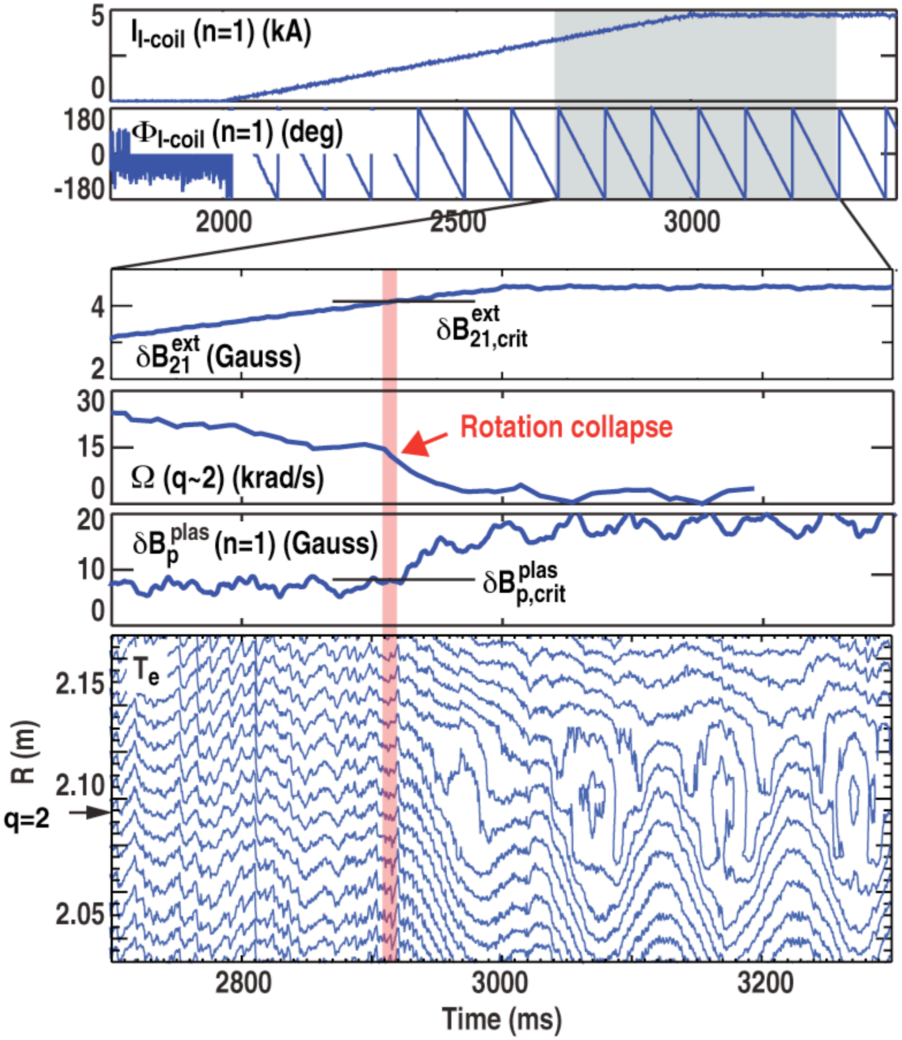
Error field tolerance in NBI heated H-modes is determined by resonant braking leading to a loss of torque balance

- **Increase the amplitude of an external $n = 1$ "*error*" field $\delta B^{\mathrm{ext}} \propto I_{\text{I-coil}}$**
- **Magnetic probes measure total δB_p including the plasma response $\delta B_p^{\mathrm{plas}}$ (due to perturbed plasma currents)**





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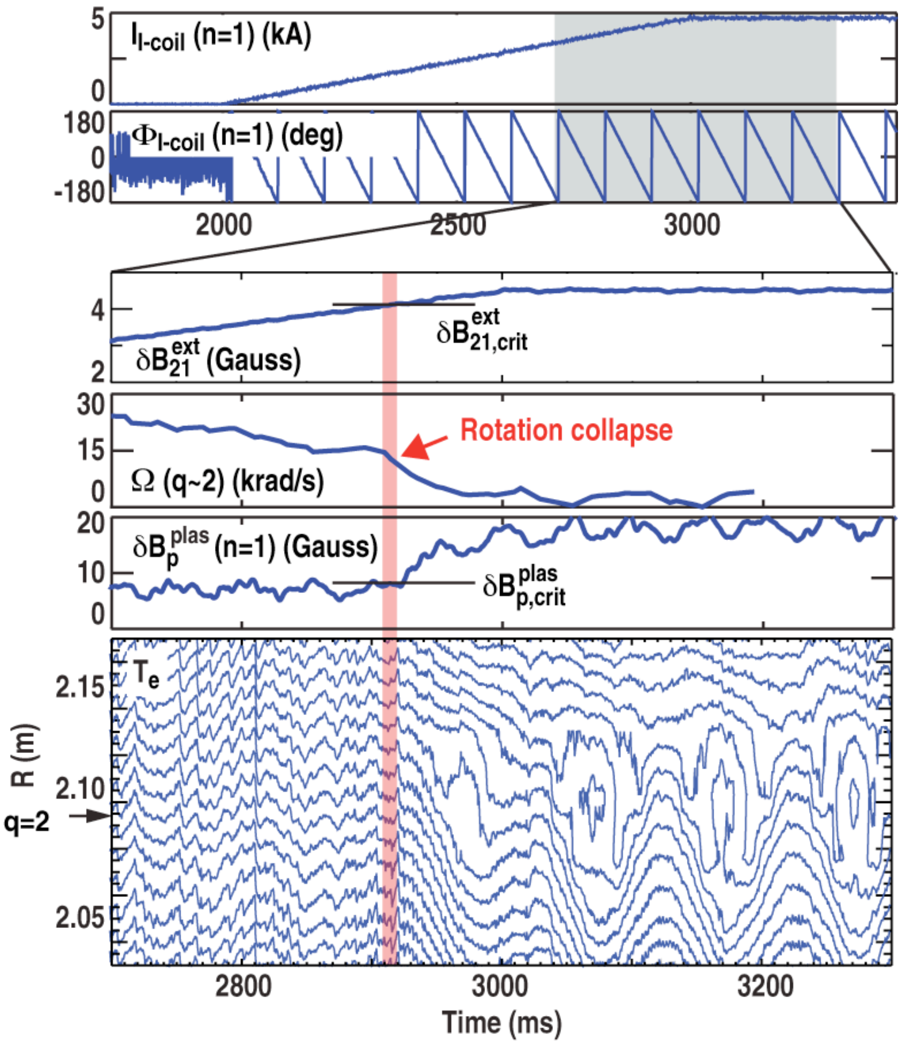
- **Rotation evolution is described by resonant braking** [Fitzpatrick, *Nucl. Fusion* (1993), Garofalo, *Nucl. Fusion* (2007)]
  - At high rotation external resonant field is shielded, but exerts a torque
  - Rotation decrease is followed by a loss of torque balance
  - Magnetic island opens after rotation collapses



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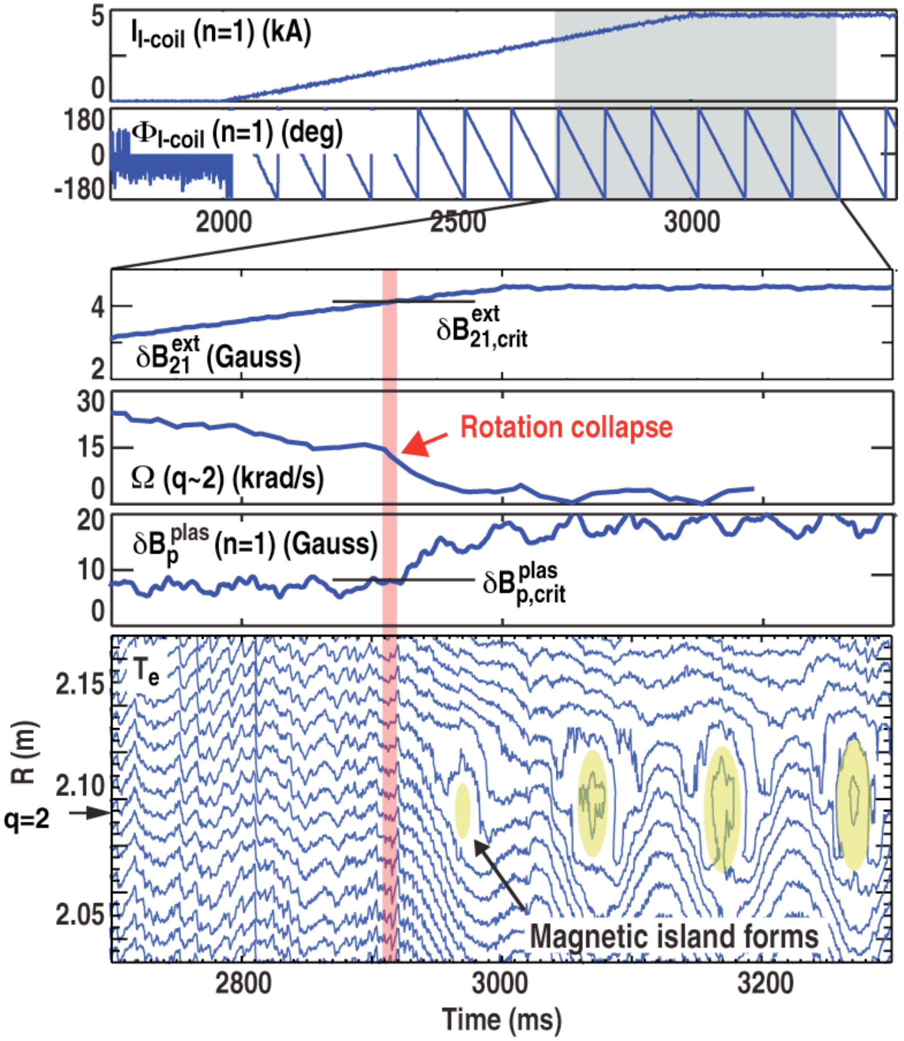
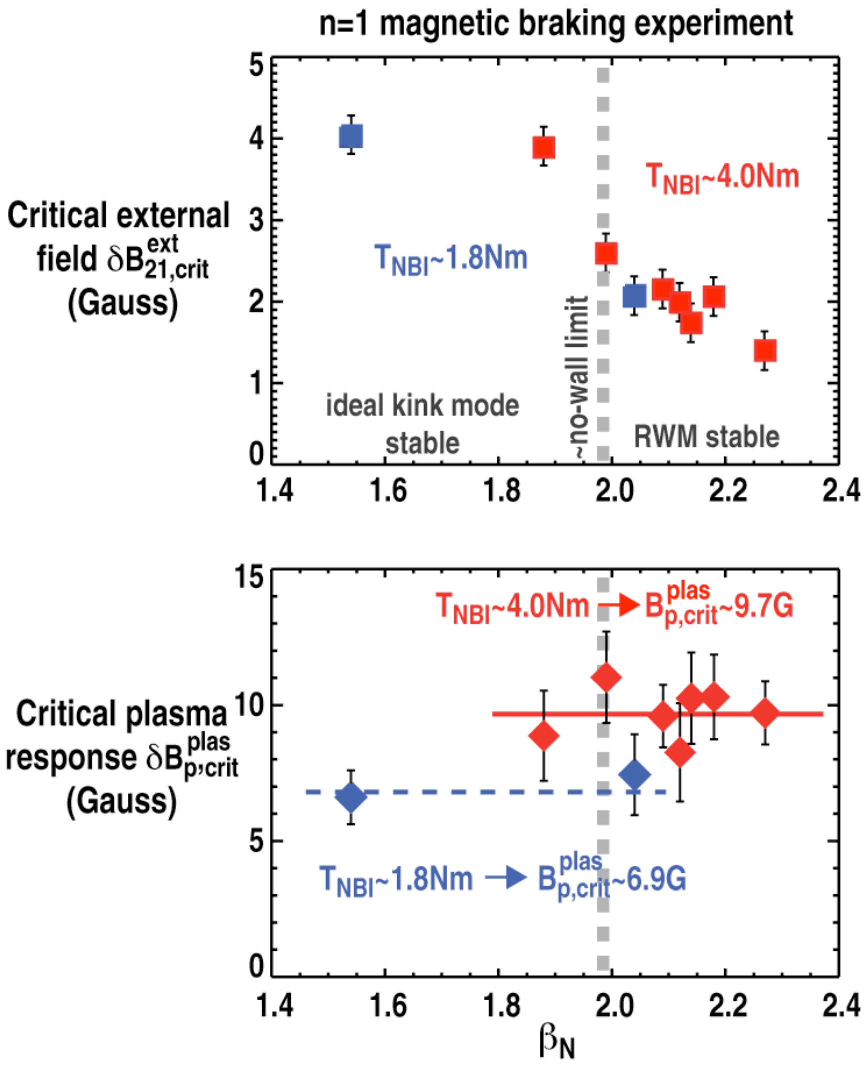


Tolerance to external n=1 perturbations decreases with increasing β_N due to plasma amplification

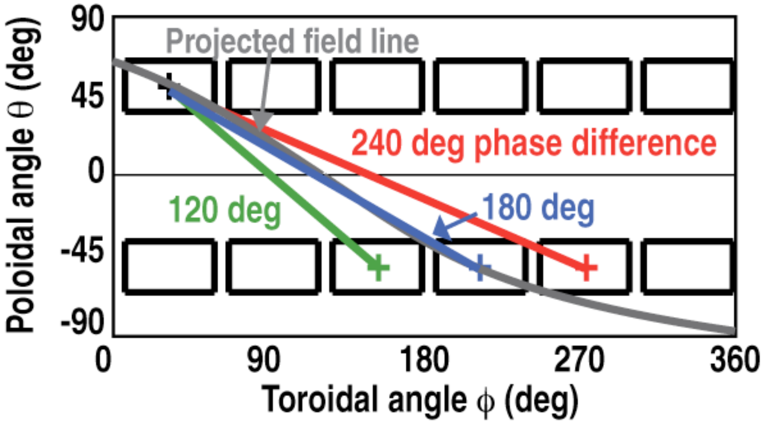
- **Decrease of critical external field $\delta B_{21,crit}^{ext}$ is particularly strong above the no-wall limit**
  - Amplification increases when ideal MHD stable n=1 kink mode converts to kinetically stabilized RWM **[see Okabayashi, EX/P9-5]**

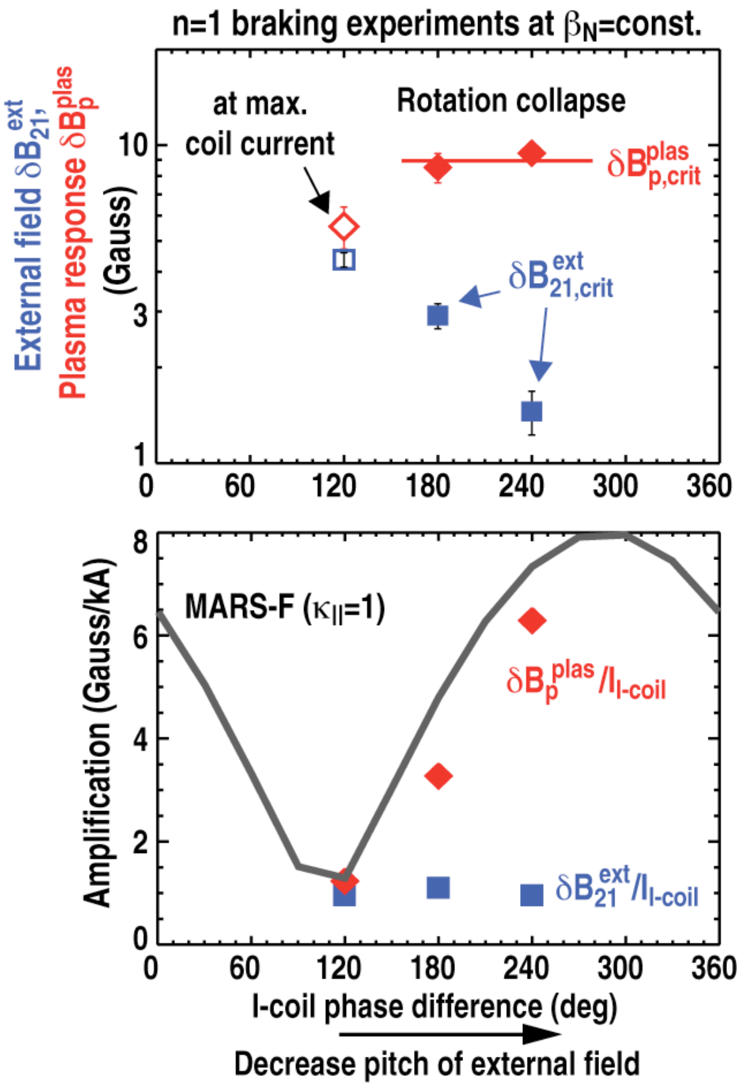


- **Rotation collapse occurs at a fixed plasma response $\delta B_{p,crit}^{plas}$**
- **Critical plasma response $\delta B_{p,crit}^{plas}$ increases with NBI torque T_{NBI}**

Plasma is very sensitive to the poloidal spectrum (pitch angle) of the external perturbation

- **Vary poloidal spectrum of external *n*=1 perturbations applied with I-coil**





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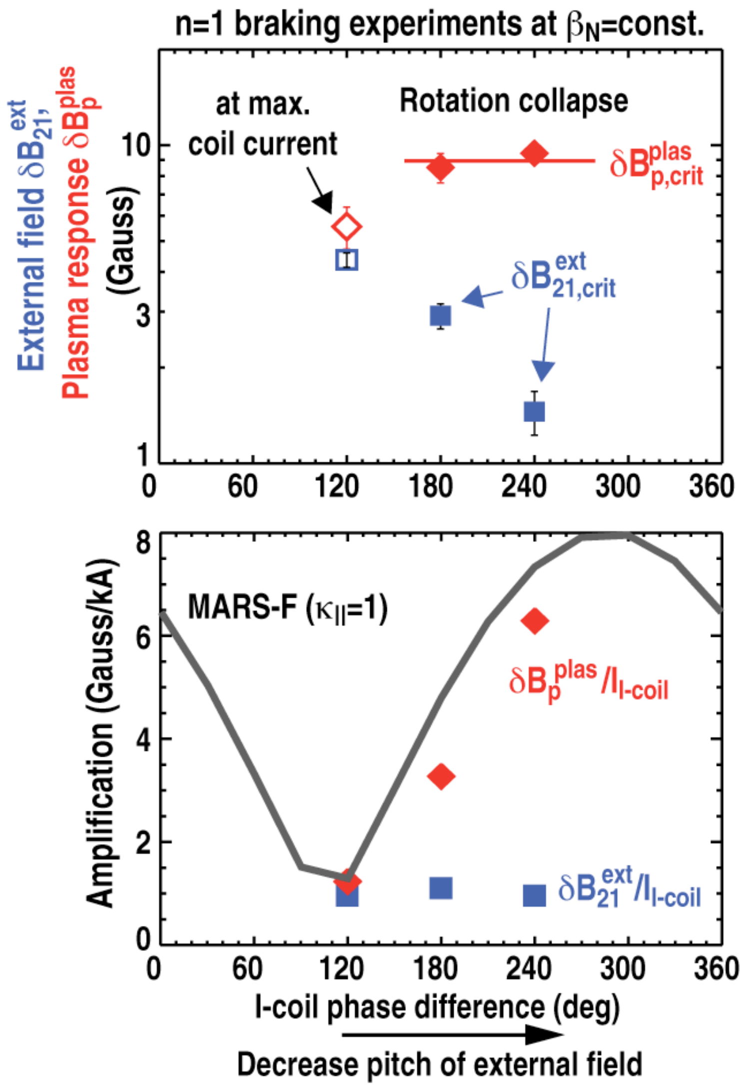
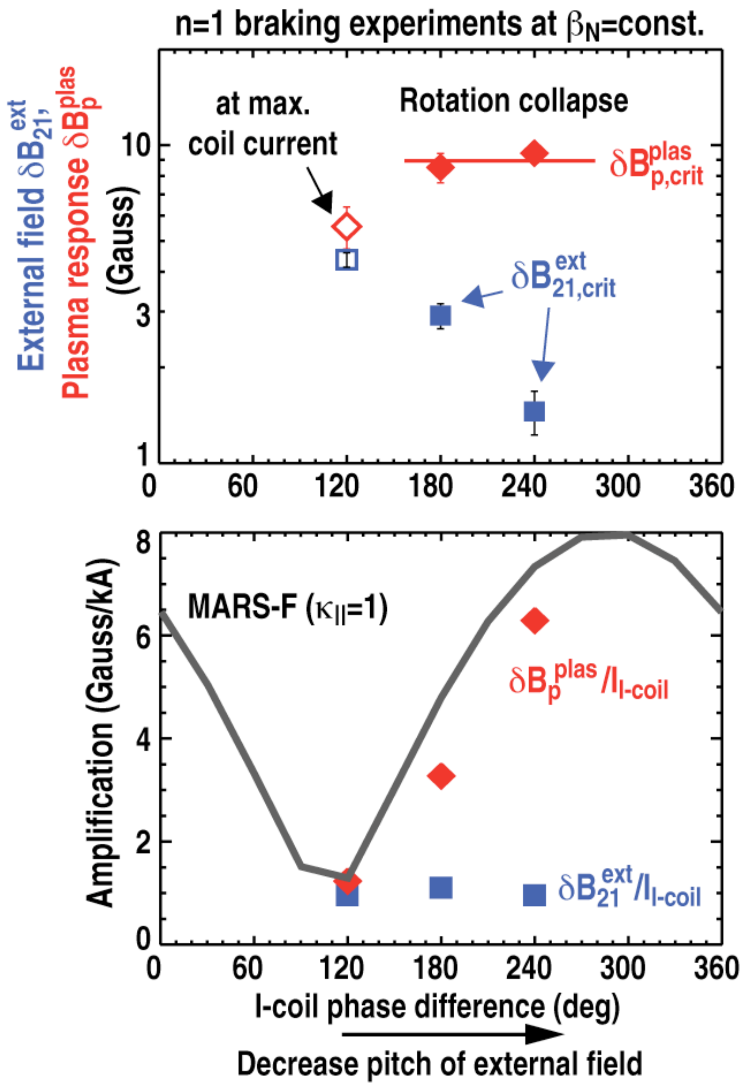


Plasma is very sensitive to the poloidal spectrum (pitch angle) of the external perturbation

- **Vary poloidal spectrum of external *n*=1 perturbations applied with I-coil**
- **Rotation collapse occurs at a fixed plasma response $\delta B_{p,crit}^{plas}$**
- **Amplification largest for external perturbation with a lower pitch than the equilibrium field at the outboard midplane**

↓

Described by coupling to stable *n*=1 kink mode (MARS-F code)



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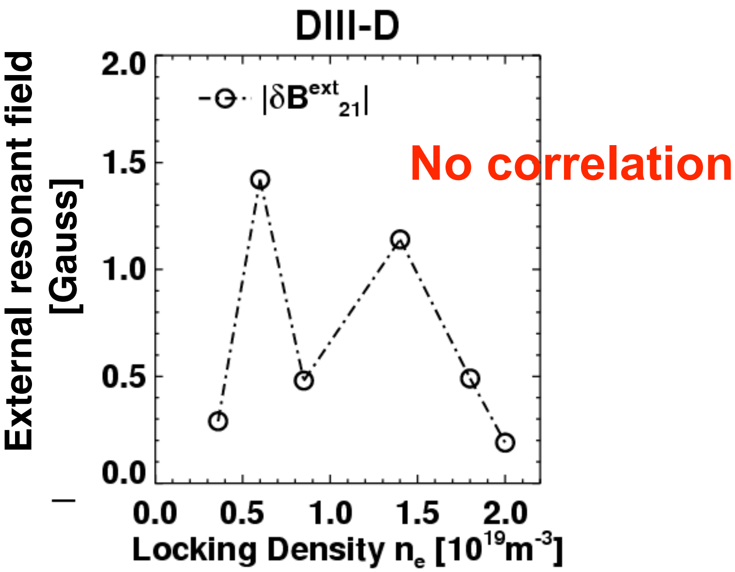
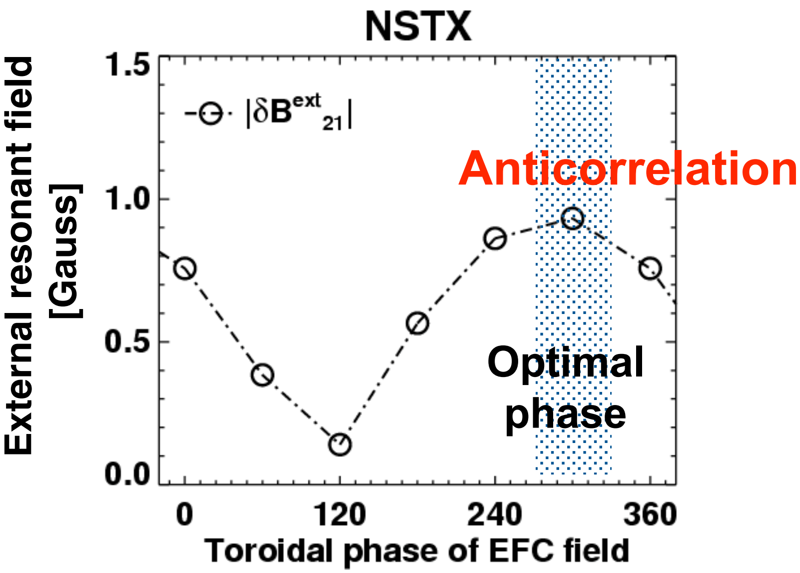
Ignoring the plasma response even at low β leads to paradoxical results in error field correction experiments

- **External resonant field :** $\delta B_{21}^{ext} = \delta B_{21}^{intrinsic} + \delta B_{21}^{correction}$ **at *q*=2 surface**
  - **Experiments in many tokamaks have shown that the plasma density at locking increases proportionally with the external field**
- **However, the external resonant field …**



… shows no correlation with locking density in DIII-D



… is largest when the locking density is lowest (optimal phase) in NSTX

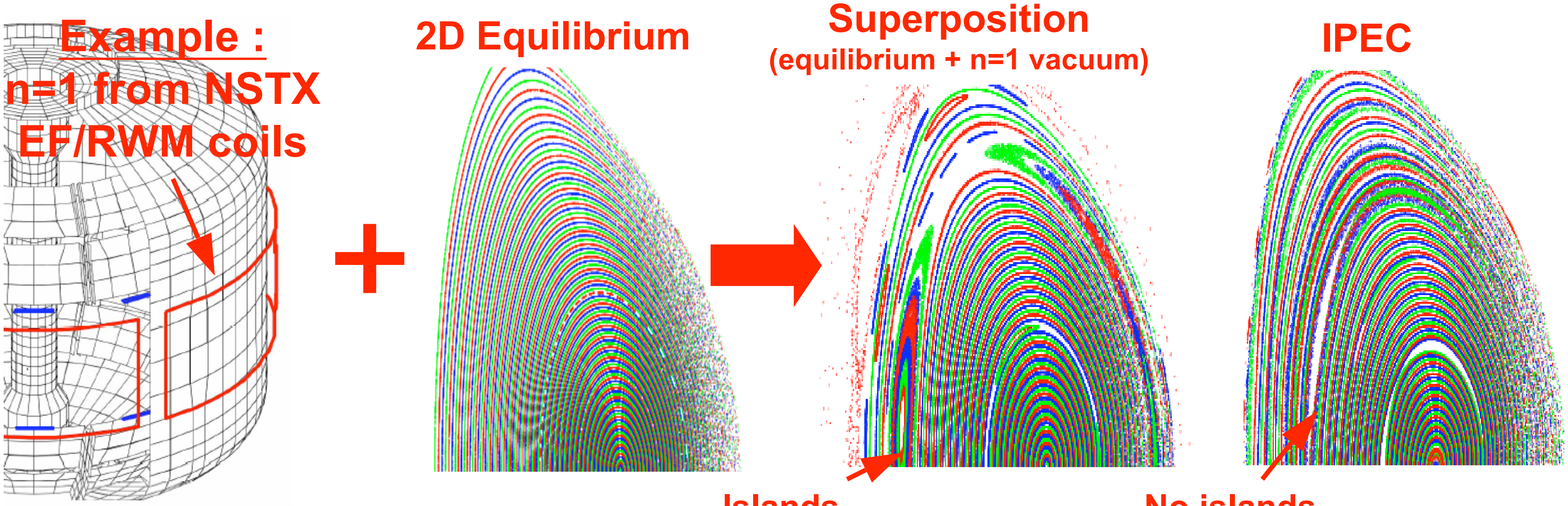
→ Self-consistent resonant field including plasma response (perturbed plasma current) is necessary

Plasma response given by
Ideal Perturbed Equilibrium Code (IPEC)

- **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, *Phys. Plasmas* (2007)]

1) **Islands are shielded by rotation before locking, so plasma remains ideal**
   → **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, not at fixed points in space (as used in vacuum superposition method)**



Example :
n=1 from NSTX EF/RWM coils

+

2D Equilibrium

Superposition
(equilibrium + n=1 vacuum)

IPEC

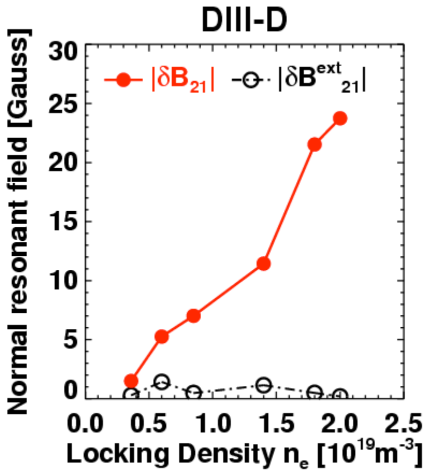
Islands
Flux surface destruction

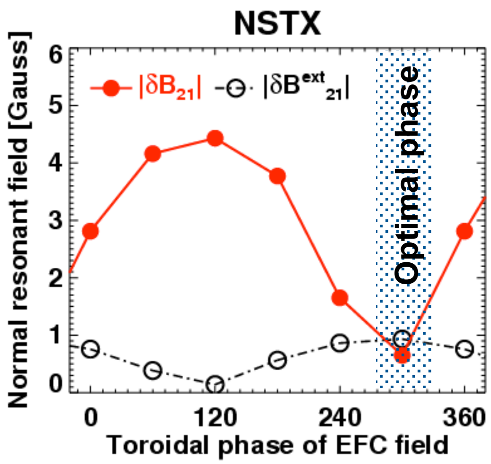
No islands
Flux surface deformation

Total resonant field including plasma response explains paradoxical NSTX and DIII-D low β experiments

- **Total resonant field δB_{21} :**
  - restores the linear density scaling (DIII-D)
  - is consistent with the optimal performance (NSTX)

[Park, *Phys. Rev. Lett.* (2007)]



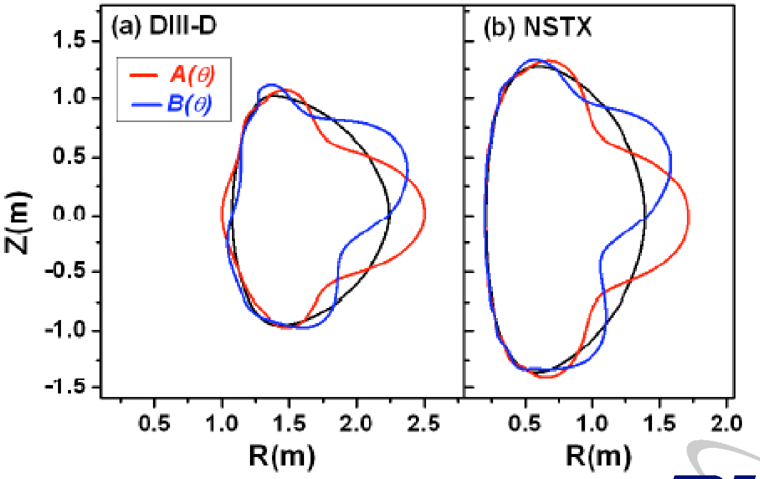


- **External field that maximizes the total resonant field is :**
  - **1) Similar to a kink-type distribution** (consistent with MARS-F code)
  - **2) Almost independent of plasma parameters**

[Park, *Nucl. Fusion* (2008)]

Most sensitive external field at plasma boundary

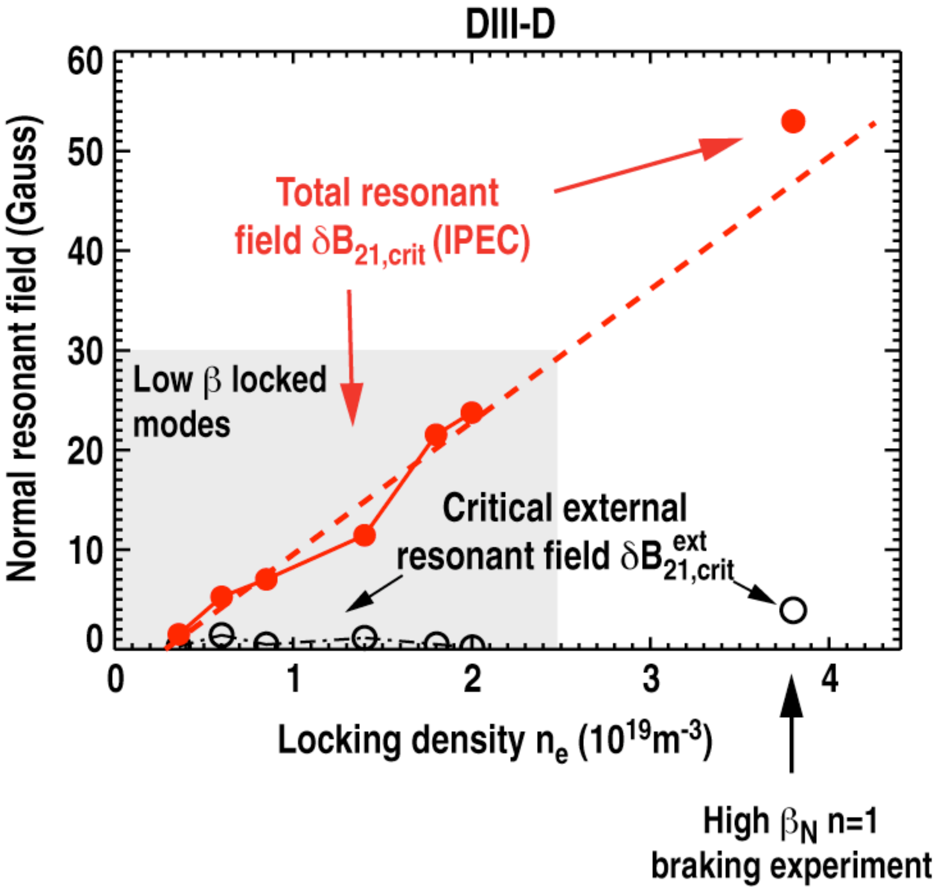
$$\delta B^{ext}(\theta,\varphi,b)=A(\theta)\cos\varphi + B(\theta)\sin\varphi$$



Plasma response (IPEC) connects error field tolerance at high β with Ohmic plasmas via the linear density scaling

- **Critical resonant field (IPEC) at β_N=1.5 and low NBI torque in good agreement with the low-β density scaling**
  - NSTX *n*=1 resonant field amplification experiments validate IPEC up to the ideal MHD no-wall limit

    [see Park, EX/5-3Rb poster]



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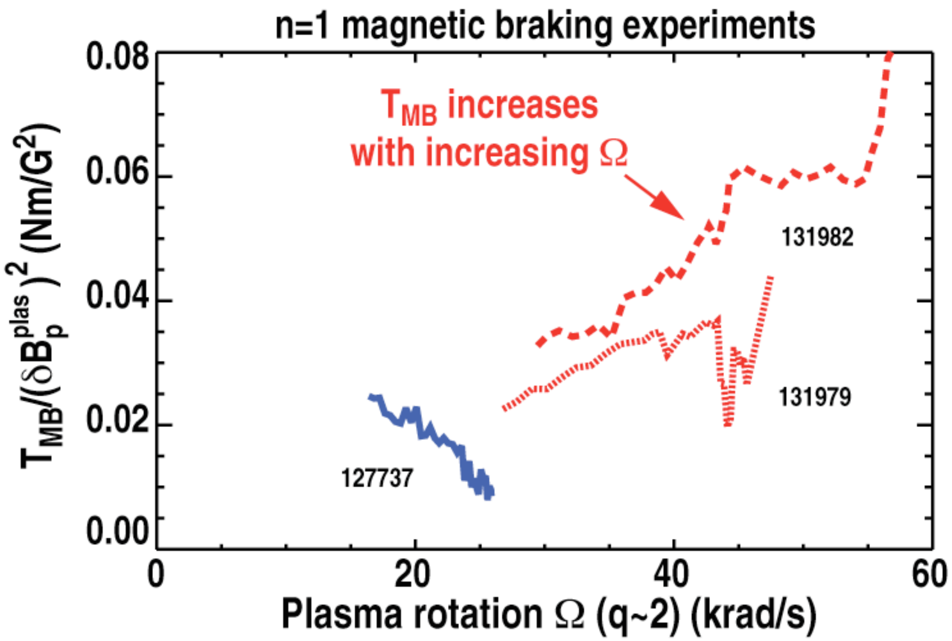
Measured n=1 braking torque reveals importance of a non-resonant magnetic braking component

- **Measured angular momentum evolution yields magnetic braking torque T_{MB}**

$$T_{MB} = T_{NBI} - \frac{L}{\tau_{L,0}} - \frac{dL}{dt}$$

  - Assume $T_{MB} \propto (\delta B^{plas})^2$ to reveal rotation dependence



- **At low rotation T_{MB} increases with decreasing Ω consistent with a resonant torque**
- **At high rotation T_{MB} increases with Ω → typical for a non-resonant torque** [Shaing, *Phys. Plasmas* (2003)]

Non-resonant magnetic braking reduces the benefit of additional torque input

- **Torque balance with a resonant torque only yields**

$$\delta B_{\mathrm{crit}} \propto T_{\mathrm{in}} + T_{\mathrm{NBI}}$$

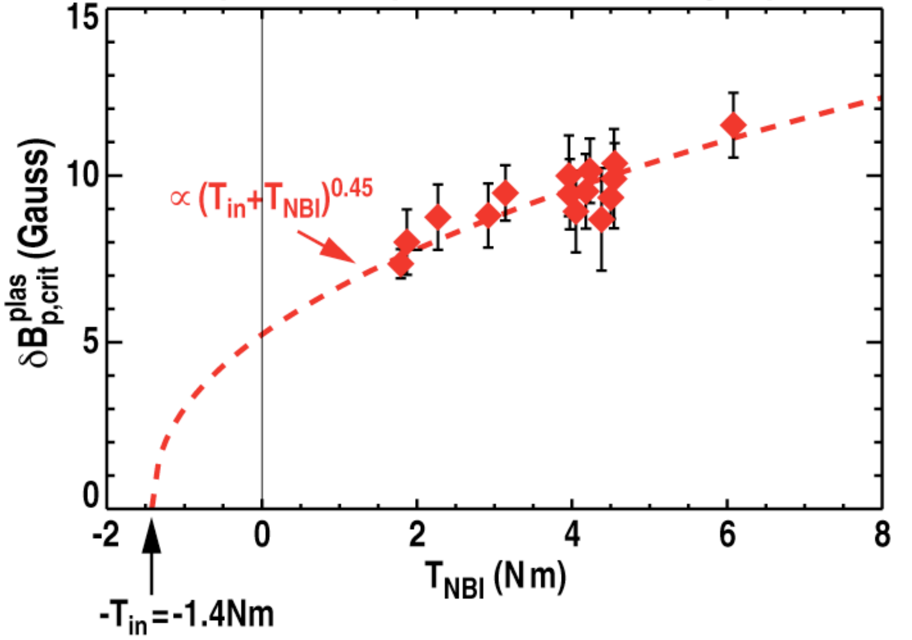
with T_{in} being the intrinsic torque

[see Solomon, EX/3-4 for T_{in}]

- **Adding a non-resonant torque reduces the dependence of δB_{crit} on T_{NBI} to**

$$\delta B_{\mathrm{crit}} \propto \left(T_{\mathrm{in}} + T_{\mathrm{NBI}}\right)^{0.5}$$

Tolerable plasma response in n=1 braking experiments



- **Observed increase of the *n*=1 error field tolerance with NBI torque is consistent with a significant contribution of non-resonant braking**

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Neoclassical Toroidal Viscosity (NTV) theory gives the toroidal torque for non-resonant braking

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

(1) (a), (b) and (c) are all ignored

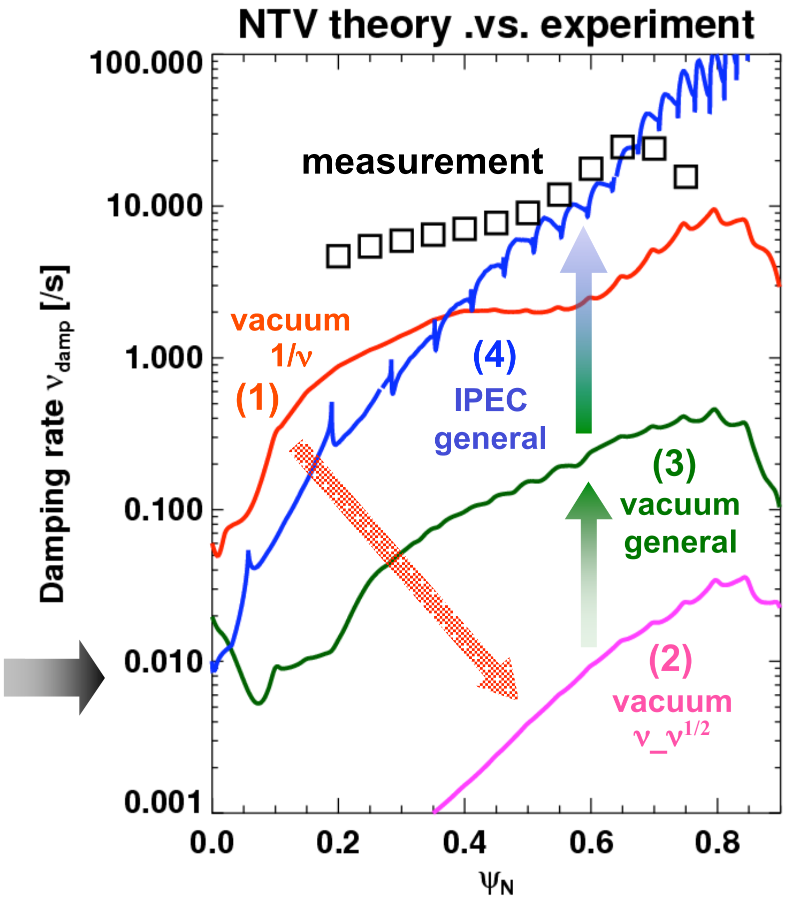
(2) (a) is included

(3) (a) and (b) are included

(4) (a), (b) and (c) are all included

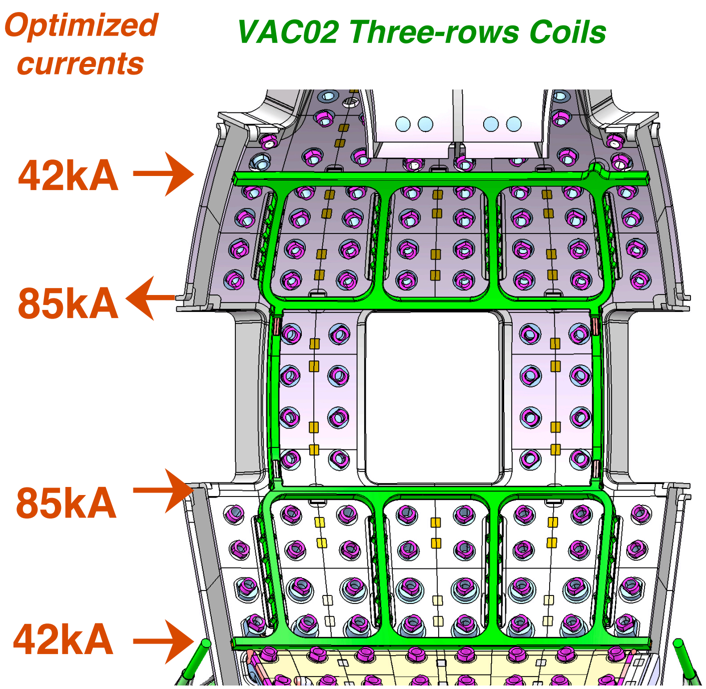
[see Park, EX/5-3Rb poster & Becoulet, TH/2-1Rb]

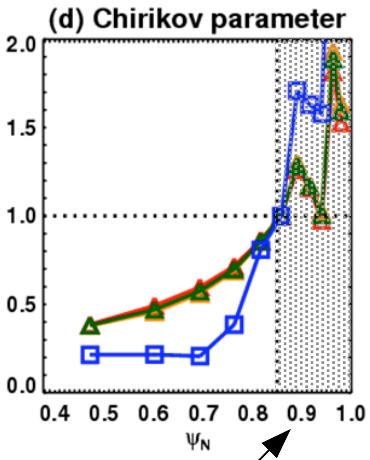
NSTX
n=3 rotation braking
experiment



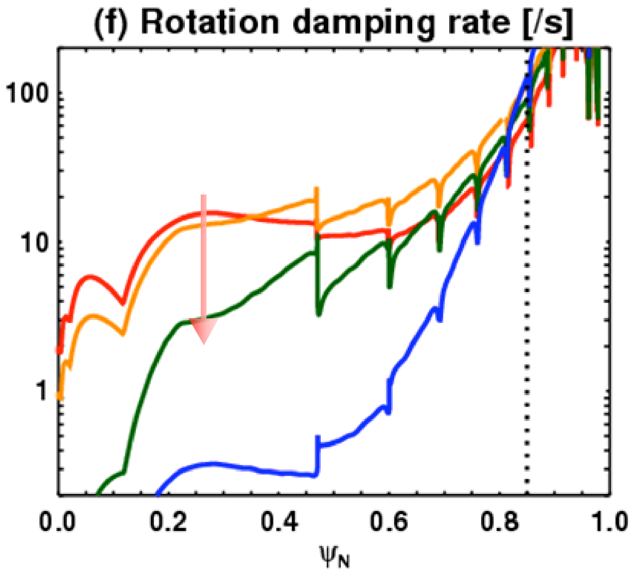
Resonant Magnetic Perturbation (RMP) control of ELMs on ITER can be optimized using IPEC and NTV theory

- **Three requirements for optimization :**
  1) **Islands overlap for $\psi_N > 0.85$** [see Evans, Ex/4-1]
  2) **Minimize $\sum(\delta B_{mn})^2 / \sum(\delta B^{ext}_{mn})^2_{boundary}$ for $\psi_N < 0.8$**
  3) **Maximize $\sum(\delta B_{mn})^2 / \sum(\delta B^{ext}_{mn})^2_{boundary}$ for $\psi_N > 0.8$**





Islands overlap



In the ITER baseline inductive scenario

— One row of the midplane coils
— Two rows of the off-midplane coils
— Three rows of the coils
— Theoretically best field

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Summary

- **Plasma response to external non-axisymmetric perturbations is key in understanding the *n*=1 error field tolerance in high β, H-mode as well as in low β, L-mode plasmas**
  - Plasma response in rotating plasmas with values of β up to the ideal MHD stability limit is described by ideal perturbed equilibrium theory (IPEC code)
  - Measurements and calculations show that plasmas are most sensitive to a kink and ballooning-type external perturbation rather than external resonant perturbations

- **Magnetic braking of the plasma rotation is caused by shielding of resonant perturbations and by the distortion of magnetic flux surfaces enhancing neoclassical toroidal viscosity (NTV)**
  - Non-resonant braking reduces the benefit of additional torque input
  - Description of non-resonant braking has to include the variations of the field strength on deformed magnetic surfaces and particle bounce/precession resonances