Plasma Rotation Driven by Static Nonresonant Magnetic Fields

by

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in collaboration with

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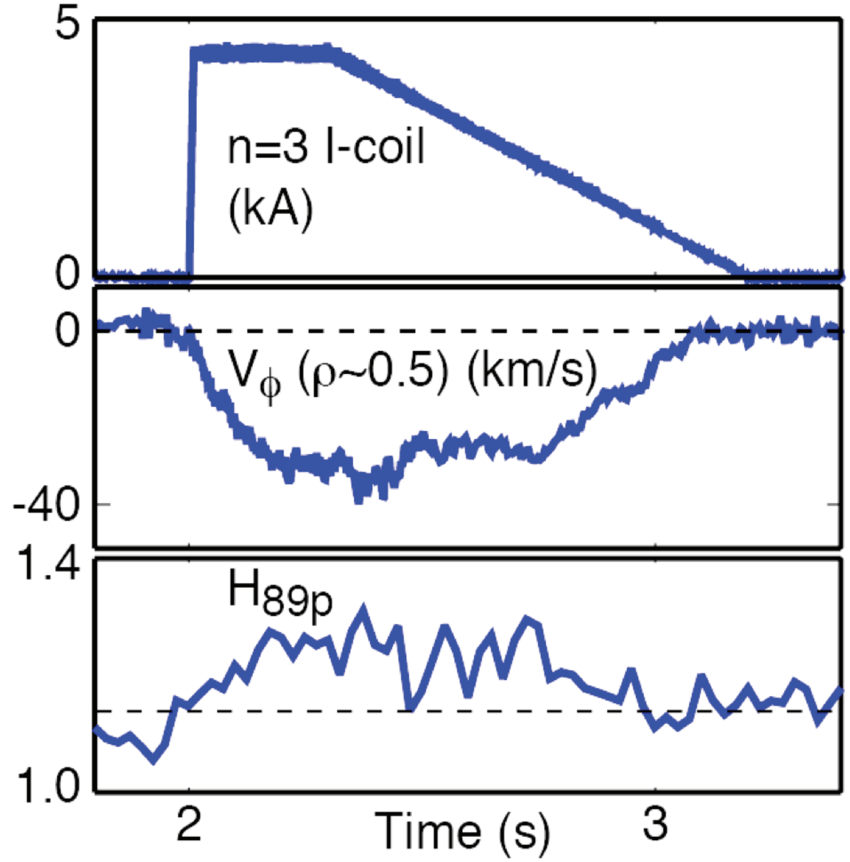

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GENERAL ATOMICS

Effect of Nonaxisymmetric Field on Plasma Depends Qualitatively on Matching to Equilibrium Field Pitch

- **Resonant magnetic field: matching helicity → can open magnetic island**
  - Applies localized toroidal torque at resonant surface
    - $T \propto 1/V_\phi$ [Fitzpatrick, *Phys. Plasmas*, 1998]

- **Nonresonant magnetic field (NRMF): mismatched helicity → cannot open island**
  - Applies diffused toroidal torque
    - $T \propto V_\phi$ [Stix, *The Theory of Plasma Waves,* 1962]

Neoclassical Offset Rotation Associated With Torque Driven by NRMFs

- **Extensive literature coverage of NRMF torque since early 70s**
  - **NRMFs produce "ripples" in the magnetic field strength**
    - Particles can be trapped in new magnetic wells
    - Orbits of banana-trapped particles can be significantly modified
  - **Both effects cause increased collisional transport, with greater loss rate for ions**

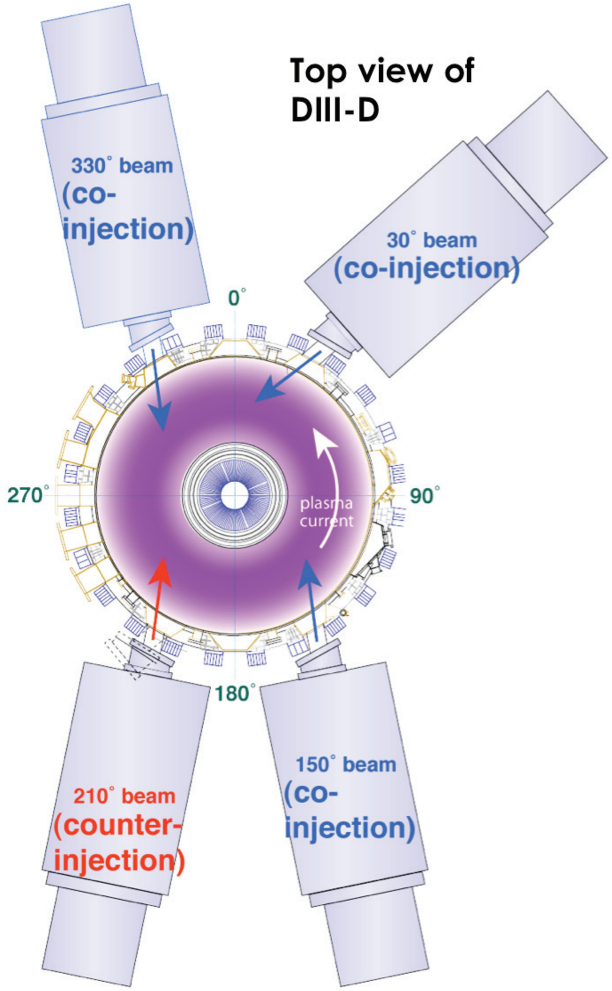
    => radial current evolves to maintain neutrality

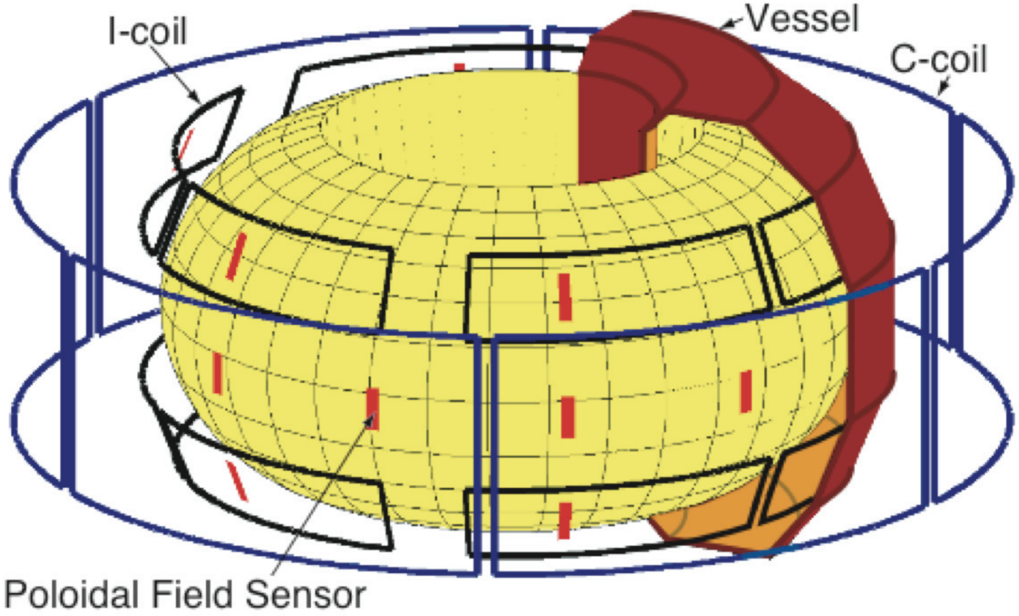
    => toroidal torque = $J_r x B_\theta$
- **New development:**
  - T_{NRMF} **drags flow to an "offset" rotation, comparable to ion diamagnetic frequency, in direction opposed to plasma current**
    - $T_{NRMF} \propto (V_\phi - V_\phi^{0,NC})$, $\quad V_\phi^{0,NC} \propto (dT_i/dr)/Z_i e B_\theta$

      [Cole, Hegna, and Callen, Phys. Plasmas (2008)]

DIII-D Has Unique Tools to study Rotation and Nonaxisymmetric Fields

- **Independent control of heating and injected torque**





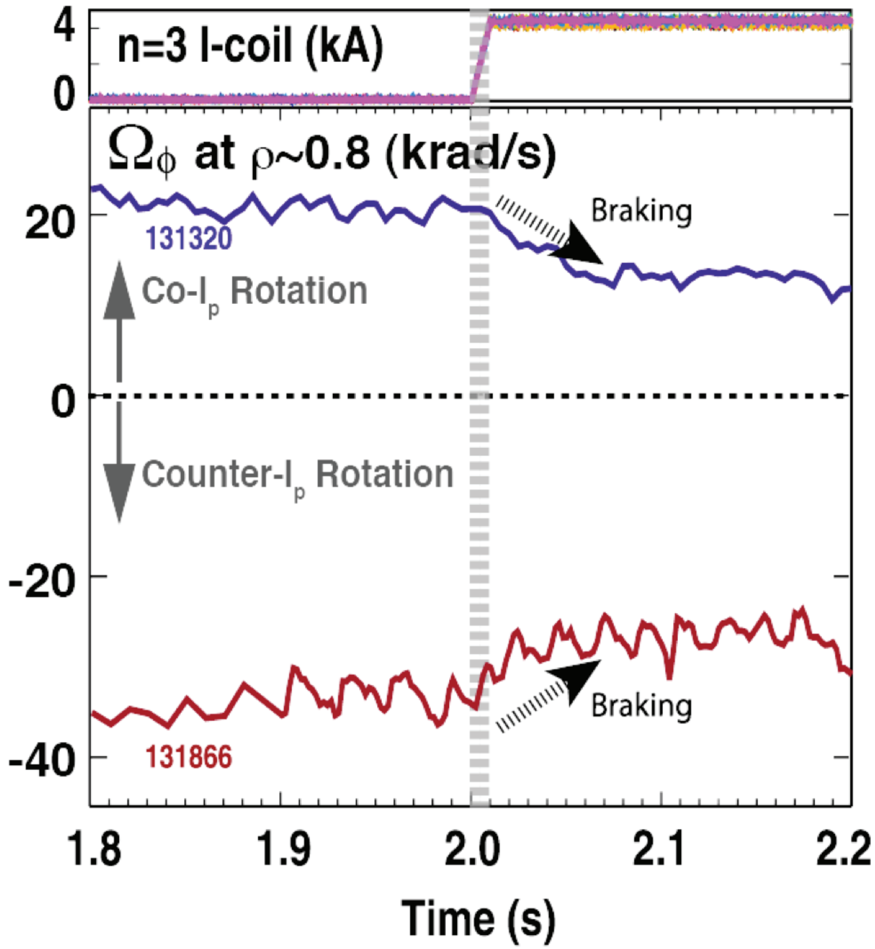
- **Two sets of non-axisymmetric coils**
  - C-coil, and I-coil
  - Apply nonresonant fields while optimally correcting resonant error fields

Outline

- Evidence of offset rotation
- Comparison to neoclassical prediction
- Analysis of torque scaling
- Role of plasma response
- Implications for ITER

First Clear Evidence of Offset Rotation Associated to Nonresonant Magnetic Fields (NRMF)

- **Static *n*=3 NRMF applied to plasmas with different toroidal rotation**
  - Constant NBI torque in each discharge



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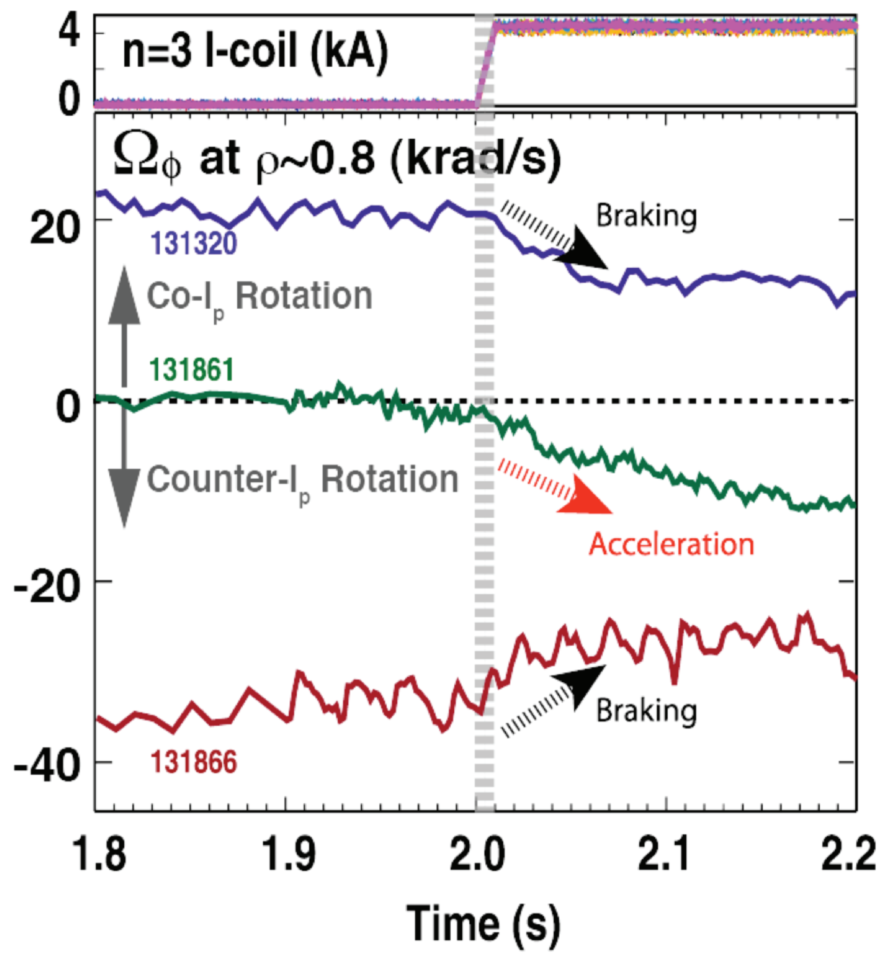

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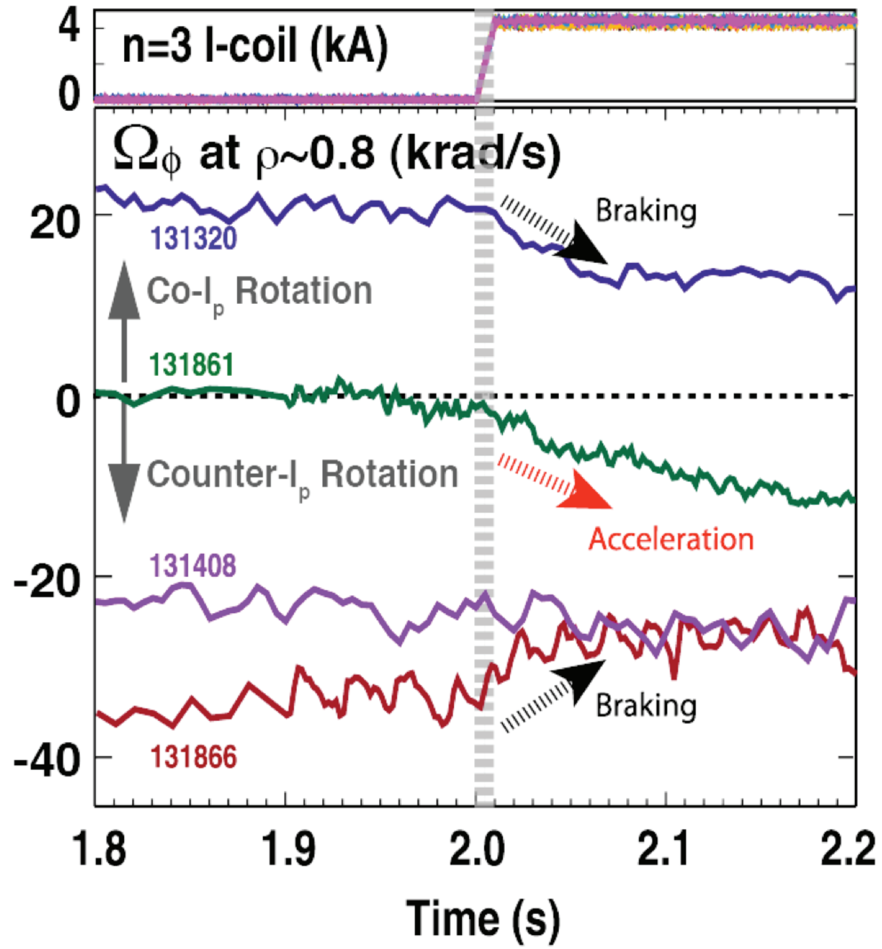
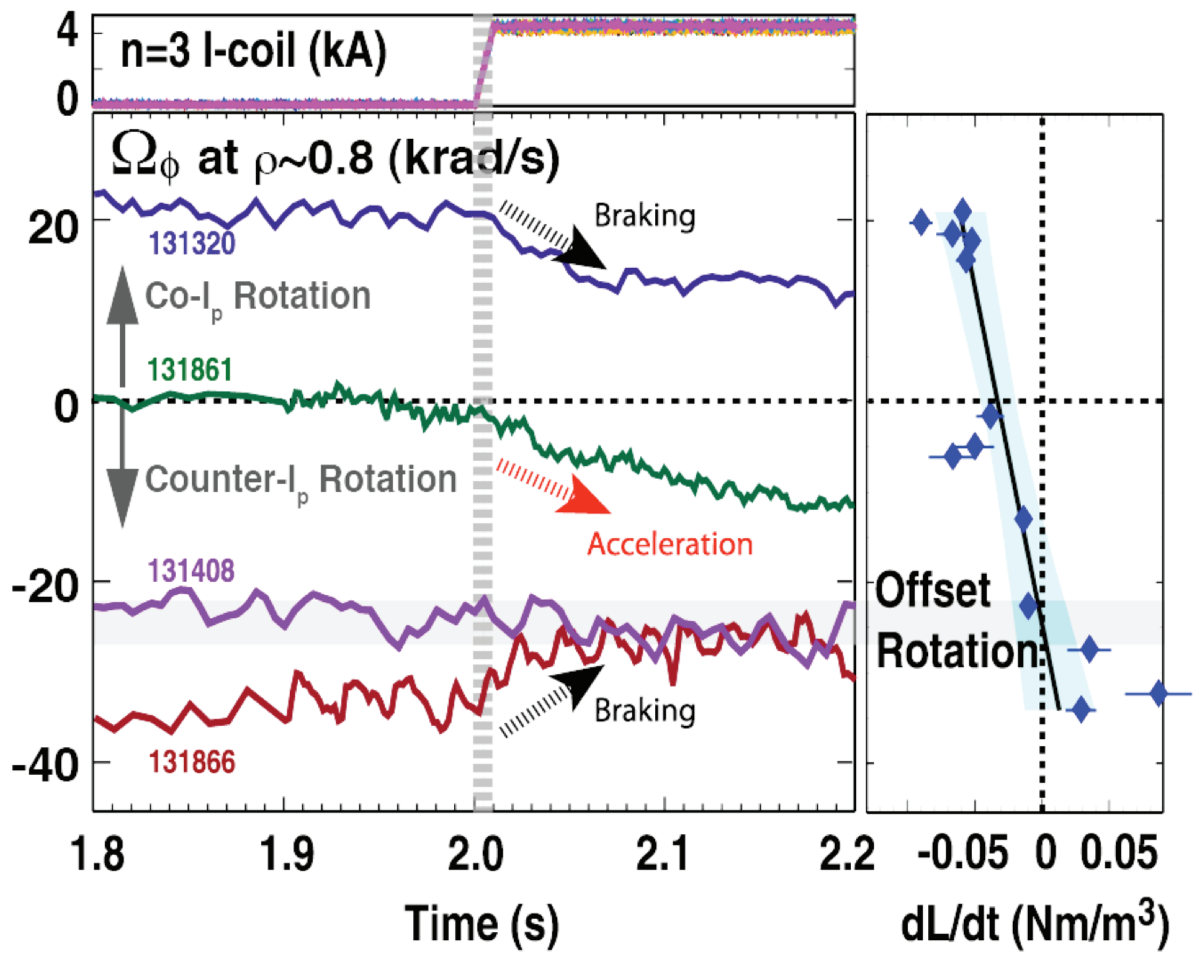


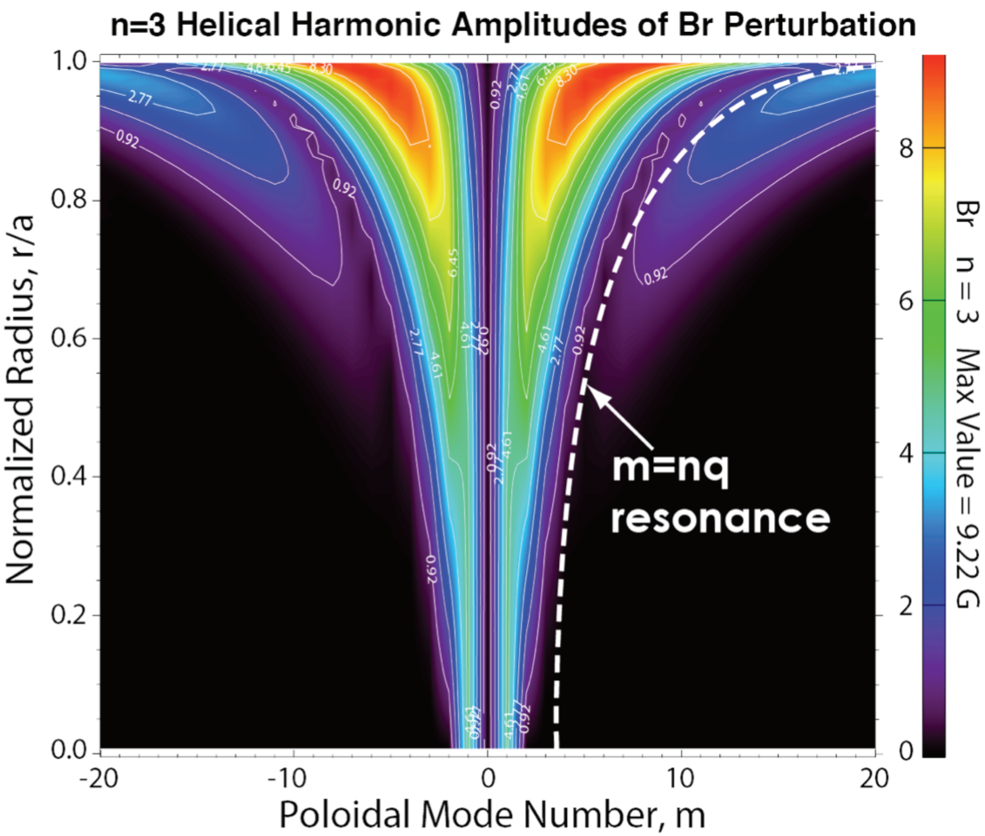
First Clear Evidence of Offset Rotation Associated to Nonresonant Magnetic Fields (NRMF)

- **Static *n*=3 NRMF applied to plasmas with different toroidal rotation**
  - Constant NBI torque in each discharge
- **T_{NRMF} drags flow toward offset rotation in counter I_p direction**
  - Can lead to plasma acceleration
- **Acceleration not due to correcting intrinsic error field since braking observed at higher counter-rotation**

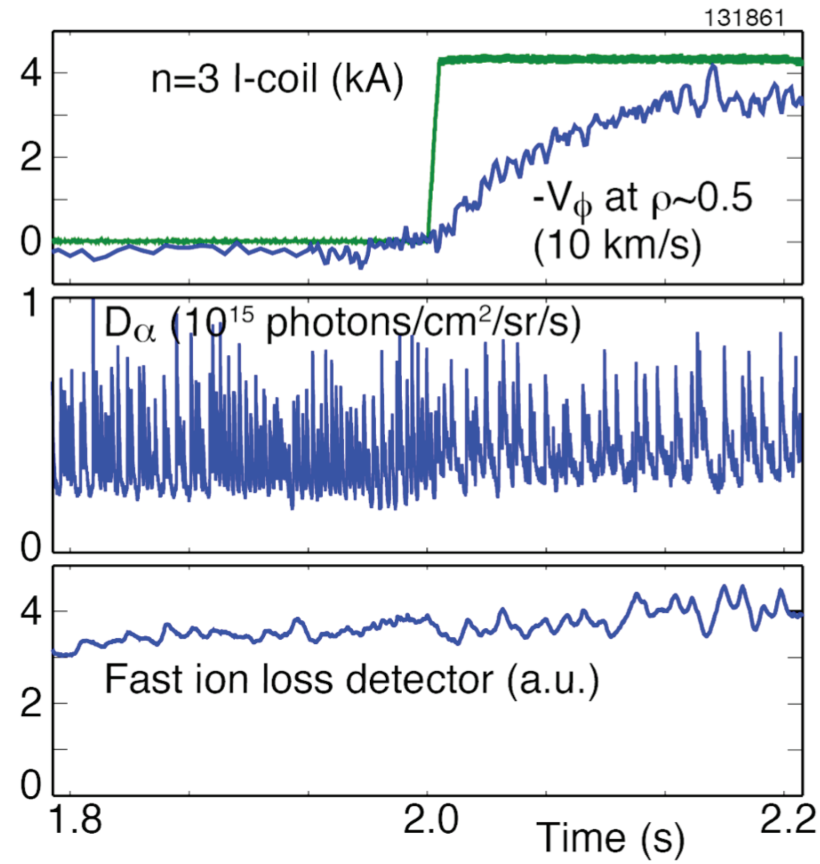


Experiments Aimed at Isolating Effect of NRMF on Rotation

- Applied *n*=3 field is almost purely nonresonant

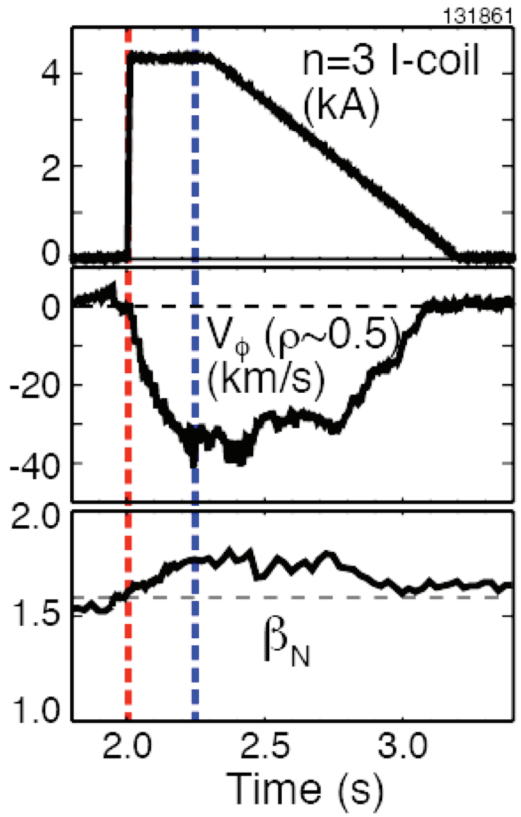


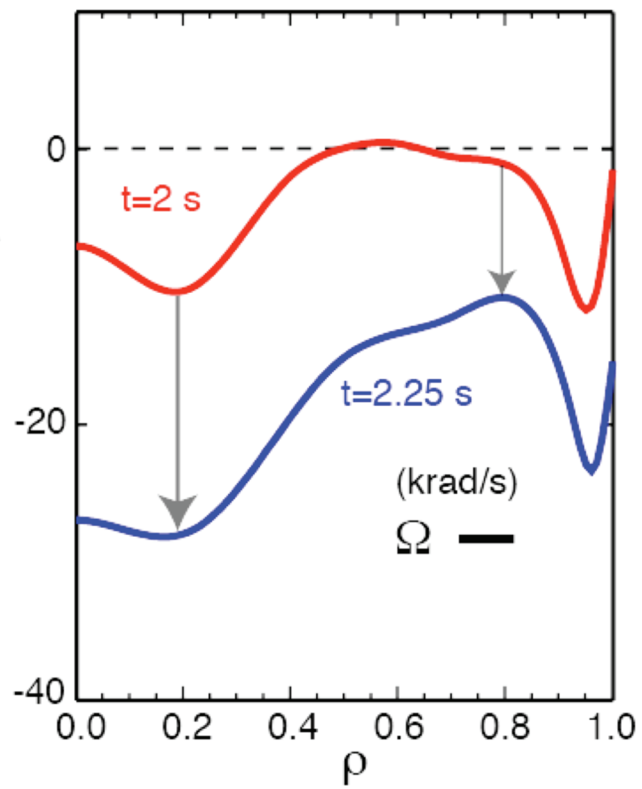
- No change in ELMing character
- No enhancement of fast ion loss



n=3 NRMF at Slow Rotation Produces Acceleration and Improvement in Global Energy Confinement

- **NBI power and torque constant during time range shown**
- **Increase of rotation observed at all minor radii in:**
  - Measured carbon impurity ion rotation





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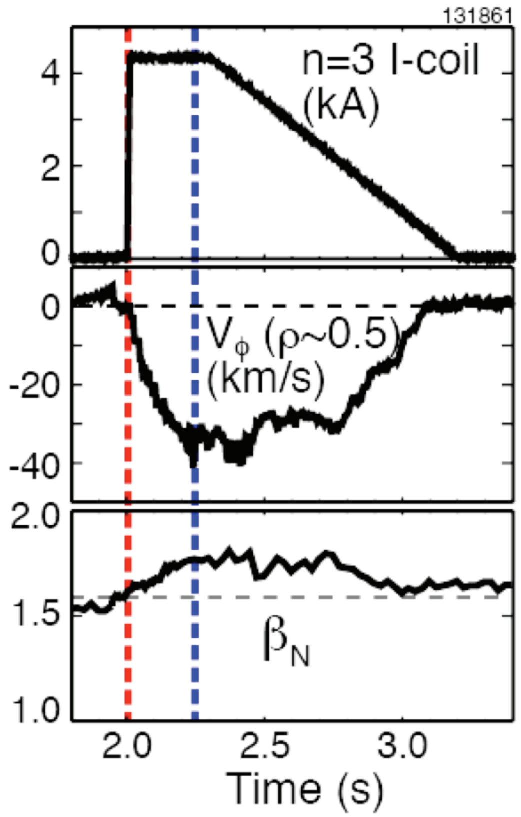
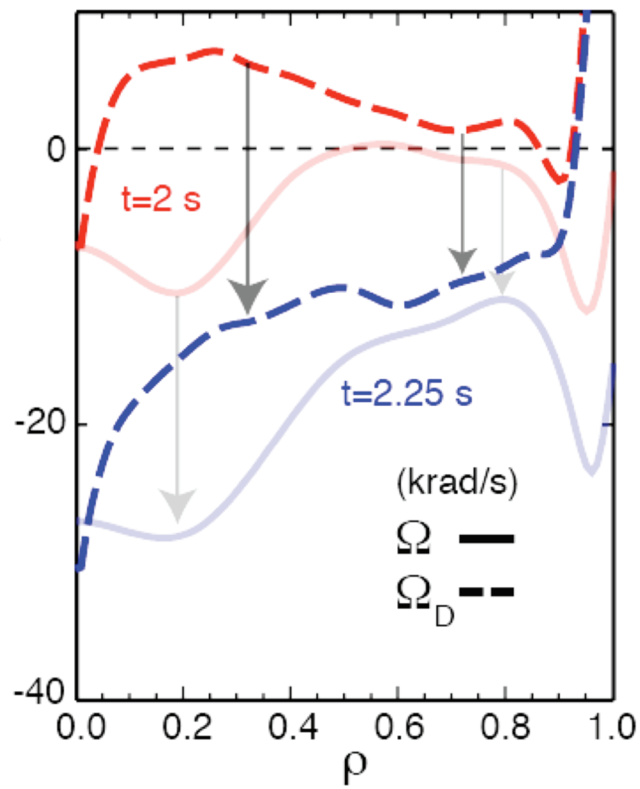
  - NCLASS calculated main ion (deuterium) rotation





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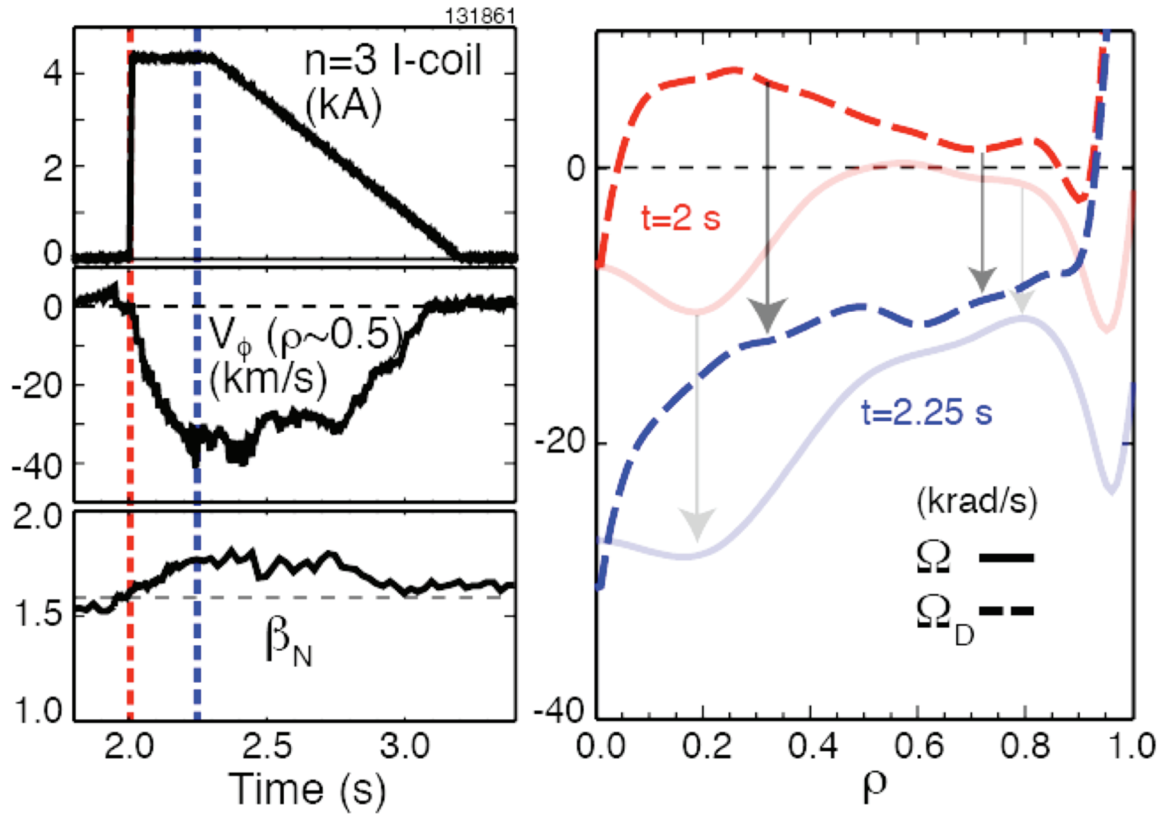
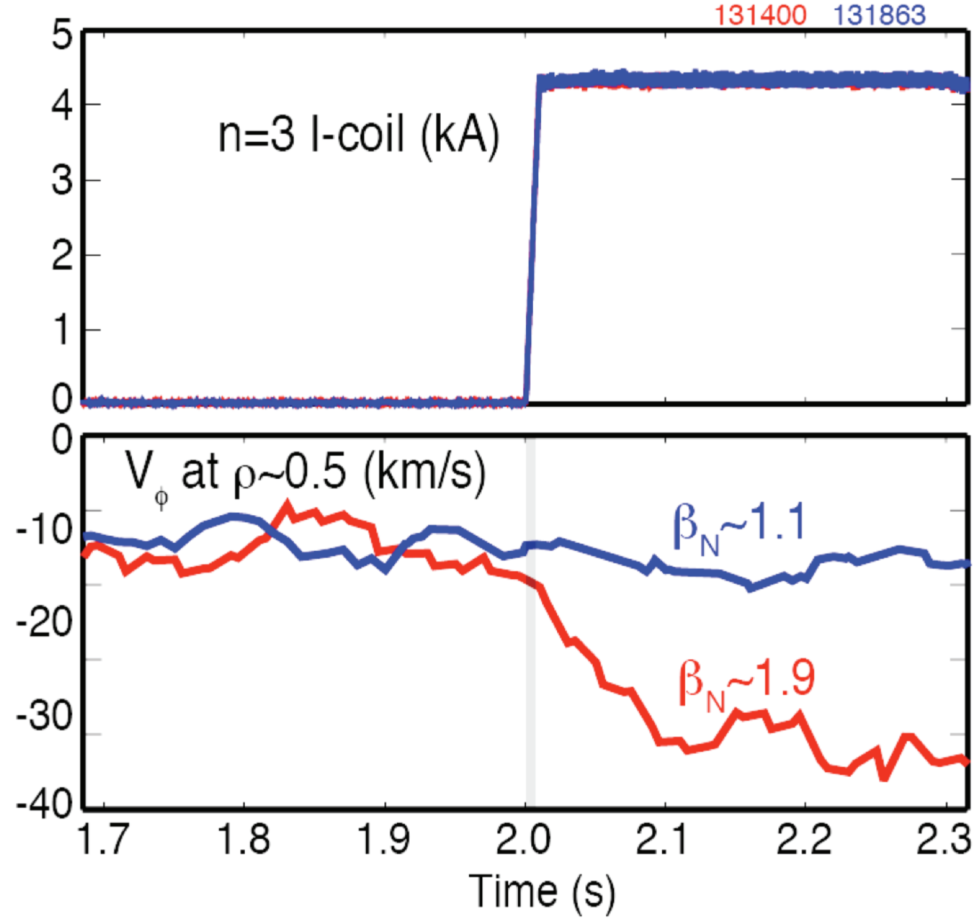


- **Small β_N increase consistent with *ExB* shear stabilization**
  - Small reduction in calculated ITG growth rates

Little or No Acceleration Observed at Low Plasma β

- **Slow counter-I_p rotation discharges**
- **Both NRMF torque and offset rotation may be reduced at lower β_N**
  - Discussed later



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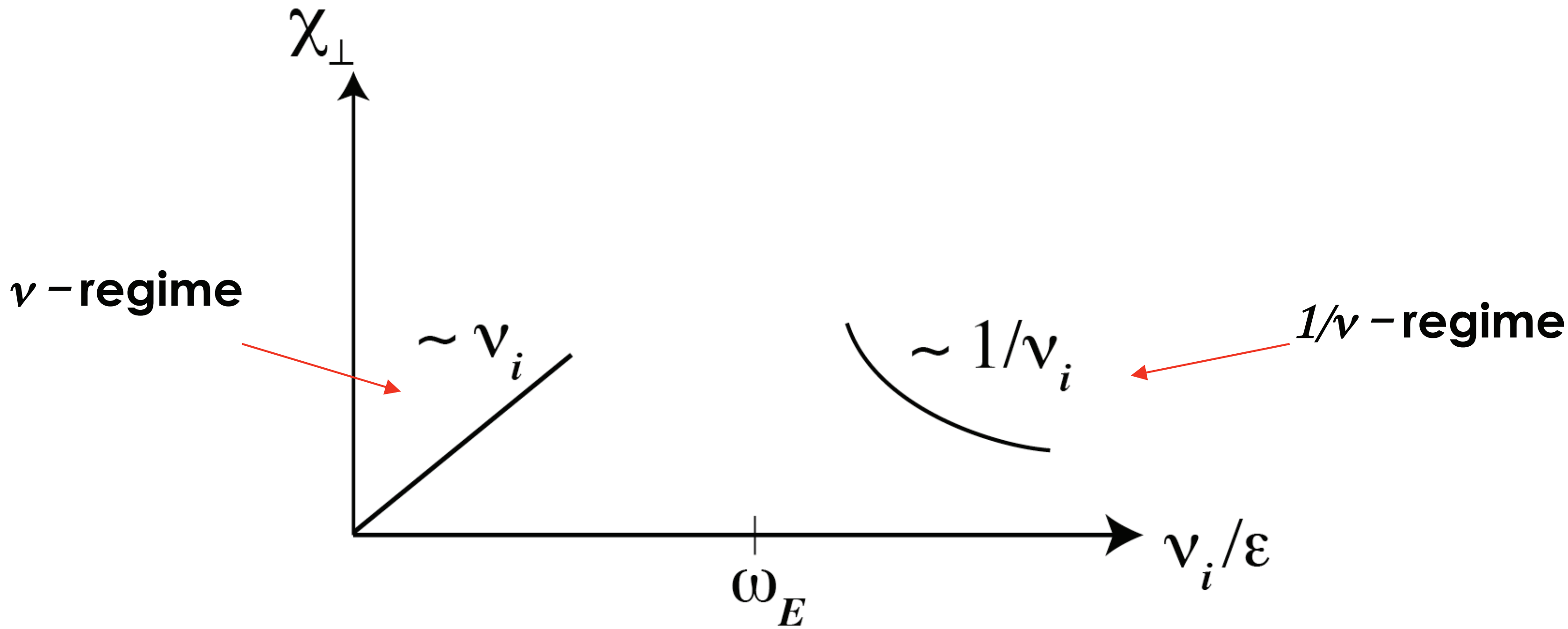
- Evidence of offset rotation
- **Comparison to neoclassical prediction**
- Analysis of torque scaling
- Role of plasma response
- Implications for ITER

Neoclassical NRMF Torque Is Associated With Increased Collisional Transport

- **Low ion collisionality (ν_ι) limit: transport increases as ν_ι**
  - De-correlation rate ~ banana toroidal-drift rate ~ $\omega_E = E_r/RB_\theta$
- **Higher collisionality limit: trapped particle effects diminish as $1/\nu_\iota$**



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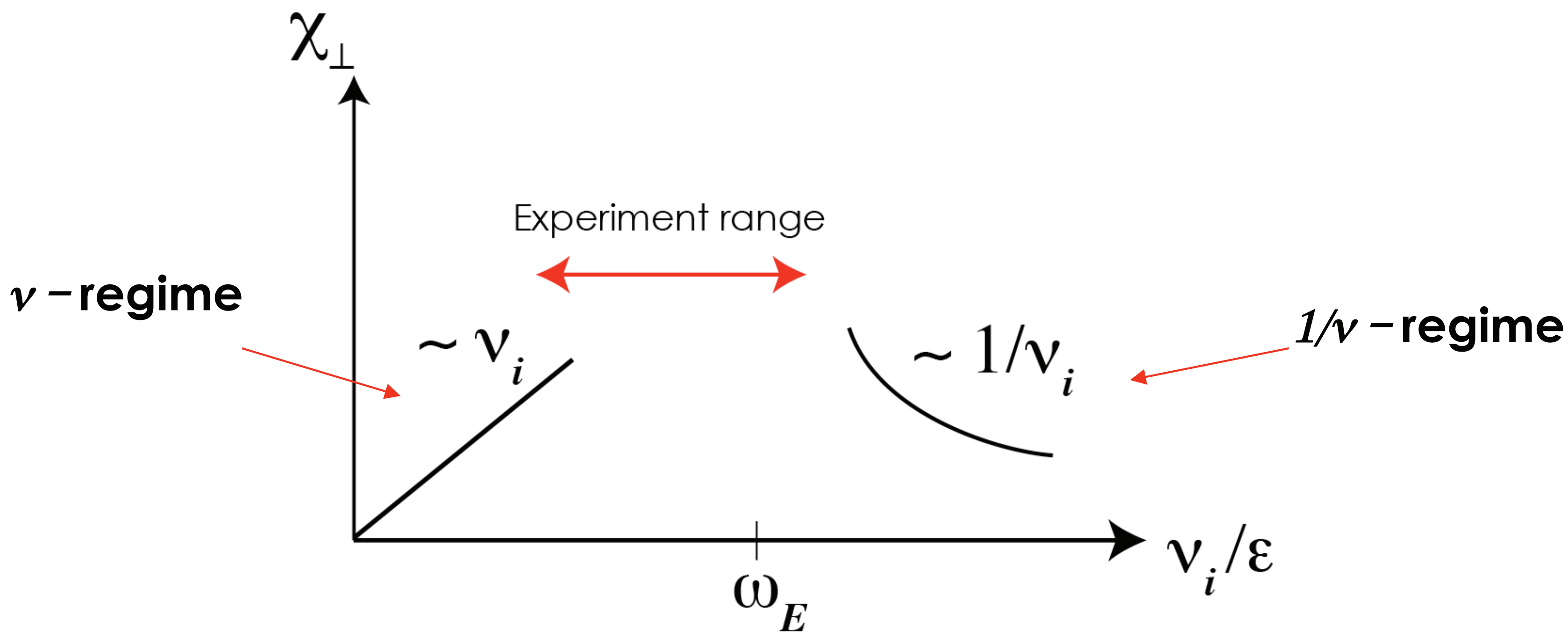
- **Higher collisionality limit: trapped particle effects diminish as $1/\nu_i$**
- **Detailed theory is still being developed in-between limits**



Magnitude and Radial Dependence of Offset Rotation Are Consistent with Theory

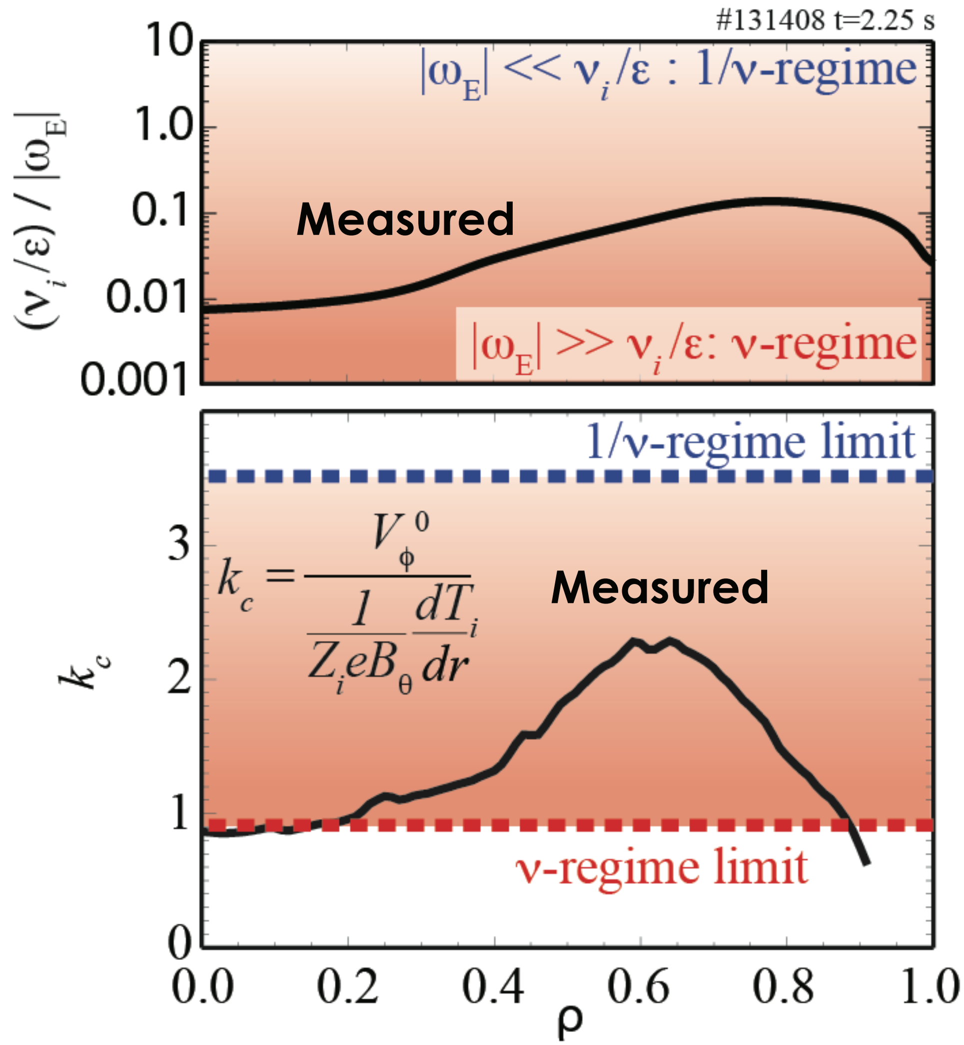
- **Neoclassical model gives offset rotation**

  $V_\phi^{0,NC} = k_c (dT_i/dr)/Z_i e B_\theta$

  with k_c depending on collisionality regime

  - ν regime limit $\rightarrow k_c = 0.9$
  - $1/\nu$ regime limit $\rightarrow k_c = 3.5$

- **V_ϕ^0 = experimental offset rotation**
- **Values of $k_c(\rho)$ fall within theoretical limits for ν and $1/\nu$ regimes**



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Dominant Scaling Factors in Neoclassical NRMF Torque Depend on Collisionality Regime

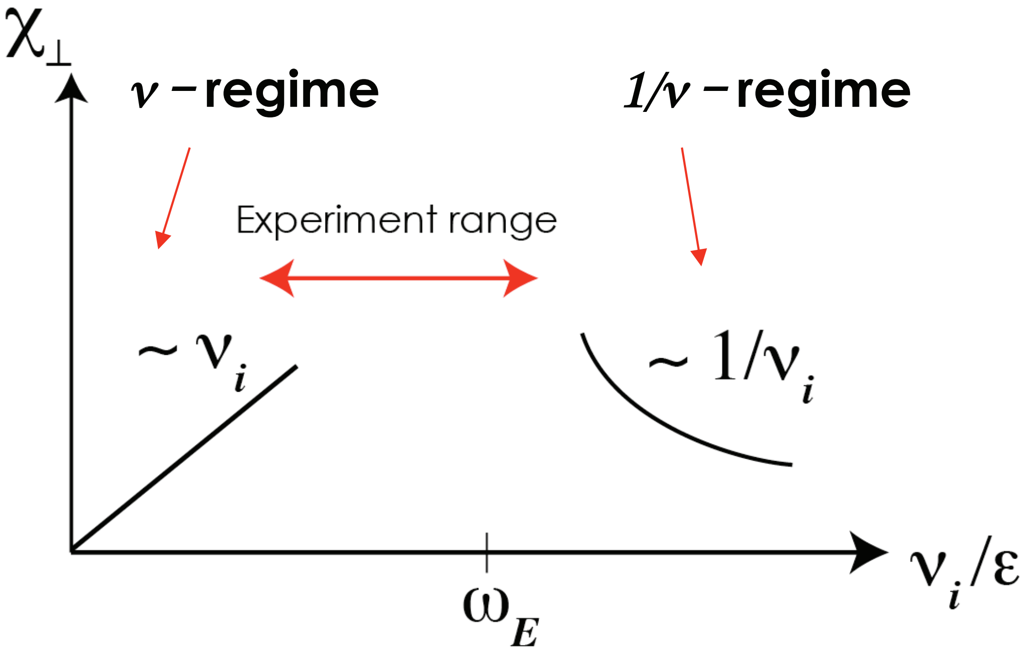
- **Low collisionality ν-regime:**

$$T_{NRMF,\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\, n_i T_i^{-1/2} \omega_E^{-2}$$

- **Higher collisionality $1/\nu$-regime:**

$$T_{NRMF,1/\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\, n_i^{-1} T_i^{5/2}$$

- δB = magnetic perturbation $\propto \delta I_{I\text{-coil}}$



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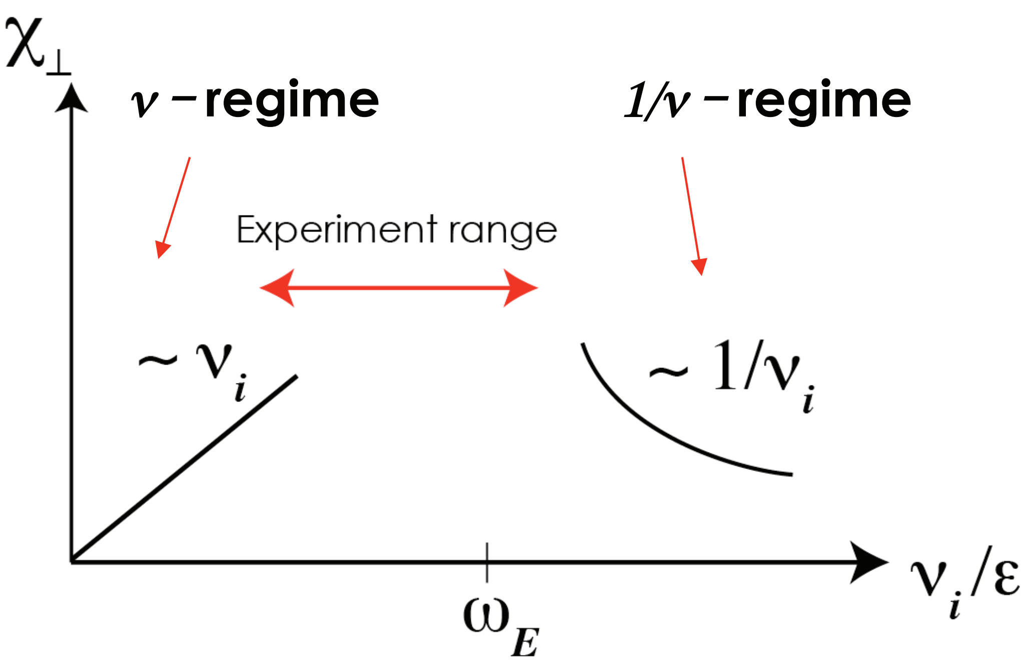
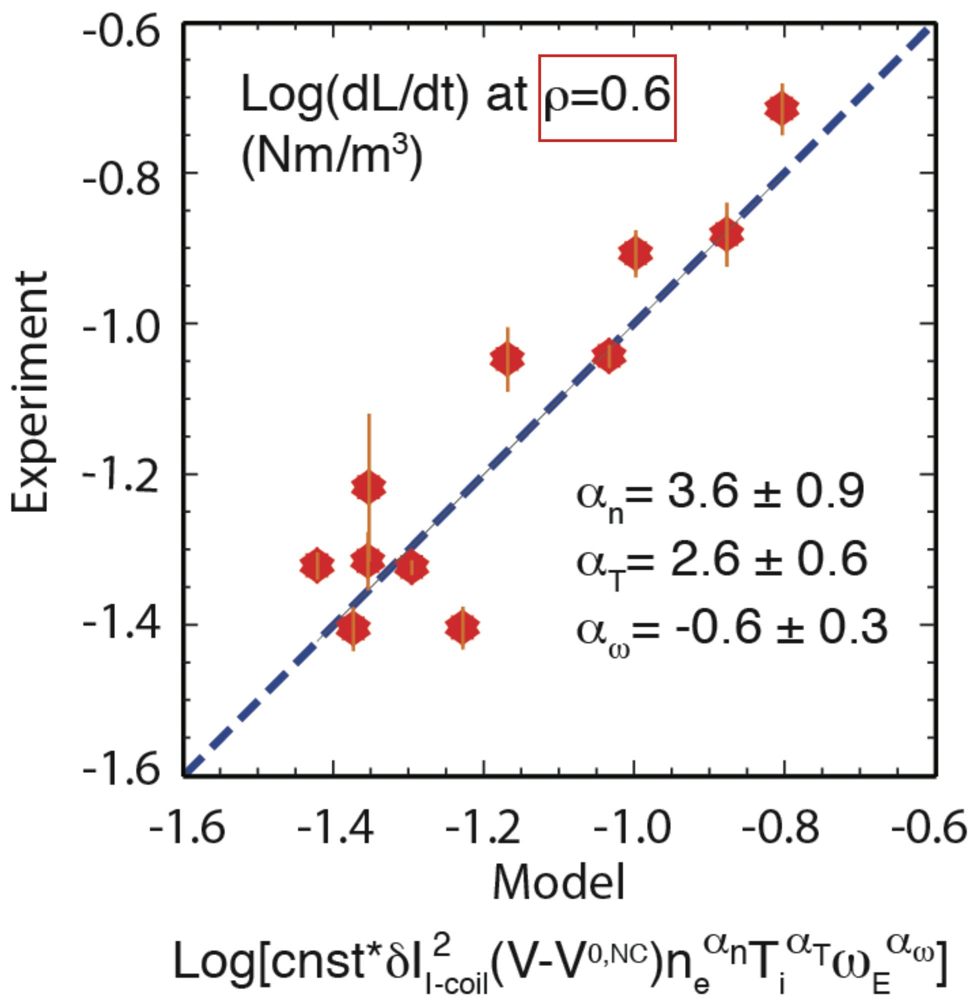


Exponents

	ν		$1/\nu$
$\delta I_{I\text{-coil}}$	2		2
$V_\phi - V_\phi^{0,NC}$	1		1
ω_E	-2		0
n_i	1		-1
T_i	-0.5		2.5

Database Analysis Shows Strong Dependence of NRMF Torque on n_i, Above Expected



- Co-I_p rotation discharges
- ±20% variation in V_ϕ
- ±15% variation in β_N
- ±25% variation in n_i and T_i

	ν	*Exp.*	$1/\nu$
$\delta I_{I\text{-coil}}$	2	2	2
$V_\phi - V_\phi^{0,NC}$	1	1	1
ω_E	-2	-0.6	0 ✓
n_i	1	3.6	-1 ⃠
T_i	-0.5	2.6	2.5 ✓

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Measured Plasma Response to External n=3 Field Shows Significant β-dependence

- **Magnetic measurements:**

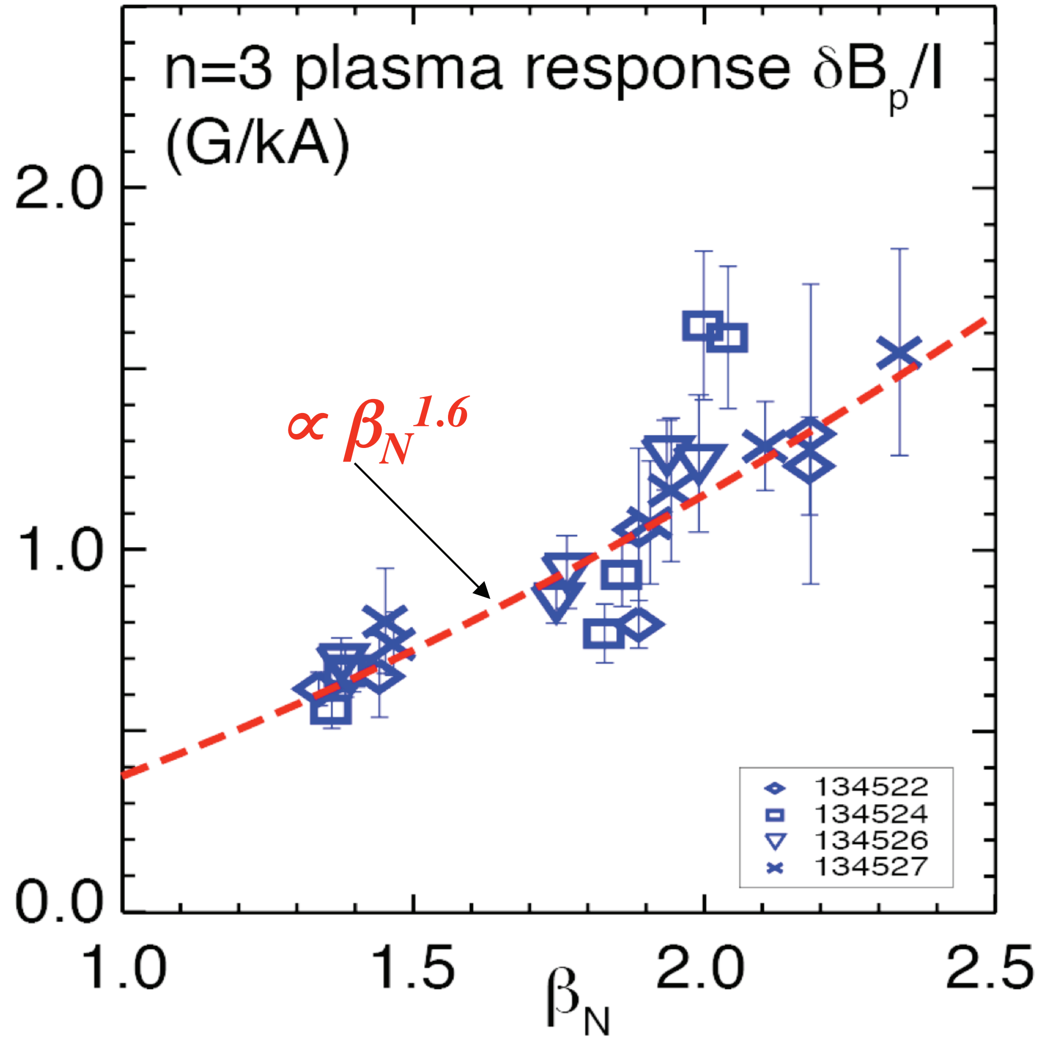
$$\delta B^{plasma} \propto \delta I_{I\text{-}coil}\, \beta_N^{1.6}$$

- **If** $\delta B^{plasma} > \delta B^{external}$ **(inside plasma):**

$$\delta B^2 = (\delta B^{pl} + \delta B^{ext})^2 \sim (\delta B^{pl})^2$$

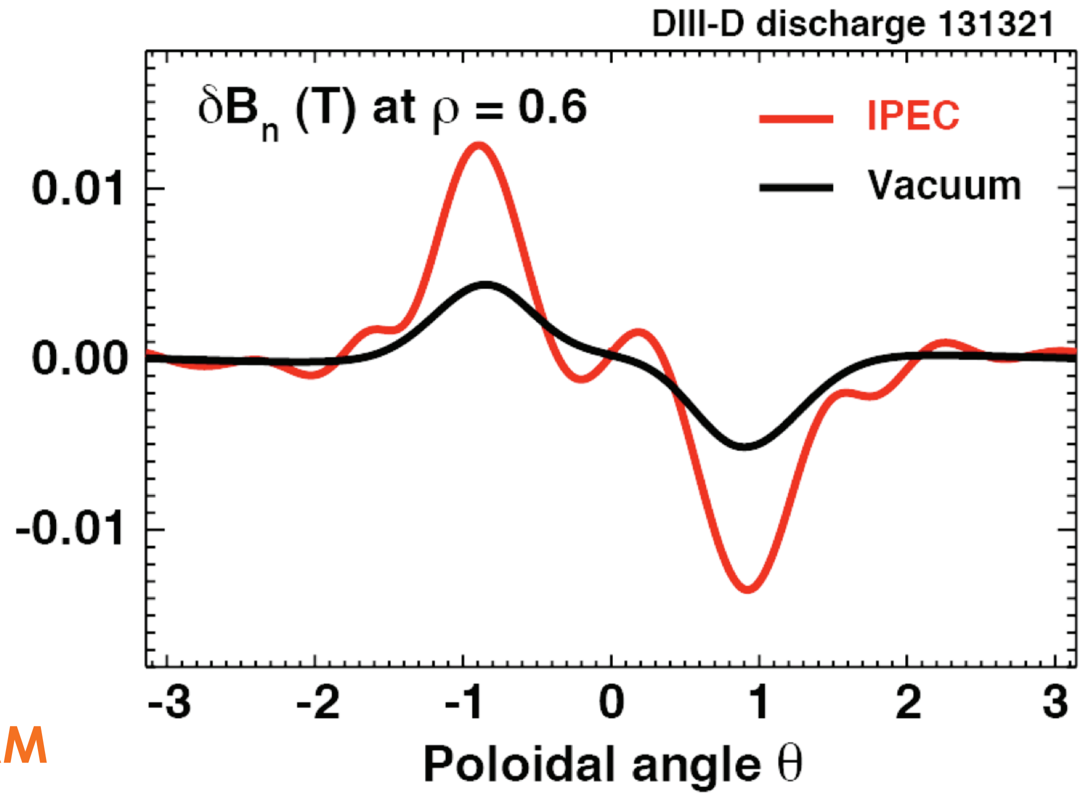
$$\propto (\delta I_{I\text{-}coil}\, \beta_N^{1.6})^2$$

$$\sim (\delta I_{I\text{-}coil})^2\, (n_i T_i)^{3.2}$$



Ideal MHD Modeling Supports Hypothesis That $\delta B^{plasma} > \delta B^{external}$ Inside Plasma

- **IPEC simulation of n=3 mode excitation by I-coil**
  - [IPEC is based on DCON and VACUUM stability codes] [Park, Boozer, and Glasser, Phys. Plasmas (2007)]
- $\beta_N = 1.8 \ll \beta_N^{no\text{-}wall,n=3} \sim 2.7$



Park, GI1.00005, Tuesday AM

Modifications of Model to Account for Plasma Response

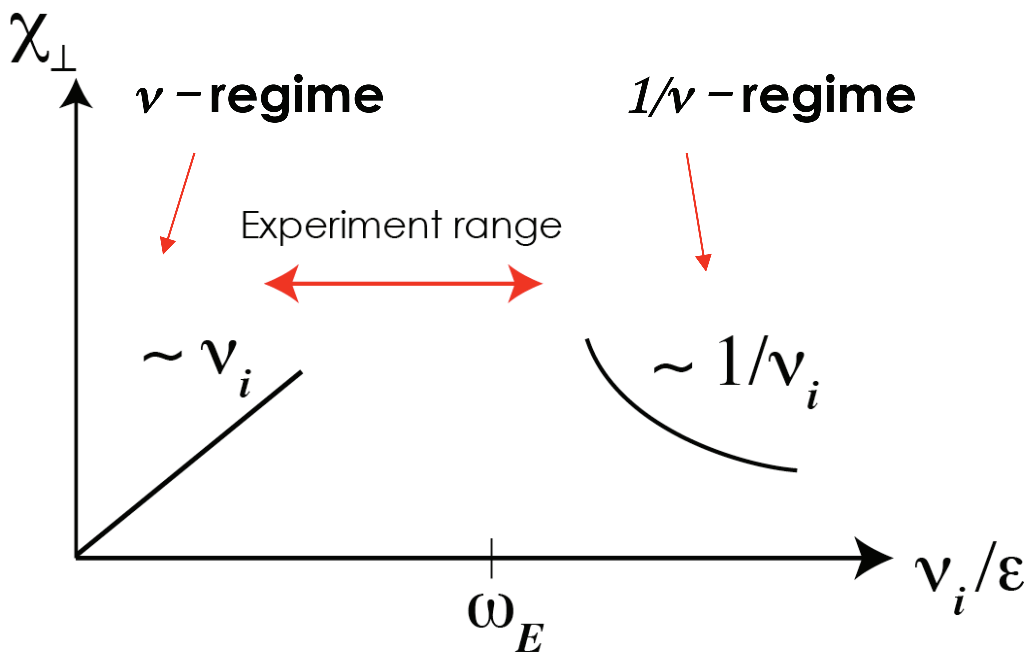
- **Low collisionality ν-regime:**

$$T_{NRMF,\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\, n_i T_i^{-1/2} \omega_E^{-2}$$

- **Higher collisionality $1/\nu$-regime:**

$$T_{NRMF,1/\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\, n_i^{-1} T_i^{5/2}$$

- ***δB = magnetic perturbation $\propto \delta I_{I\text{-}coil} (n_i T_i)^{1.6}$***



	ν	Exp.	$1/\nu$
$\delta I_{I\text{-}coil}$	2	2	2
$V_\phi - V_\phi^{0,NC}$	1	1	1
ω_E	-2	-0.6	0
n_i	1+3.2	3.6	-1+3.2
T_i	-0.5+3.2	2.6	2.5+3.2

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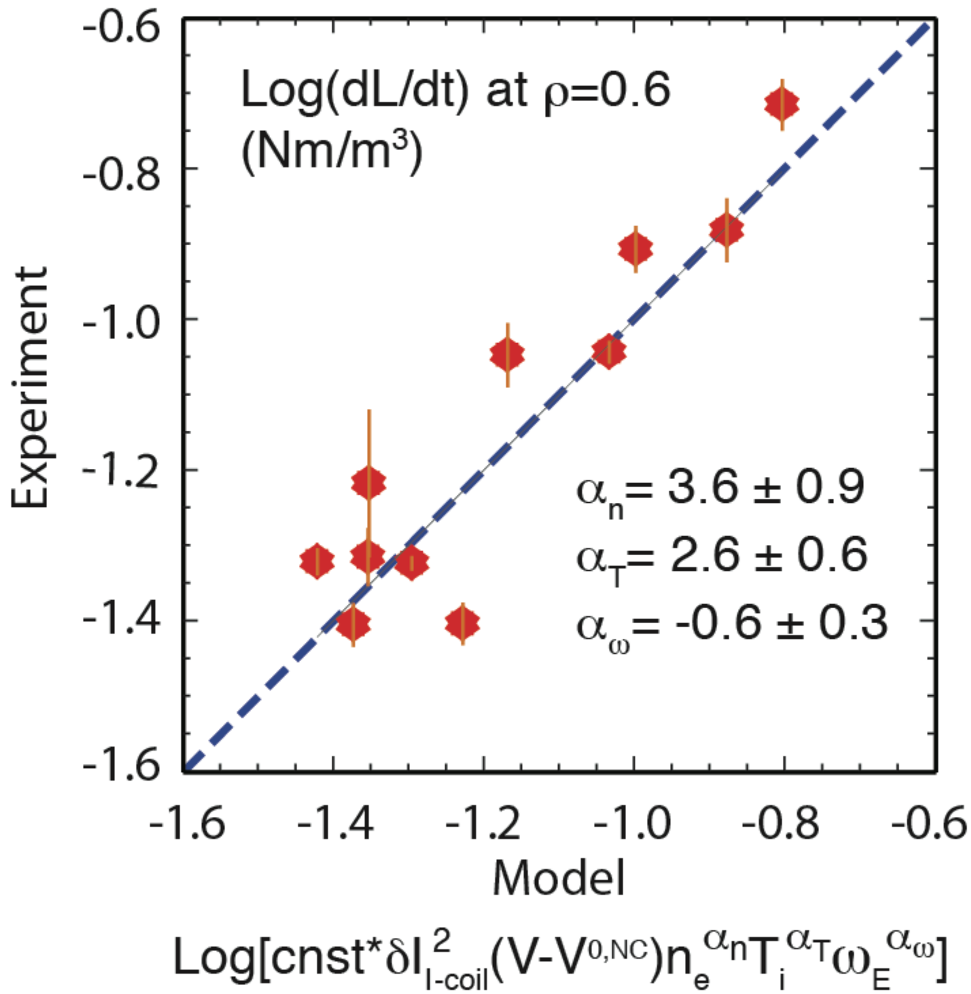
Empirical Scalings Within Theoretical Limits for ν and $1/\nu$ Regimes, with Modifications for Plasma Response



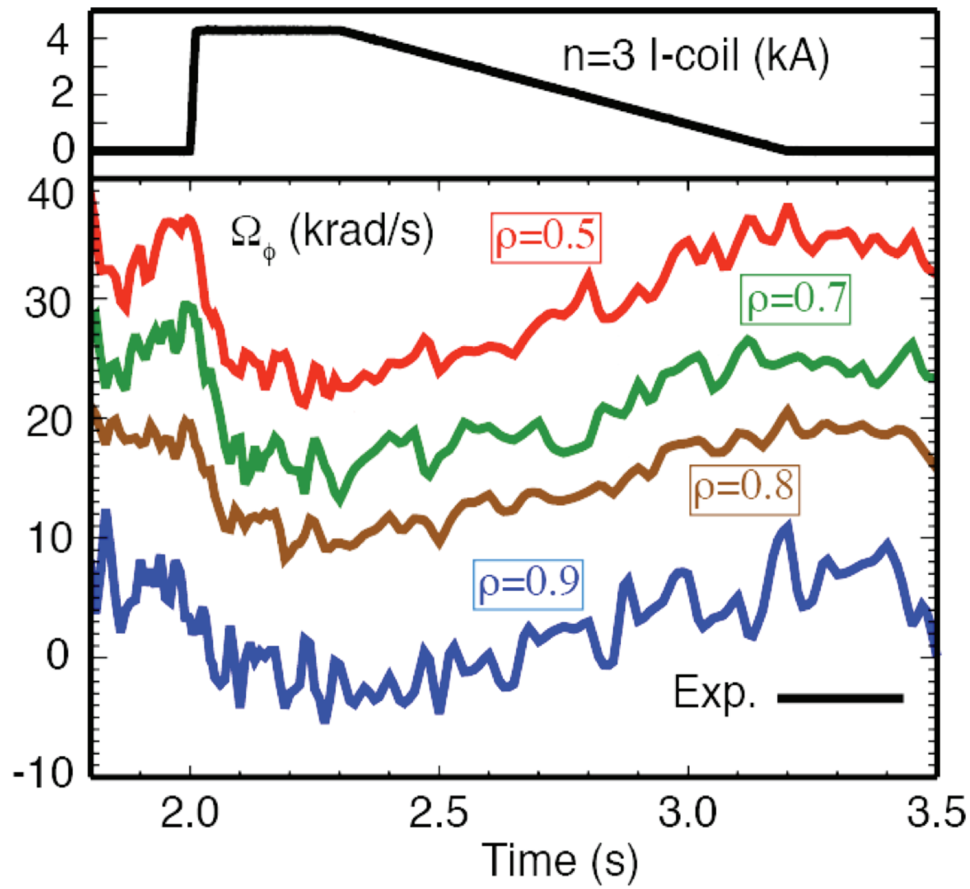
- **Co-I_p rotation discharges**
- **±20% variation in V_ϕ**
- **±15% variation in β_N**
- **±25% variation in n_i and T_i**

	ν	*Exp.*	$1/\nu$
$\delta I_{I\text{-}coil}$	2	2	2
$V_\phi - V_\phi^{0,NC}$	1	1	1
ω_E	-2	-0.6	0
n_i	4.2	3.6	2.2
T_i	2.7	2.6	5.7

Rotation Profile Evolution Consistent with Measured Torque Varied According to Empirical Scalings

- **Evolve measured torque profile according to:**

$$T_{NRMF} \propto \delta I_{Ic}^{2} (V_{\phi} - V_{\phi}^{0,NC})^{1} n_{i}^{3.6} T_{i}^{2.6} \omega_{E}^{-0.6}$$



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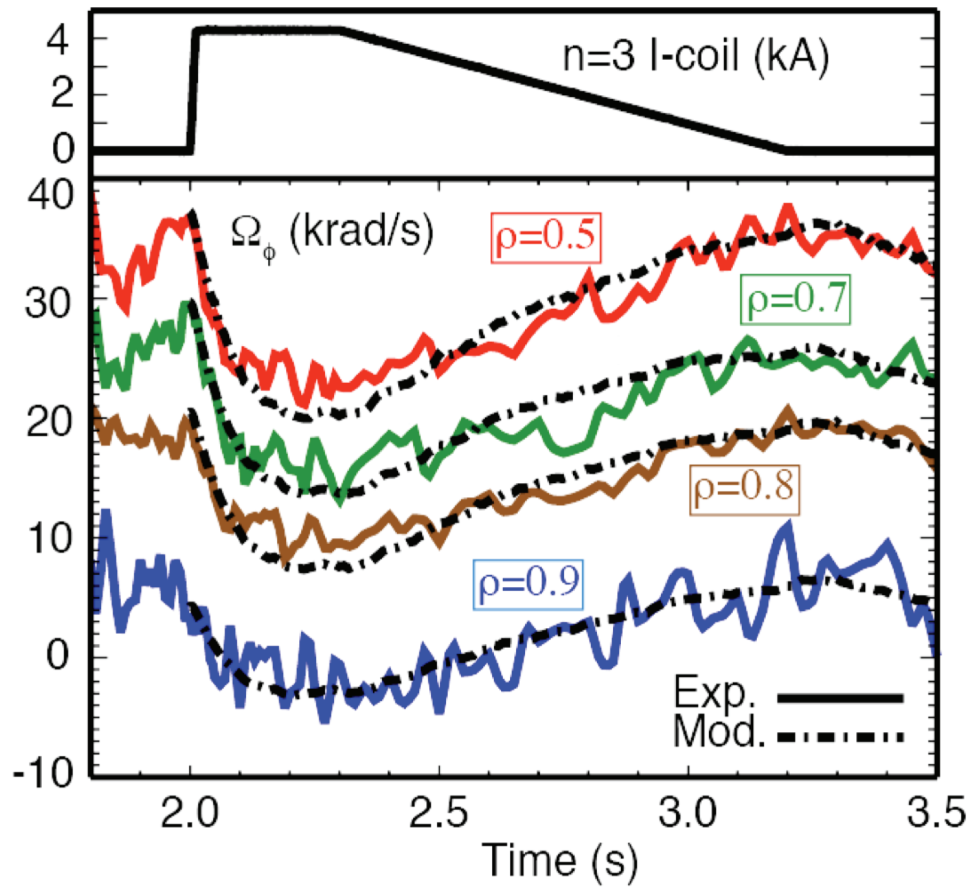
$$T_{NRMF} \propto \delta I_{Ic}^{\,2} (V_\phi - V_\phi^{0,NC})^1 n_i^{3.6} T_i^{2.6} \omega_E^{-0.6}$$

- **Simulate rotation evolution using momentum balance in TRANSP**

$$mnR\frac{\partial V_\phi}{\partial t} = \sum T + \nabla \cdot \left(mnR\chi_\phi \frac{\partial V_\phi}{\partial r} \right)$$

- **Use momentum diffusivity χ_ϕ from evolution without NRMF**



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Large NRMF Torque Is Associated with High-n Fields Planned for ELM Suppression in ITER

- **Expected NRMF damping time from ELM-suppression fields:**

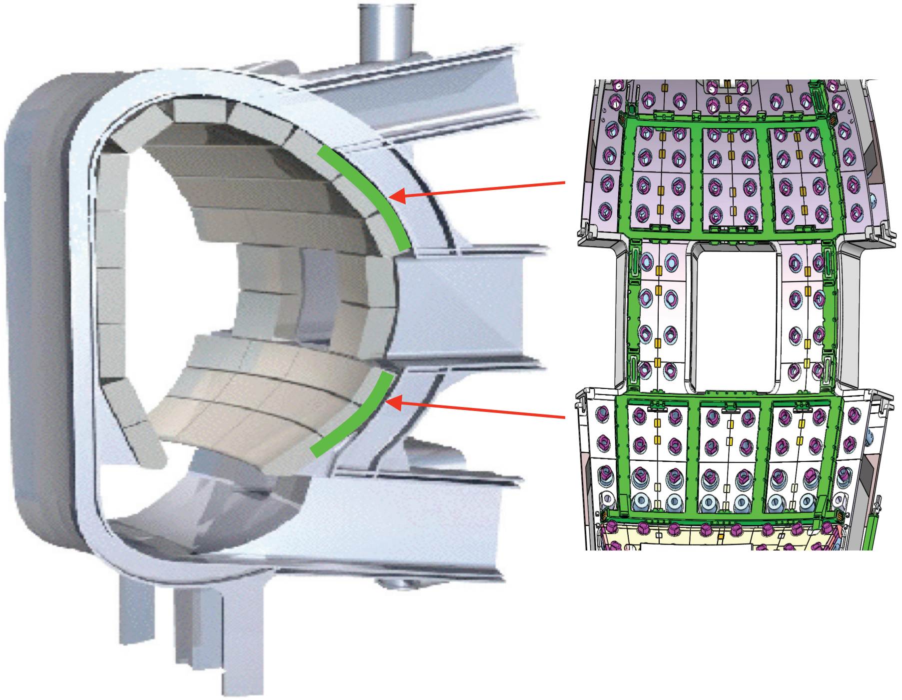
  τ_{dam} **~ 10 ms**

  [Becoulet et al., IAEA (2008)]

  τ_{dam} **~ 10-100 ms**

  [Park et al., IAEA (2008)]

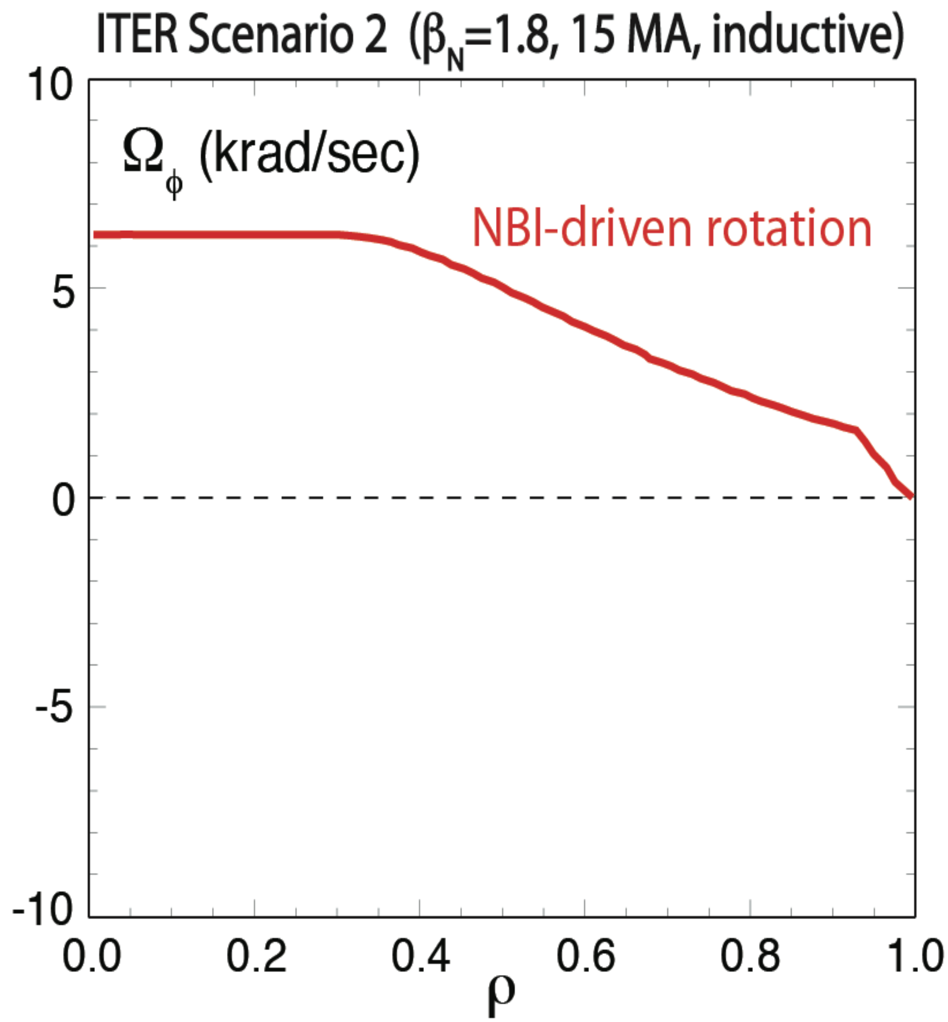
- **Rotation in ITER will depend on T_{NRMF} / T_{NBI} (= τ_L / τ_{dam})**
  - $\tau_L \sim \tau_E = 3.7$ s
- **T_{NRMF} ~ 40-400x T_{NBI}**



T_{NRMF} >> T_{NBI} in ITER May Force Plasma Flow in Counter-Ip Direction, Close to "Offset" Rotation

- **NBI-driven rotation from ASTRA Code simulation**

  [Polevoi et al., Nucl. Fusion (2005)]



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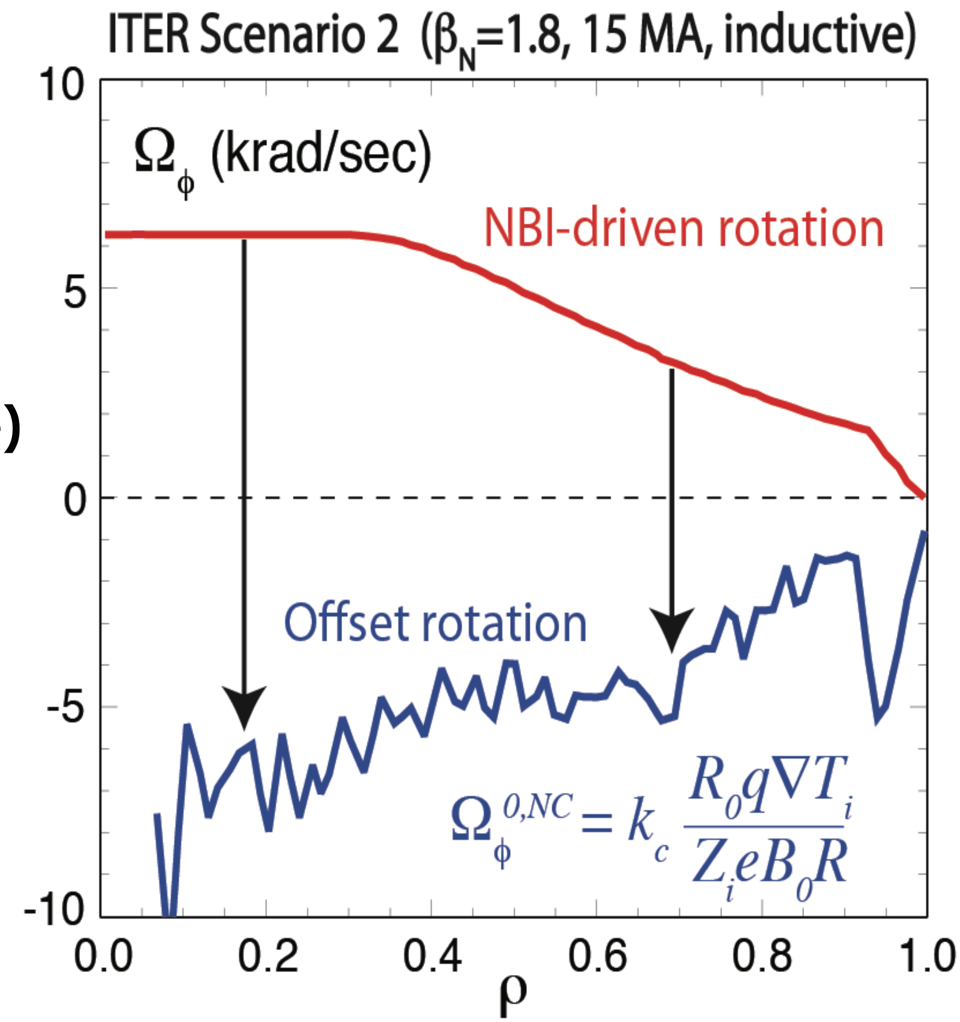
- **NBI-driven rotation from ASTRA Code simulation**
  [Polevoi et al., Nucl. Fusion (2005)]

- **Neoclassical offset rotation with k_c from DIII-D experiments (ν-regime)**
  - $\Omega_\phi^{0,NC} \sim 0.4\% \Omega_A$
  - May be sufficient to benefit confinement and stability



Summary

- **Evidence that static NRMF can accelerate plasma rotation toward "offset" value, consistent with neoclassical theory**
- **NRMF torque parameter scalings within theoretical limits for ν and $1/\nu$ regimes, when plasma response to NRMF is included**
  - β-dependence of plasma response accounts for strong NRMF torque dependence on $n_i T_i$
- **ELM suppression fields in ITER may force counter-Ip (rapid) rotation, even with co-Ip NBI**