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The response of tokamak plasmas to 3D magnetic field perturbations

J.E. Menard, PPPL

with contributions from:
J.-K. Park, **A.H. Boozer**, M. Bécoulet, M. Chance, C.-S. Chang,
T. Evans, D.A. Gates, S.P. Gerhardt, A.G. Glasser, R.J. Hawryluk, S.R. Hudson,
G.-Y. Park, S.A. Sabbagh, M.J. Schaffer, and the NSTX Research Team

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Overview

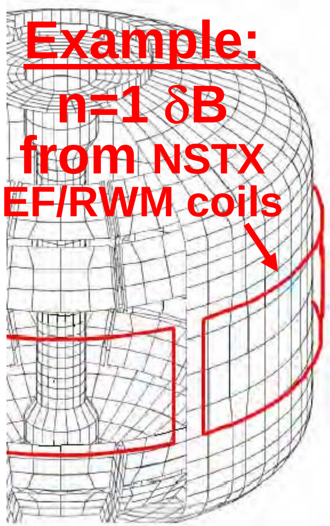
- Ideal Perturbed Equilibrium Code (IPEC)
  - Developed by J.-K. Park, PPPL (Ph.D. thesis)
  - New tool for studying 3D field effects in tokamaks
- Applications of IPEC
  - Locked modes, toroidal flow damping, ITER ELM control
- NSTX: Importance of n > 1 error fields

IPEC computes tokamak ideal plasma response to 3D fields

- Augments DCON + VACUUM with external field while preserving q(ψ), p(ψ)
  - Equivalent surface current supports perturbed plasma equilibrium:

$$\vec{f}_{ideal}(\vec{\xi}) = \vec{0} = \vec{\nabla}\delta \boldsymbol{p} + \delta\vec{\boldsymbol{J}} \times \vec{\boldsymbol{B}} + \vec{\boldsymbol{J}} \times \delta\vec{\boldsymbol{B}}$$

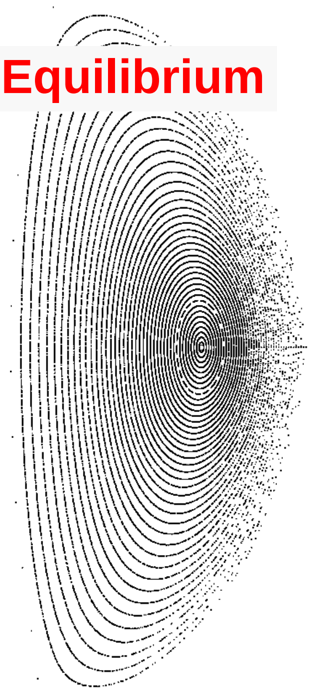
- DCON/IPEC solutions preserve magnetic topology → singular currents flow on q surfaces to shield out islands otherwise excited by external δB
  - Treat solutions as equivalent to resistive plasma with islands shielded by flow



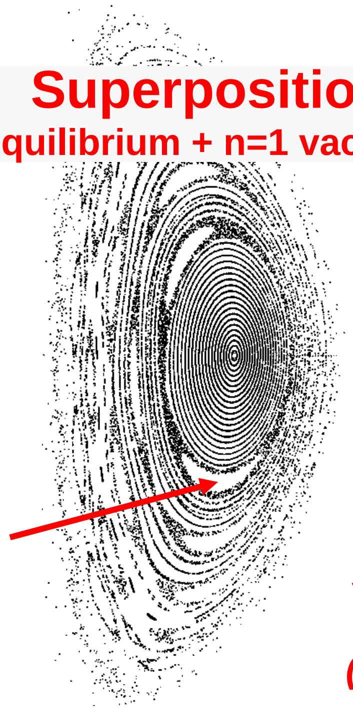
Example:

n=1 δB from NSTX EF/RWM coils

+



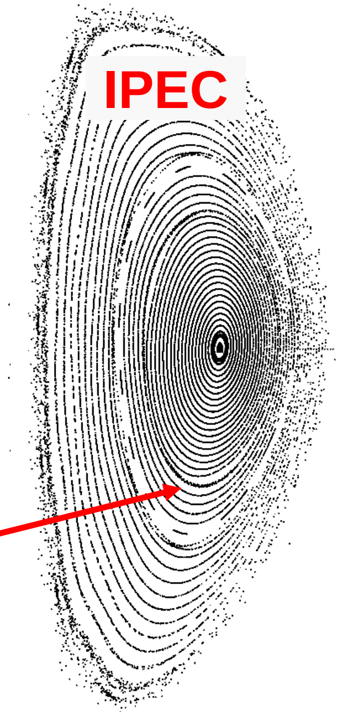
Equilibrium



Superposition

(equilibrium + n=1 vacuum)

Islands open



IPEC

Flux surfaces distort

(no islands)

IPEC solutions include important plasma response effects

- Poloidal mode coupling due to toroidicity
  - External field of given helicity excites different helicity inside plasma
  - Important for locked-modes/error-fields, especially at low aspect ratio
- Lagrangian field modification: $\delta \boldsymbol{B}_L(\vec{\boldsymbol{x}}+\delta\vec{\boldsymbol{x}}) = \delta\boldsymbol{B}(\vec{\boldsymbol{x}}) + \vec{\xi}(\vec{\boldsymbol{x}})\cdot\vec{\nabla}\boldsymbol{B}(\vec{\boldsymbol{x}})$
  - Flux-surface displacement important in Lagrangian δB_L
  - Important for neoclassical toroidal viscosity model of rotation damping
- Field amplification from finite β and $J_{||}$
  - IPEC assumptions and solutions valid for β below ideal no-wall limit
    - IPEC requires usage of dissipation model to achieve equilibrium (and reasonable amplification values) when used above ideal no-wall limit
  - Important for all applications involving field amplitude

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  - New tool for studying 3D field effects in tokamaks

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  - Locked modes, toroidal flow damping, ITER ELM control

- NSTX: Importance of n > 1 error fields

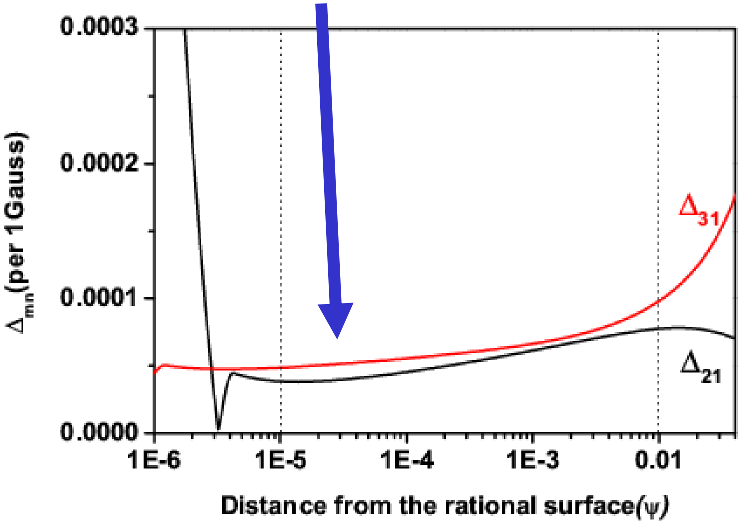
IPEC computes the singular currents and total resonant normal fields important in mode locking physics

- Singular currents computed from jump in derivative of normal B

$$j_{sing} \propto \Delta_{mn} \qquad \Delta_{mn} = \left[\frac{\partial}{\partial\psi}\left(\frac{\delta\vec{B}\cdot\vec{\nabla}\psi}{\vec{B}\cdot\vec{\nabla}\varphi}\right)\right]_{mn}$$

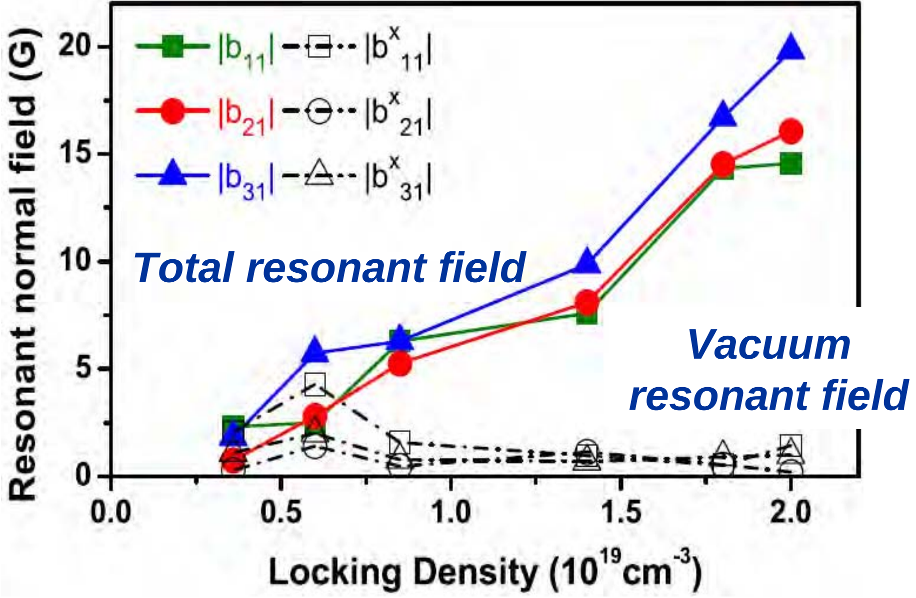
- Singular currents well defined and very well resolved by DCON

Δ_{mn} → constant near singular surface



- The total resonant magnetic field $(\delta\vec{B}\cdot\hat{n})_{mn}$ from the j_{sing} shielding out islands **can differ significantly** from the applied vacuum resonant field

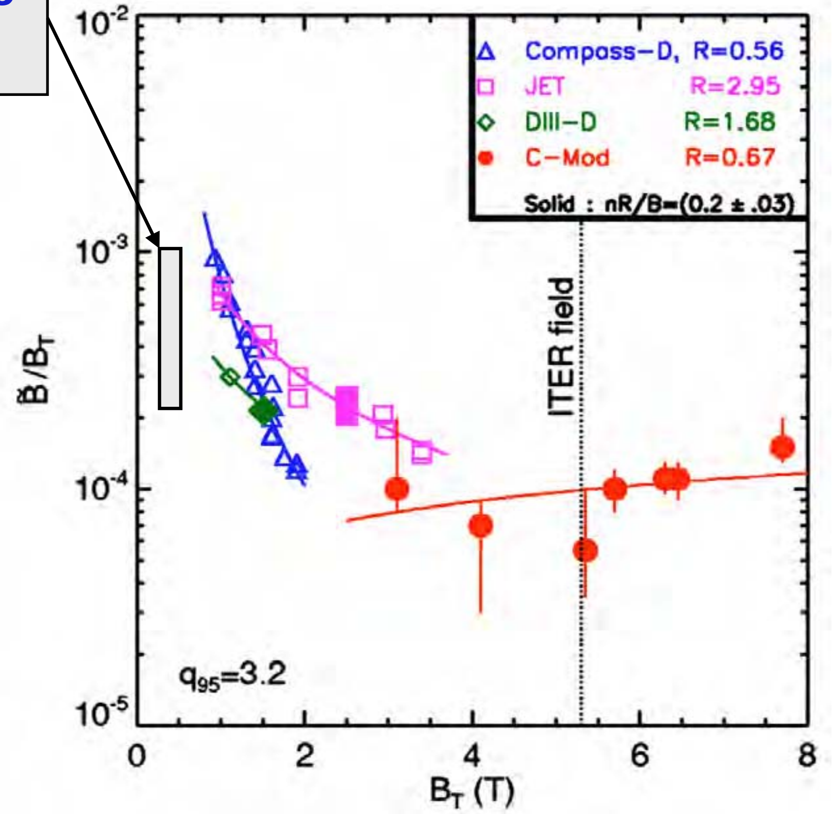
DIII-D locking experiment



Locking $n_e \propto$ total δB, not vacuum δB

NSTX locked mode (LM) studies test locking theories in an extended parameter regime, and establish scalings for the ST

NSTX LM data extends database to low B_T and low aspect ratio

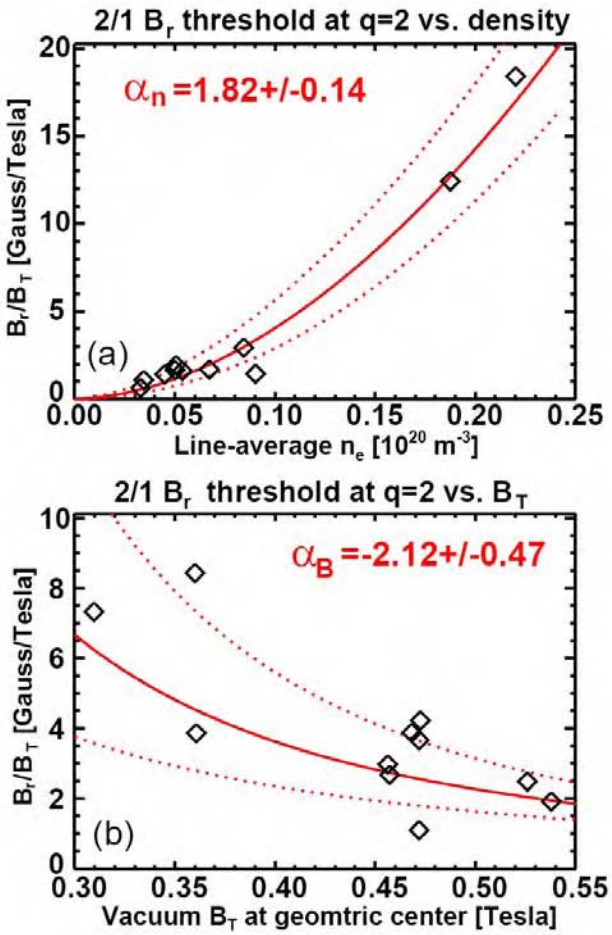

Wolfe *et al.* Phys. Plasmas **12**, 056110 (2005)

- Linear n=1 EF ramp applied by EF coils to induce LM detected with magnetics
- Span factor of 4 in $n_e = 0.5 – 2\times10^{19}m^{-3}$
- Span nearly factor of 2 in B_T = 3 – 5.5kG
- Sawteeth avoided due to $q_0 > 1$
  - Commonly used q_{95} not well correlated with magnetic shear at core resonances

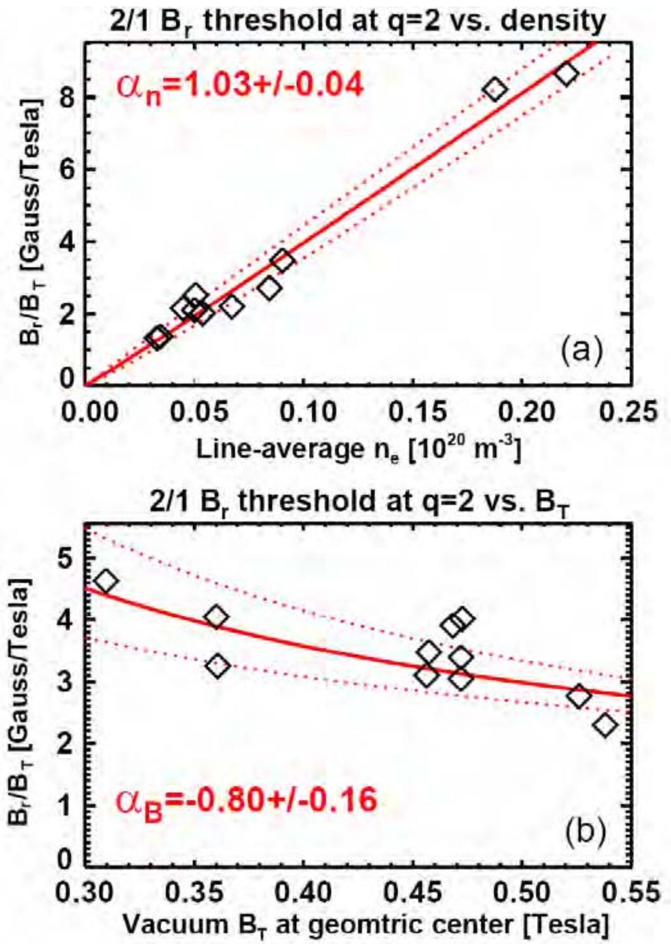
NOTE: Scaling form used here: $B_{21}\,(\mathrm{lock}) / B_T \propto n^{\alpha_n} B_T^{\alpha_B} q^{\alpha_q} R^{\alpha_R}$

IPEC results help determine which magnetic shear parameters best correlate with n=1 locked-mode threshold

- q_{95}, q^*, l_i not good shear parameters
  - Unphysical (quadratic) scaling with n_e
  - Large fit error in B_T scaling exponent

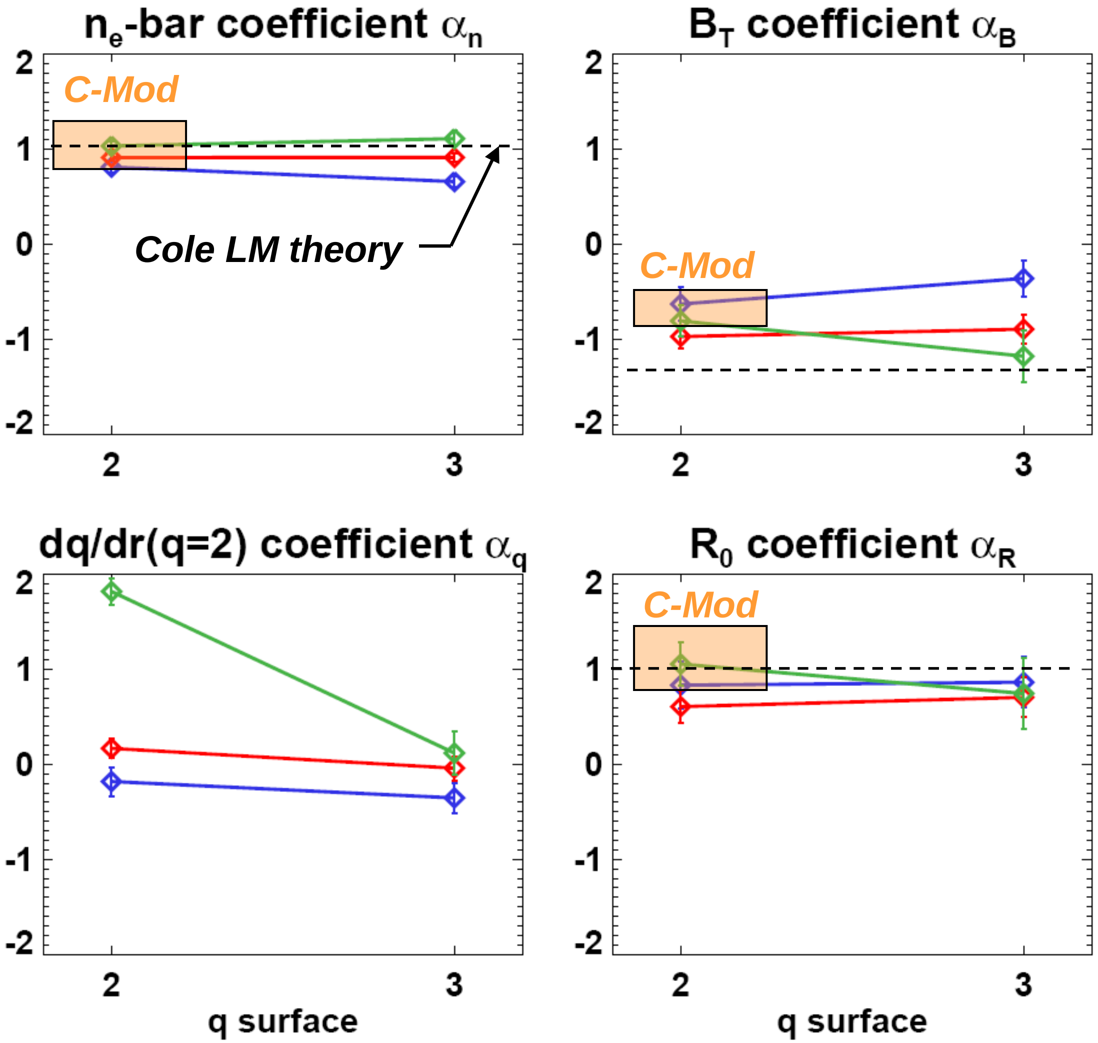


- Local shear at q=2, 3 better parameters
  - Obtain expected linear scaling with n_e
  - 3× smaller error in B_T scaling exponent



IPEC + NSTX LM fits using shear at q=2 → linear n_e and inverse B_T scaling consistent with higher-A, B_T tokamaks and recent theory

Data also allows assessment of impact of different calculations of perturbed B-field:


n_e-bar coefficient α_n

B_T coefficient α_B

dq/dr(q=2) coefficient α_q

R_0 coefficient α_R

Vacuum $\delta B_\perp$ (most commonly used)
Vacuum perturbed helical flux $\delta\psi_h$
Include plasma response (IPEC)

Assume size scaling coefficient:

$$\alpha_R = 2\alpha_n + 1.25\alpha_B$$

(Connor-Taylor invariance)

Mean coefficients using q=2 and 3:

α_n = 0.73	α_B = -0.50	α_R = 0.85
α_n = 0.91	α_B = -0.93	α_R = 0.66
α_n = 1.07	α_B = -0.99	α_R = 0.90

IPEC-derived coefficients are the most consistent with recent theory by A. Cole:

$$\left|\frac{b_{r,nm}^{\mathrm{vac}}}{B_\phi}\right|_{\mathrm{crit}} \propto n_e B_\phi^{-1.3} R_0 \tau_V^{-1/2} \sigma.$$

PRL **99**, 065001 (2007)

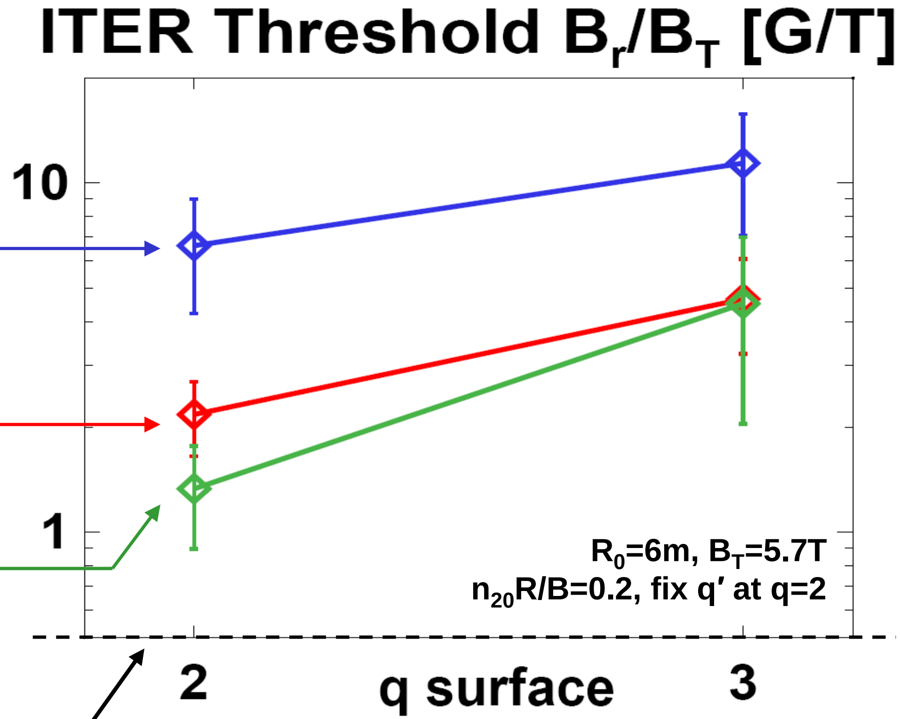
Extrapolation to ITER from NSTX data illustrates the importance of the plasma response, and has favorable projection for ITER

Vacuum $\delta B_{\perp}^{mn}$ (most commonly used) threshold **2-5** × **higher** than IPEC

→Vacuum $\delta B_{\perp}^{mn}$ ***not valid*** for NSTX

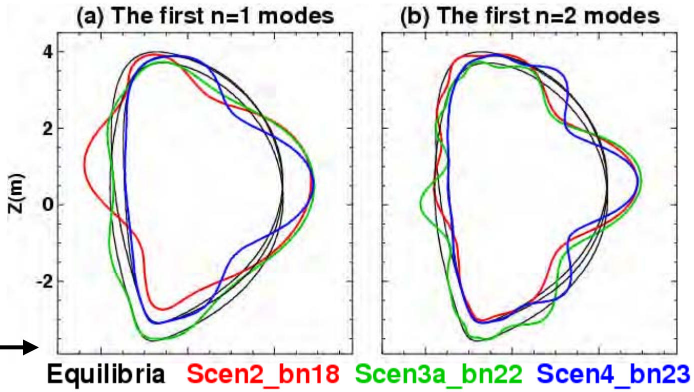
Vacuum $\delta\psi_{h}^{mn} \propto (|\nabla\psi|\mathbf{R^2B_{\perp}})^{\mathbf{mn}}$ threshold **1-2** × **higher** than IPEC

Include plasma response (IPEC)



Minimum threshold B_r / B_T = 1- 4 G/T is 2-3× higher than minimum EF correction capability of ITER (favorable result)

IPEC also used to model optimal multi-scenario EF mitigation for ITER



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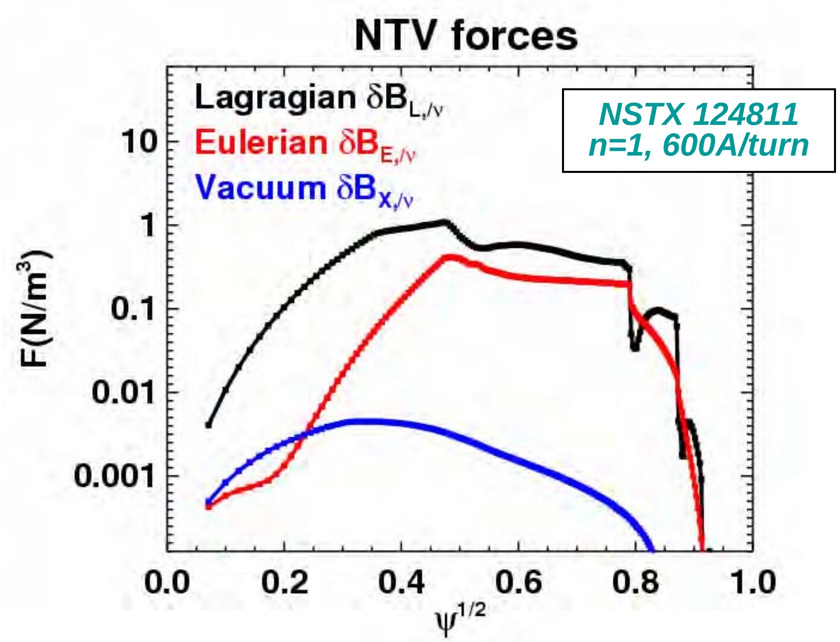
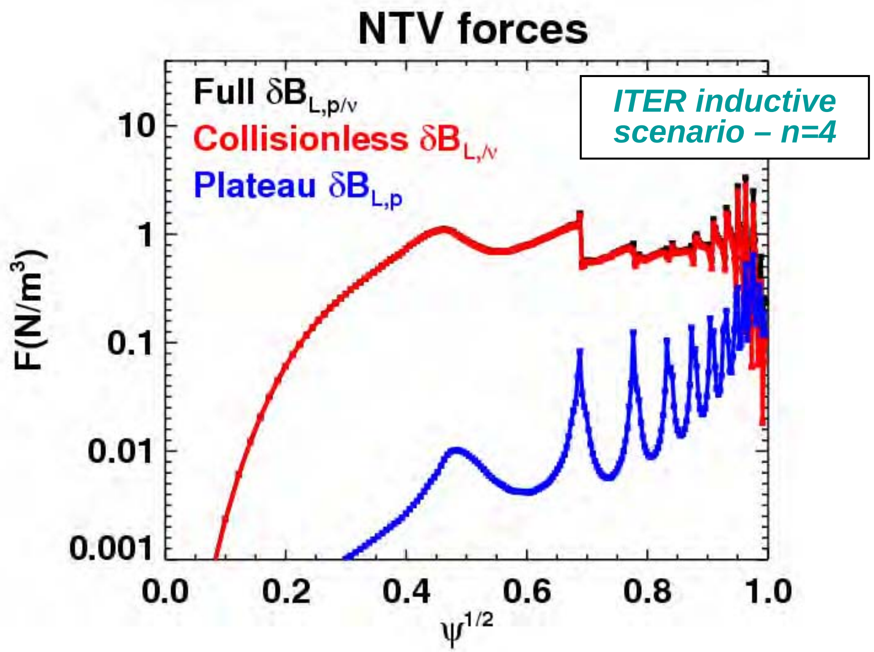
Neoclassical Toroidal Viscosity (NTV) calculation highlights importance of plasma response, Lagrangian δB, and low ν_i

- ☐ K.C. Shaing's analytic formulae for NTV use Lagrangian δB: $\delta B_L(\vec{x})$

$$\underset{\textit{Lagrangian}}{\underline{\delta B_L(\vec{x}+\delta\vec{x})}} = \underset{\textit{Eulerian}}{\underline{\delta B(\vec{x})}} + \vec{\xi}(\vec{x})\cdot\vec{\nabla}B(\vec{x})$$

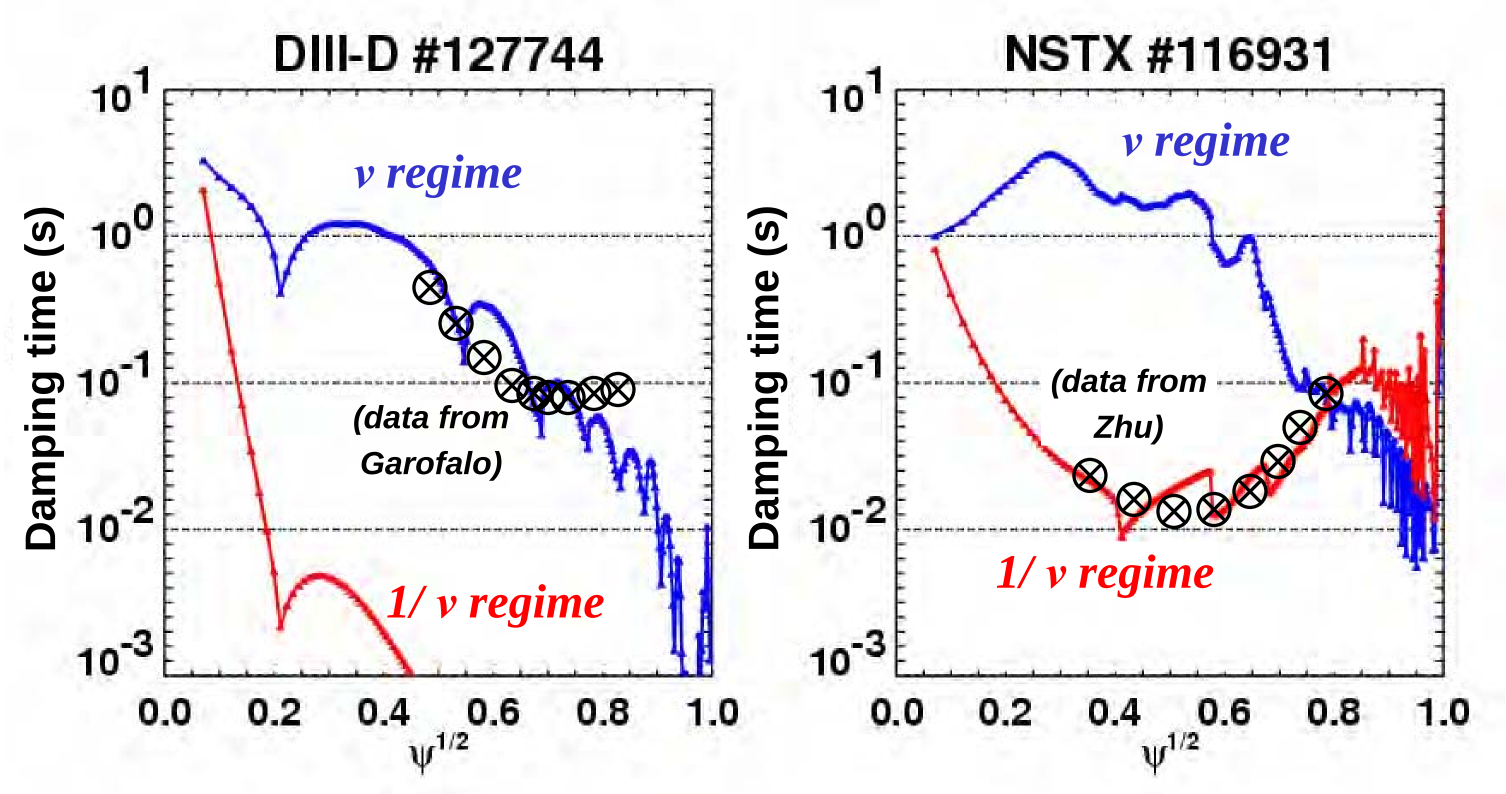




$$F_{NTV} = \underset{\textit{Plateau}}{\underline{C_1 \frac{\sqrt{\pi}\,p_i}{V_{Ti}} \Omega_\phi q \sum_{n,m\neq 0} \left(n^2 \left|\delta B_{Lnm}\right|^2 \frac{\mu_{ps1}}{\frac{2\sqrt{\pi}}{3}\frac{\nu_i}{V_{Ti}/R_0 q} + \mu_{ps1}\left|m-nq\right|} \right)}} + \underset{\textit{Collisionless}}{\underline{C_2 \frac{\varepsilon^{3/2}\lambda_{1i}\,p_i}{\sqrt{2}\pi^{3/2}\nu_i} \Omega_\phi \sum_{n,m,m'} \left(n^2 \delta B_{Lnm}\,\delta B^*_{Lnm'}\,W_{nmm'} \right)}}$$

Initial comparisons between experiment and NTV theory show some agreement, but questions remain

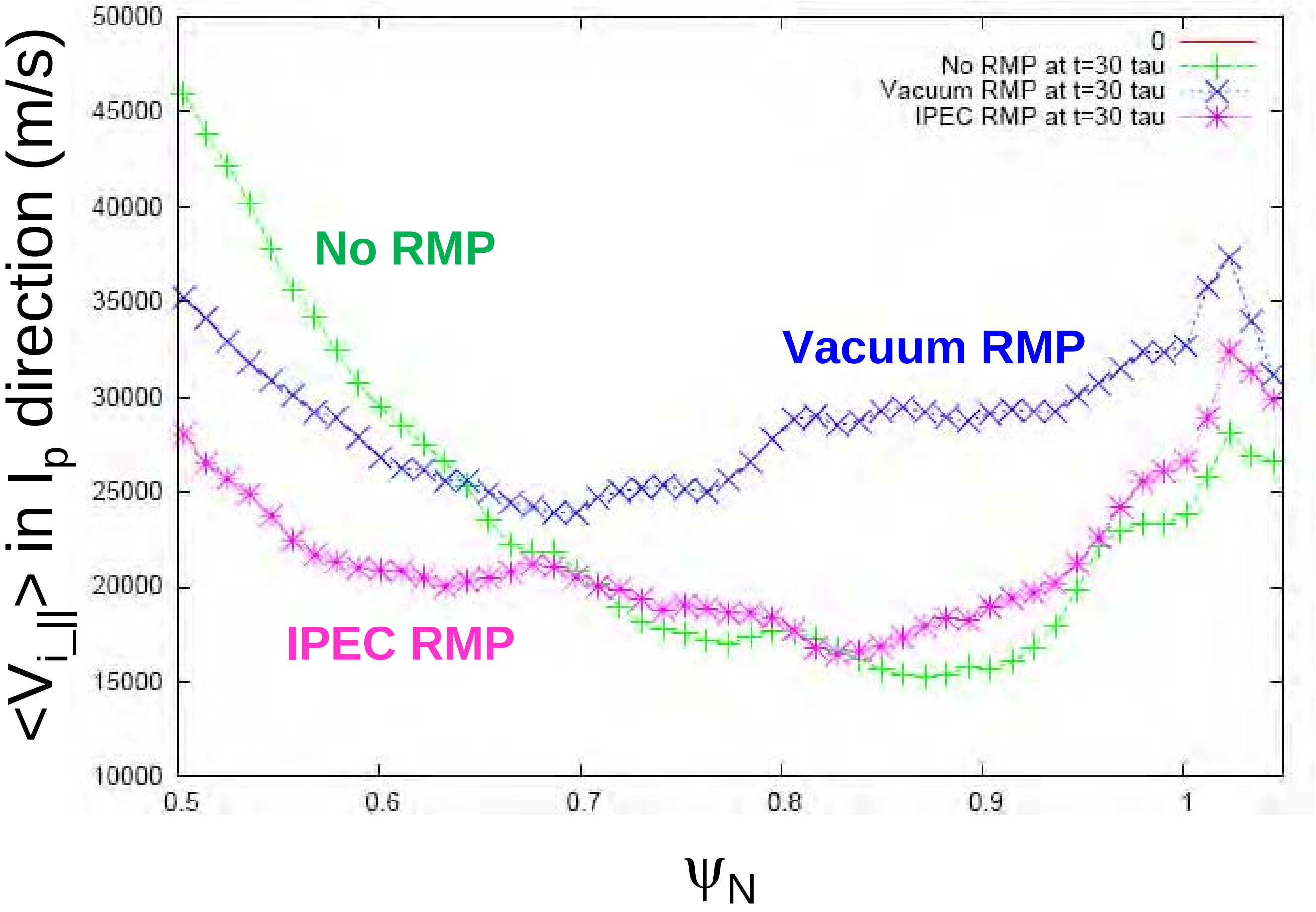
- DIII-D damping time consistent with ν-regime NTV using IPEC Lagrangian δB
- NSTX consistent with $1/\nu$ regime in core, but may actually be in ν regime…



- More complete theory is under development to address:
  - ν regime fluxes singular as trapped-passing boundary approached → $\nu^{1/2}$ regime
  - Significant overlap in relevant frequencies (ν_{eff}, ω_b , ω_{ExB}, …)

3D kinetic code XGC0 shows qualitative agreement with NSTX experiment when IPEC plasma response is used

- n=3 rotation damping observed in experiment - stronger in plasma core
- Vacuum RMP causes ***increase*** in rotation in edge region – **inconsisent**
- IPEC RMP shows little damping in edge, stronger in core – **consistent**



- IPEC: Ideal MHD response removes stochastic B → little enhancement in electron transport

- Ion rotation drag by magnetic perturbations remains.

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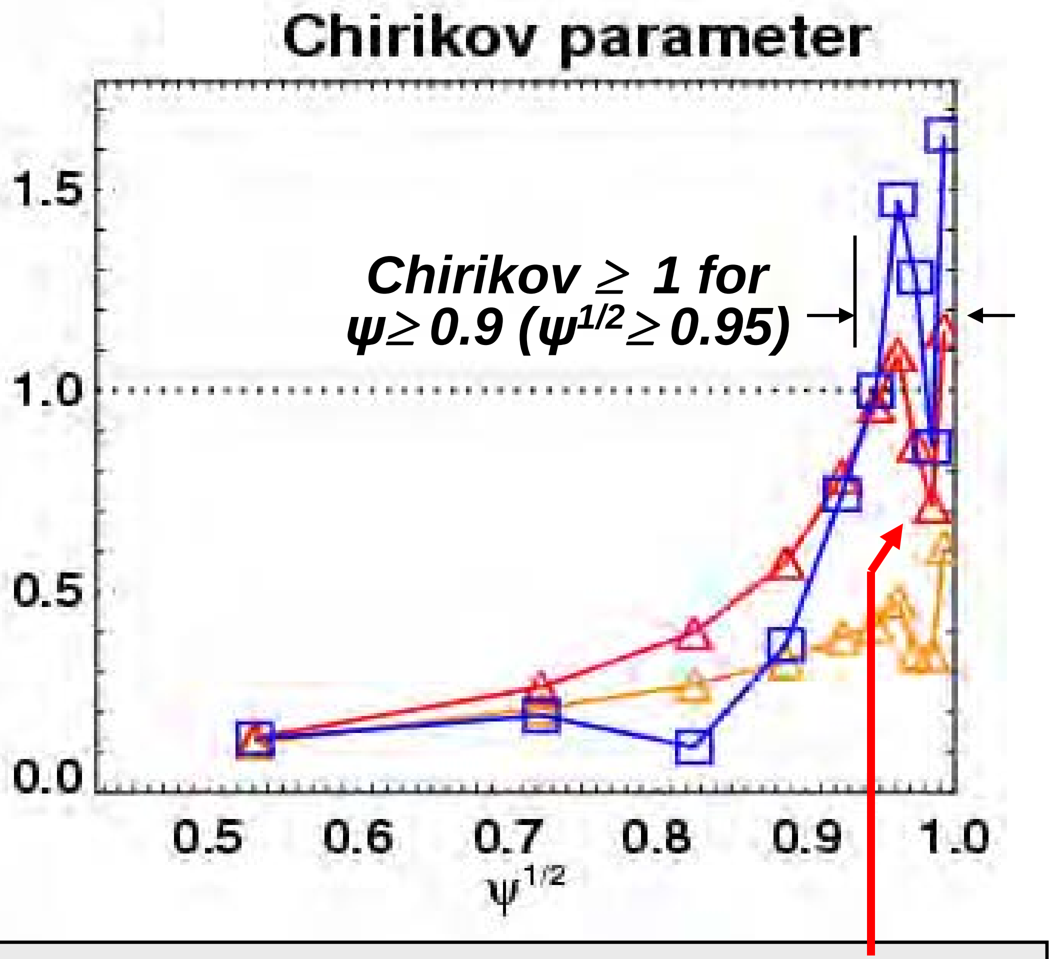
IPEC calculation of ergodization in pedestal region consistent with observed DIII-D ELM suppression with RMP

DIII-D #126006, n=3 field

- "Even" parity
  - ELM suppression observed
  - Consistent with IPEC calculated Chirikov > 1
  - Approaches IPEC **theoretical optimum**

- "Odd" parity
  - No suppression observed
  - Consistent with IPEC calculated Chirikov << 1



Chirikov $\geq$ 1 for $\psi \geq 0.9$ ($\psi^{1/2} \geq 0.95$)

- ***Is small region of good surfaces needed to retain H-mode w/o ELMs?***
- ***To what extent does rotation shield resonant RMP fields in pedestal?***

IPEC RMP optimization algorithm aims to ergodize edge while minimizing core flow damping

RMP optimization constraints:

1. Generate edge perturbation sufficient to satisfy Chirikov > 1
   - $w_{island} \propto \mathrm{SQRT}\left(\delta\vec{\boldsymbol{B}} \cdot \hat{\boldsymbol{n}}\right)_{mn}$

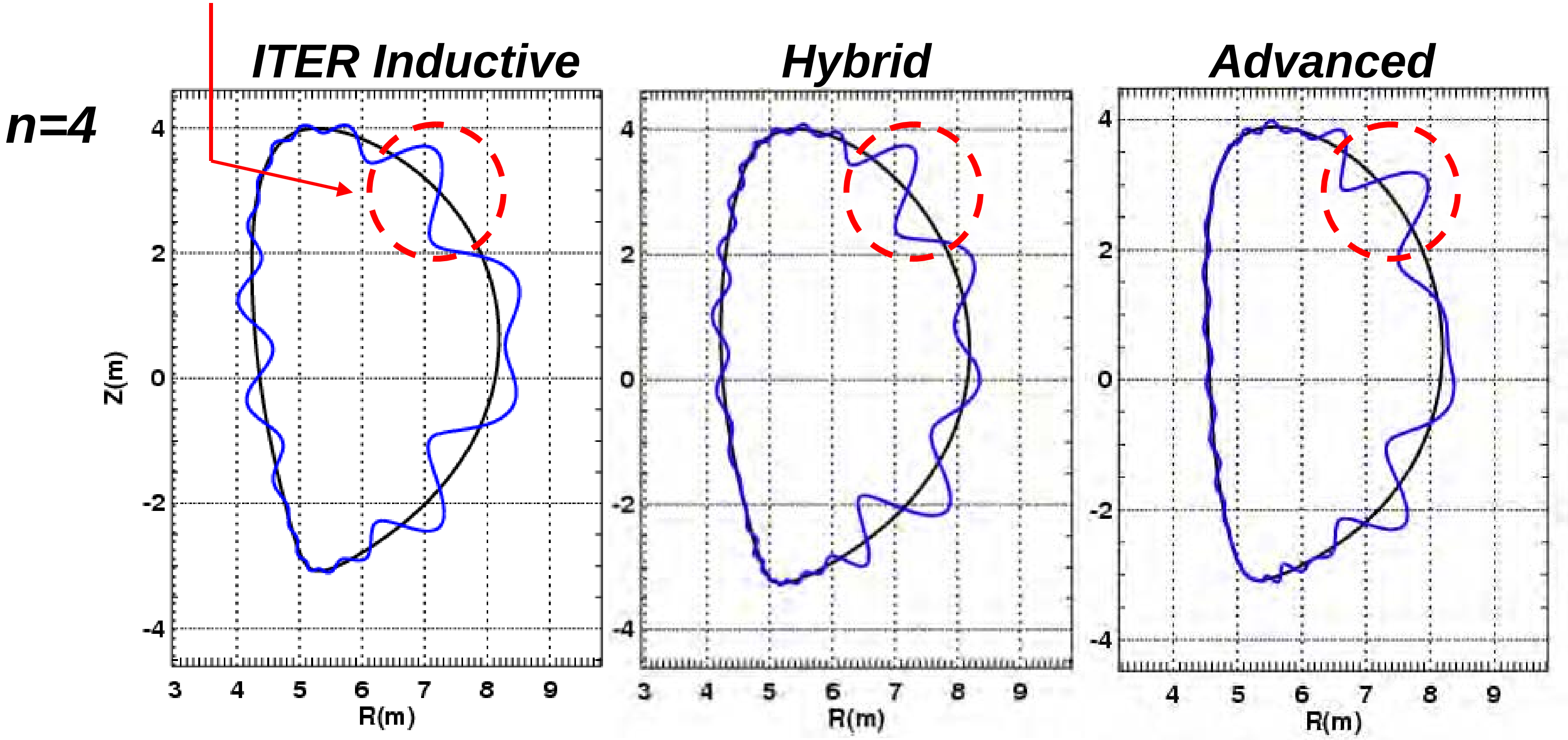
2. Minimize NTV torque $\propto |\delta B_L|^2_{m,n}$

- **IPEC constraints:** determine external field spectrum that maximizes/minimizes total resonant δB_{mn} in particular region
  - Utilizes the linear matrix relationship between total & external fields:

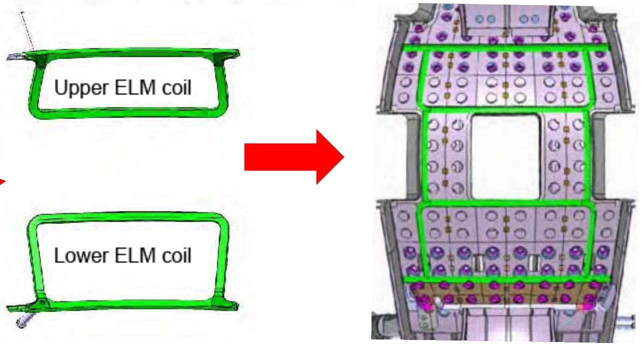
$$\left(\delta\vec{\boldsymbol{B}} \cdot \hat{\boldsymbol{n}}\right)_{mn} = \left(\overleftrightarrow{\boldsymbol{C}}\right)_{mm'n} \left(\delta\vec{\boldsymbol{B}}^{x} \cdot \hat{\boldsymbol{n}}_{b}\right)_{m'n}$$

ITER optimal field distribution has robust off-midplane structure

- **Large $\delta B_{\perp\text{-vac}}$ ~ 45° above/below midplane, nearly independent of equilibrium:**

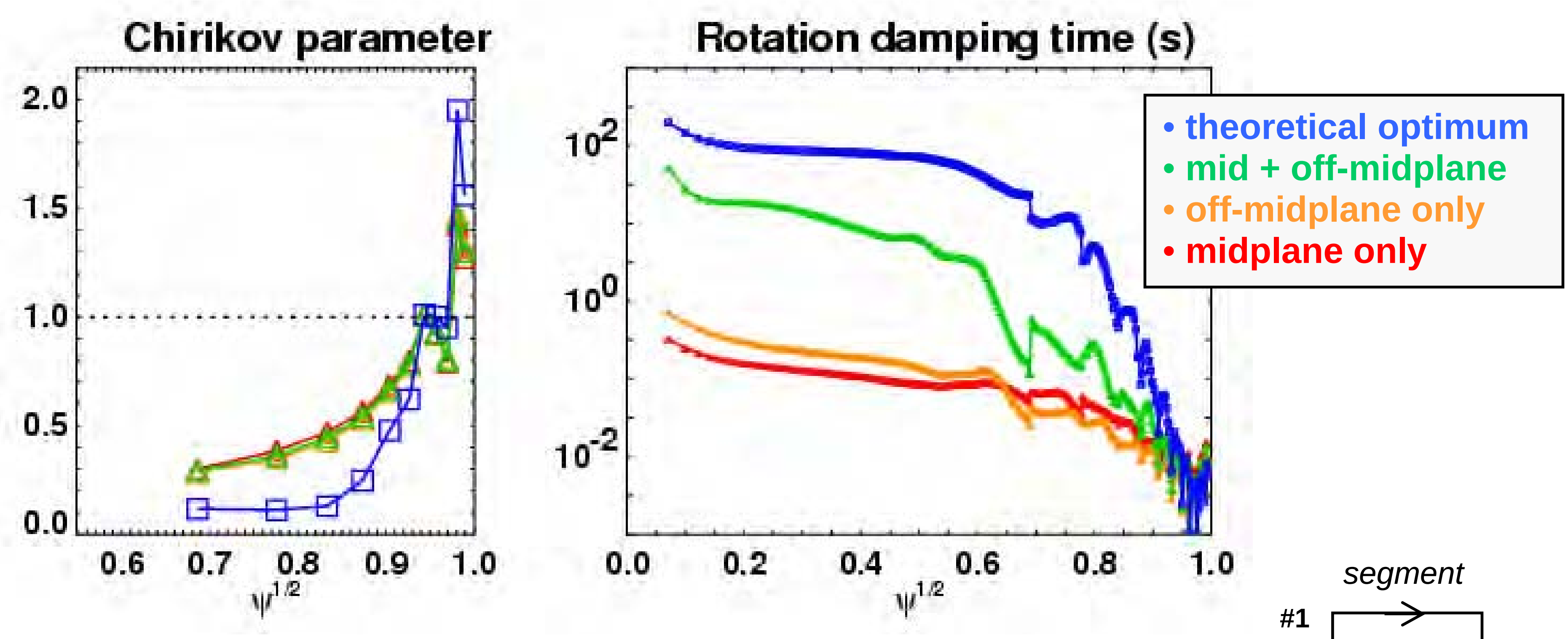


- **Midplane + off-midplane coils produce $\delta B_{\perp\text{-vac}}(\theta)$ approaching optimum**
  - **ITER presently favors this approach**
  - **Coils also useful for vertical control**

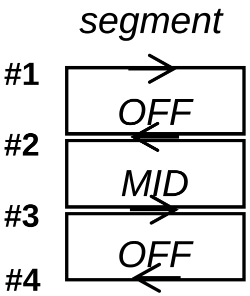


Midplane + off-midplane coils in ITER can satisfy ergodization criterion while maximizing core rotation damping times

ITER inductive scenario:



	MID	OFF	#1	#2	#3	#4
VAC02	- 25kA	25kA	25kA	- 50kA	50kA	- 25kA



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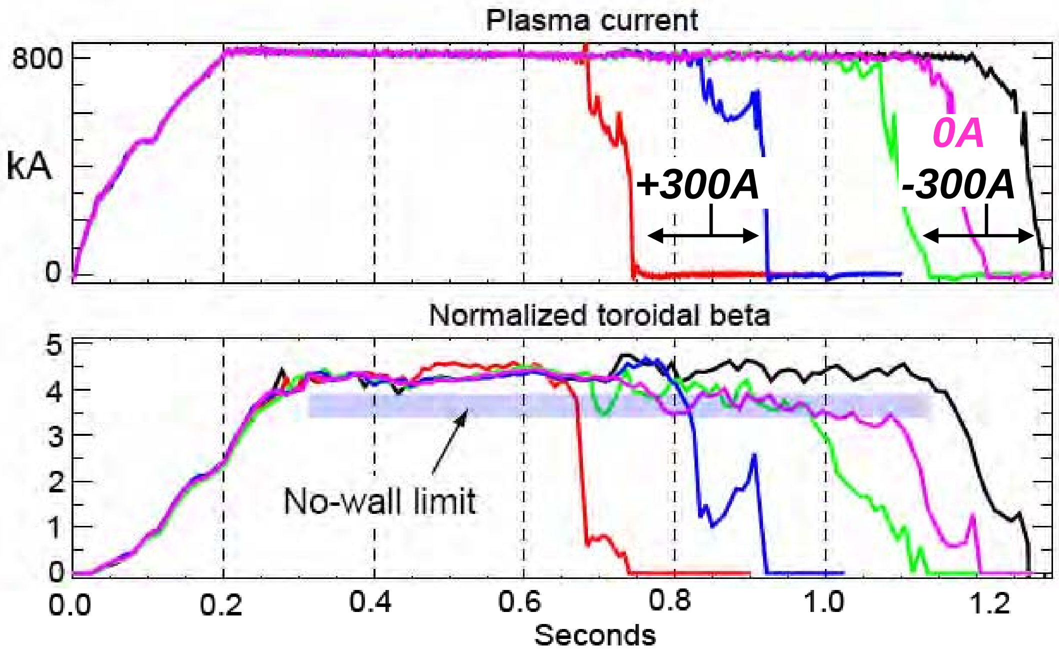
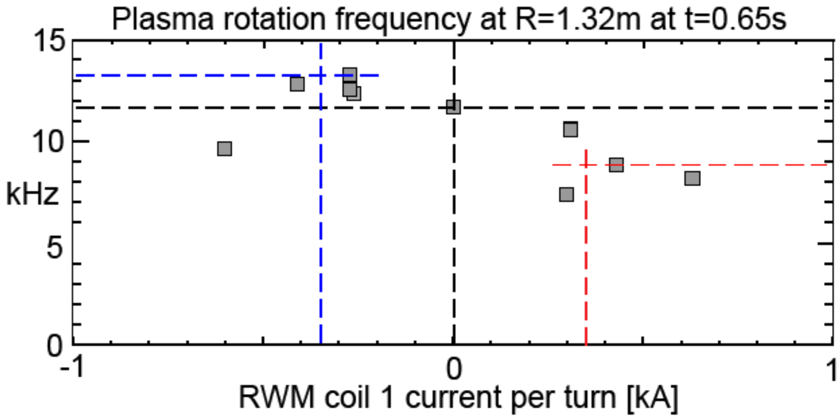
NSTX observes high-n (n=3) error fields important at high β_N



- Pulse-length depends on polarity of applied n=3
  - Anti-corrective polarity disrupts I_P and β
- Plasmas operate above n=1 no-wall limit
  - Observe unstable n=1 RWM for n=3 field in anti-corrective direction

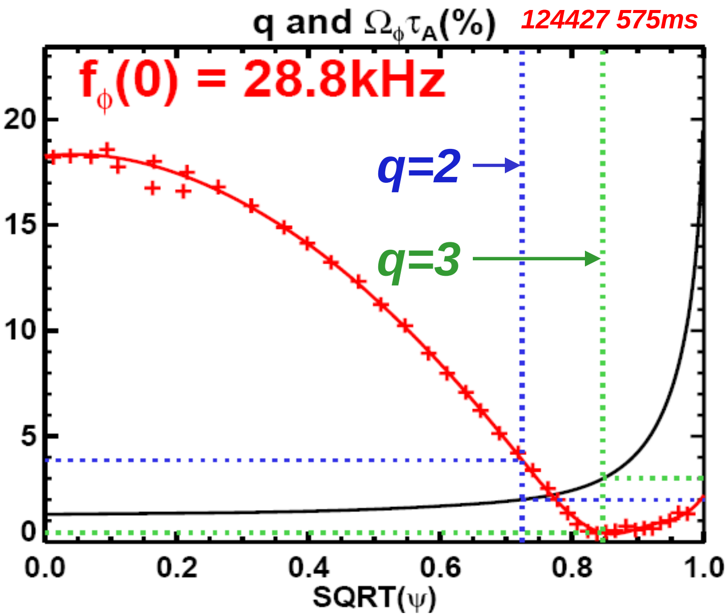


- Rotation depends on polarity of applied n=3

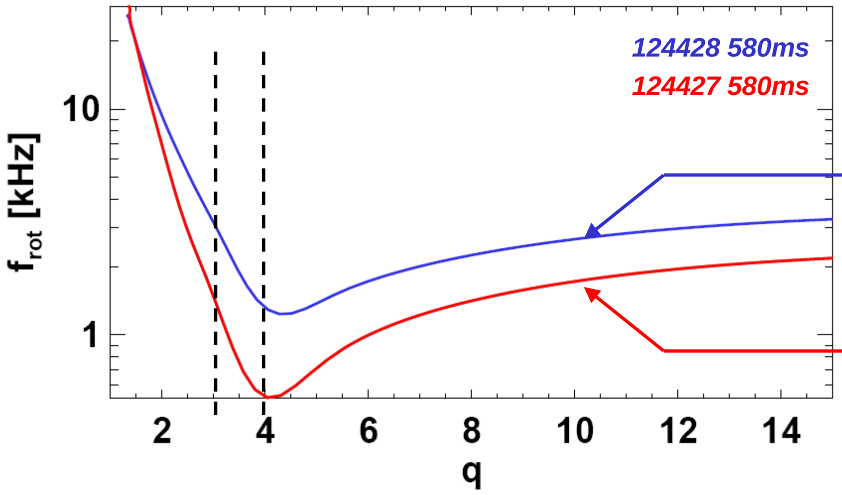
- **Implication: n=3 EF can destabilize n=1 RWM**

- ***n > 1 error fields not commonly addressed in present devices, or in ITER***

In the n=3 EFC experiments, edge rotation for $\rho > 0.75$ determines stability of discharges and resultant pulse-length



- Discharges in n=3 EFC studies have low rotation at low-order rationals relative to high rotation in core
  - Core: $\Omega_\phi\tau_A = 18\%$
  - q=2: $\Omega_\phi\tau_A = 4\%$ (4.5 × lower)
  - q=3: $\Omega_\phi\tau_A = 0.4\text{-}1\%$ (18-45 × lower)

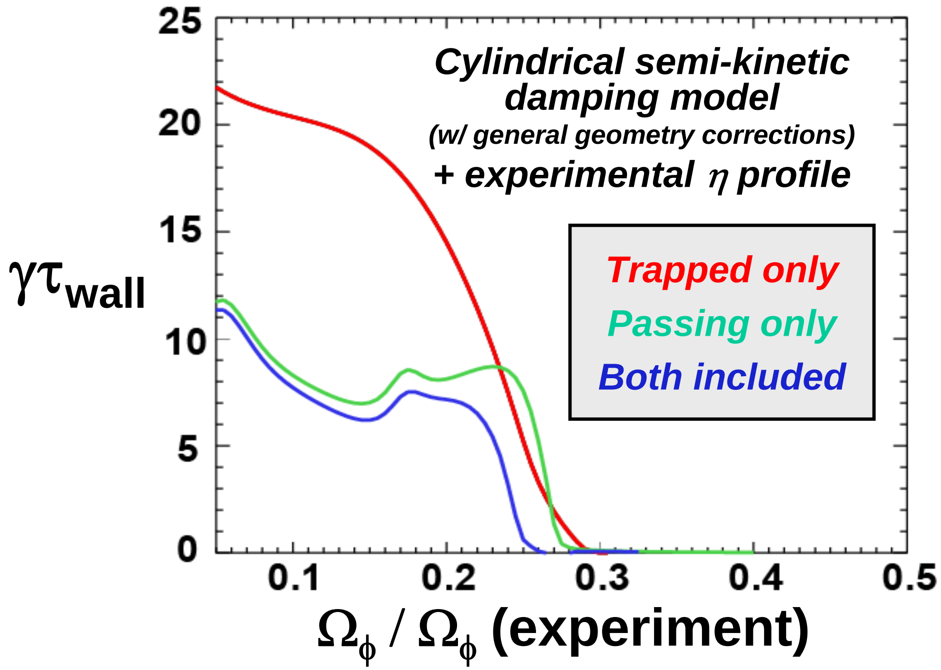


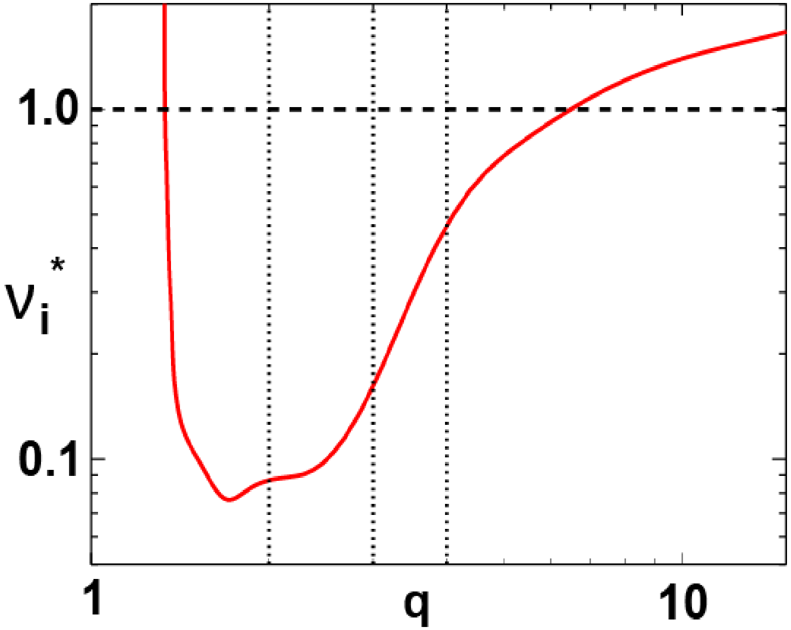
- n=3 EFC increases the rotation primarily on surfaces with q ≥ 3

With n=3 EFC, rotation is sufficient to stabilize n=1 RWM

Without n=3 EFC, rotation is lower and discharge has RWM disruption

n=3 EFC experiments also enable comparison to n=1 RWM theory → MARS-F underestimates n=1 RWM critical rotation for NSTX



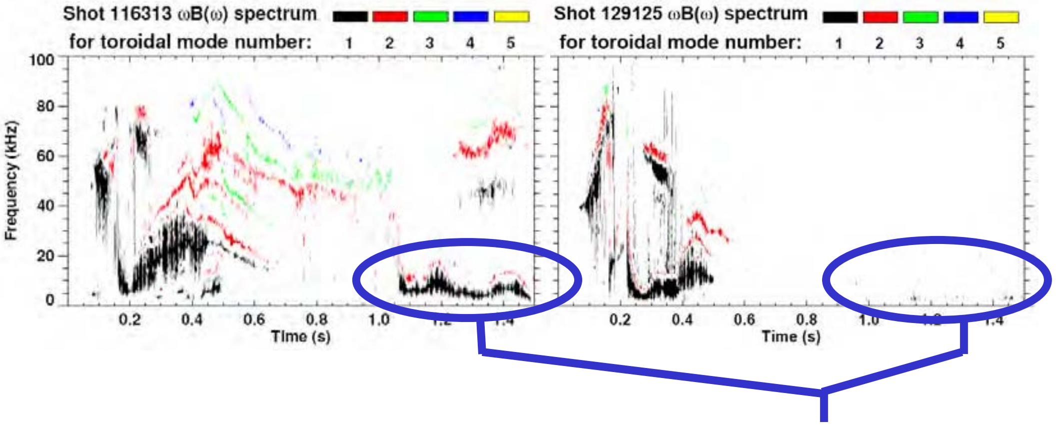


- Passing particles dominate dissipation, create local minima in γ vs. rotation
- Several kinetic effects ignored in MARS-F (ω_{diam}, drift precession, etc…)
  - Kinetic effects have been theoretically shown to provide stabilization at low Ω_ϕ
  - But, can kinetic effects be *destabilizing* at high rotation?
- Another possibility: collisions reduce stabilization by barely-passing ions
  - Ion collisionality ν_i^* → 1 for q ≥ 4 at large r/a in NSTX

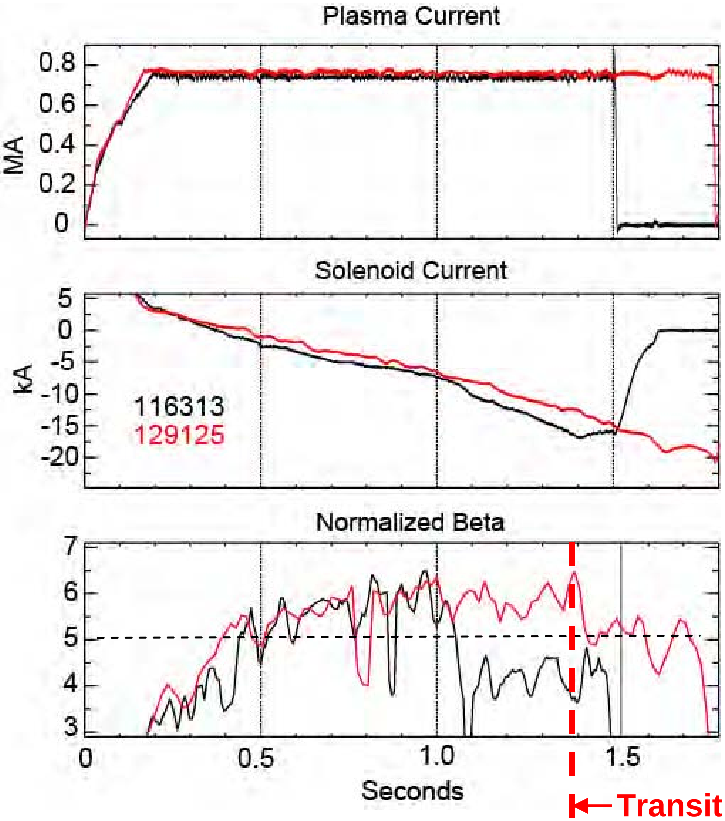
n=3 EF correction combined with n=1 RFA/RWM feedback and Li wall conditioning extends NSTX sustained high-β_N

- P1.009 – Kaita (Improvements from Lithium)
- P1.059 – Sabbagh (Global mode stabilization)

116313 – no mode control or Li
129125 – with mode control + Li



Late n=1 rotating modes avoided



NSTX record pulse-length = 1.8s

Flux consumption reduced by sustained high β + Li conditioning

- Pulse-length limited by TF flat-top limit

$\beta_N \geq 5$ sustained for 3-4 τ_{CR}

- EF/RWM control helps sustain rotation, high β

Transition to regime with larger, more frequent ELMs

New understanding of the impact of 3D magnetic field perturbations on tokamak plasmas has been obtained

- Importance of plasma response effects clarified with Ideal Perturbed Equilibrium Code (IPEC)
  - Poloidal mode coupling
  - Lagrangian field modification
  - Amplification

- IPEC has been successfully applied to experiment
  - LM thresholds, NTV theory tests, RMP ELM control

- n > 1 error fields can be important at high β_N
  - Error fields can reduce rotation, destabilize n=1 RWM
  - Observe $q \geq 3$ surfaces can determine n=1 RWM stability