Effect of Non-axisymmetric Fields on Toroidal Rotation Dynamics

By

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In collaboration with

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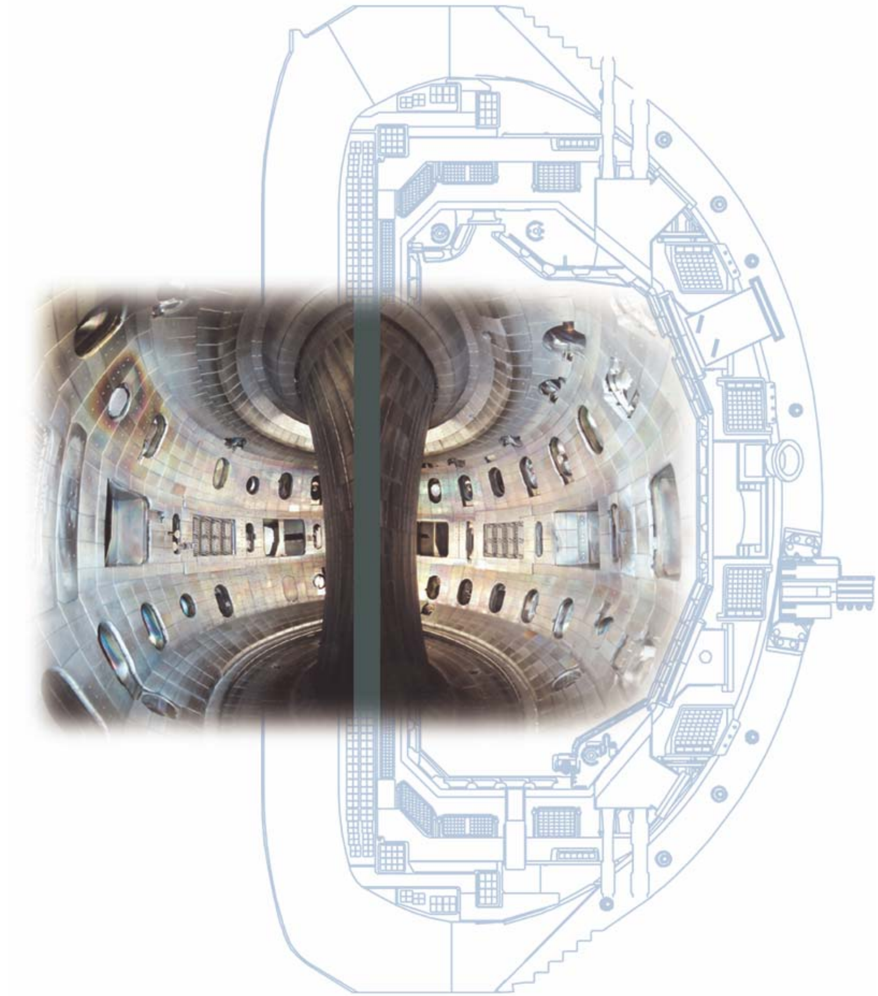

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

Motivation

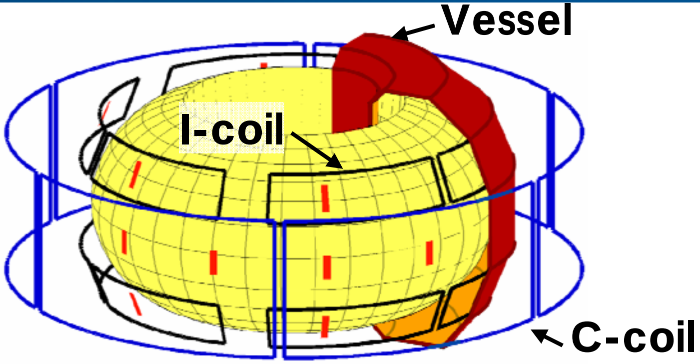
- Rotation is generally considered beneficial to fusion plasmas
- Performance of future devices may be influenced by attained rotation profile
- However, external momentum input from neutral beams in burning plasma devices expected to be small
  - Need to develop new tools for driving rotation
- The use of non-axisymmetric fields provides new opportunity for rotation control

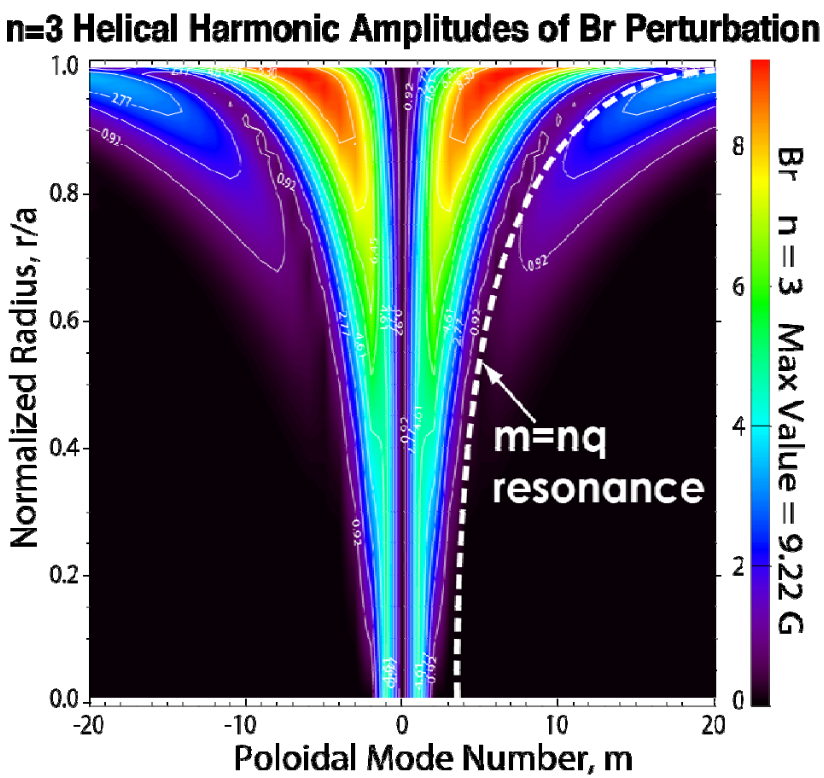
Non-Axisymmetric Fields Are Produced Using Coils; Rotation Control Through Use Of Co+Counter Beams

- **Non-axisymmetric magnetic spectrum can be configured to produce predominantly non-resonant components**
  - Opposite "parity" compared with resonant magnetic perturbation (RMP) ELM suppression

- **External torque from neutral beams can be adjusted at constant power**
  - Up to 10 MW power with balanced momentum input

- **Together provide excellent tools for investigating the effect of non-resonant magnetic fields (NRMFs) on rotation**





Outline

- **Modeling of torque from NRMFs**
- **Interaction of NRMF torque with intrinsic rotation drive**
- **Enhancement of NRMF torque at low rotation**

Application of NRMF Drags Plasma Rotation to Neoclassical Offset Rotation

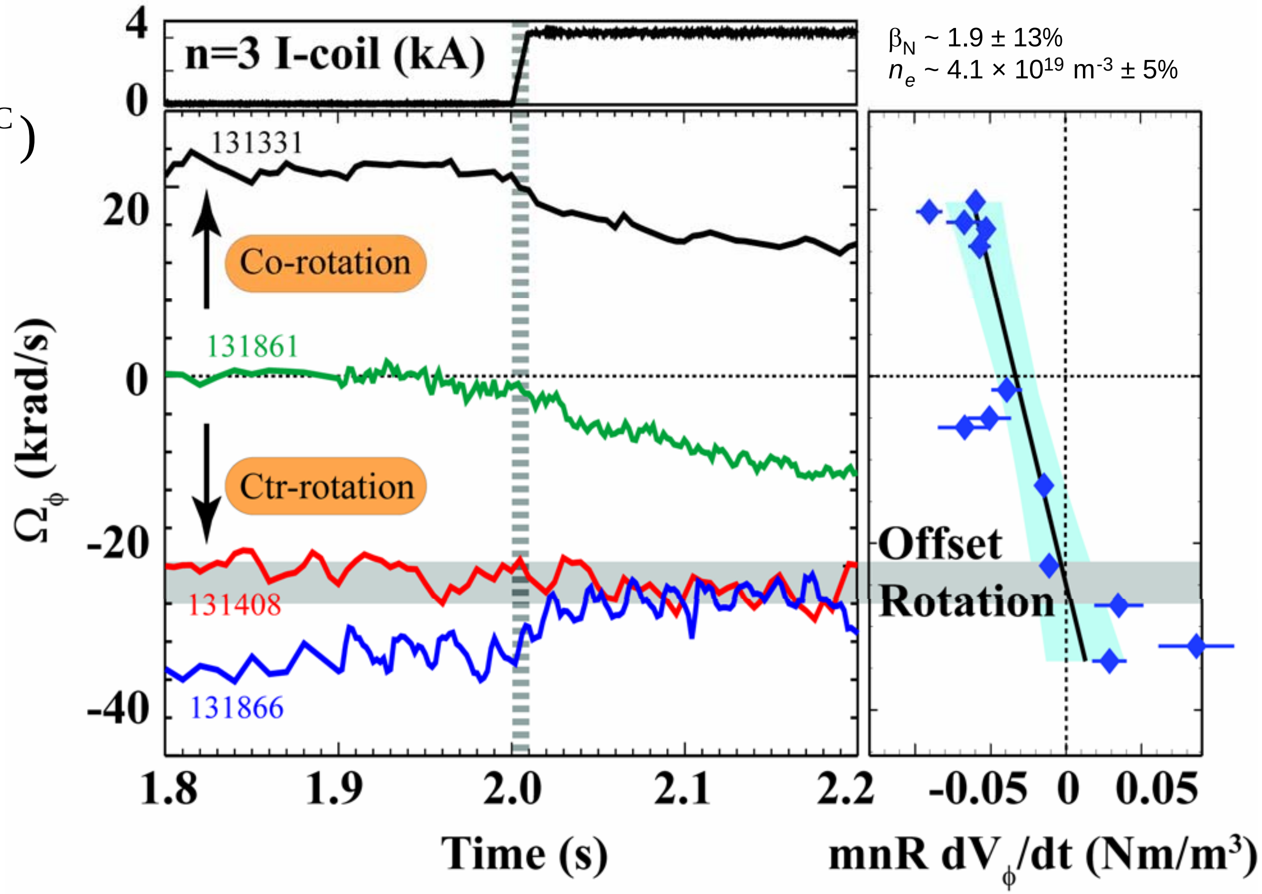
- **NRMF torque minimized at neoclassical "offset rotation"**
  [Cole et al PRL 2007]

$$\eta_{\mathrm{NRMF}} \sim -\delta B^2 (V_\phi - V_\phi^{0,\mathrm{NC}})$$

$$V_\varphi^{0,\mathrm{NC}} \cong \frac{k}{Z_i e B_\theta} \frac{dT_i}{dr}$$

- **Offset rotation in counter I_p direction**

- **Measured torque exhibits offset linear relationship**



Garofalo et al, PRL (2008)

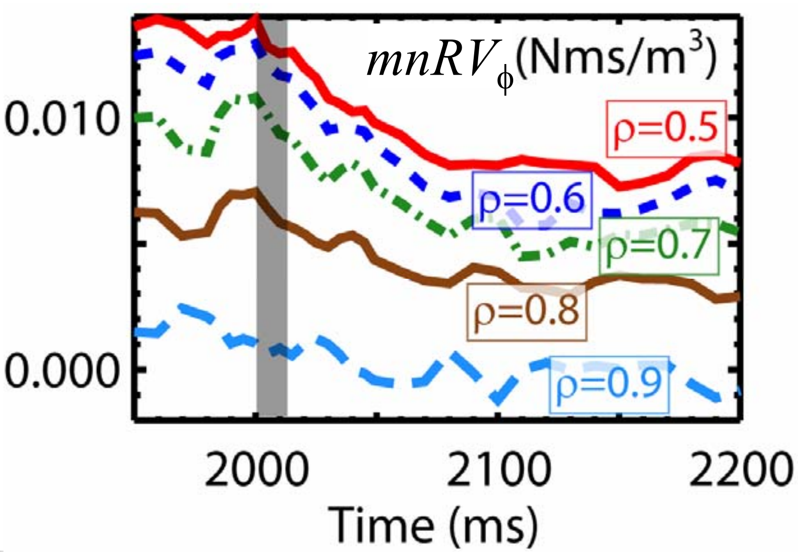
The NRMF Torque Profile As Inferred From Initial Change in Angular Momentum is Relatively Broad

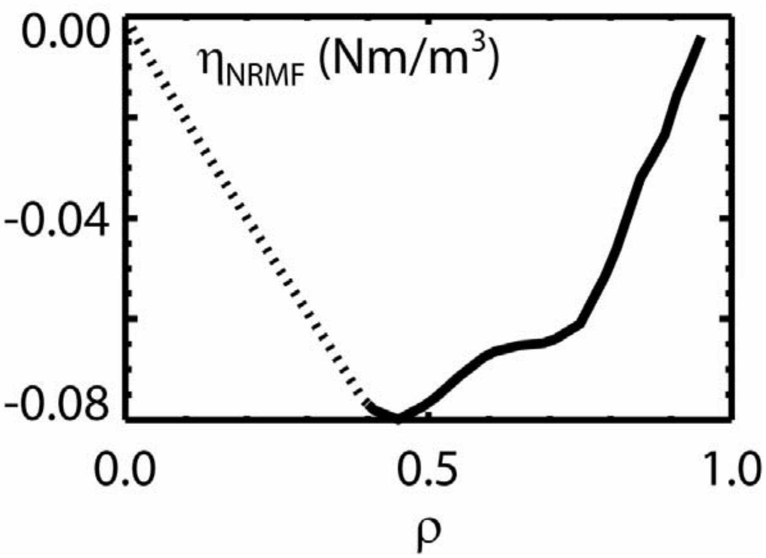
- **CER rotation data converted into angular momentum density**

$$mnRV_\phi$$

- **When field turns on, angular momentum responds to NRMF torque**

$$\frac{d}{dt}\left(mnRV_\phi\right) \sim \eta_{NRMF}$$





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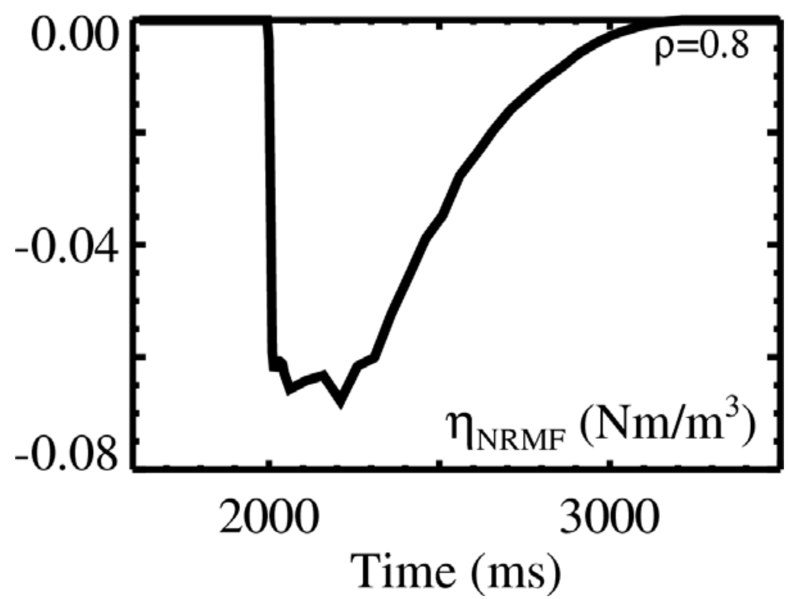
Evolution of the Rotation Profile Is Performed Using TRANSP

- **Evolve rotation using momentum balance**

$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of momentum}} = \underbrace{\sum \eta}_{\text{Momentum sources/sinks}} + \underbrace{\nabla\cdot\left(mnR\chi_\phi^{eff}\frac{\partial V_\phi}{\partial r}\right)}_{\text{Transport}}$$

- **NB torque calculated in TRANSP**



- **Scale initial NRMF torque profile in time as**

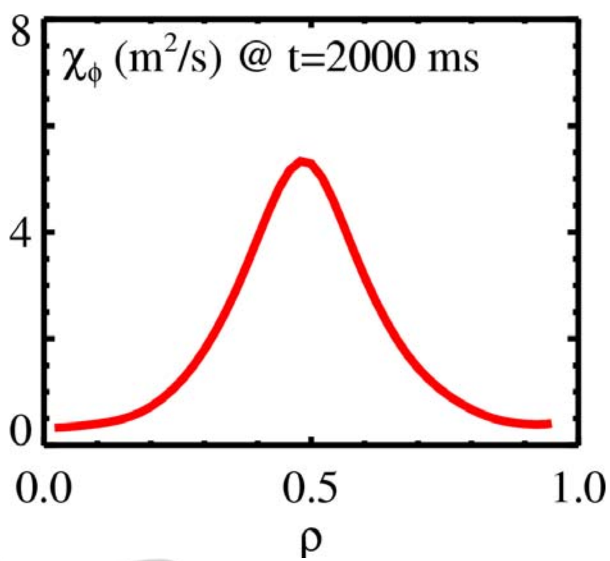
$$\eta_{\mathrm{NRMF}} \sim \delta I^2 n_e^{3.6} T_i^{2.6} \omega_E^{-0.6} (V_\phi - V_\phi^0)$$

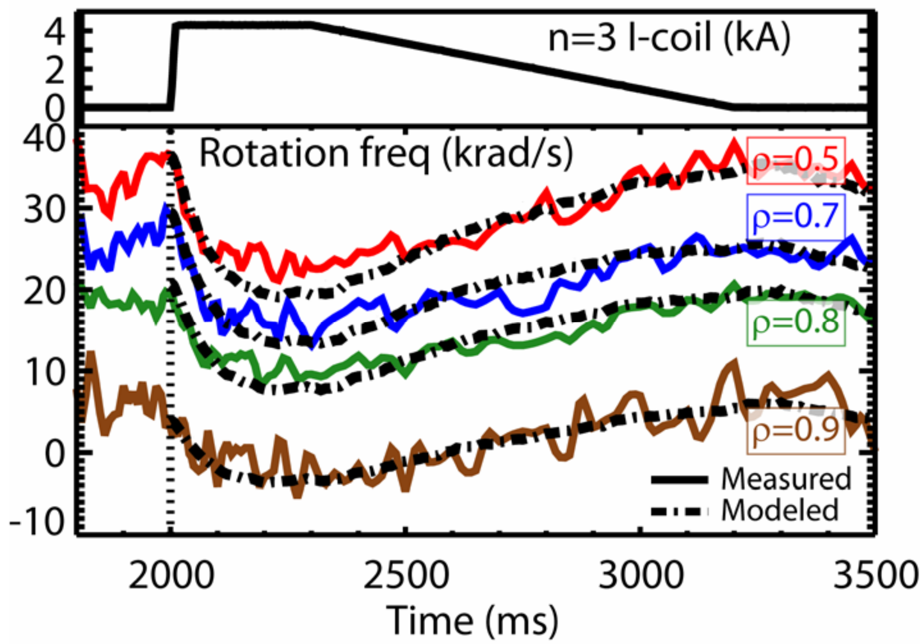
  – Using experimentally determined exponents
  [Garofalo et al, PoP 2009]

Effect of NRMF on Plasma Rotation Is Adequately Modeled Throughout the Discharge

- **Transport characterized by effective momentum diffusivity**
  - Determined from steady state before and after NRMF applied

$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of momentum}} = \underbrace{\sum \eta}_{\text{Momentum sources/sinks}} \underbrace{+\nabla\cdot\left(mnR\chi_\phi^{eff}\frac{\partial V_\phi}{\partial r}\right)}_{\text{Transport}}$$

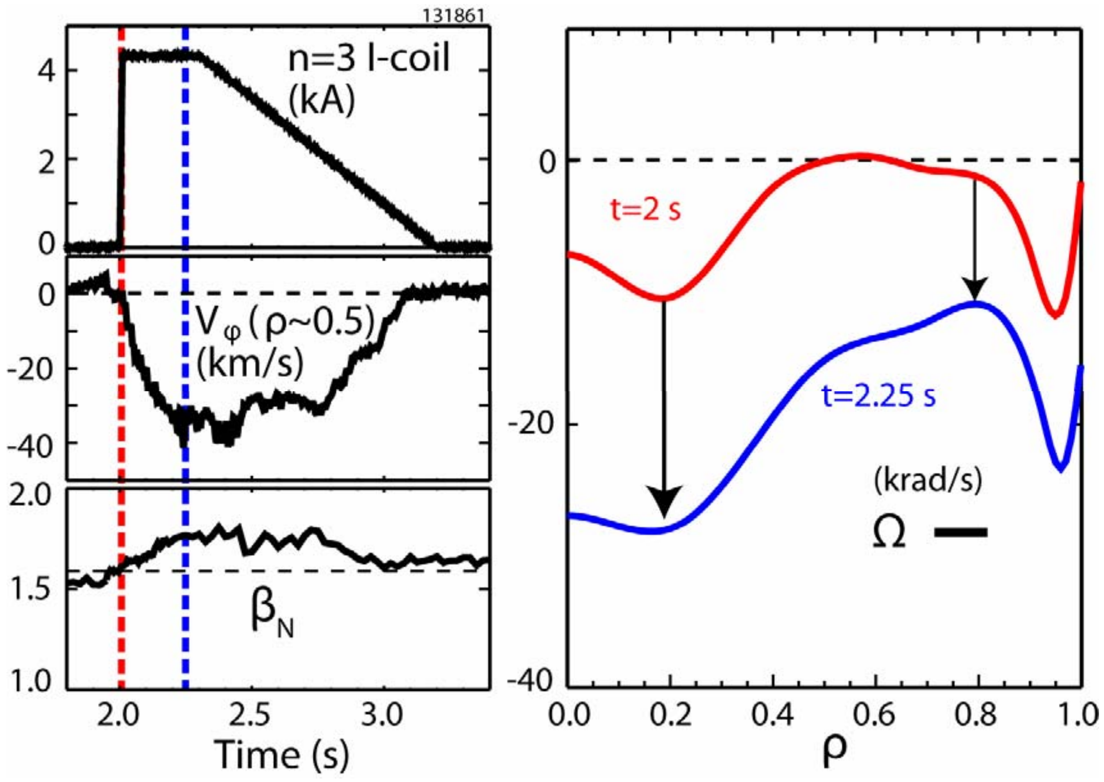




Solomon et al, NF (2009)

n=3 NRMF Leads to Improvement in Energy Confinement at Low Rotation Through Acceleration

- **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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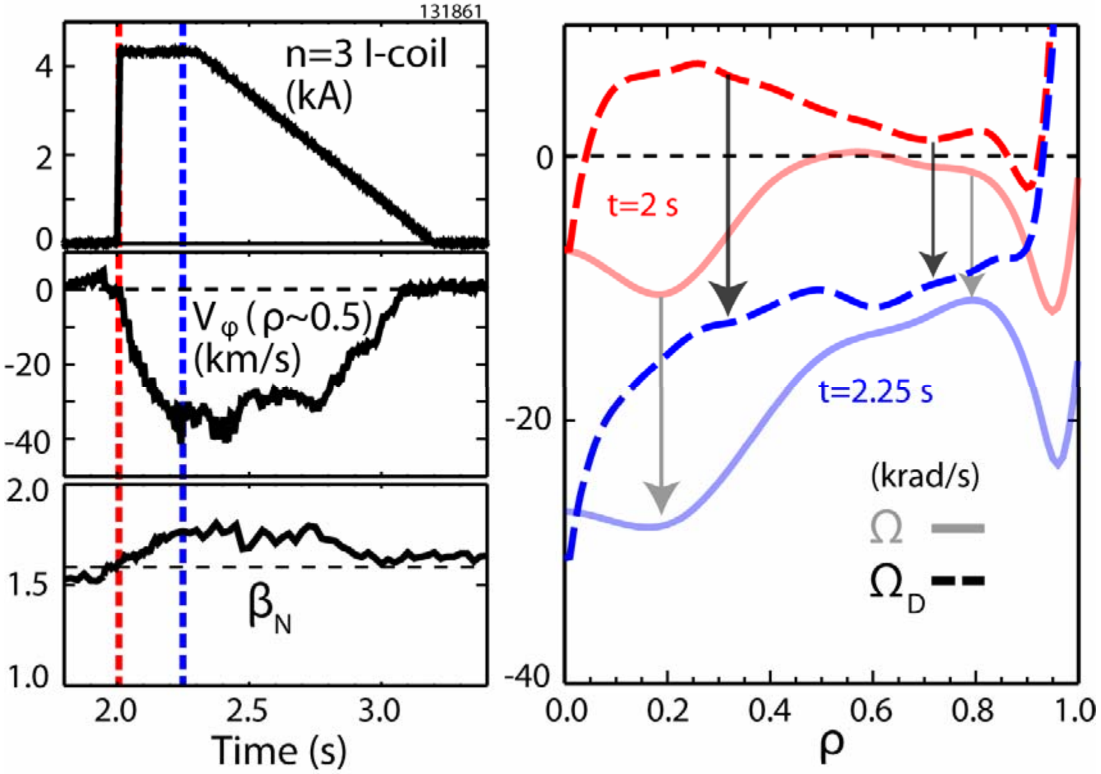


Outline

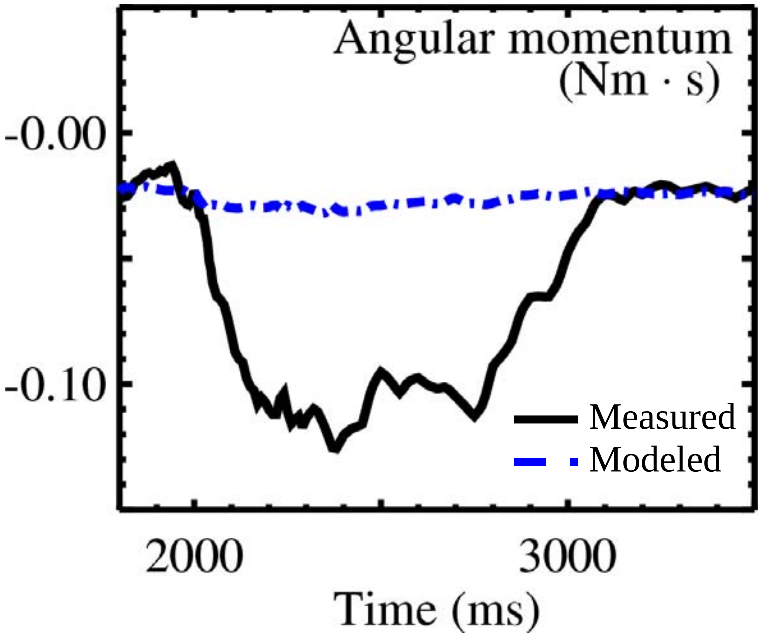
- Modeling of torque from NRMFs
- **Interaction of NRMF torque with intrinsic rotation drive**
- Enhancement of NRMF torque at low rotation

At Low Rotation, Intrinsic Rotation Must Be Considered When Modeling Angular Momentum

- **Again, evolve measured NRMF torque profile in time**

$$\frac{dL}{dt} = -\frac{L(t)}{\tau_\phi(t)} + T_{\mathrm{NBI}}(t) + T_{\mathrm{NRMF}}(t)$$

- **Estimate τ_ϕ before NRMF pulse, then scale τ_ϕ with τ_E**
- **Initial τ_ϕ appears very small**
  - τ_ϕ ~ 7 ms vs τ_E > 50 ms ???
- **Low τ_ϕ means angular momentum barely responds to NRMF torque**
- **Low τ_ϕ artifact of neglecting intrinsic rotation**



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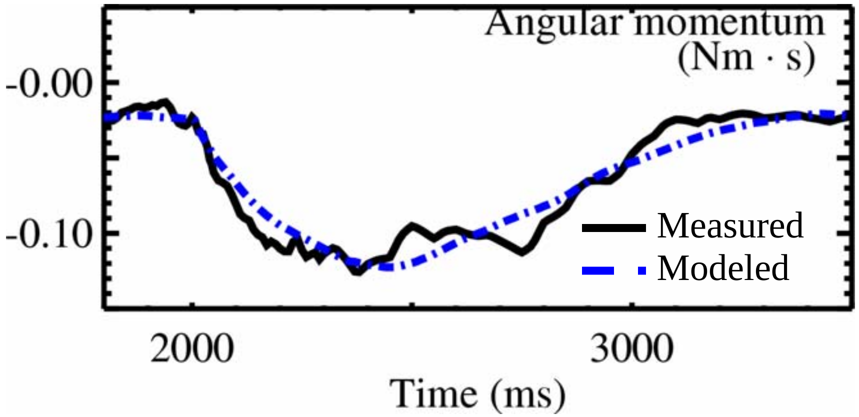
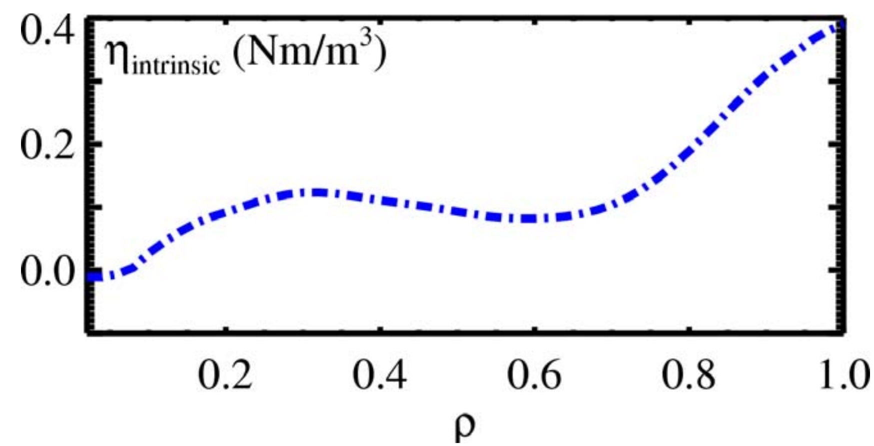
After Accounting For Intrinsic Rotation, Angular Momentum Evolution Can Be Reproduced

- **Include torque associated with intrinsic rotation**
- **Use non-linear least squares fitter to solve for intrinsic source that best reproduces angular momentum evolution**
- **For each ρ, peel off shells to uncover effective intrinsic torque density profile $\eta_{intrinsic}$**
- **Is such an intrinsic source plausible?**

$$\frac{dL}{dt} = -\frac{L(t)}{\tau_\phi(t)} + T_{NBI}(t) + T_{NRMF}(t) + T_{intrinsic}$$





Solomon et al, NF (2009)

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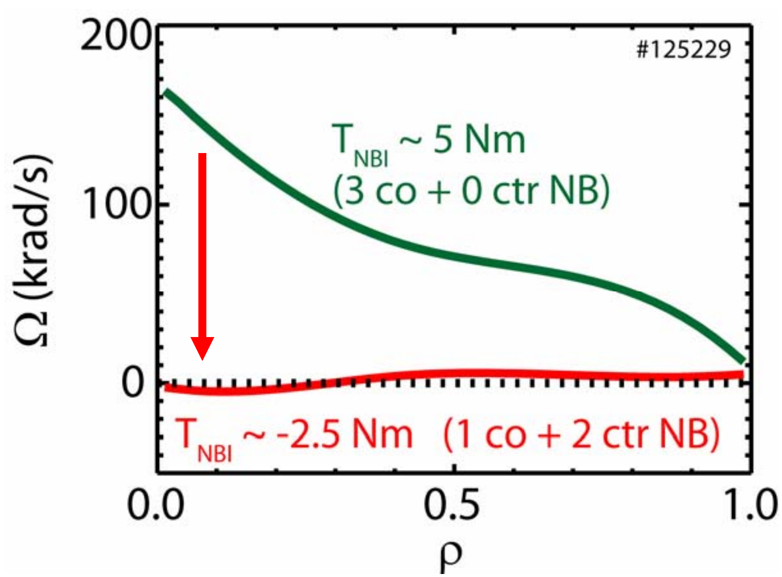
A Finite External Torque Is Required To Overcome Intrinsic Rotation and Bring The Plasma To Rest

- **In steady state, sources balanced against momentum flows**

$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of momentum}} = \underbrace{\sum \eta}_{\text{Momentum sources/sinks}} - \nabla \cdot \left(-mnR\left(\underbrace{\chi_\phi \frac{\partial V_\phi}{\partial r}}_{\text{diffusion}} - \underbrace{V_\phi V_{pinch}}_{\text{pinch}} \right) + \underbrace{\Pi_{RS}}_{\substack{\text{Residual stress} \\ \text{"Intrinsic source"}}} \right)$$



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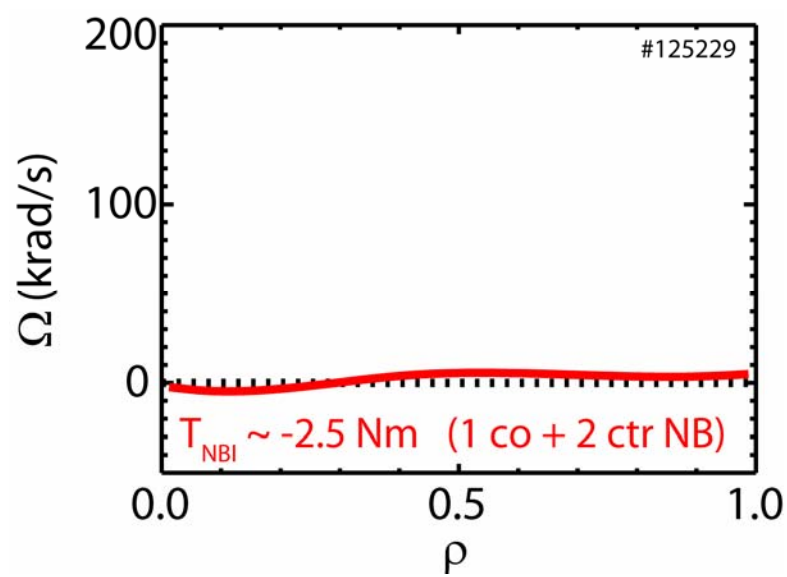
- **Additional non-diffusive off-diagonal contribution from "residual stress"**
  [Dominguez and Staebler, PoFB 1993
  Gurcan et al PoP 2007, Ida et al PRL 1995]

- **When V_ϕ zero, applied NBI torque balances "residual stress" drive**



Intrinsic Source Approximately Equivalent to One Co-Neutral Beam Source

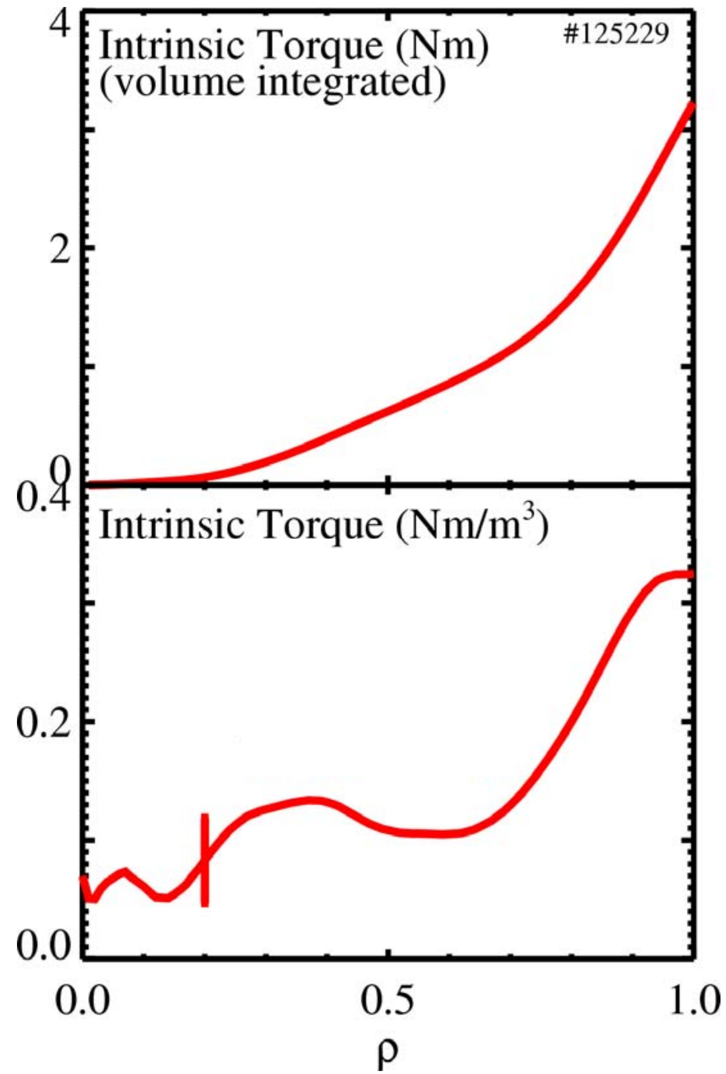
- **Residual stress appears like an intrinsic source**

$$\eta_{\text{intrinsc}} = -\nabla \cdot \Pi_{RS}$$

- **External NBI torque cancels this effective intrinsic source**

$$\eta_{NBI} + \eta_{\text{intrinsic}} = 0$$

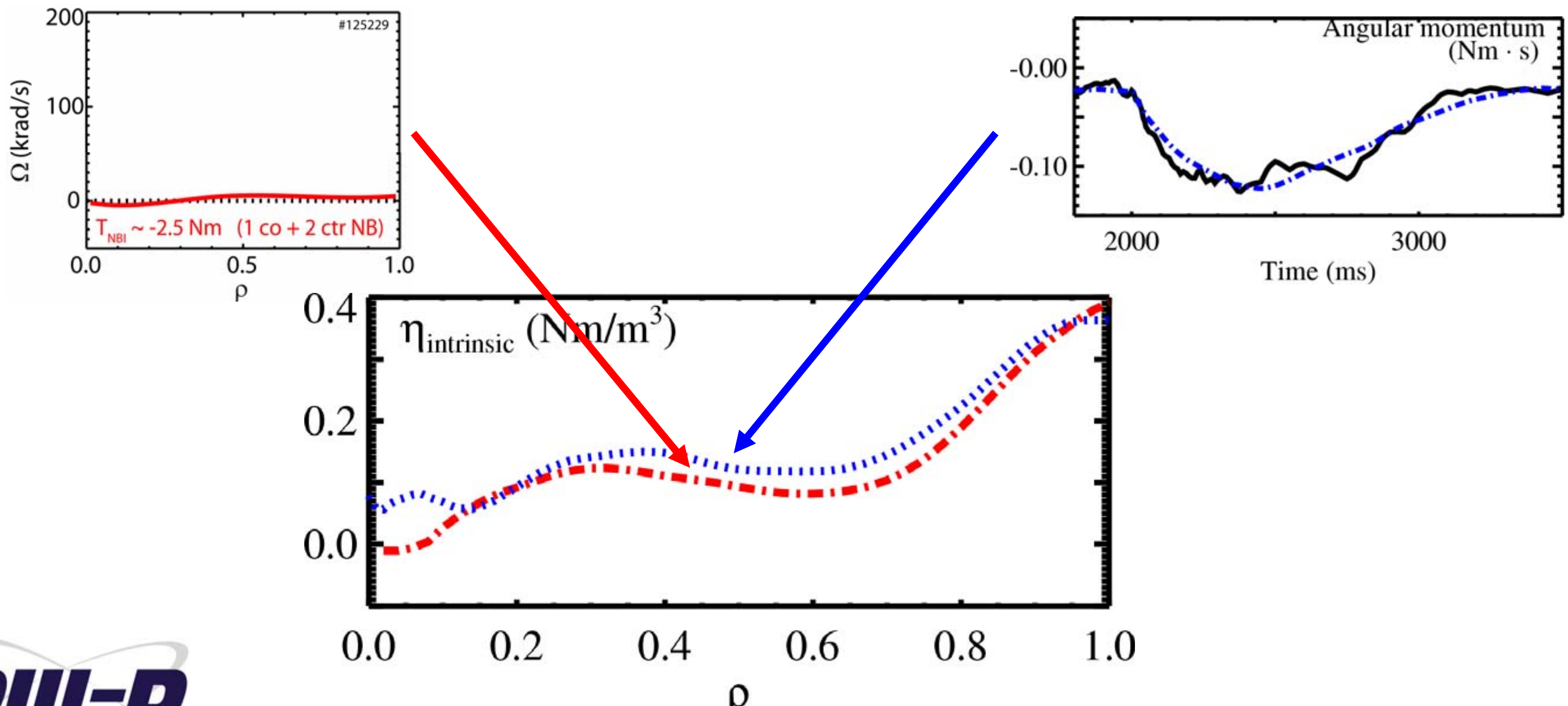
$$\rightarrow \quad \eta_{\text{intrinsic}} = -\eta_{NBI}$$



Solomon et al, PPCF (2007)

Modeling of Rotation Evolution With NRMF Torque Is Consistent With Expectations for Intrinsic Source

- **Different plasmas, but similar β_N, plasma current, toroidal field, density…**
  - Torque profile scaled following intrinsic scaling to account for mior difference in stored energy
- **Result: Torques combine linearly**
  - NRMF torque does not interfere with intrinsic rotation



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Large NRMF Torque Predicted in ITER When Operating With ELM Suppression Coils

- **Short damping time compared to momentum confinement time calculated for ITER Edge Localized Mode (ELM) suppression fields**

$$\tau_{NRMF} = \frac{L}{dL/dt} \sim \frac{L}{T_{NRMF}} \sim 10\ \text{ms}$$

[Becoulet et al., IAEA 2008]

vs

$$\tau_\phi \sim \tau_E \sim 3.7\ \text{s}$$

- **Implies NRMF torque may be more than two orders of magnitude greater than NBI torque**

- **Intrinsic torque estimated to be comparable to NBI**
  [Rice et al, IAEA 2008]

- **Final rotation will depend on balance of these torques**

- **Considerable uncertainty in estimates, but NRMF torque may well dominate**
  - If NRMF dominant, then magnitude of offset rotation critical

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Outline

- Modeling of torque from NRMFs
- Interaction of NRMF torque with intrinsic rotation drive
- **Enhancement of NRMF torque at low rotation**

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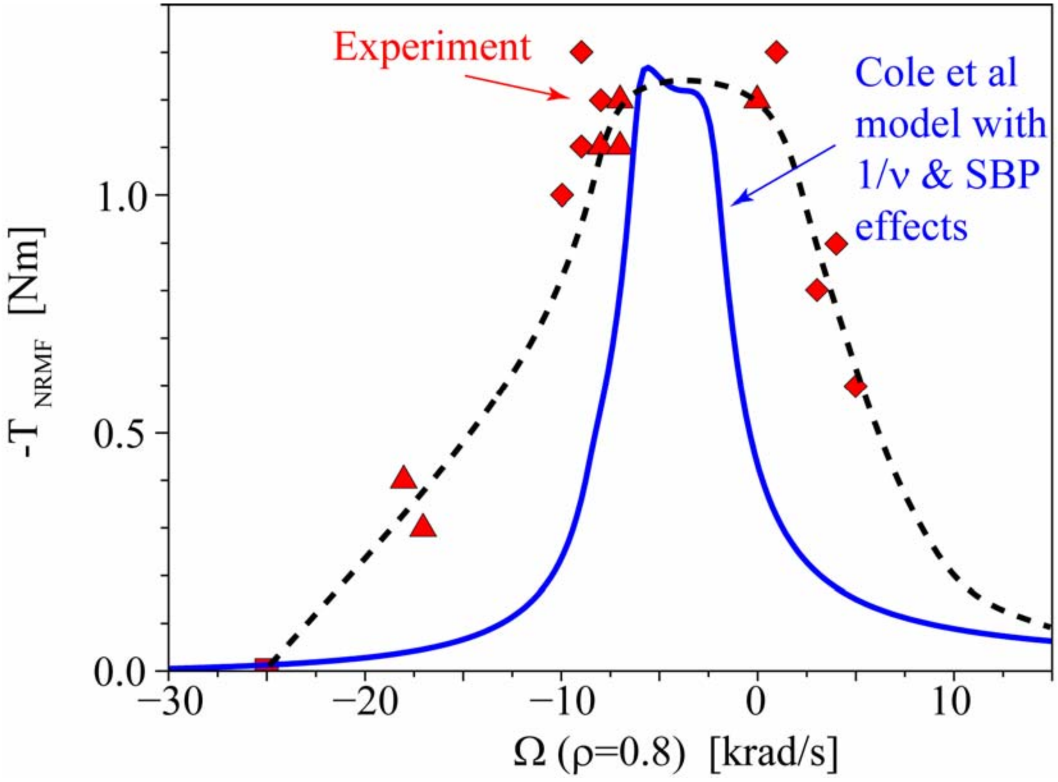
Evidence Found for Increased Torque as Enter Regime of Low Rotation / Radial Electric Field

- **NRMF torque theoretically expected to be enhanced at low rotation**
  - $\omega_E < \nu/\varepsilon$ then transition to $1/\nu$ and super-banana plateau regimes

See Cole C-01, this meeting

- **Strong peaking of torque found at low radial electric field**



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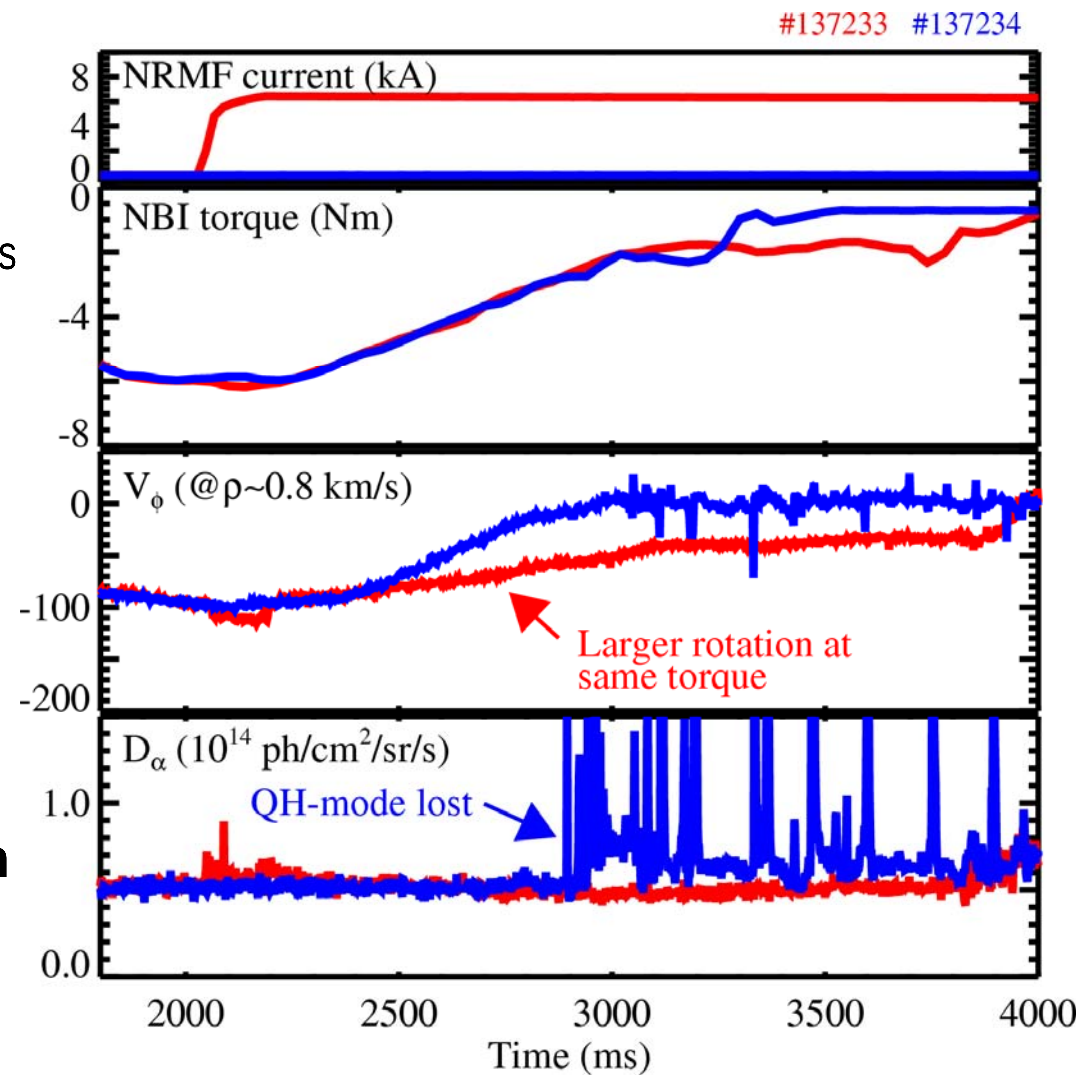
Enhanced NRMF Torque at Low Rotation Helps Expand Operating Space of QH-Mode Plasmas

- **QH-mode plasmas have H-mode pedestal without ELMs**
  - Edge harmonic oscillator (EHO) replaces role of ELMs
- **Torque ramps used to investigate minimum rotation requirements**
- **Application of NRMF adds counter torque to the plasma**
  - Maintains larger plasma rotation for the same torque
- **NRMF torque at low rotation acts as barrier to prevent further slowing of rotation!**



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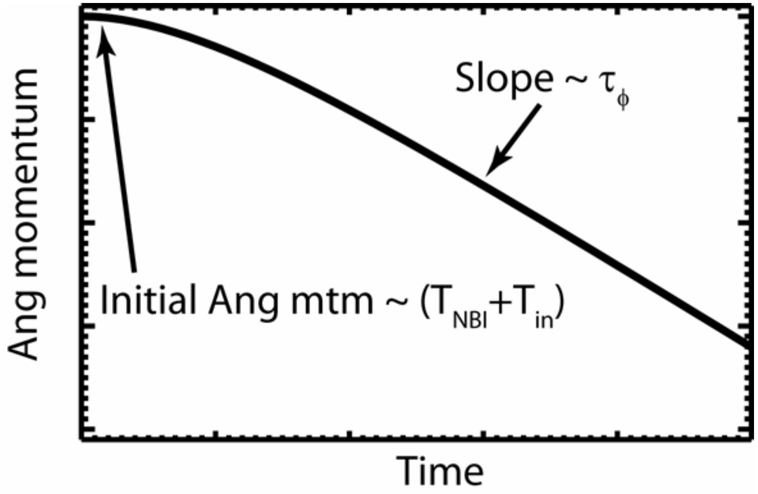
Discharge Without NRMF Provides Information On Intrinsic Torque and Momentum Confinement Time

- **From angular momentum versus time plot, for fixed NBI torque ramp rate:**
  - The slope is proportional to the momentum confinement
  - The intercept is proportional to the sum of the NBI and intrinsic torque

- **Reference discharge therefore provides key momentum transport characteristics of plasma**



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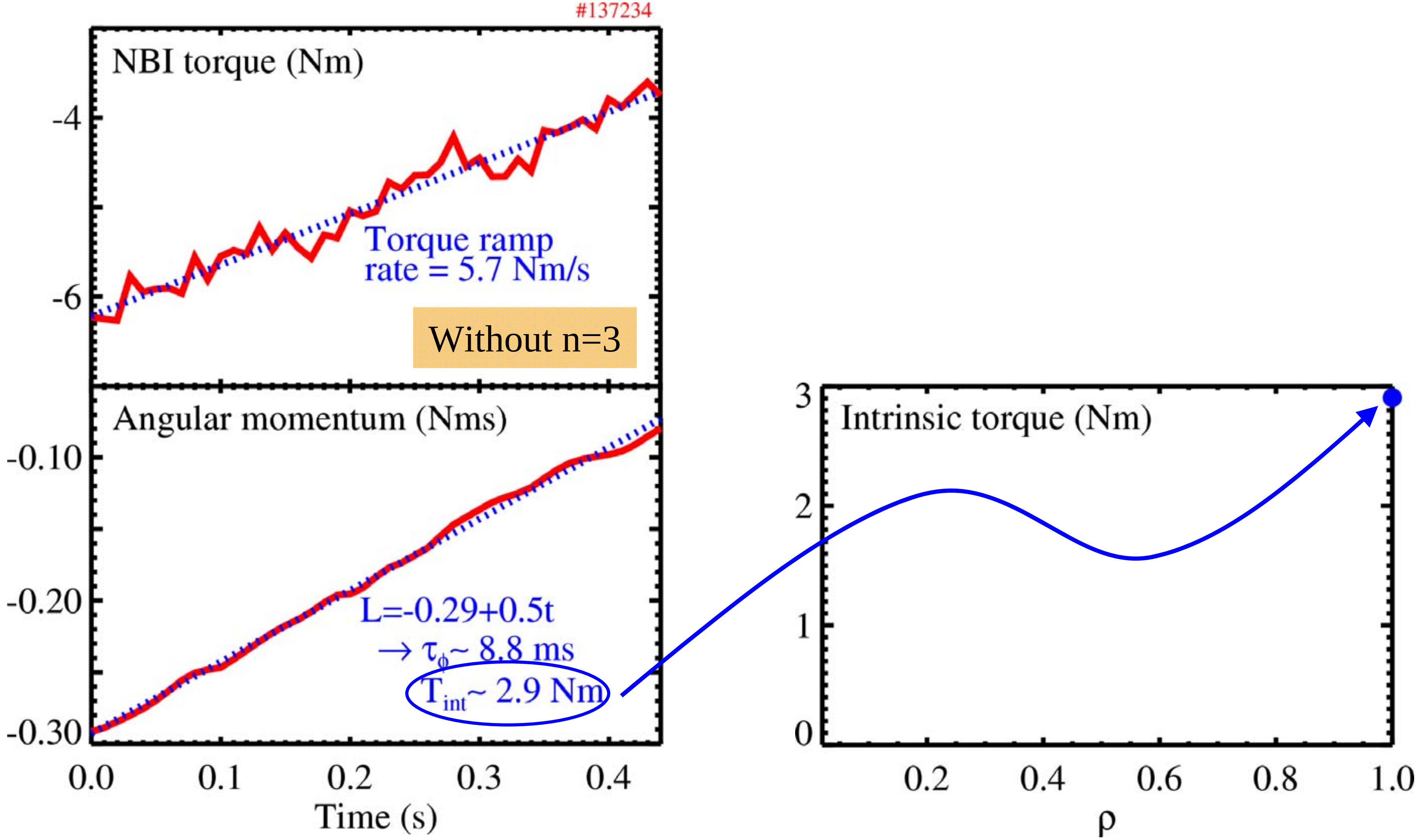
Intrinsic Torque Inferred From Rate of Change of Angular Momentum During Torque Ramp



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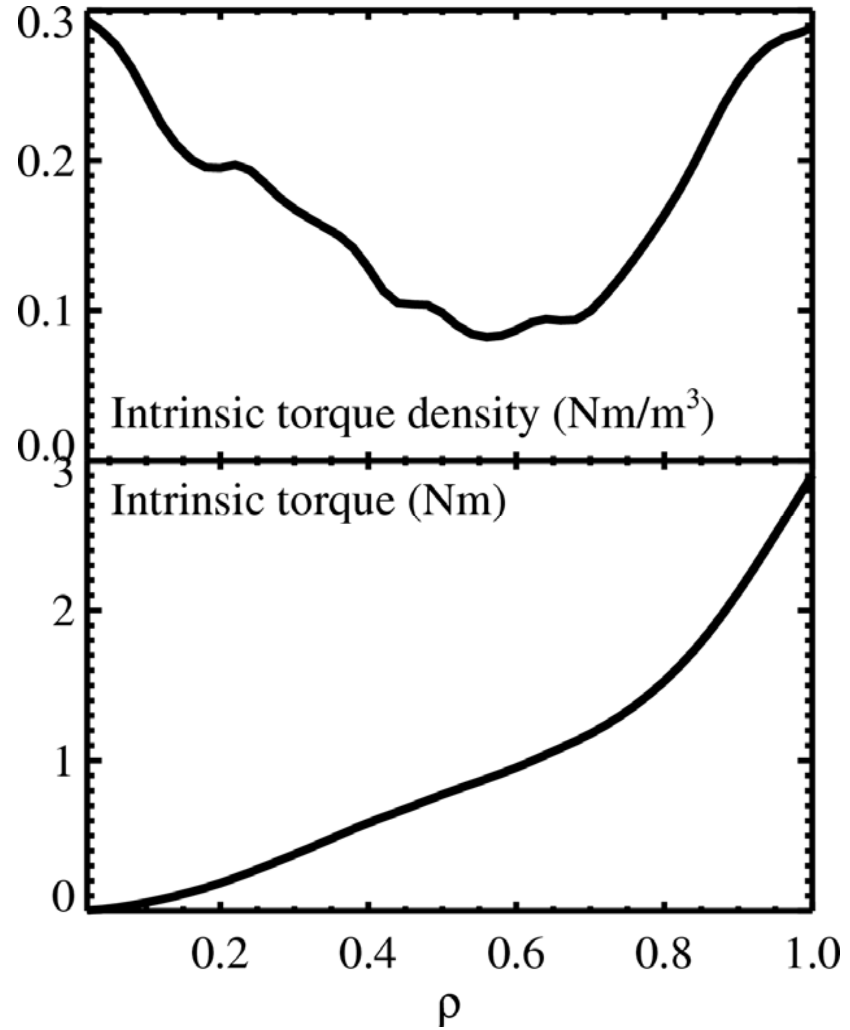
Edge Intrinsic Torque Profile Qualitatively Consistent With Previous Measurements

- **As before, peel back shells of angular momentum and applied NBI torque to build up intrinsic torque profile**
- **Edge intrinsic torque typical of many discharges**
- **Core intrinsic drive larger than "typical"**
  - Wide variety of core intrinsic rotations observed
  - Richer physics mechanisms for drive



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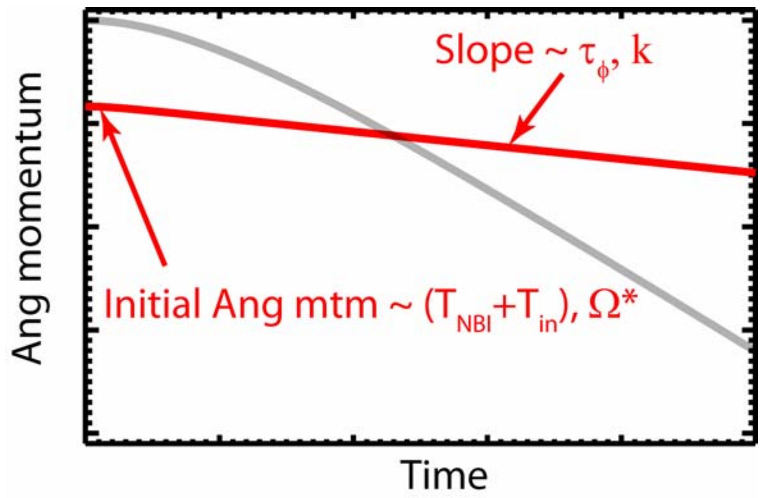
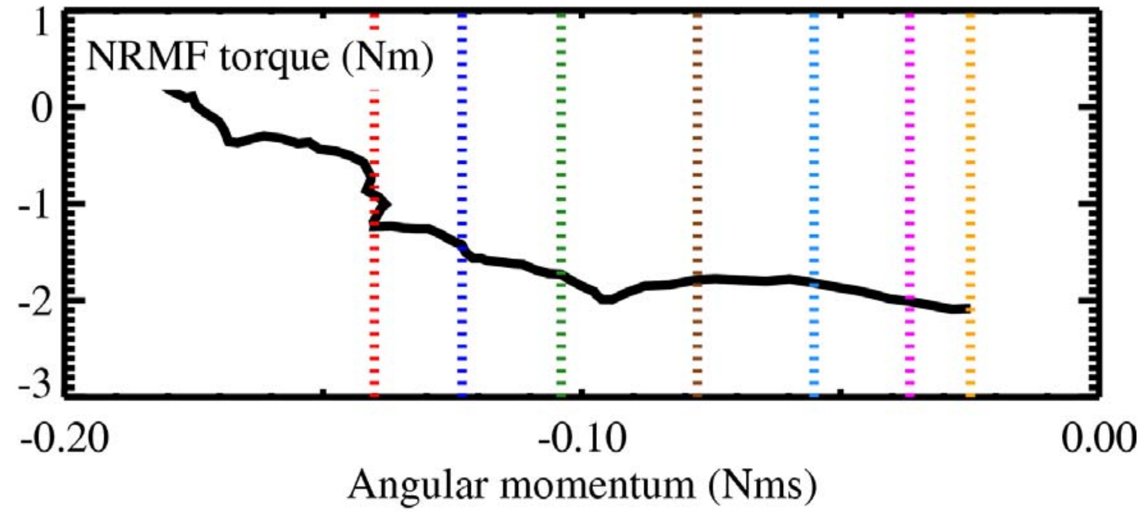
When NRMF Applied, Torque And Offset Rotation Profile Imprinted On Angular Momentum Trajectory

- **Slope is modified relative to the reference, reflecting strength of NRMF torque**
- **Initial angular momentum modified relative to the reference, reflecting proximity to offset rotation**
- **Using momentum confinement time and intrinsic torque profile from reference shot without NRMF, can uniquely solve for both quantities**

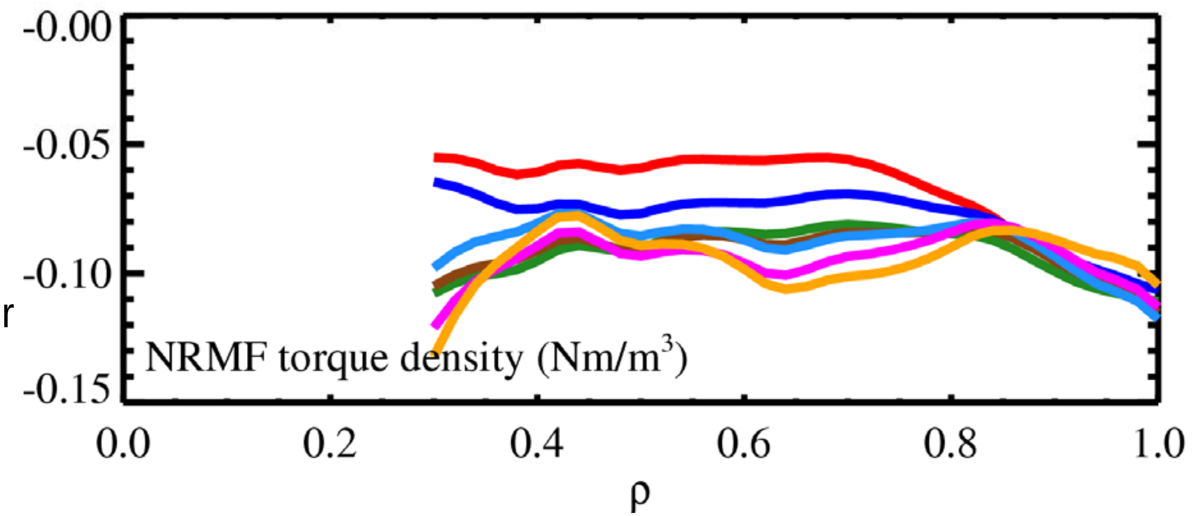


Analysis of Time History of Rotation Indicates NRMF Torque Increases Significantly At Low Rotation

- **Use momentum transport characteristics from reference discharge in plasma with NRMF**
  - NRMF torque is the excess torque after including NBI + intrinsic and viscous drag from reference shot



- **NRMF torque profile can again be extracted by peeling of shells**
  - NRMF torque density increases at low angular momentum



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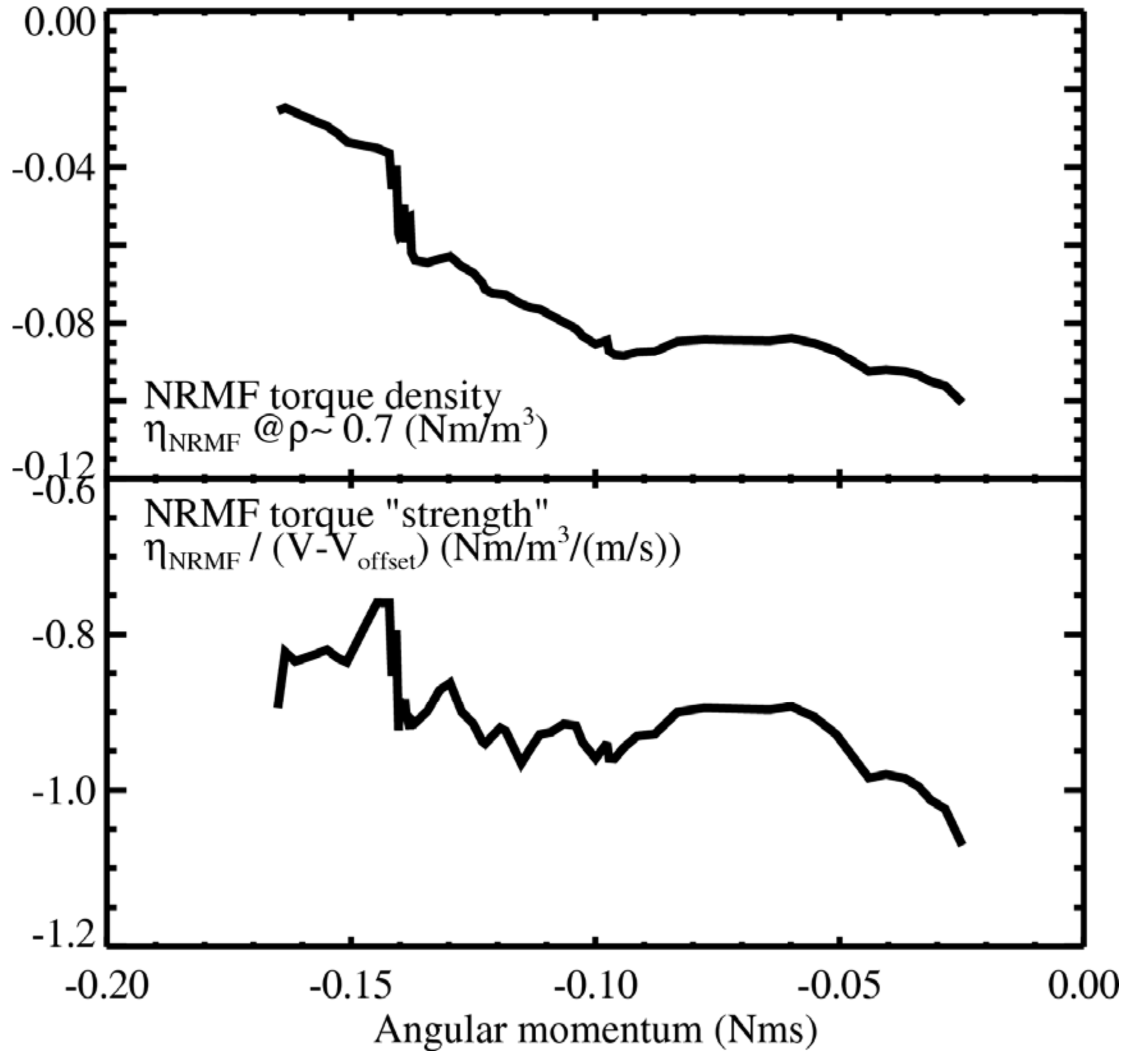
NRMF Time History Consistent With Peaking of NRMF Torque

- **Plot of local NRMF torque density at ρ~0.7 shows increase**
  - Some is due to ($V-V_{offset}$) contribution
- **If remove the standard linear rotation dependence, then we get a measure of the strength enhancement**
  - Approx 20-30% increase



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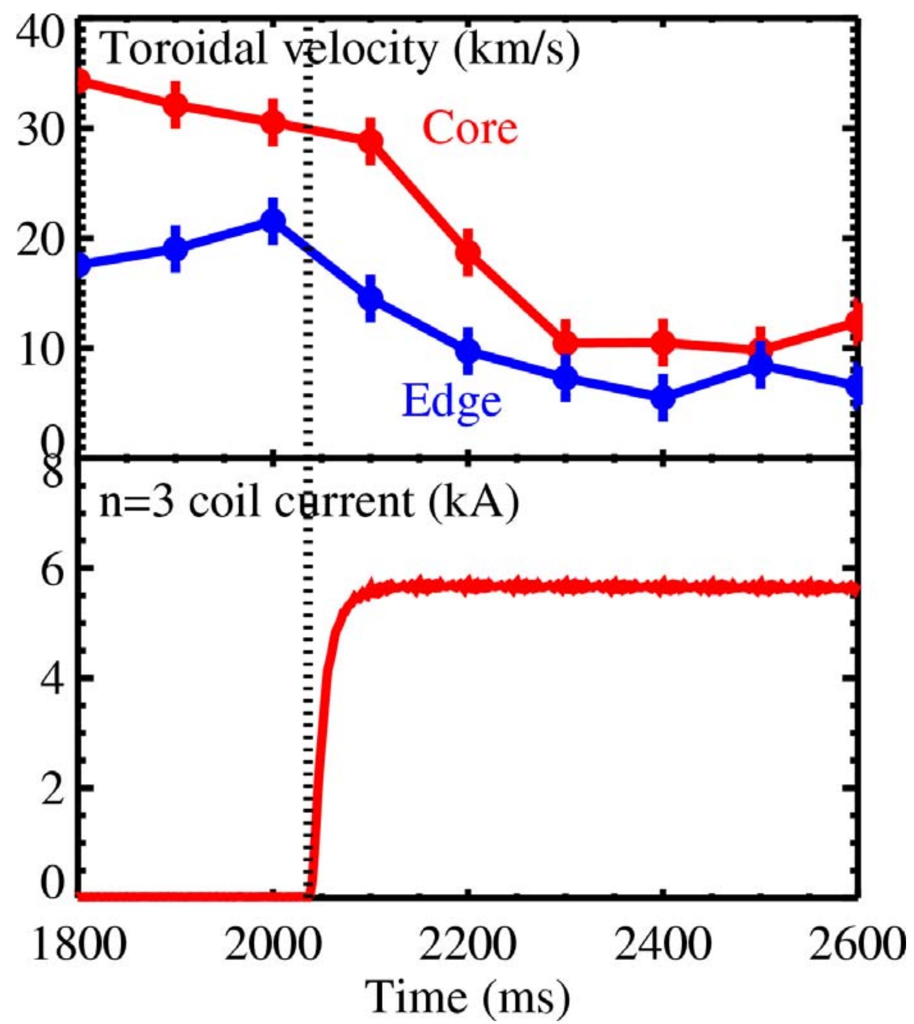
Conclusions

- **Non-resonant magnetic fields apply a torque on the plasma**
  - Drags rotation toward the offset rotation, which results in a spin up of the plasma when initial rotation is low
- **Modeling of NRMF torque accurately reproduces rotation profile evolution for typical initial rotation conditions**
  - Including effective source for intrinsic rotation
- **NRMF torque does not appear to eliminate or alter intrinsic rotation (torques appear to combine linearly)**
- **NRMF torque found to be enhanced at low rotation**
  - Expand operating space of QH-mode operation
- **NRMF torque may be beneficial in future devices**
  - Alternate means of driving rotation

NRMF Effect on Rotation Cannot Be Solely Due to Fast Ion Loss Caused By Increased Toroidal Field "Ripple"

- **Start from "intrinsic" rotation levels in ECH plasma**
  - No external momentum input
  - No significant source of fast ions
- **When n=3 field applied, strong effect is still observed on rotation**
  - No longer follows intrinsic scaling
  - Of course, one may wonder whether these fields modify the intrinsic drive…



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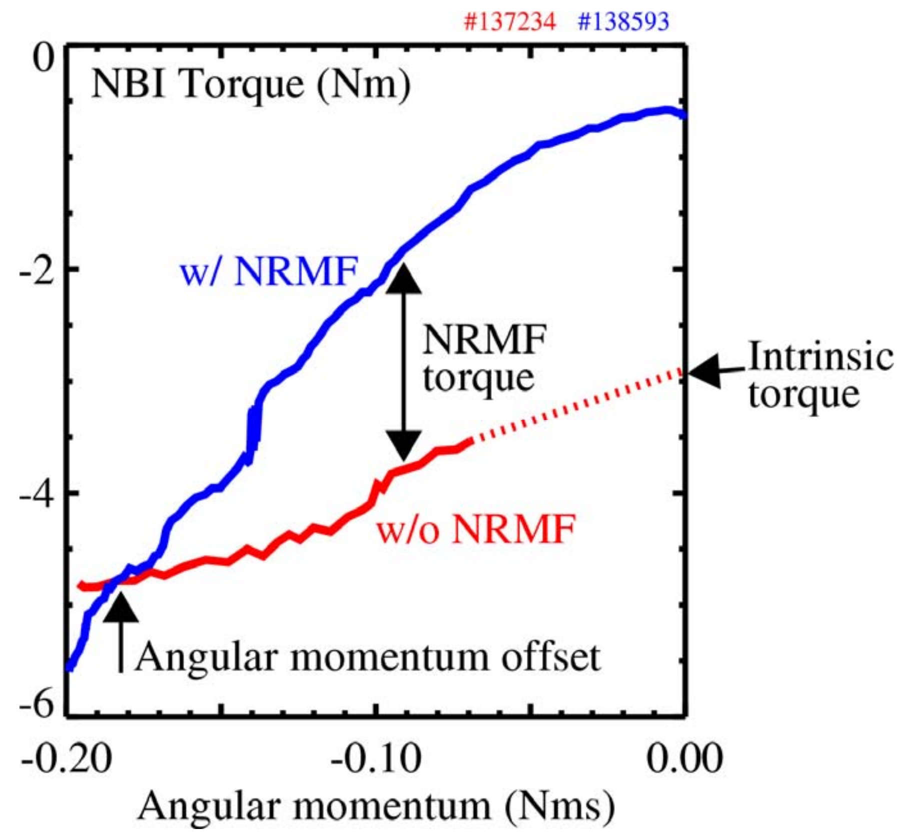
Comparison of Angular Momentum Evolution For Discharges With/Without NRMF Reveals Key Torques

- **With no NRMF, zero angular momentum occurs when NBI torque balances effective intrinsic torque**

- **Difference in NBI torque between cases gives a measure of NRMF driven torque**
  - Assuming otherwise similar momentum confinement

- **Crossing of curves indicates approximate offset angular momentum**



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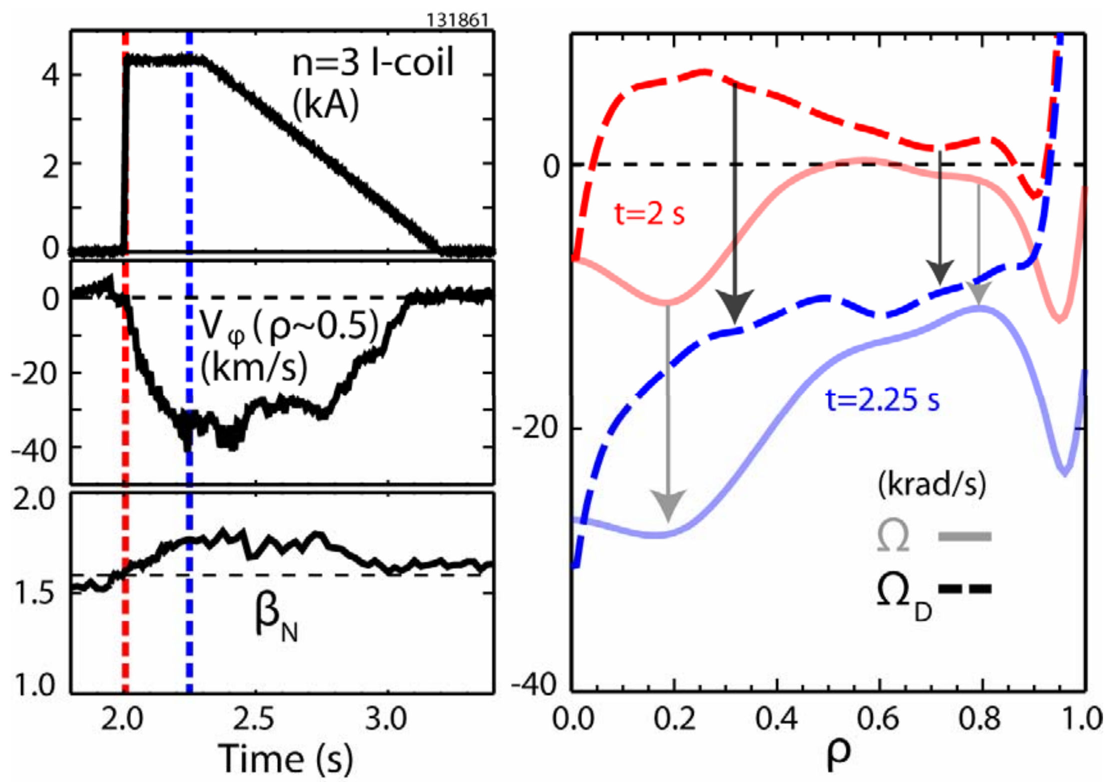

- **β_N increase qualitatively consistent with *E x B* shear stabilization**
  - Small reduction in calculated ITG growth rates