Generation and Sustainment of Rotation in Tokamaks

By

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In Collaboration with

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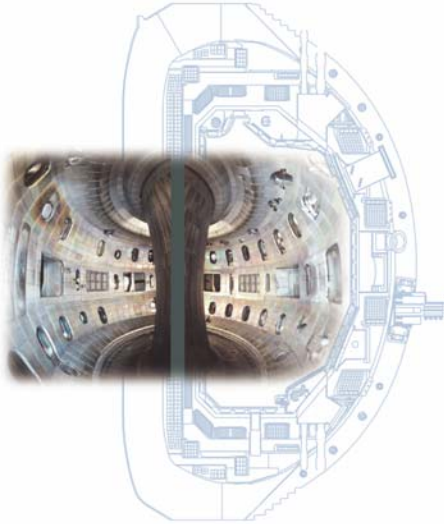

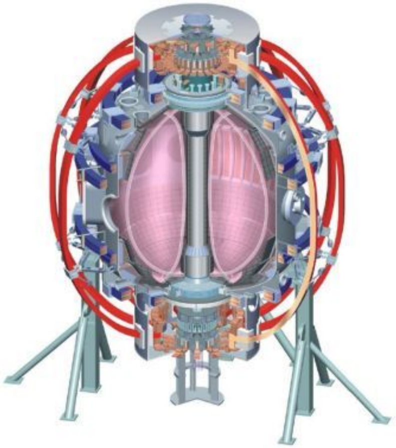

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

PPPL PRINCETON PLASMA PHYSICS LABORATORY

NSTX

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**

- **Strong need for alternate means of driving rotation in ITER**

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

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

- **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

- **Expand transport term in angular momentum balance equation**

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

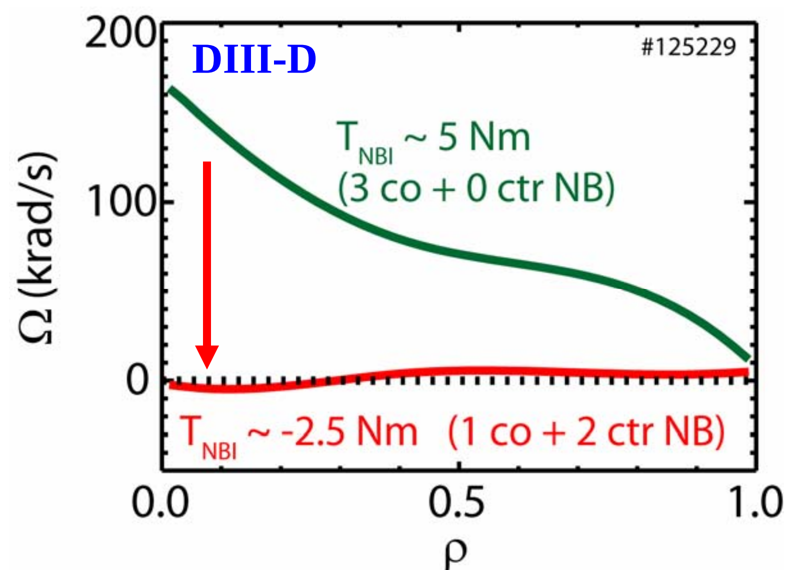
- **Non-diffusive momentum transport recognized both experimentally and theoretically**
  [Ida et al PRL 1995, Coppi NF 2002, Hahm PoP 2007, Yoshida NF 2007, Solomon PPCF 2007, ...]
- **Terms independent of V_ϕ → "Residual stress"**
  - ExB shear [Dominguez and Staebler PoFB 1993; Gurcan et al PoP 2007]
  - Up-down asymmetries in geometry [Camenen, PRL 2009
  - Fluctuation intensity shear [Diamond PoP 2008]

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**

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

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

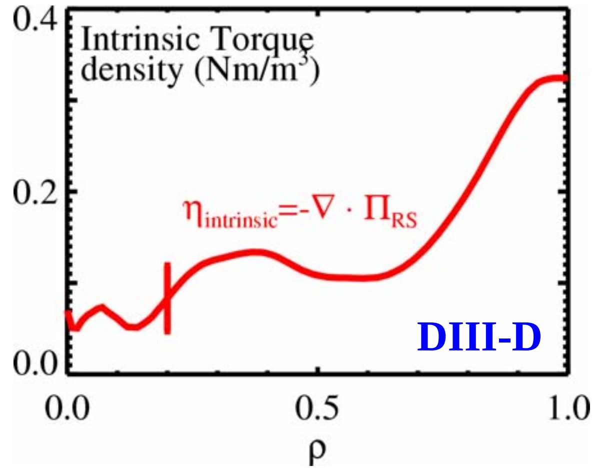


Good Correlation Found Between Edge Intrinsic Drive and Total Edge Pressure Gradient

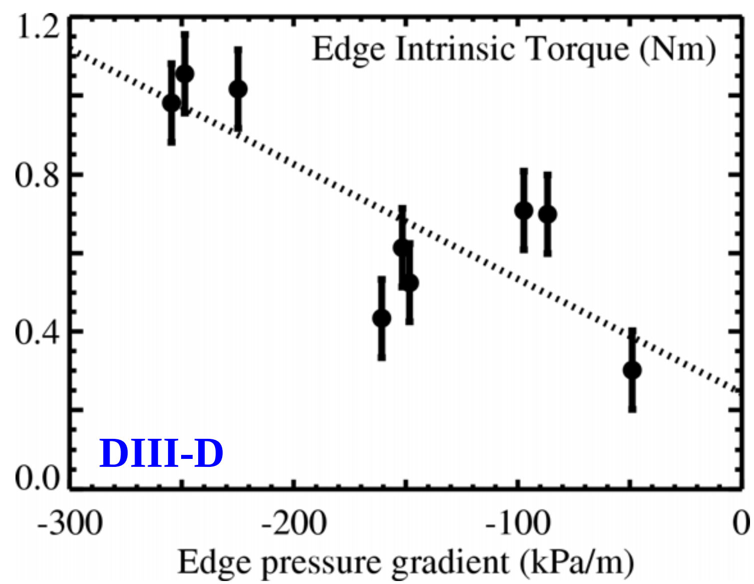
- **Residual stress drives effective intrinsic source, worth about one co-neutral beam source**

$$\eta_{\text{intrinsc}} = -\nabla \cdot \Pi_{RS} \qquad \eta_{NBI} + \eta_{\text{intrinsic}} = 0$$

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



- **Significant drive of torque at edge**
- **H-mode pedestal provides universal mechanism to drive residual stress**
  [eg Diamond et al NF 2009]
- **GTS simulations show residual stress driven from ITG increases with R/L_{Ti}**
  [See W. Wang, Thurs UP8.00083]
- **Means of achieving edge rotation in future devices**



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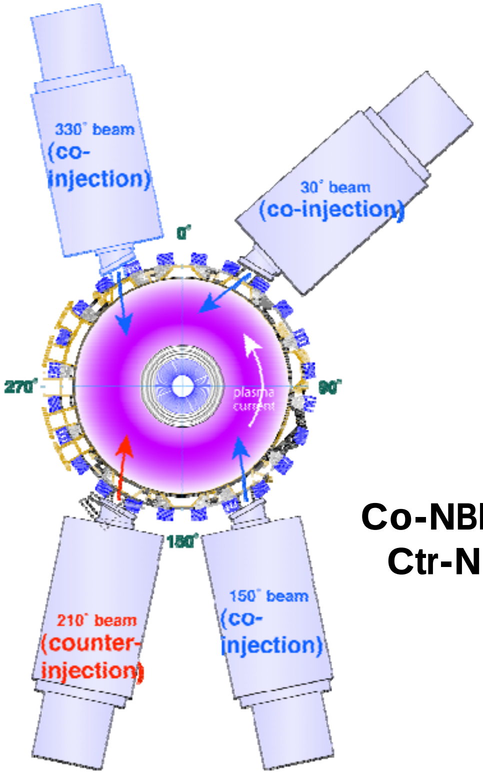
Momentum Pinch Velocities Are Investigated on Both NSTX and DIII-D Using Perturbative Techniques

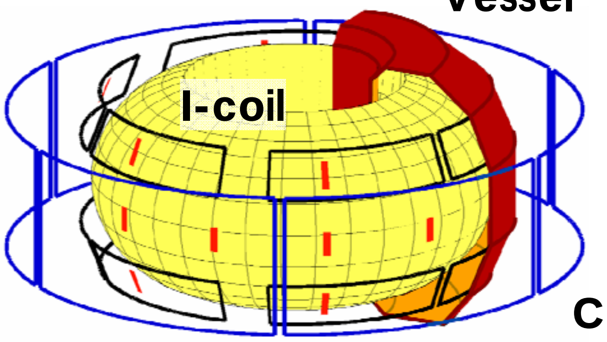
- On DIII-D, co/counter beams

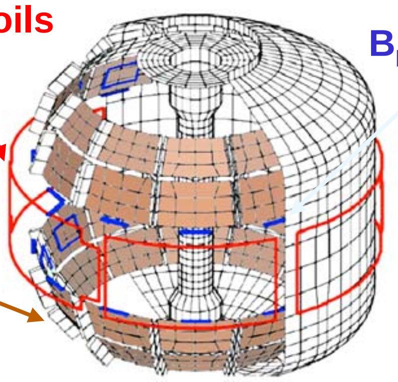


Co-NBI 12.5 MW
Ctr-NBI 5 MW

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

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





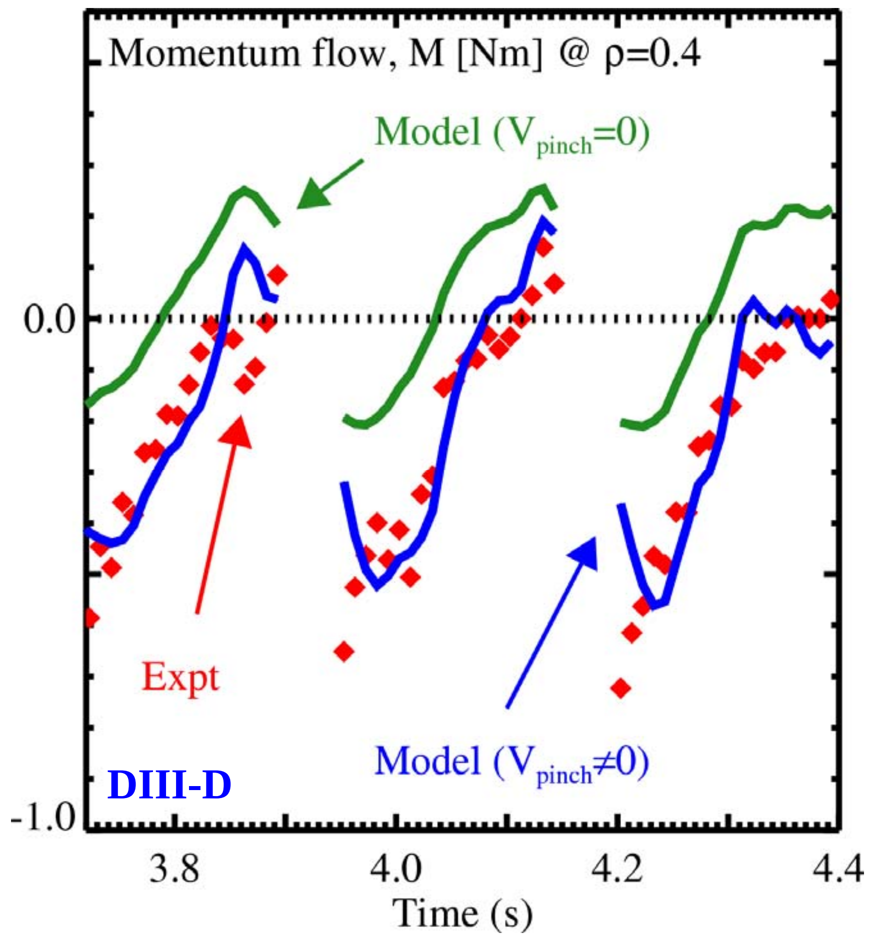
Diffusive And Pinch Model Necessary To Describe Momentum Flow Evolution

- **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**



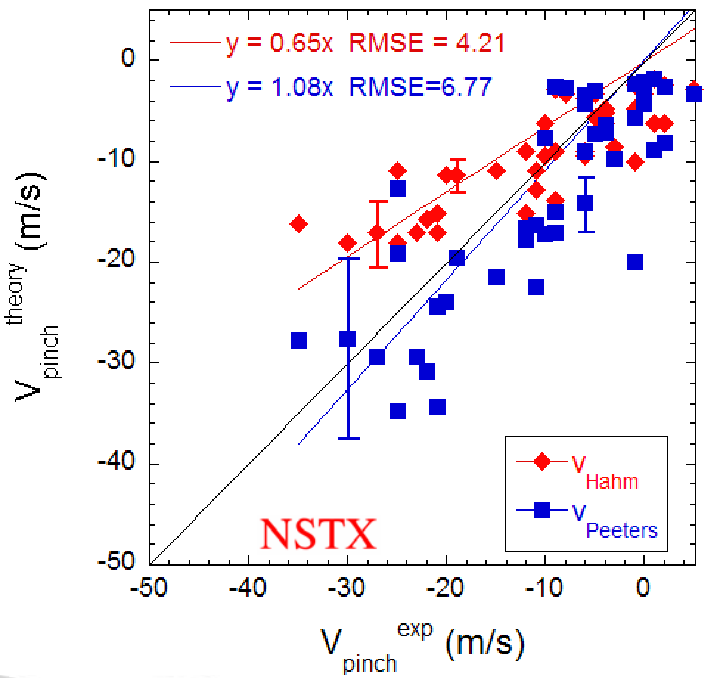
Good Agreement Found Between Theory And Experiment On Both NSTX And DIII-D

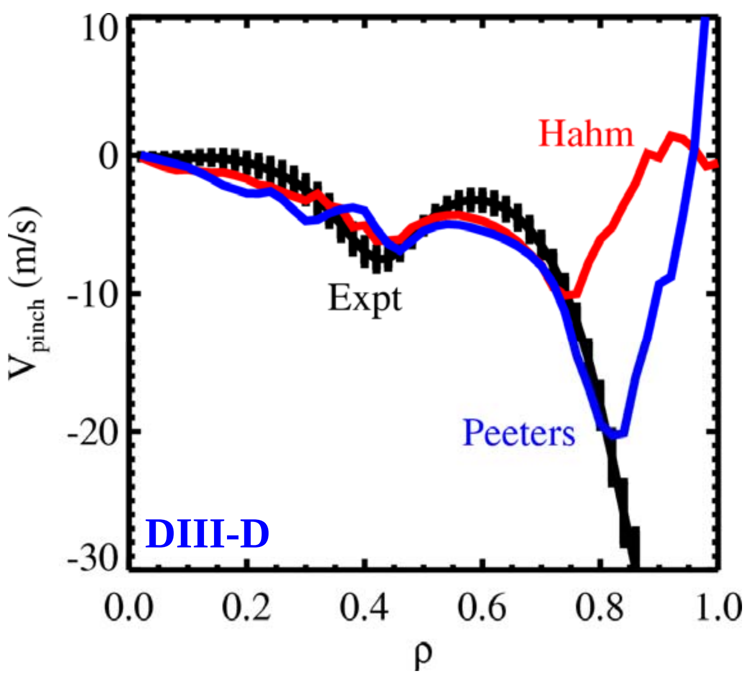
- **Theory predicts drive of momentum pinch through low-*k* turbulence**
  - Peeters *et al.* PRL (2007)

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

  - Hahm *et al.* PoP (2007)

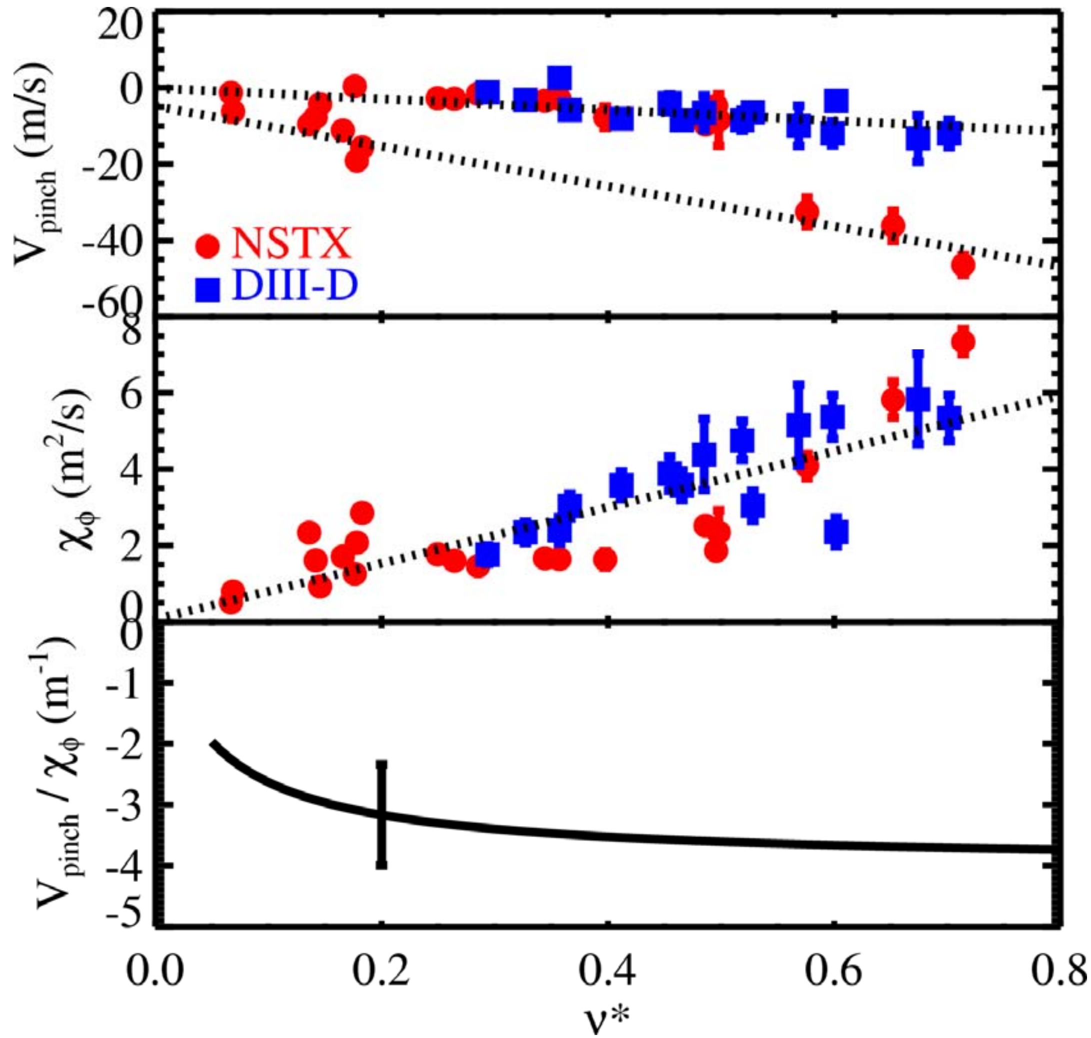
$$V_{Hahm} = \frac{\chi_\phi}{R}[-4]$$





Rotation Peaking From Pinch Only Shows Weak Dependence on Collisionality

- **Data shows both pinch and diffusivity reduced at low collisionality**
- **Overlap between datasets likely fortuitous**
  - NSTX: H-mode
  - DIII-D: L-mode
- **What physics responsible for enhanced pinch “branch”?**
- **Ratio of V_{pinch}/χ_ϕ determines peaking**
  - Slight reduction at very low collisionality [cf Yoshida NF 2009]



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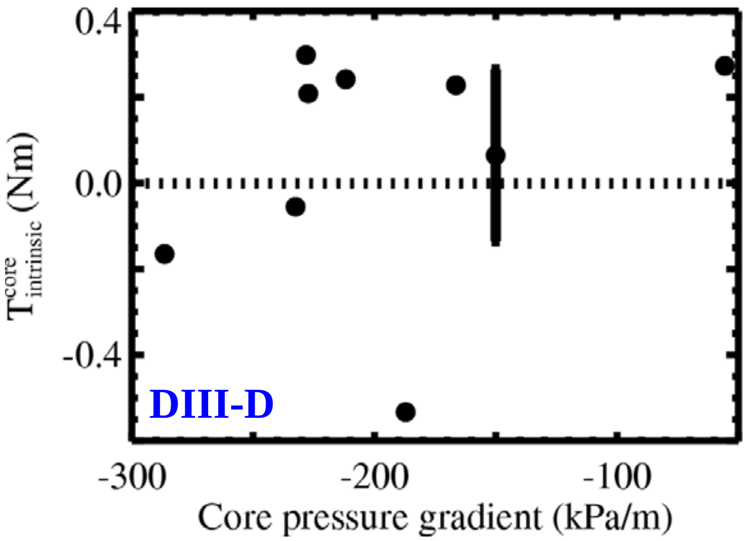
ECH Is Found To Modify Intrinsic Rotation In Core; Evidence of ECH-Induced Drive of Counter Rotation

- **GYRO simulations can generate momentum flows of the correct magnitude**
  - But extreme sensitivity to profiles
- **Generally core intrinsic torque relatively small compared with edge…**



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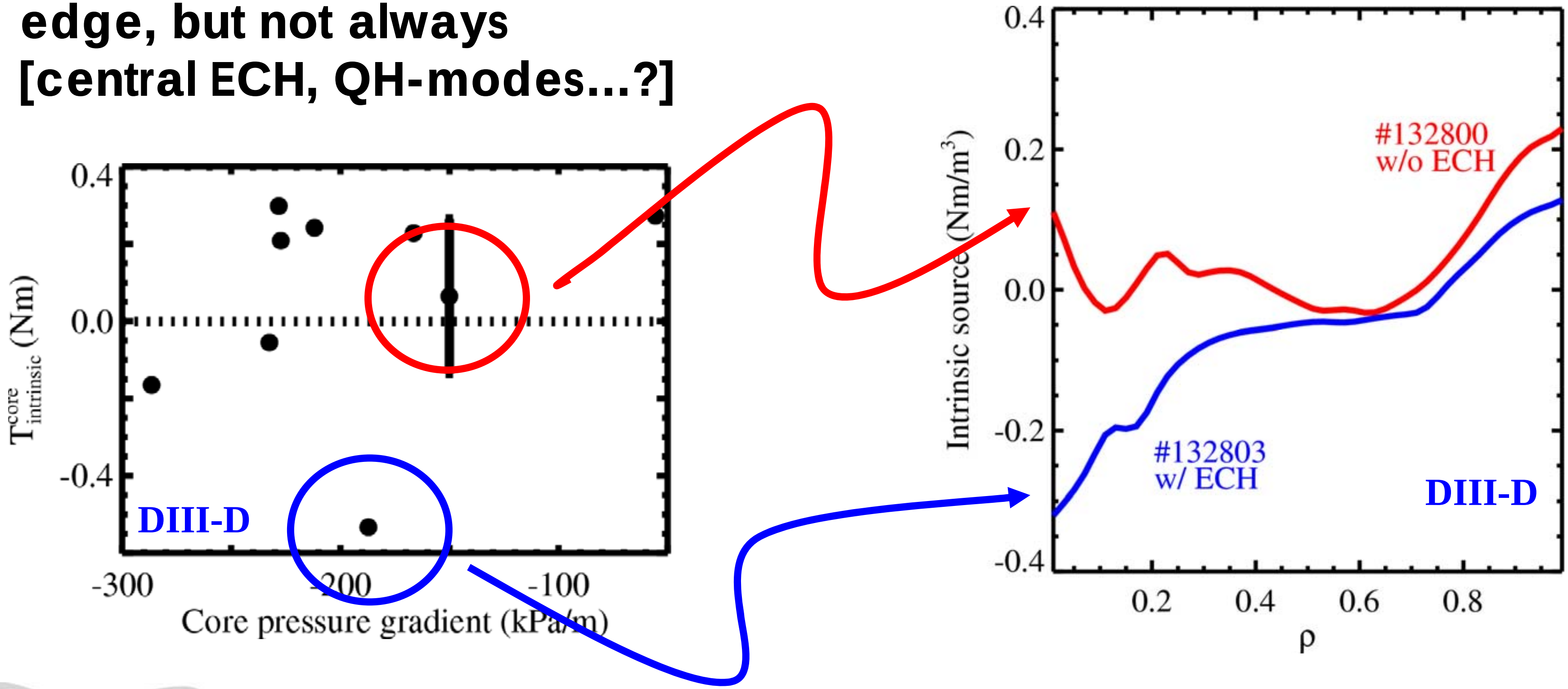
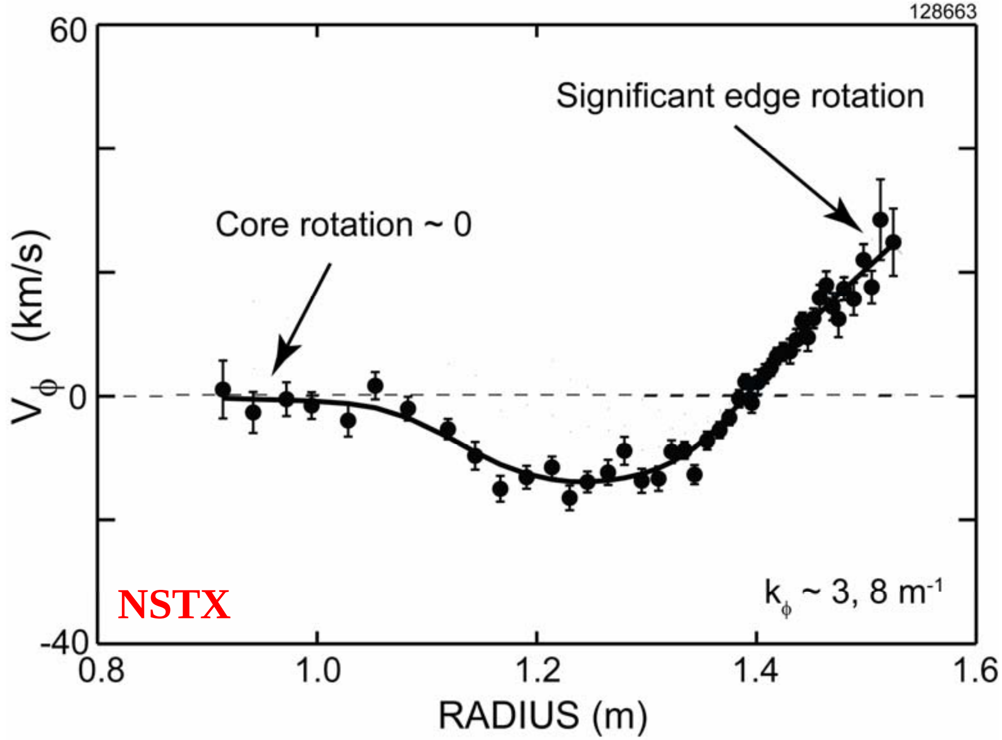


Application of High Harmonic Fast Wave Heating on NSTX Also Appears To Drive Counter Torque in Core

- **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



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

- **Hollow rotation profile suggests with a counter torque in the core**
- **Other modifications to core intrinsic rotation include**
  - ECH on JT-60U (driving opposite rotation) [Yoshida PRL 2009]
  - LHCD from C-Mod [Rice NF 2009]

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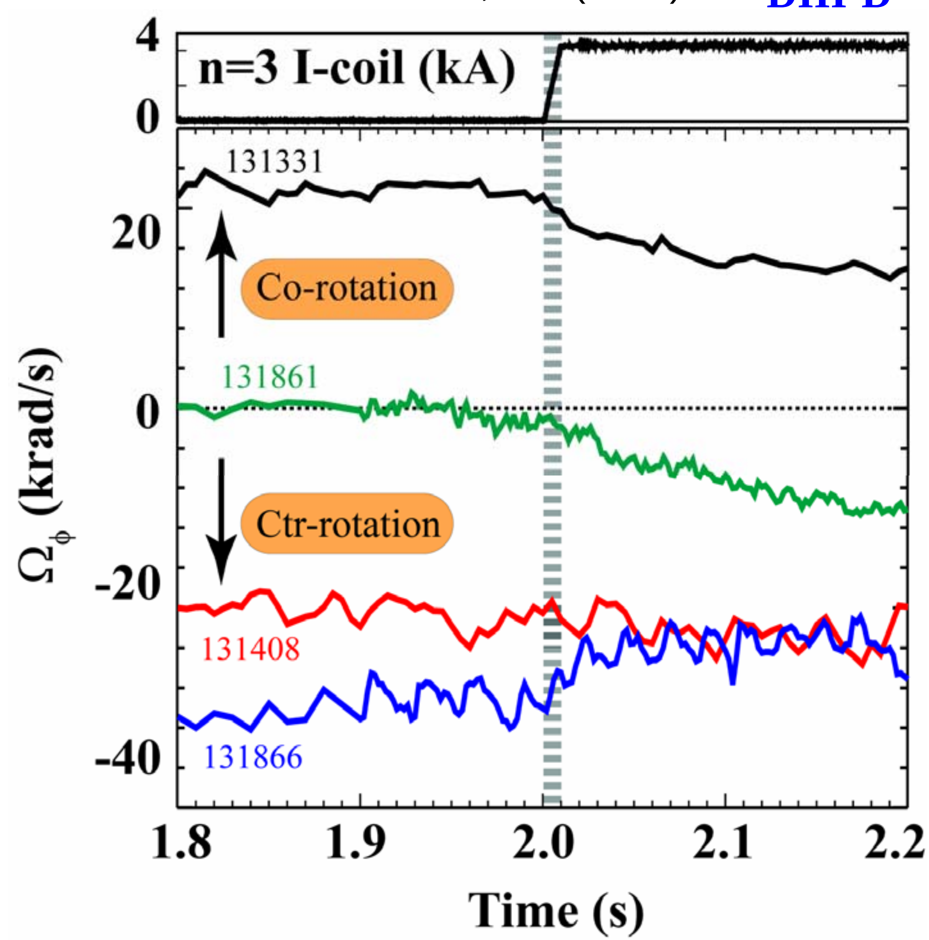
Previous Work Has Shown That Non-Resonant Magnetic Fields (NRMFs) Apply a Torque

- **Rotation dragged toward finite rotation condition ("offset rotation")**
  [Cole PRL 2007, Callen PoP 2009]

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

- **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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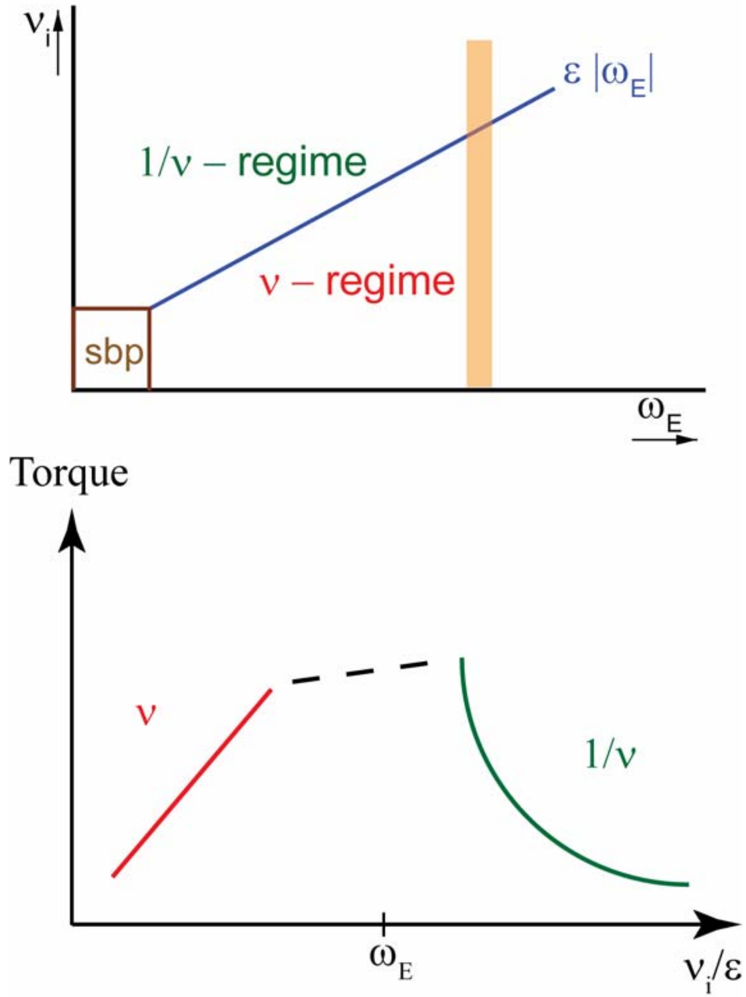
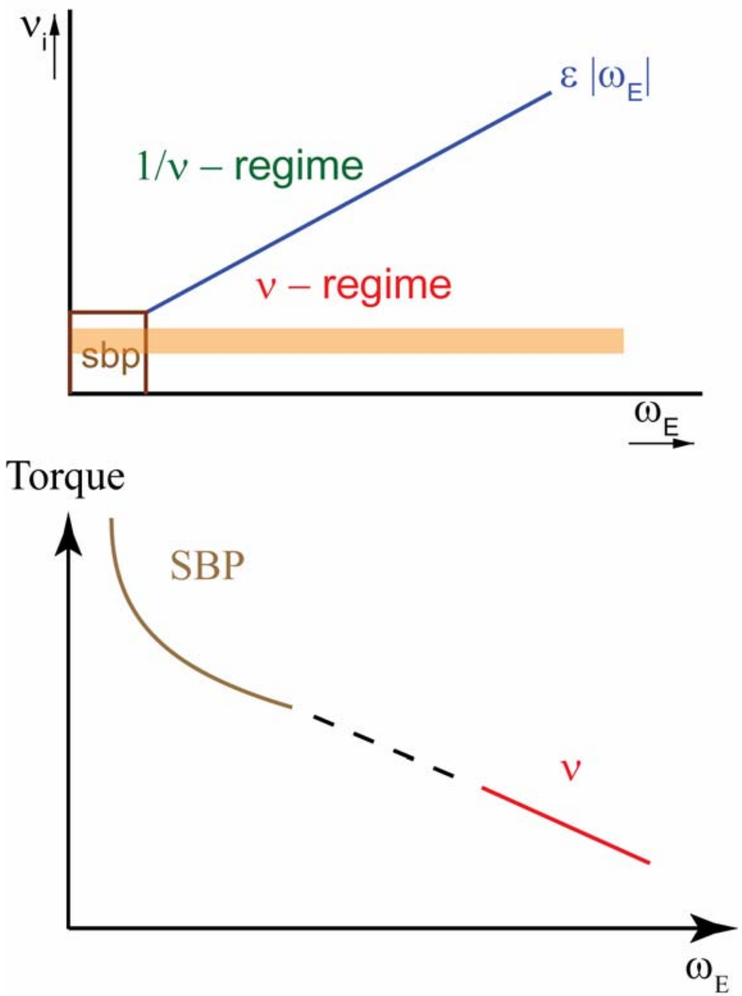
Enhanced Torque Regime Accessed At Low Collisionality and Low Rotation

- **At moderate rotation, transition from 1/ν to ν regime by reducing collisionality**



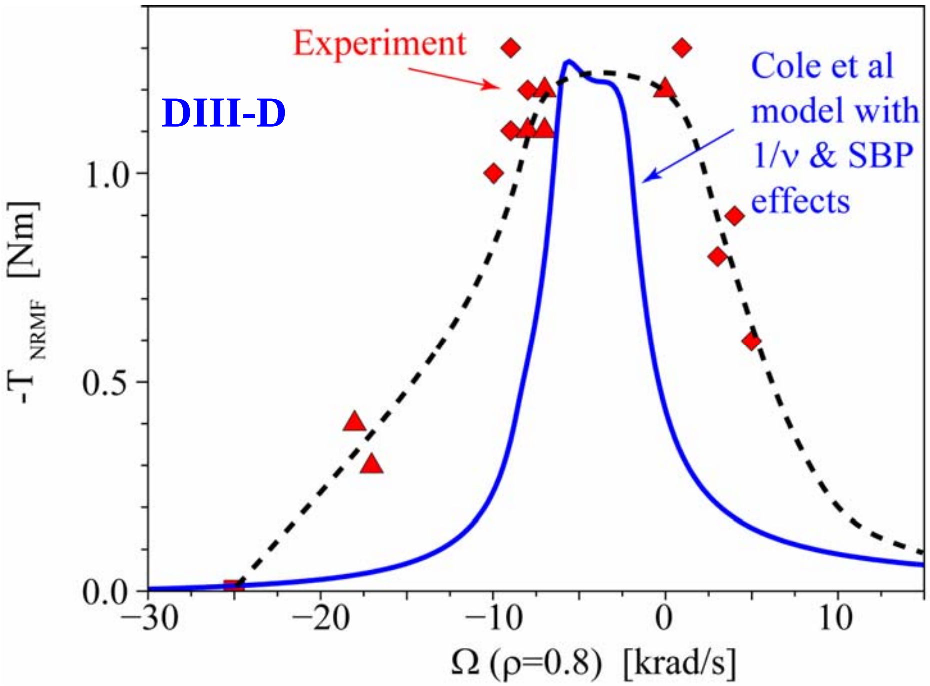
Enhanced Torque Regime Accessed At Low Collisionality and Low Rotation

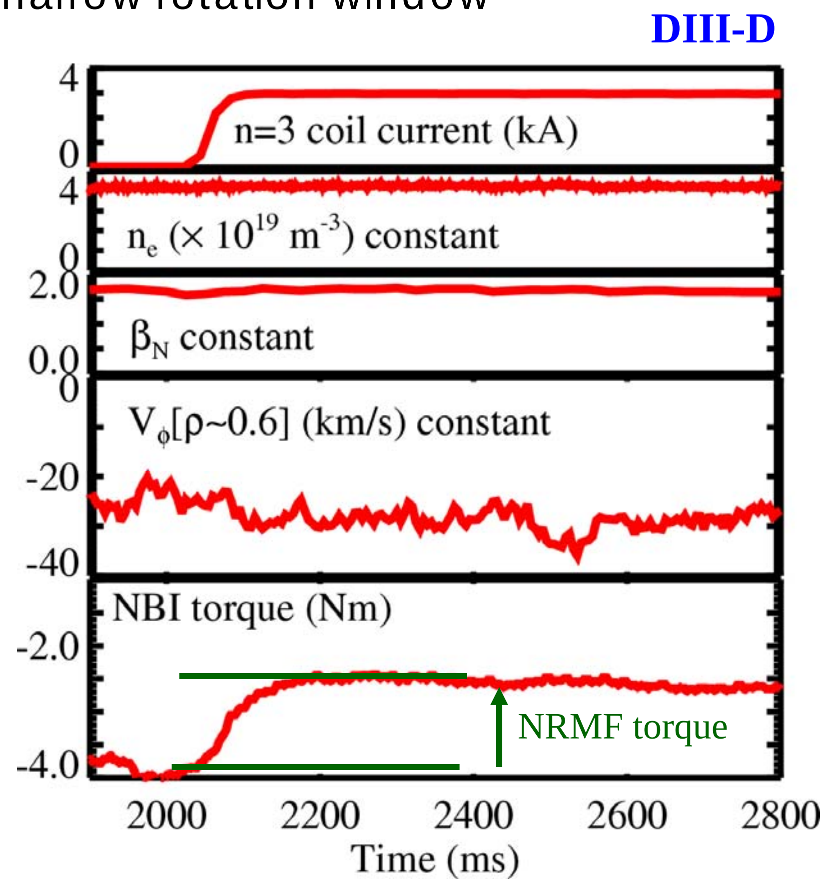
- **At moderate rotation, transition from 1/ν to ν regime by reducing collisionality**
- **At sufficiently low collisionality, transition from ν to super-banana plateau (SBP) regime by reducing rotation (ω_E)**
- **Neoclassical transport expected to be enhanced in SBP regime**



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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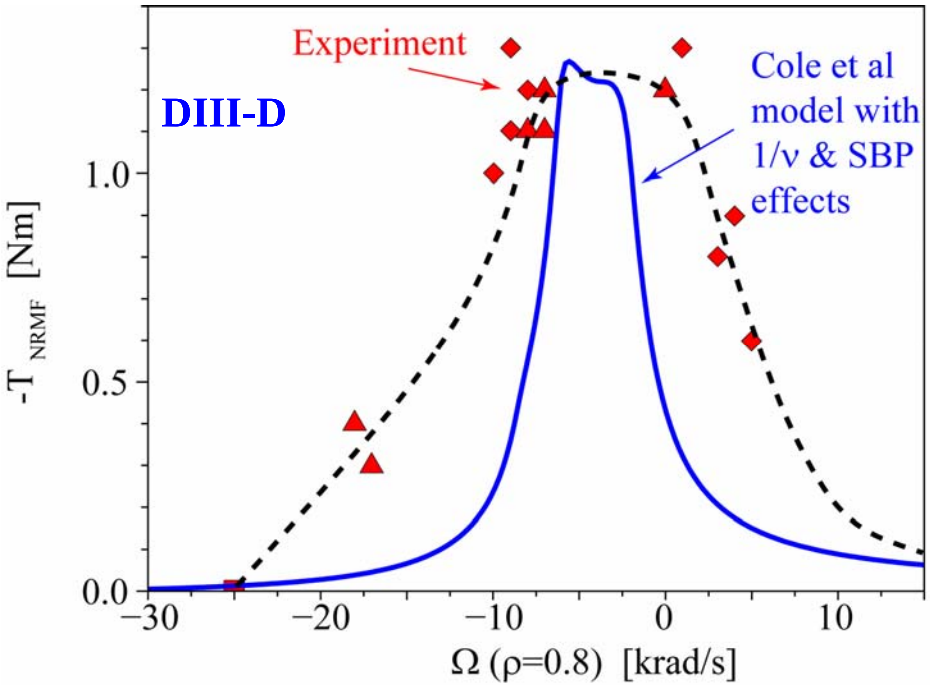
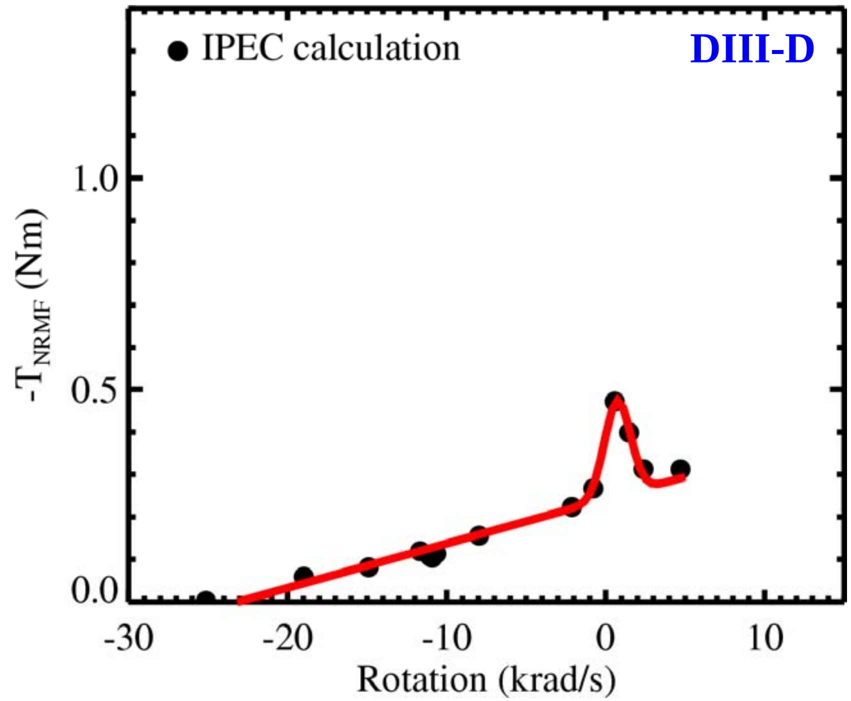
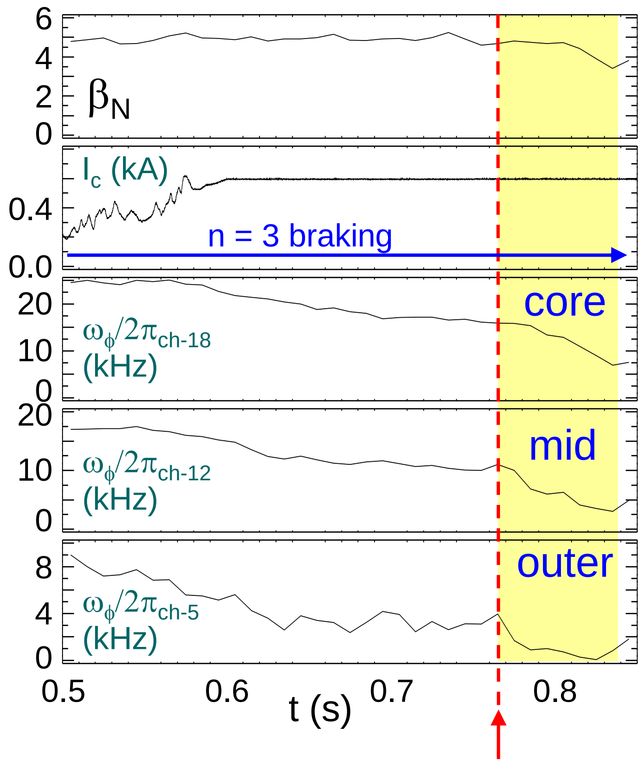




Increased NRMF Torque At Low Rotation Also Indicated On NSTX

- **Braking increases at low rotation**
  - No apparent mode activity
  - Does not appear to be resonant braking effect



Transition to faster braking?

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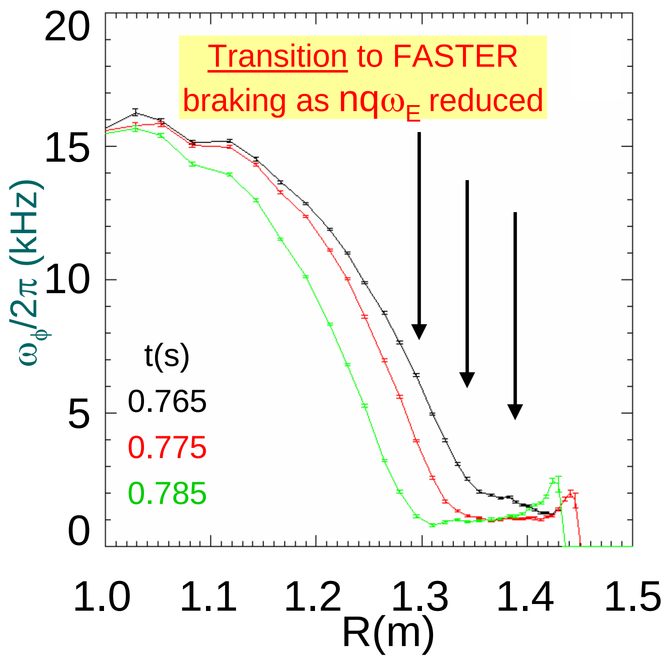

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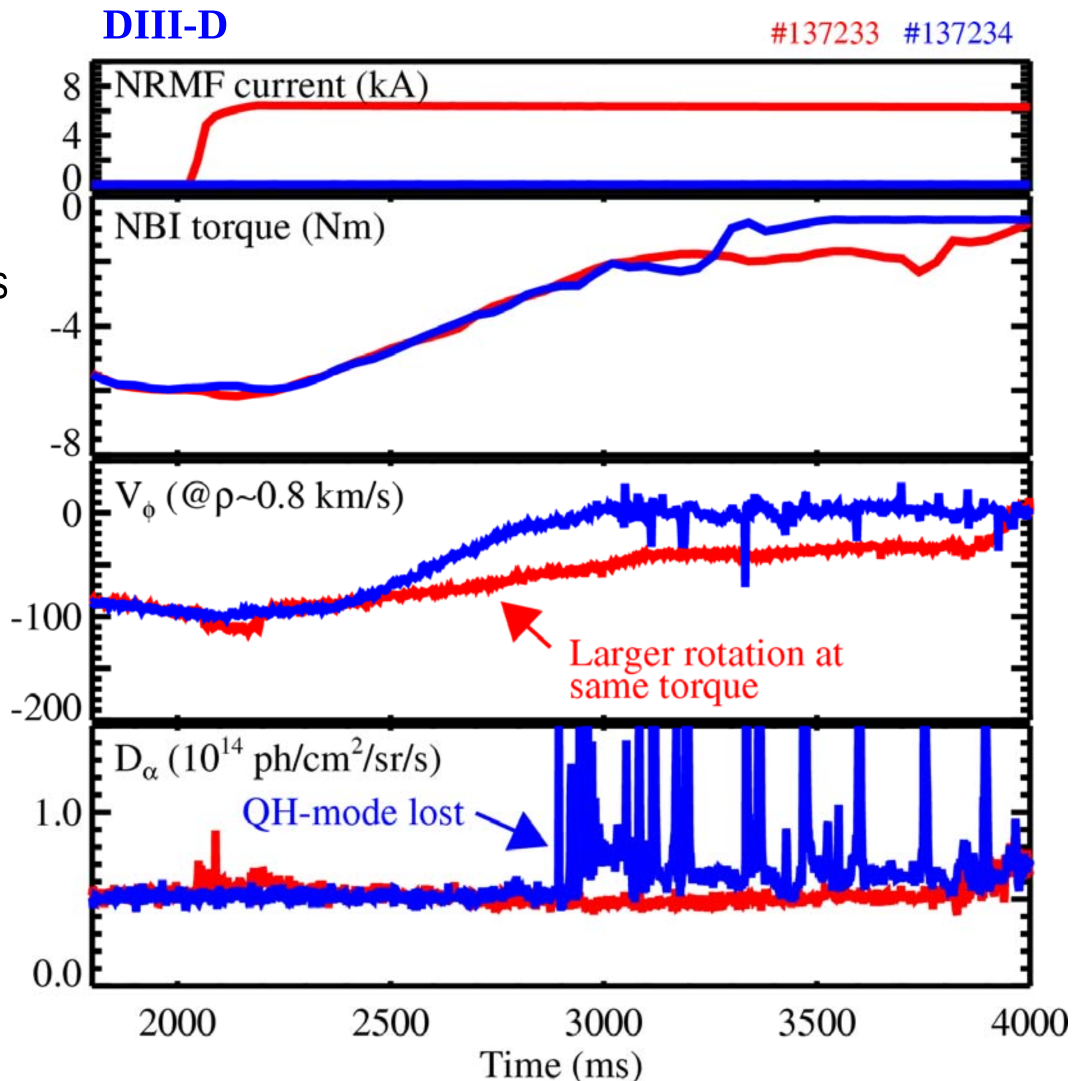
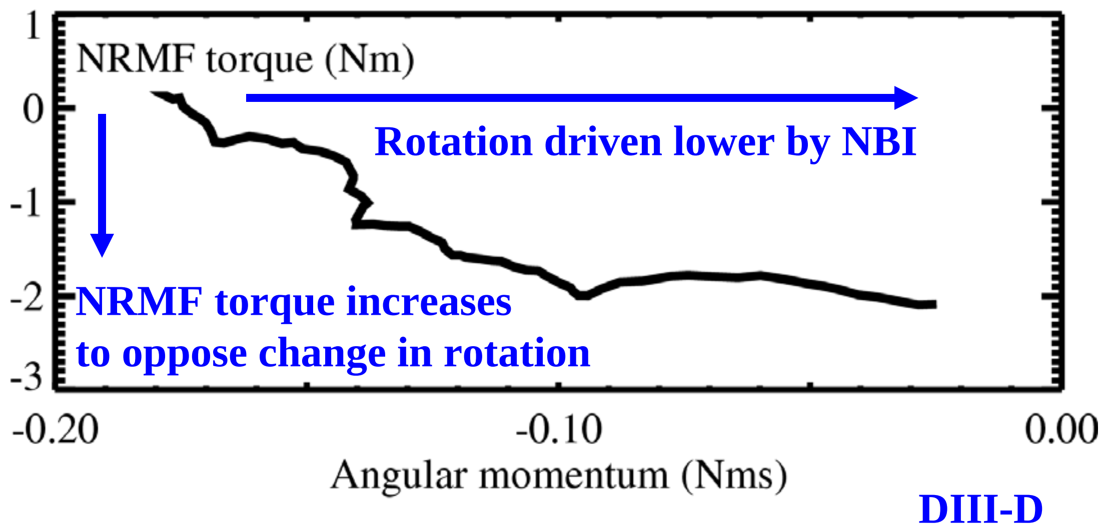
Enhanced NRMF Torque at Low Rotation Helps Expand Operating Space of QH-Mode Plasmas

- **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 At Low Rotation

- **Obtain dependence of intrinsic torque and viscous transport on angular momentum from reference shot**
- **NRMF torque in shot with n=3 is remainder after including NBI, intrinsic and viscous transport**



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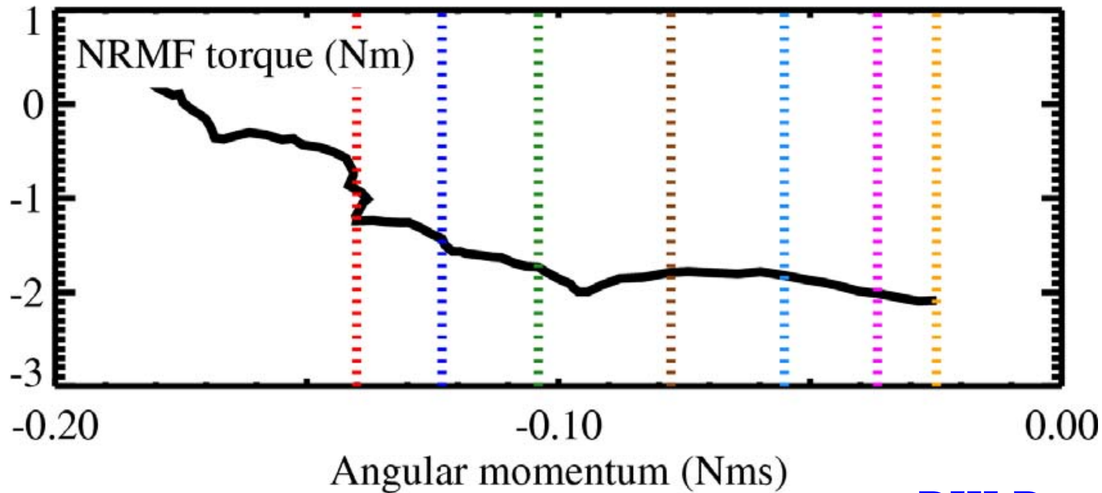
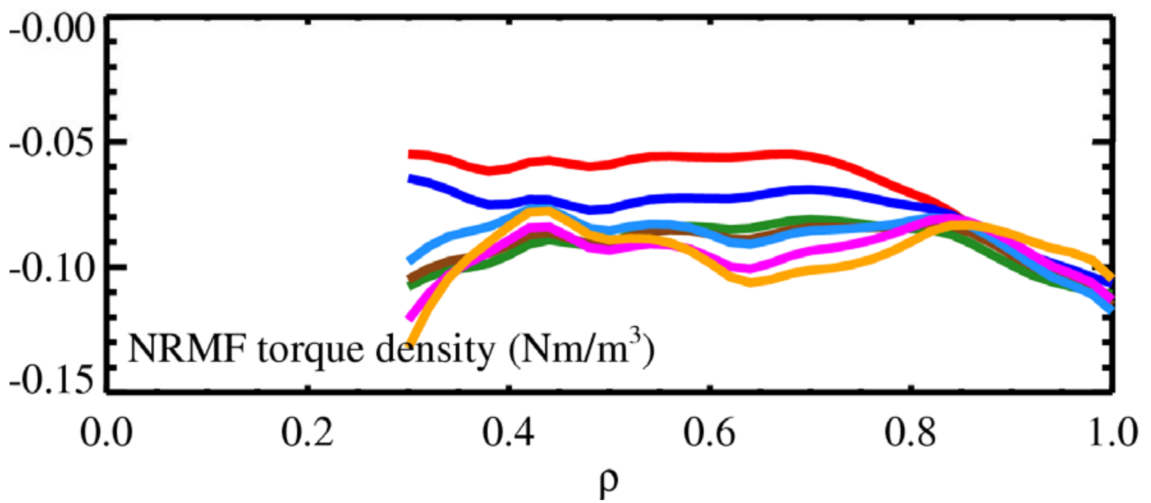
- **NRMF torque density increases at low angular momentum**
  - Consistent with SBP enhancement





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
- Physics of core residual stress is much more complicated
- Non-resonant magnetic fields can drive rotation due to existence of offset rotation
- NRMF torque found to be enhanced at low rotation
- All together, may provide many opportunities for rotation control and performance optimization for ITER