Generation and Sustainment of Rotation in Tokamaks

By
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In Collaboration with

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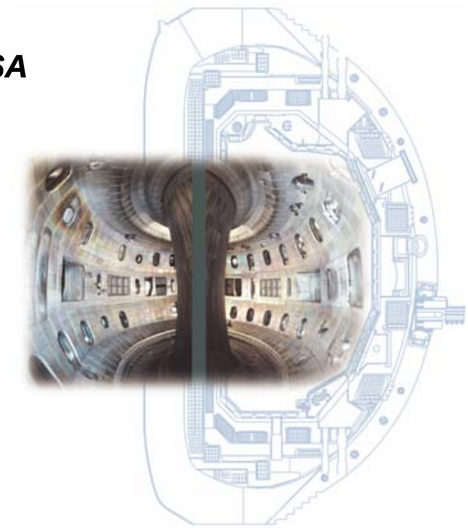

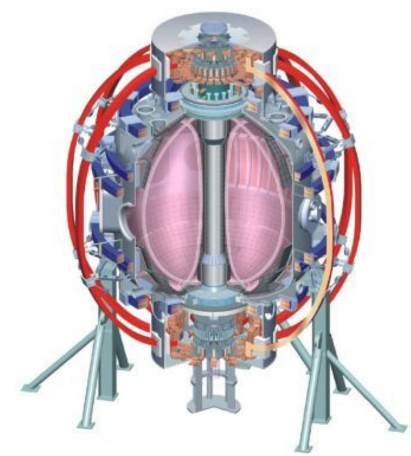

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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Motivation

- Rotation is generally considered to offer benefits to fusion performance through improvements in stability (NTM, RWM, error field tolerance) and confinement (turbulence suppression via ExB shear)
- In present devices, rotation is usually driven by external means through neutral beam input, as a by-product of heating
- In future burning plasmas including ITER, using beams for momentum input becomes increasingly challenging
- Alternate means of driving rotation needed (intrinsic, magnetic drive)

Outline:
Recent Techniques for Manipulating Rotation

$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of angular momentum}} = \underbrace{\sum \eta}_{\text{Input torque}} \underbrace{-\nabla\cdot\Pi_\phi}_{\text{Transport}} - \underbrace{\frac{mnR\left(V_\phi - V_\phi^{\ *}\right)}{\tau_{damp}}}_{\text{Viscous drag}} + \ldots$$

$\nabla\cdot\Pi_\phi$ →

- **Intrinsic Rotation Drive**

  Generation at the edge

  \+ Inward pinch of momentum

  \+ Additional drive in core

  Sheared rotation profiles

$\frac{mnR\left(V_\phi - V_\phi^{\ *}\right)}{\tau_{damp}}$ →

- **Rotation Drive By Non-Resonant Magnetic Fields**

  Drag to offset rotation

  \+ Enhancement of torque at slow rotation

  Resistance to rotation slow-down

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Intrinsic Rotation Should Manifest Itself From Residual Stress Term In Transport Equation

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

- **Non-diffusive momentum transport recognized both experimentally and theoretically**
  [Ida et al PRL 1995, Coppi NF 2002, Hahm PoP 2007, Yoshida NF 2007, Solomon PPCF 2007, ...]

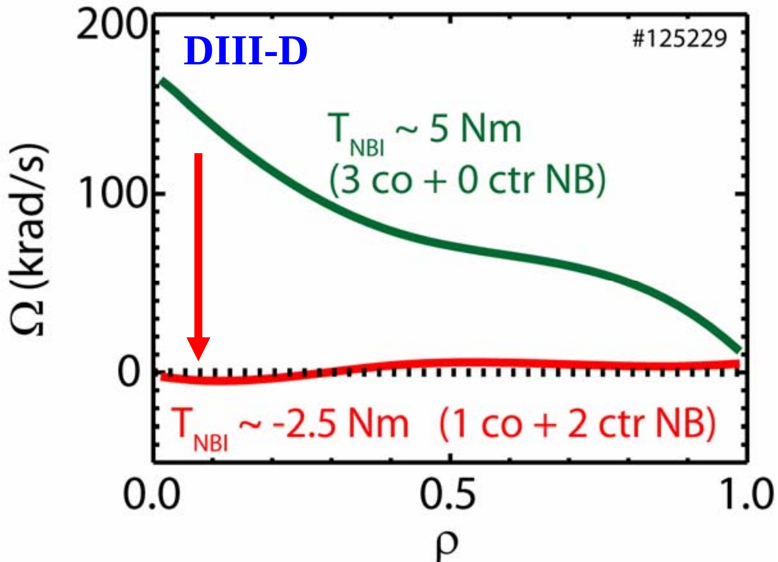
- **Terms independent of V_ϕ → "Residual stress"**
  - ExB shear [Dominguez and Staebler PoFB 1993; Gurcan et al PoP 2007]
  - Up-down asymmetries in geometry [Camenen, PRL 2009

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

- **In steady state, NBI torque balanced against momentum flows**

$$\underbrace{\cancelto{0}{mnR\frac{\partial V_\phi}{\partial t}}}_{\substack{\text{Rate of change}\\ \text{of momentum}}} = \underbrace{\sum\eta}_{\text{Input torque}} - \nabla\cdot\left(-mnR\left(\underbrace{\cancelto{0}{\chi_\phi\frac{\partial V_\phi}{\partial r}}}_{\text{diffusion}} - \cancelto{0}{V_\phi \underbrace{V_{pinch}}_{\text{pinch}}}\right) + \underbrace{\Pi_{RS}}_{\substack{\text{Residual stress}\\ \text{"Intrinsic source"}}}\right)$$

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



Intrinsic Source Approximately Equivalent to One Co-Neutral Beam Source

- **Residual stress drives an effective intrinsic source**

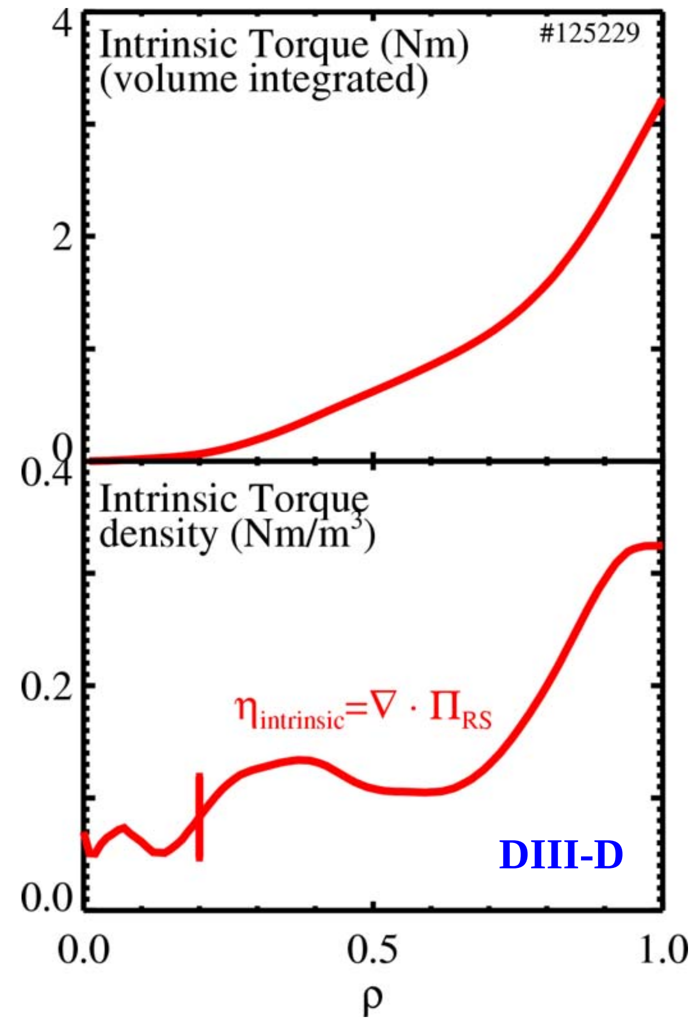
$$\eta_{\text{intrinsc}} = -\nabla \cdot \Pi_{RS}$$

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

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

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

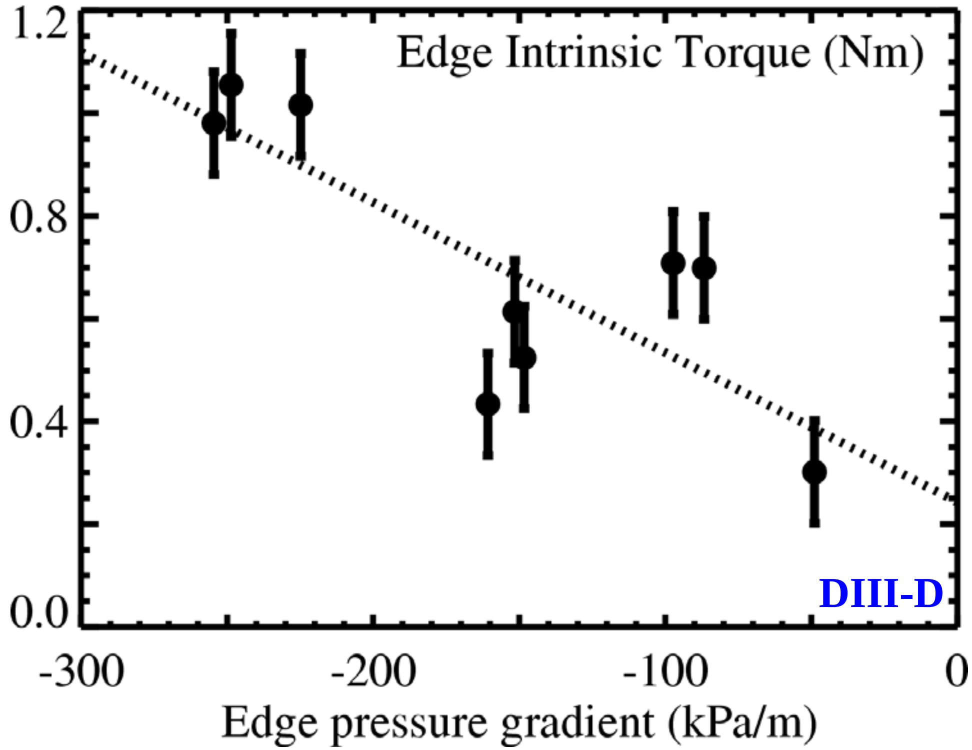
- **Significant drive of torque found at edge**



Solomon et al, PPCF (2007)

Good Correlation Found Between Edge Intrinsic Drive and Total Edge Pressure Gradient

- **Intrinsic torque estimated by using NBI to null out rotation**
- **H-mode pedestal can provide universal mechanism to drive rotation through residual stress**
  [eg Diamond et al NF 2009]
- **Looks like possible means of achieving edge rotation in future devices**
  - Can it be optimized further?



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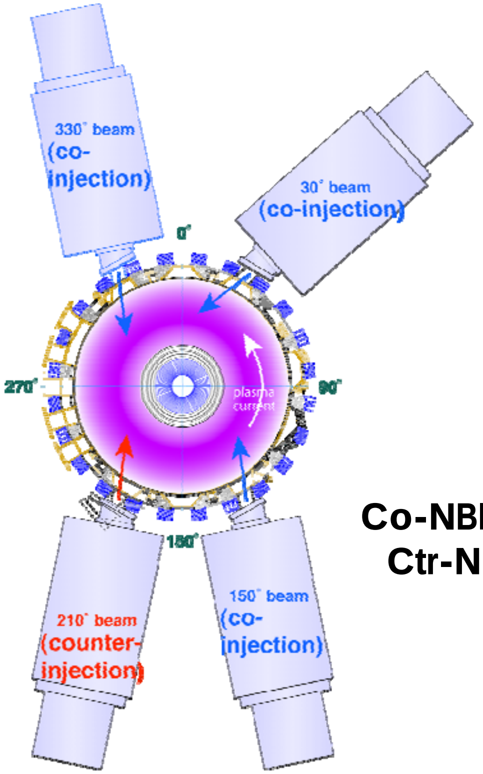
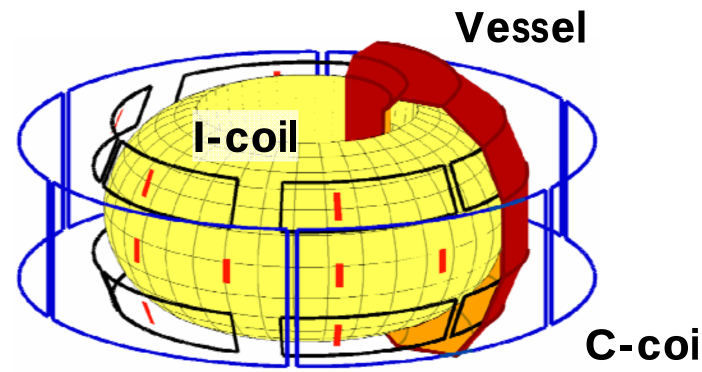
Momentum Pinch Velocities Are Investigated on Both NSTX and DIII-D Using Perturbative Techniques

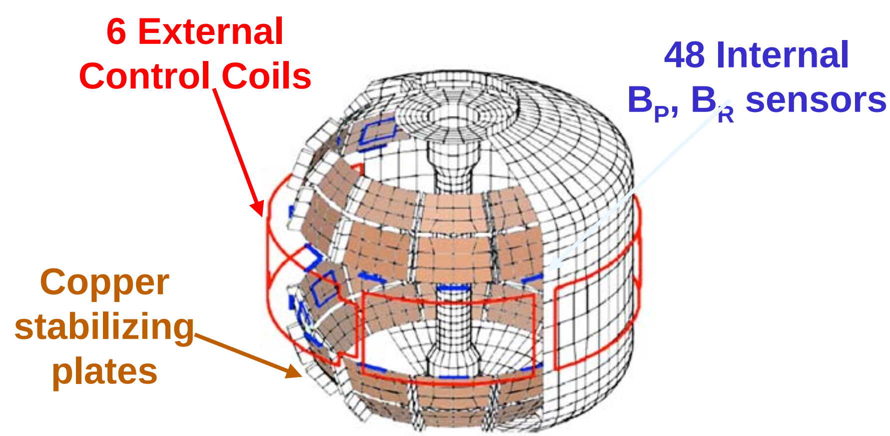
- **On DIII-D, co/counter beams**



Co-NBI 12.5 MW
Ctr-NBI 5 MW

- **On both NSTX and DIII-D, n=3 non-resonant magnetic fields**





- **NSTX has also used unbalanced NBI perturbation for core pinch studies**

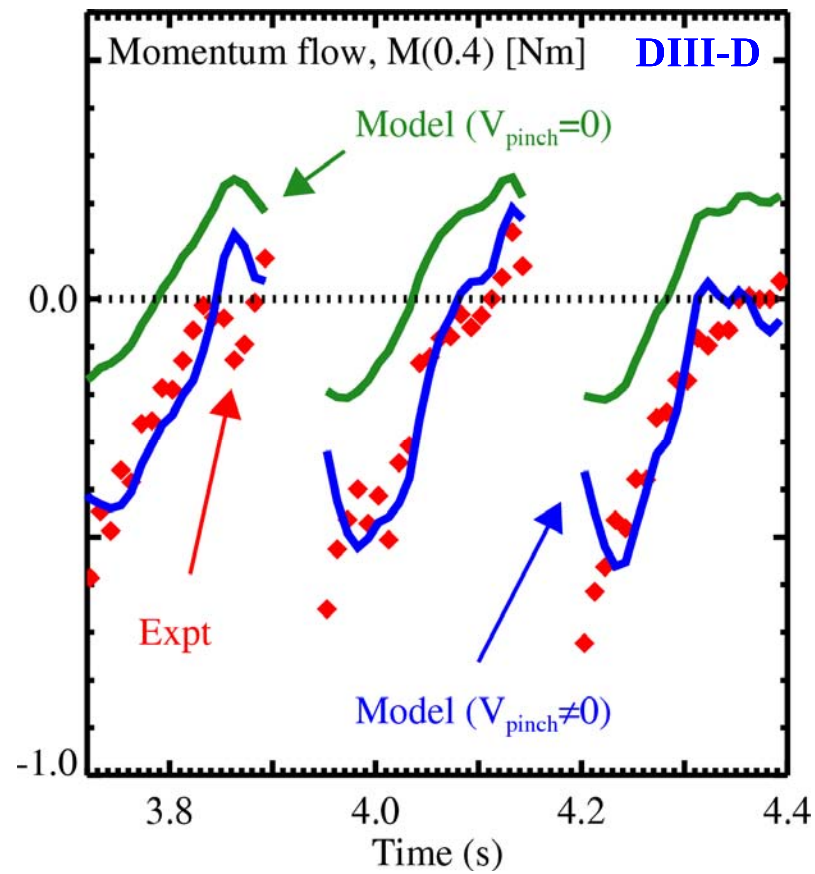
Diffusive And Pinch Model Necessary To Describe Momentum Flow Evolution

- **Flow of momentum through given radius is**

$$M(\rho) = \int_0^\rho \nabla \bullet \Pi_\phi dV$$

- **Non-linear least squares fitter used to solve for time-independent χ_ϕ and V_{pinch} to best reproduce momentum flow**
  - Fit without pinch poor

- **Although residual stress terms neglected, fit appears adequate in these plasmas**

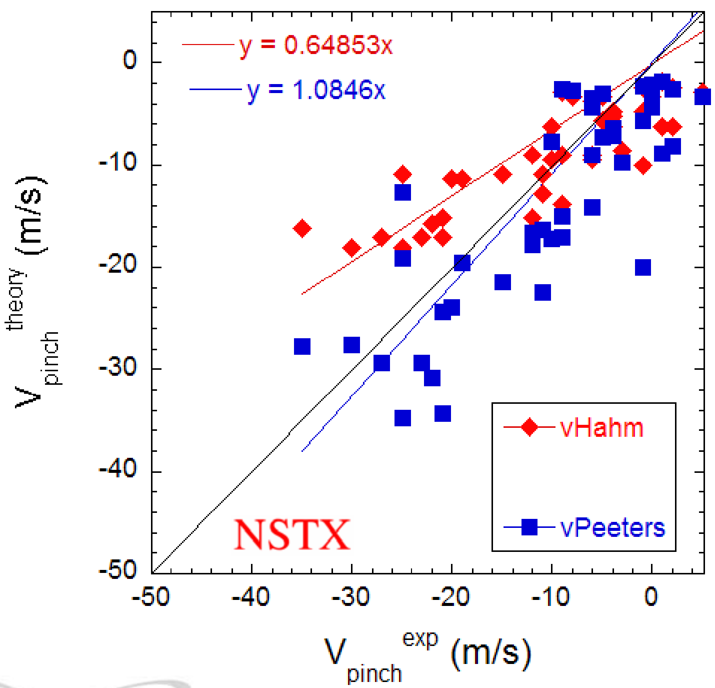


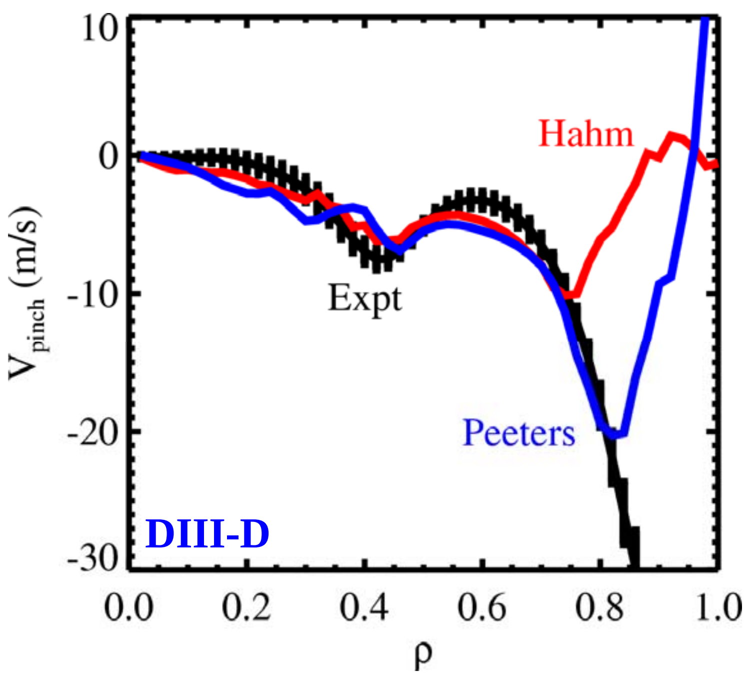
Good Agreement Found Between Theory And Experiment On Both NSTX And DIII-D

- **Theory predicts drive of momentum pinch through low-*k* turbulence**
  - Peeters *et al.* PRL (2007)
  - Hahm *et al.* PoP (2007)

$$V_{Peeters} = \frac{\chi_\phi}{R}\left[-4 - \frac{R}{L_n}\right]$$

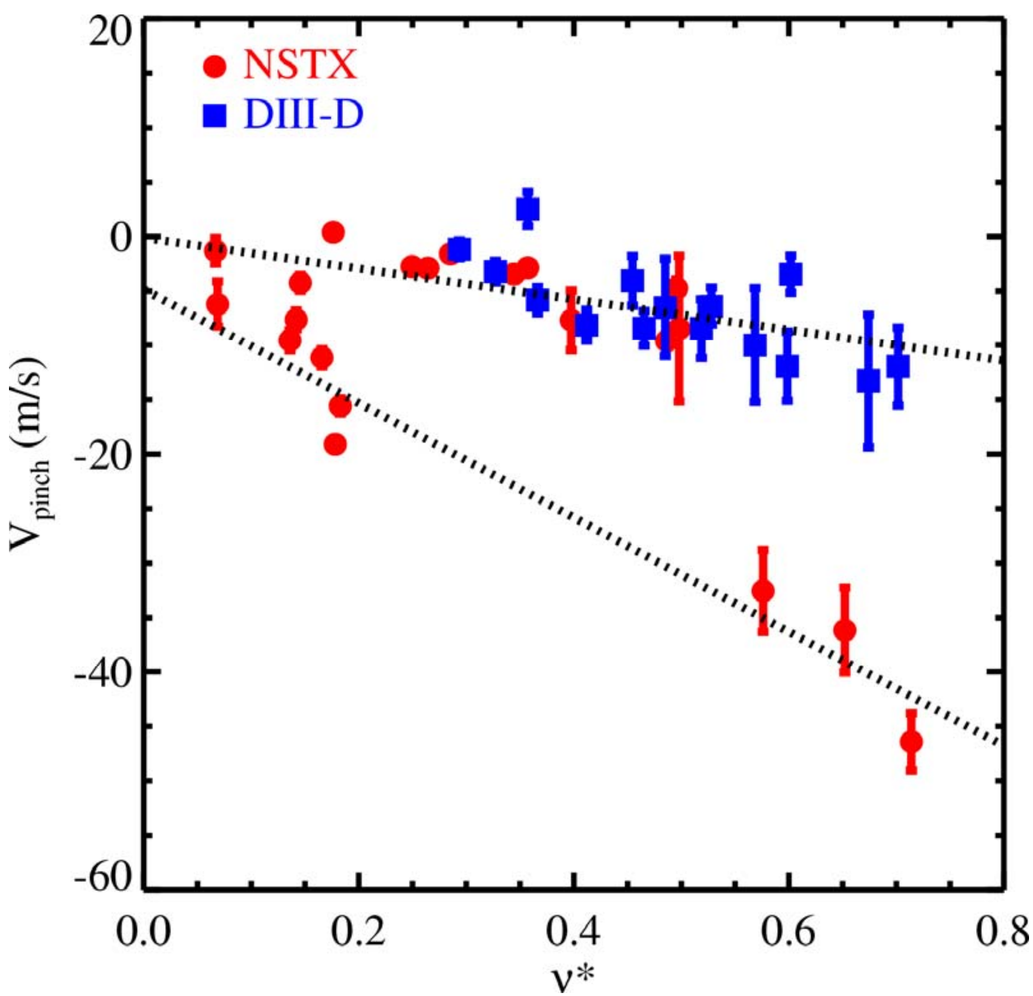
$$V_{Hahm} = \frac{\chi_\phi}{R}[-4]$$





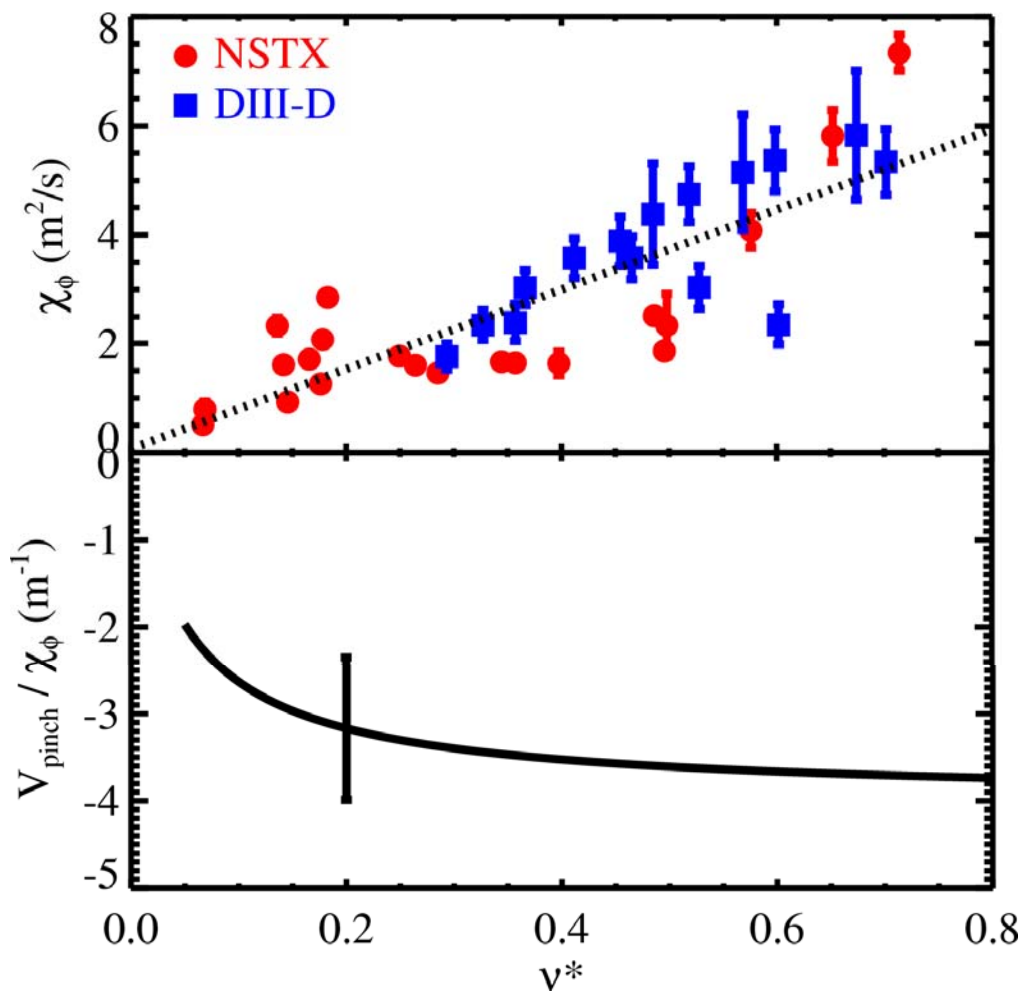
Data Suggests That Core Pinch Might Be Reduced At Low Collisionality

- **Although hard to distinguish between collisionality and R/L_n which are coupled here**
- **Overlap between datasets likely fortuitous**
  - NSTX: H-mode
  - DIII-D: L-mode
- **What additional physics responsible for enhanced pinch "branch"?**



Rotation Peaking From Pinch Only Shows Weak Dependence on Collisionality

- **In terms of rotation peaking, ratio of V_{pinch}/χ_ϕ more important than absolute pinch velocity**
- **Momentum diffusivity also shows dependence on collisionality**
- **Net result is relatively minor reduction in pinch ratio at low collisionality**



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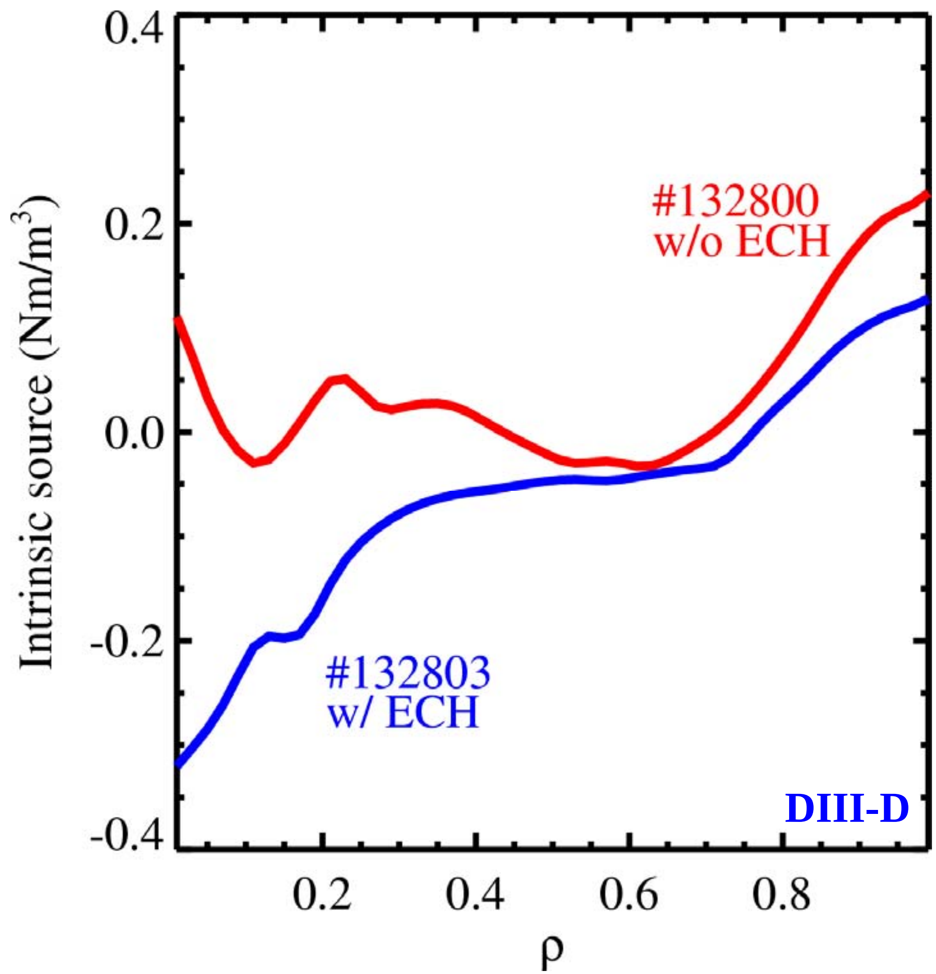
ECH Is Found To Modify Intrinsic Rotation In Core; Evidence of ECH-Induced Drive of Counter Rotation

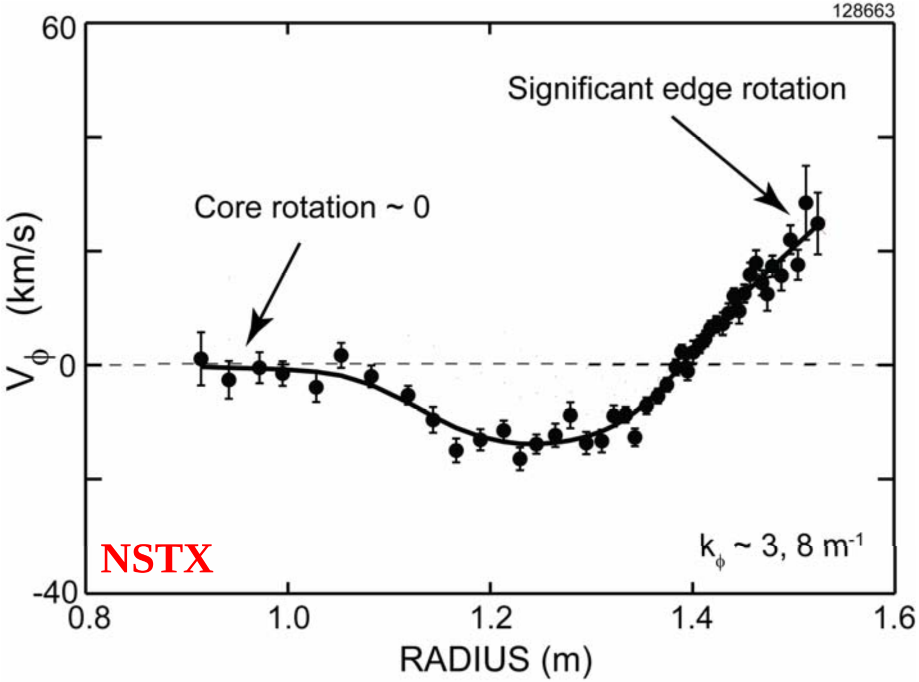
- **Other examples of modifications to core intrinsic rotation include**
  - ECH on JT-60U (driving opposite rotation) [Yoshida PRL 2009]
  - LHCD from C-Mod [Rice NF 2009]



Application of High Harmonic Fast Wave Heating on NSTX Also Appears To Drive Counter Torque in Core

- **RF only rotation profile shows significant rotation at the edge, but practically zero rotation in the core**
  - Edge intrinsic rotation + diffusion → flat rotation profile
    + inward pinch → peaked rotation profile

- **Hollow rotation profile suggests with a counter torque in the core**



Hosea, RF conference (2009)
Taylor, APS TI3.00002 (Thursday)

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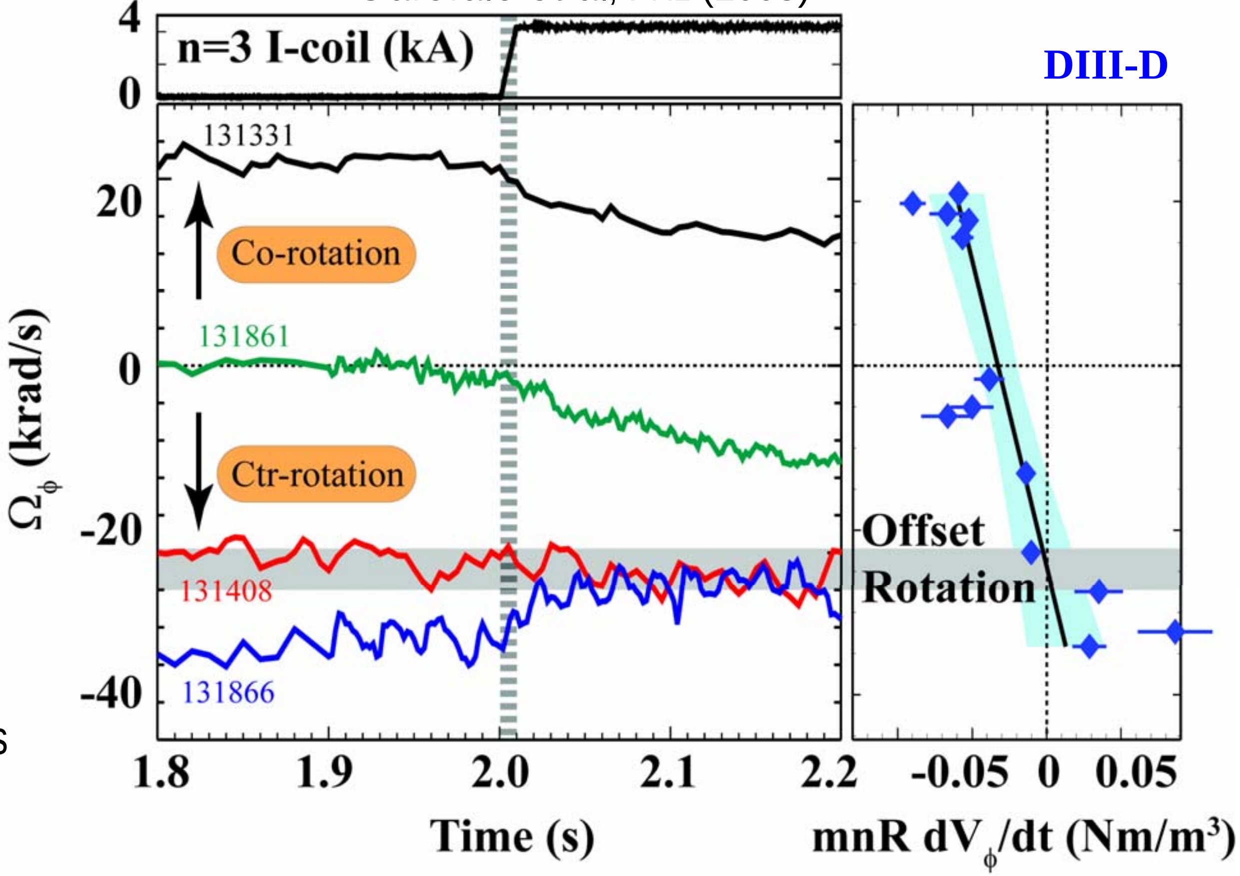
Previous Work Has Shown That Non-Resonant Magnetic Fields (NRMFs) Apply a Torque

- **Rotation dragged toward finite rotation condition ("offset rotation")**
  - Can be exploited as drive of counter rotation
- **Basic properties of NRMF torque have been characterized**
  - Validated through full time-dependent analysis of rotation profile

Garofalo et al, PRL (2008)



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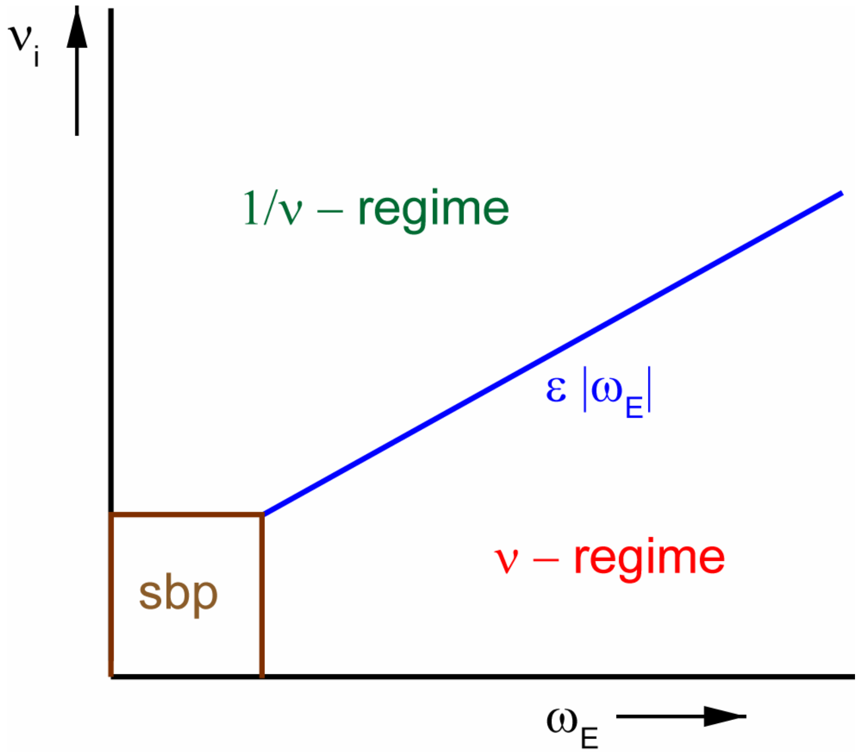
Possible To Switch Collisionality Regime At Fixed Collisionality By Altering Rotation

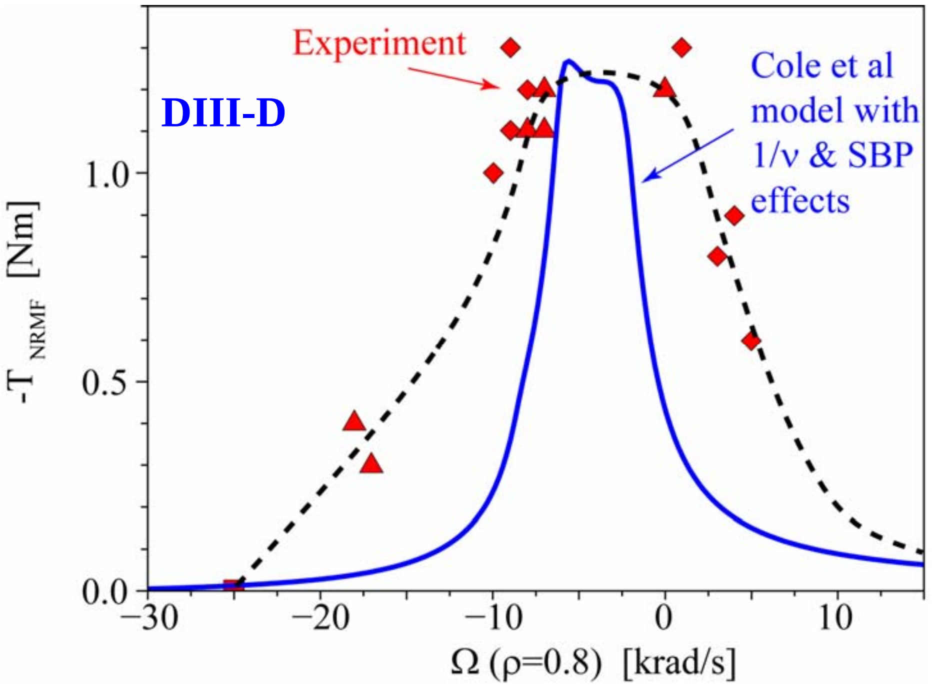
- **At moderate collisionality, transition from ν to $1/\nu$ regime at by reducing rotation**
- **At sufficiently low collisionality, reducing rotation changes regime from ν to super-banana plateau**
- **Neoclassical transport expected to be enhanced at low radial electric field**

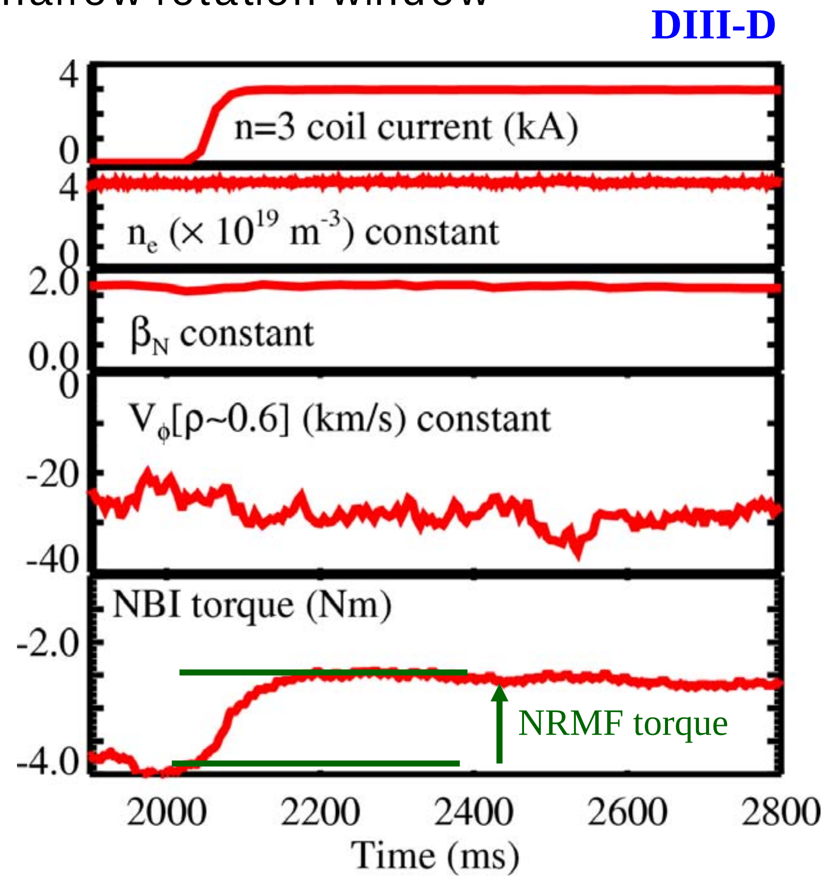


Rotation driven by radial electric field

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

- **Rotation feedback control used to measure NRMF torque**
  - NBI torque compensated to account for NRMF torque
  - Has advantage that rotation stays within narrow rotation window
- **Strong peaking of NRMF torque found at low radial electric field**





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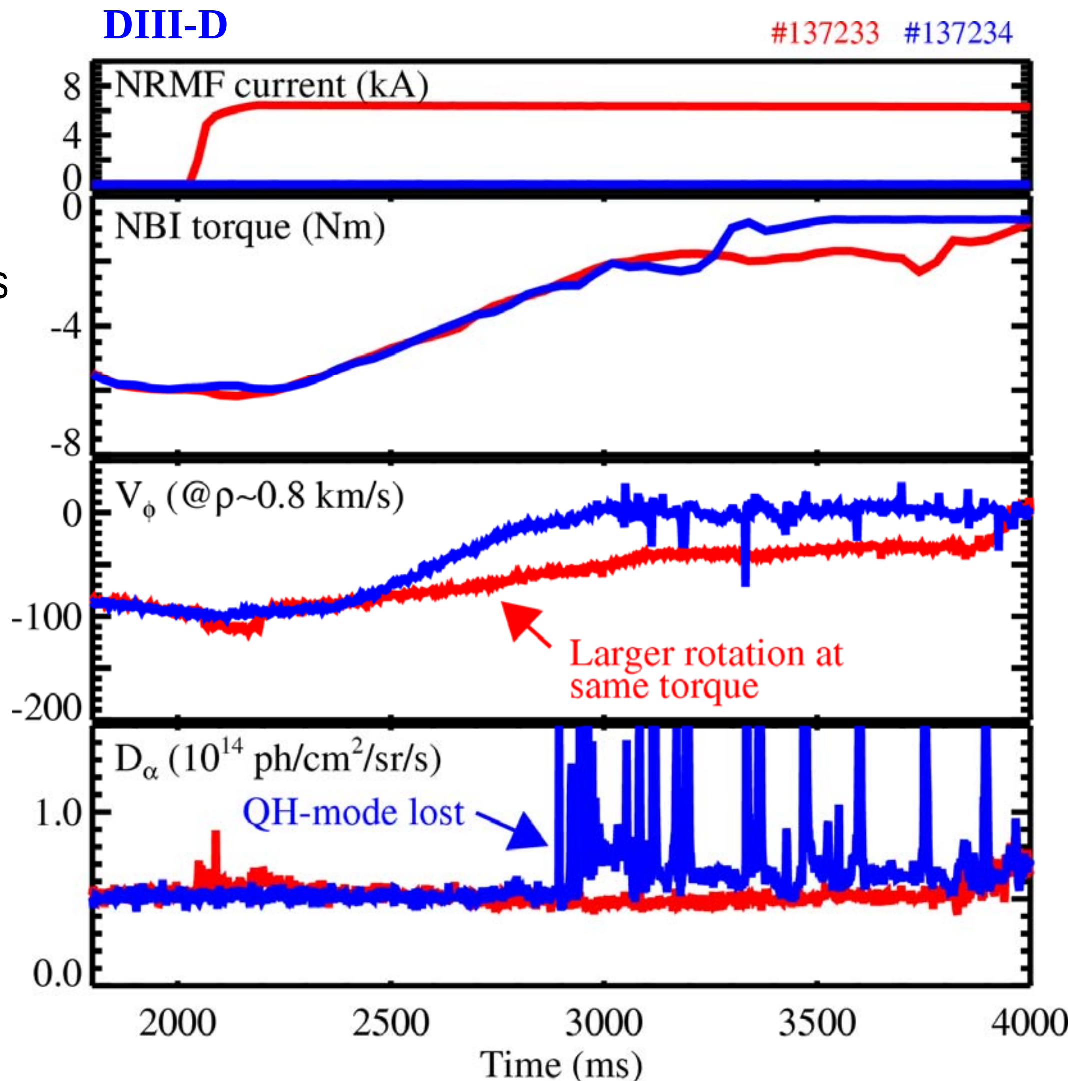
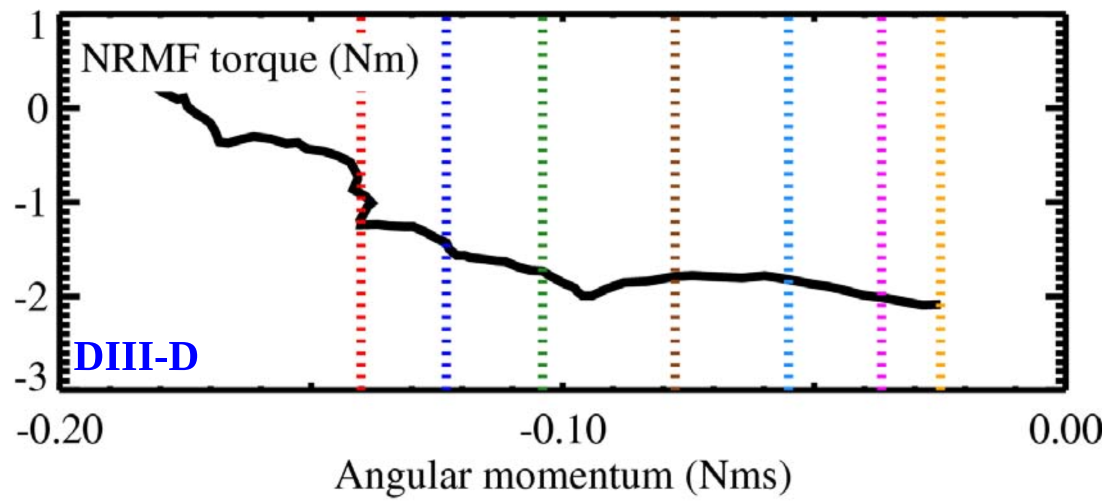
Enhanced NRMF Torque at Low Rotation Helps Expand Operating Space of QH-Mode Plasmas

- **QH-mode plasmas have H-mode pedestal without ELMs**
  - Edge harmonic oscillation (EHO) replaces role of ELMs
- **NBI 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**

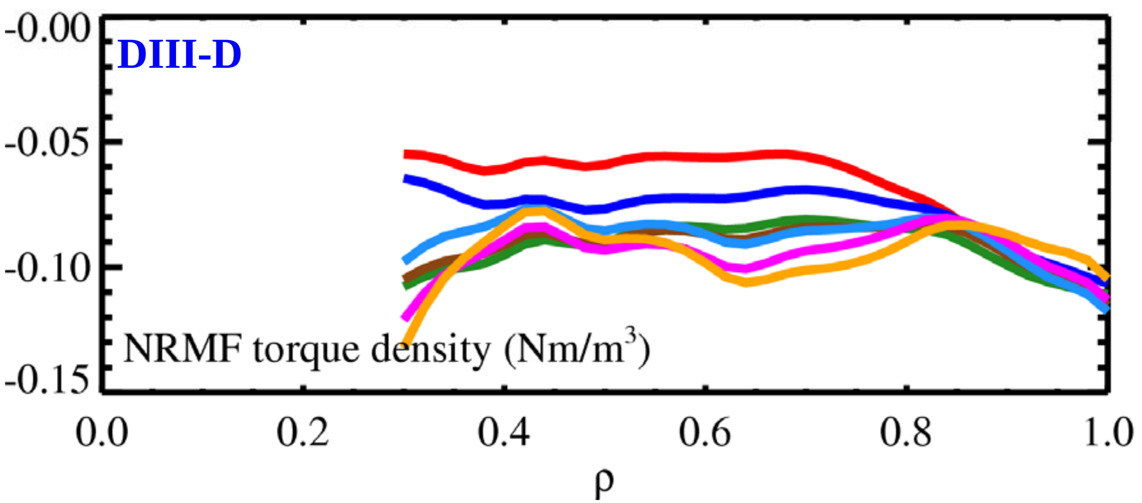


Analysis of Time History of Rotation Indicates NRMF Torque Increases Significantly At Low Rotation

- **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

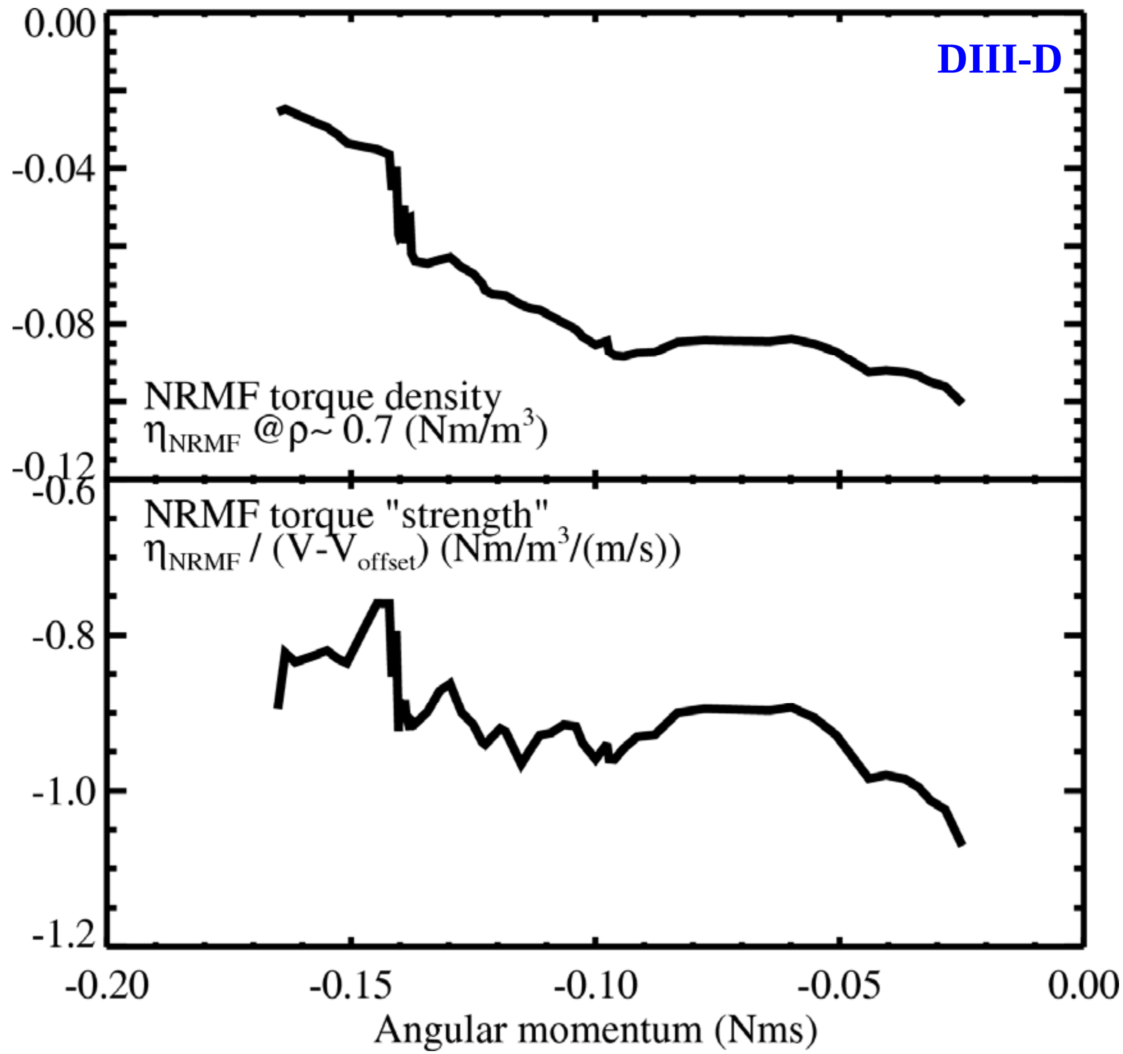


- **NRMF torque profile can again be extracted by peeling of shells**
  - NRMF torque density increases at low angular momentum



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 this standard dependence, find NRMF torque strength also enhanced**
  - Approx 20-30% increase



Conclusions

- Edge pedestal capable of creating residual stress resulting in a drive for edge intrinsic rotation
- Coupled with core pinch, can provide rotation shear in core
- Core residual stress is more complicated, can be tweaked
- Non-resonant magnetic fields can drive rotation due to existence of offset rotation
- NRMF torque found to be enhanced at low rotation
- Together, may provide many opportunities for rotation control and performance optimization