Developments in Predictive Understanding of Plasma Rotation on DIII-D

By

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In Collaboration with

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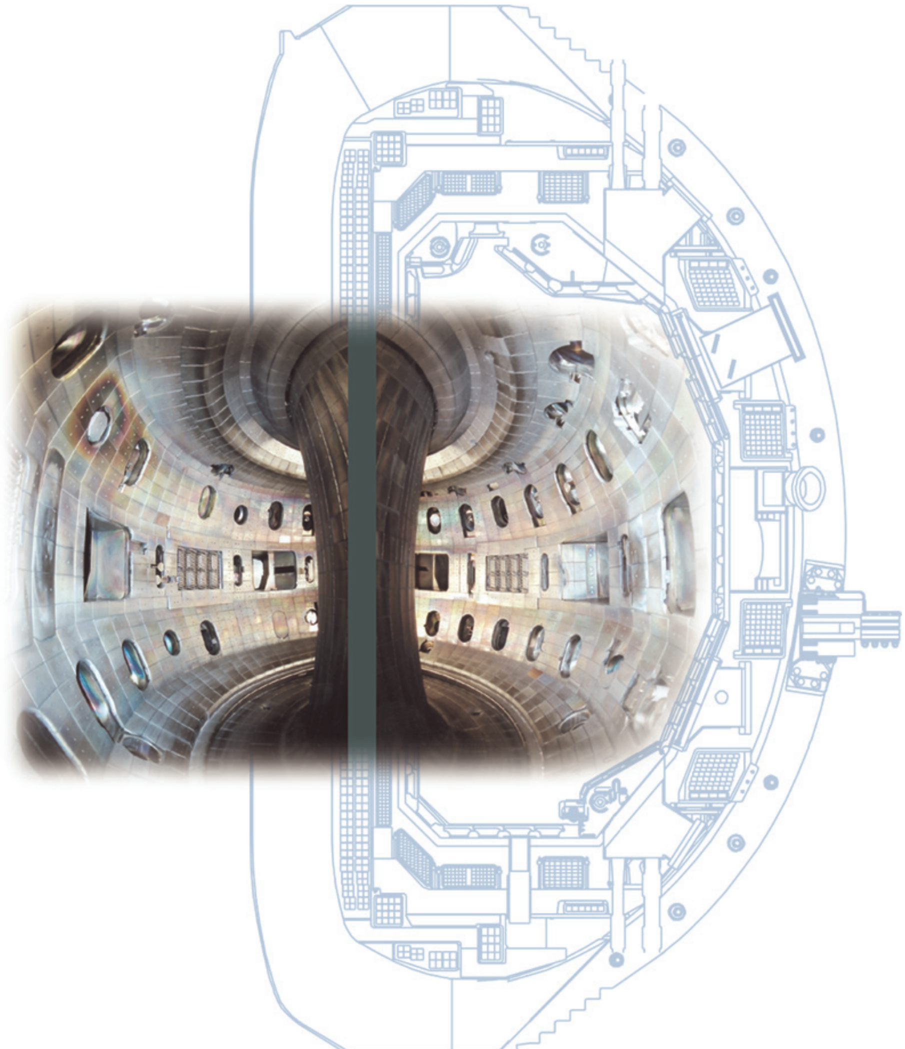

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

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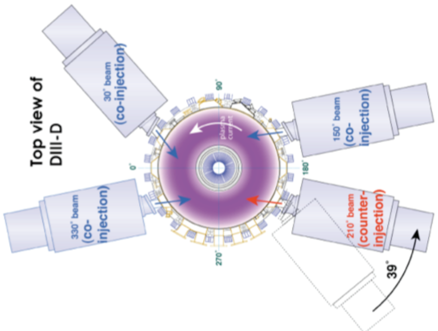
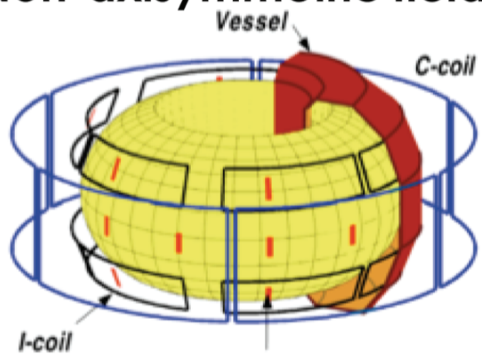
Performance of Future Devices Influenced by Attained Rotation Profile

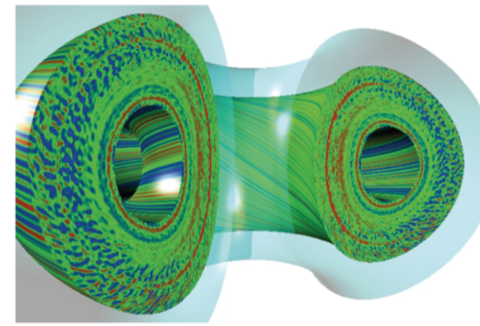
Sources:
Neutral beam, intrinsic …



Sinks:
Non-axisymmetric fields



Transport:
Diffusivity, Pinch…



Rotation

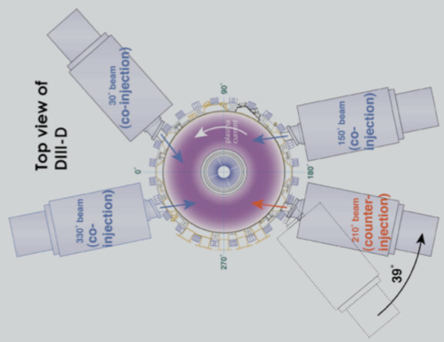
Turbulence Control
Improved confinement

Modify NTM/RWM stability

Error field thresholds
Locked mode avoidance

Outline

Sources:
Neutral beam, intrinsic …



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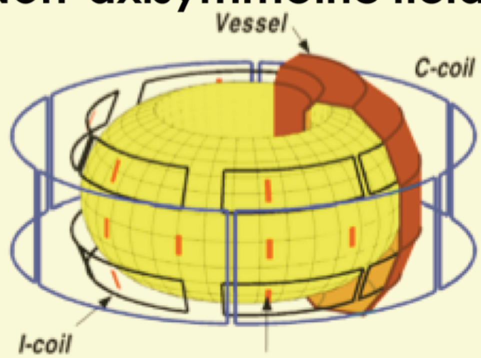

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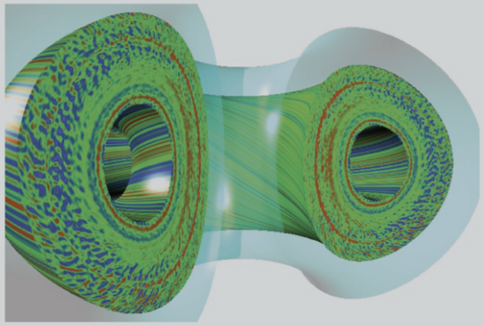
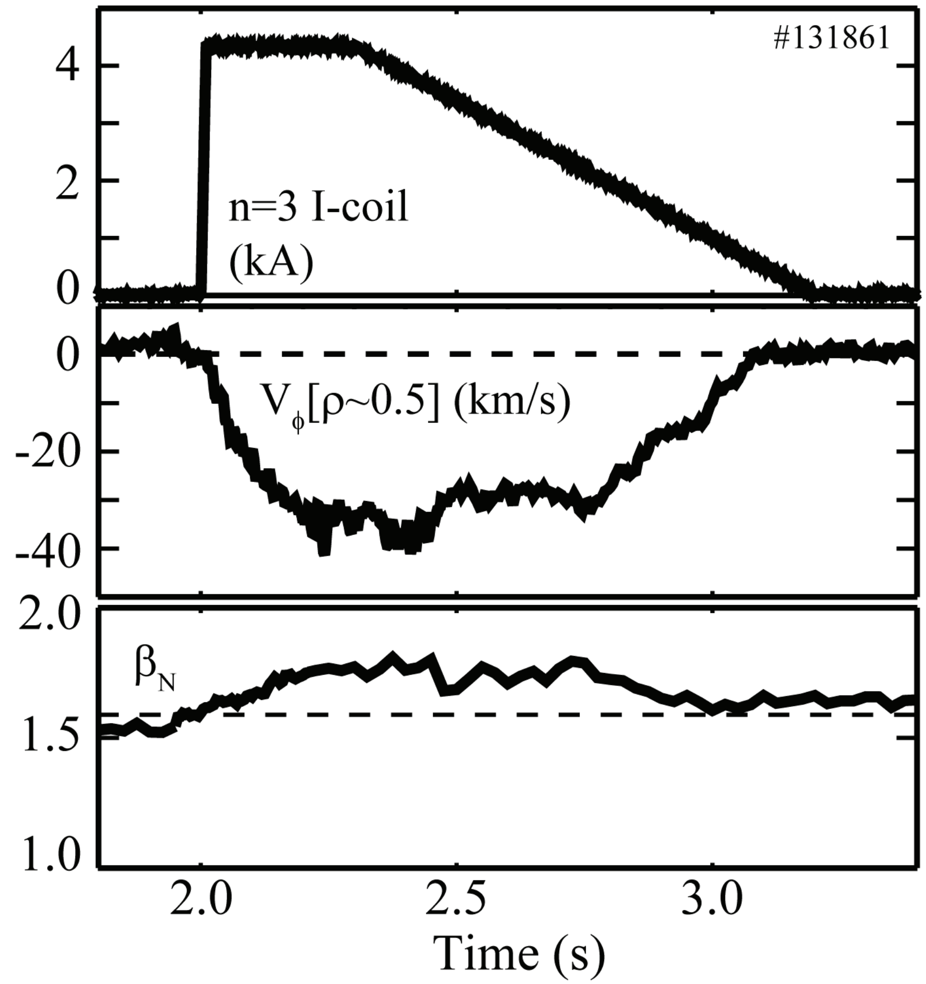


Rotation

n=3 Non-Resonant Magnetic Fields (NRMF) Applied to Slowly Rotating Plasma Leads to Rotation Spin Up

- **NBI power and torque constant during time range shown**
- **Rotation acceleration happens at all minor radii**
- **Simultaneous improvement in energy confinement**



Garofalo, PRL (accepted)

Application of NRMF Drags Plasma Rotation to Neoclassical Offset Rotation

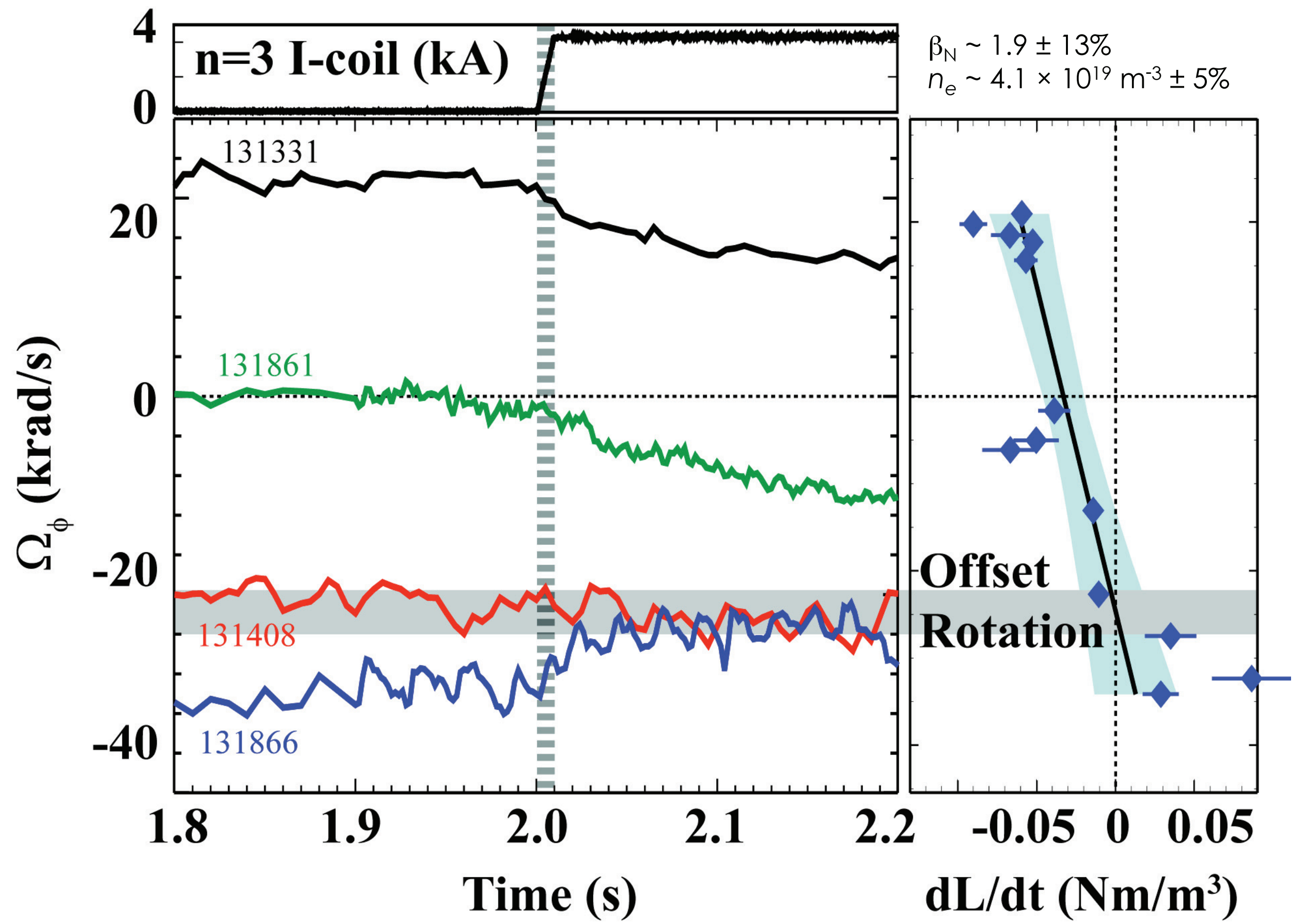
- **Neoclassical theory predicts a non-zero "offset rotation"**
  [Cole et al PRL 2007]

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

$$V_\varphi^{0,\mathrm{NC}} \cong \frac{k}{Z_\mathrm{i} e B_\theta} \frac{dT_\mathrm{i}}{dr}$$

- **Offset rotation in counter I_p direction**

- **Measured torque exhibits offset linear relationship**



Garofalo, PRL (accepted)

Effect of NRMF on Plasma Rotation Can Be Adequately Modeled Throughout the Discharge

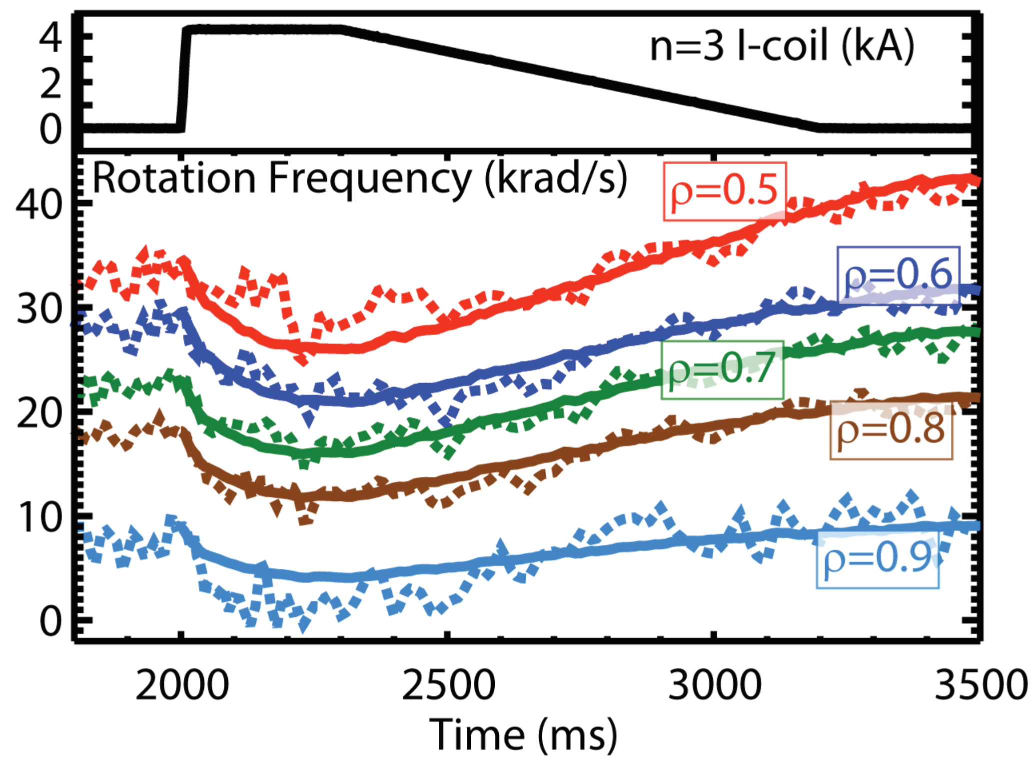
- **Evolve rotation using momentum balance in TRANSP**

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

- **Vary NRMF torque according to I-coil waveform (B^2) and velocity relative to offset**

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

- **Allow only slow, linear variation of momentum diffusivity χ_ϕ^{eff}**



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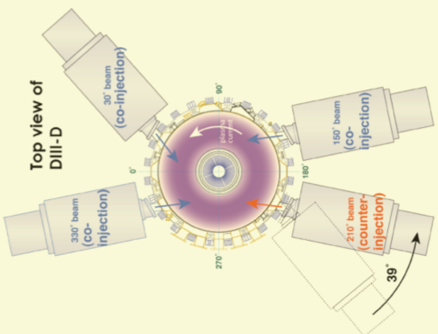

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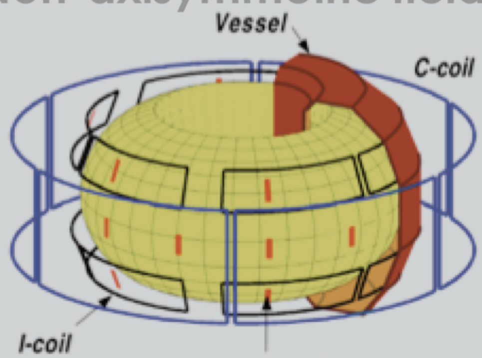
Non-axisymmetric fields



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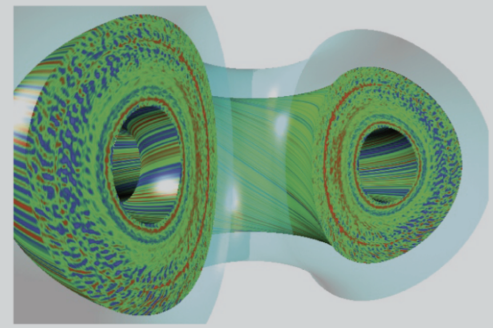
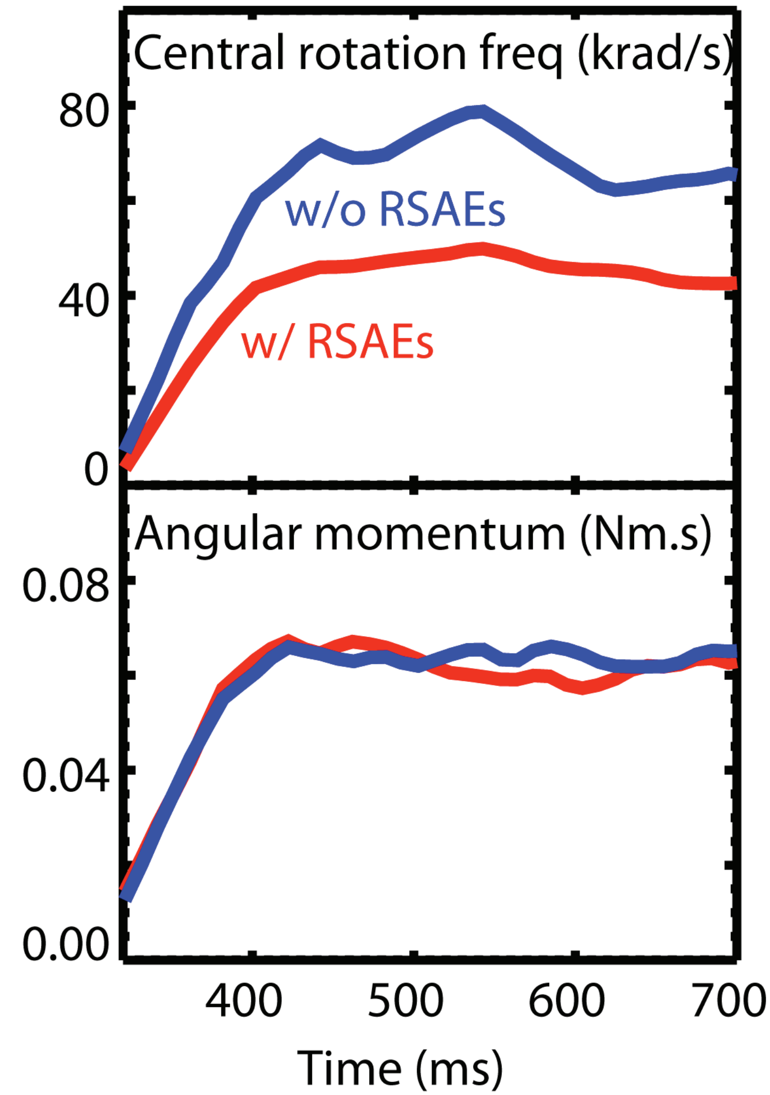


Rotation

Toroidal Rotation Can Be Modified by Strong Reverse Shear Alfvén Eigenmode (RSAE) Activity

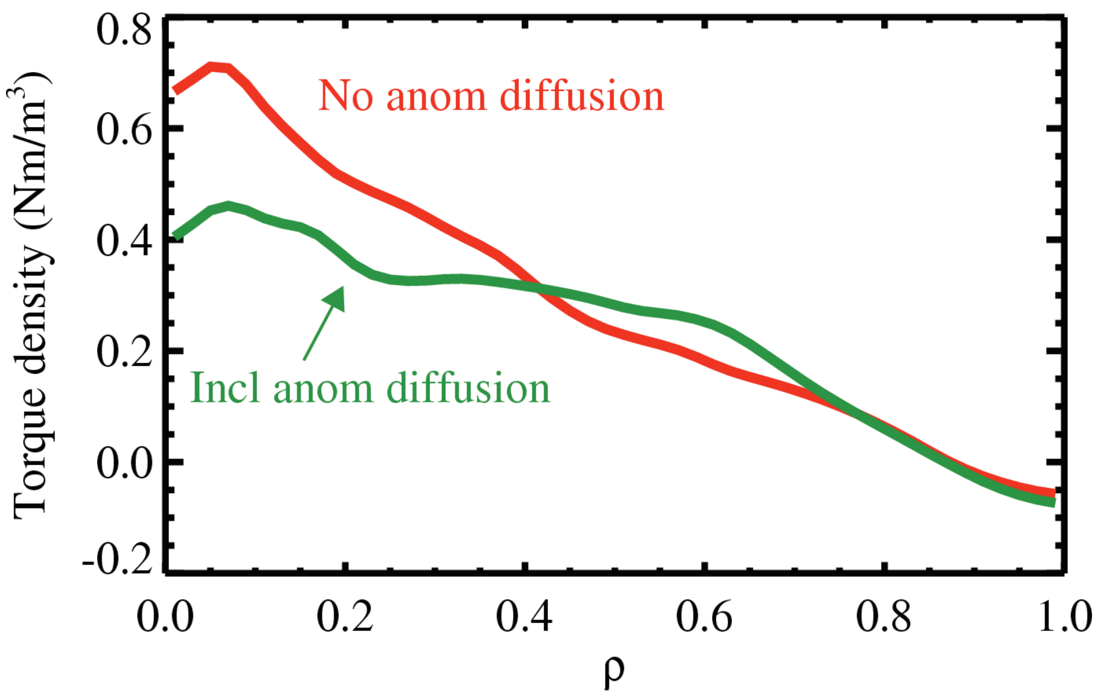
- **Central rotation almost 2x greater with RSAE activity suppressed**
- **However, total angular momentum content comparable**
- **Suggestive of redistribution of fast ions rather than complete loss**
  - Change in rotation due to changes in torque profile?



See Van Zeeland EX/6-2 on RSAE's

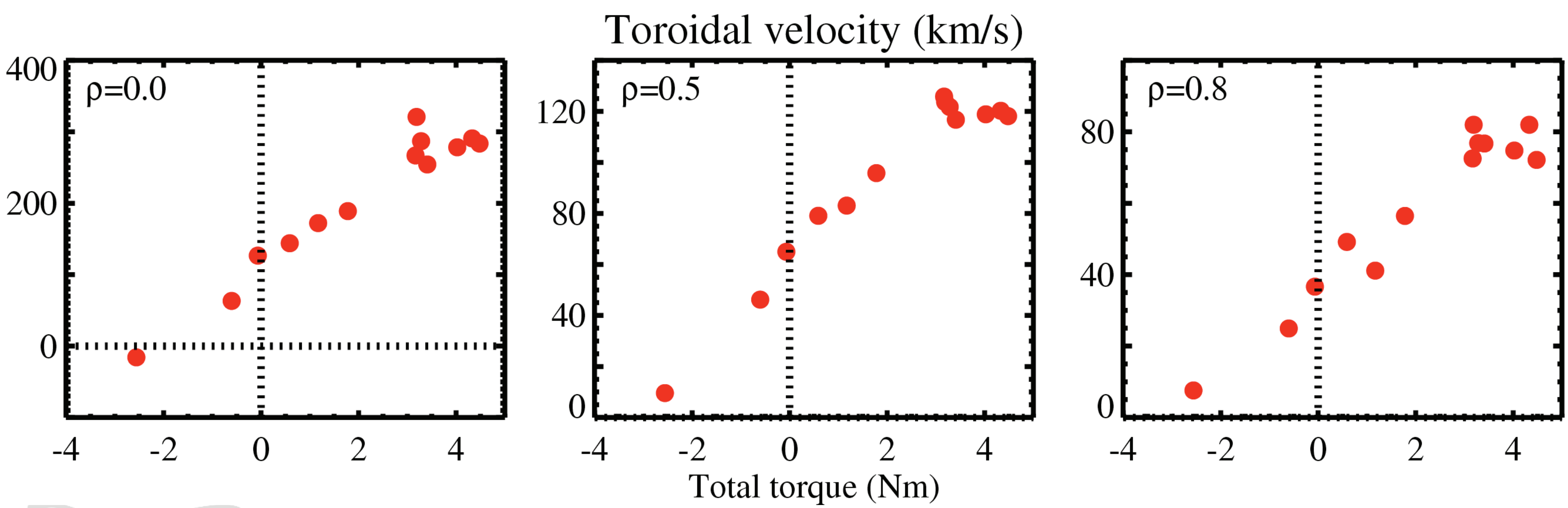
Torque Profile is Significantly Modified by RSAE-Induced Fast Ion Transport

- **Assume change in rotation due to modification of source, rather than changes in momentum transport**
- **Use ad hoc anomalous fast ion diffusion in TRANSP to account for effect of RSAE's on fast ion transport**
- **40% central NB torque reduction required to match rotation**
- **Inferred RSAE-induced fast ion transport consistent with**
  - Reduction in neutron rate
  - Reduced fast ion density



Intrinsic Rotation Plays a Role in Determining Total Plasma Rotation, Even with Neutral Beam Injection

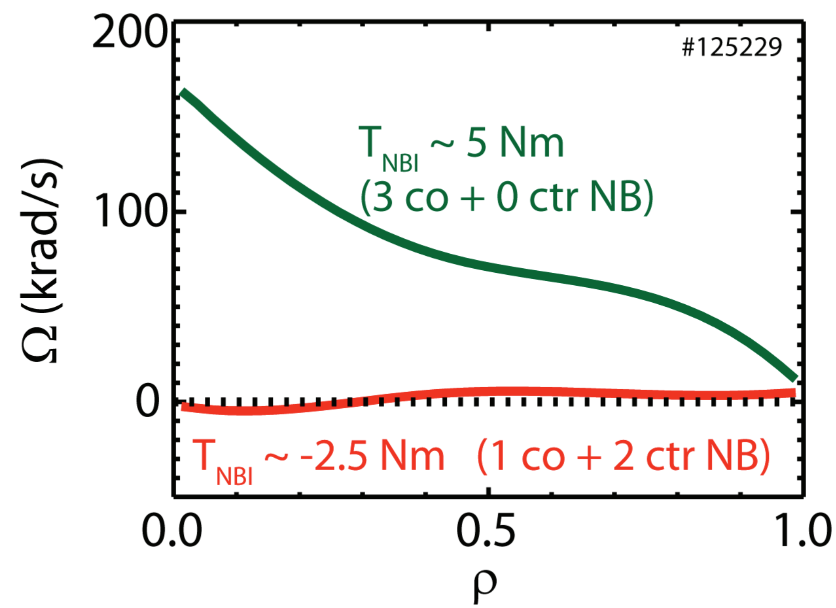
- **Intrinsic rotation = rotation without auxiliary torque**
  - Observed on C-Mod, JET, JT-60U, Tore Supra…
- **On DIII-D, torque scans performed at constant β_N~1.7±10% to investigate intrinsic + NBI**
- **Large rotation observed across profile, even with net zero torque from NB**
  - Persists even with significant counter injection



Near-Zero Rotation Profile With Finite Neutral Beam Torque Suggests an Intrinsic Torque Source

- **From momentum balance equation**

$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of momentum}} = \underbrace{\sum \eta}_{\text{Momentum sources/sinks}} - \underbrace{\nabla\cdot\Gamma}_{\text{Transport}} + \underbrace{S}_{\text{"Intrinsic torque"}} \quad , \quad \Gamma = -mnR\left(\underbrace{\chi_\phi \frac{\partial V_\phi}{\partial r}}_{\text{diffusion}} - \underbrace{V_\phi V_{pinch}}_{\text{pinch}}\right)$$



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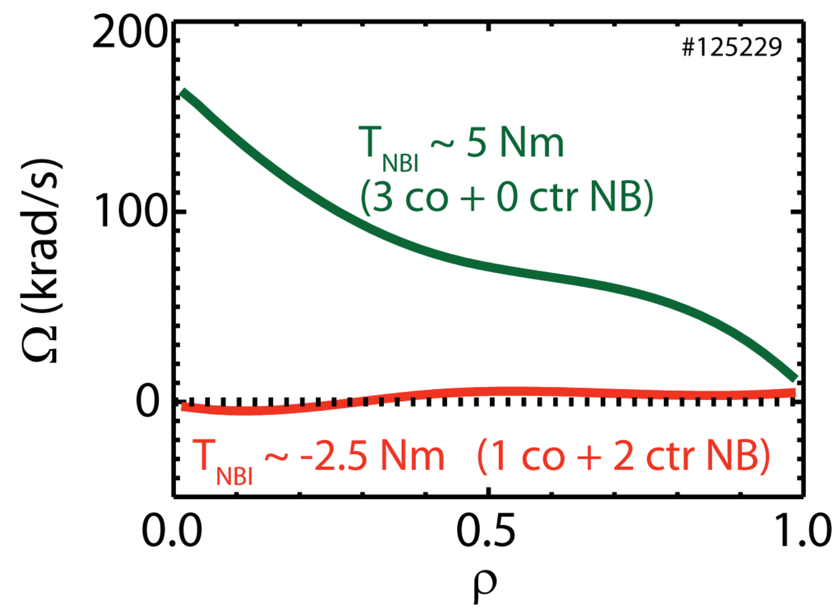
- **If V_ϕ zero and constant, then net torque to plasma must be zero**

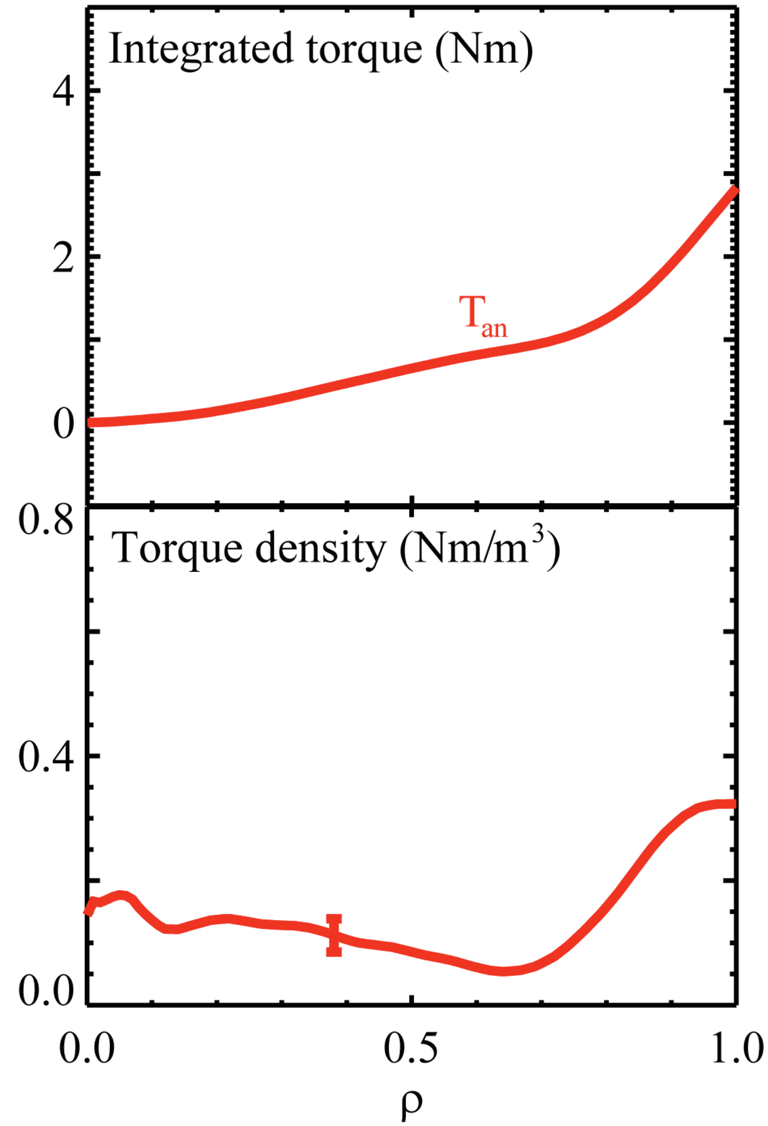
- **Situation essentially realized here**
  - Despite one net counter NB source
  - Direct evidence of intrinsic source



Intrinsic Source Approximately Equivalent to One Neutral Beam Source

- **Intrinsic source must cancel NBI torque**

$$\eta_{NBI} + S = 0 \quad \rightarrow \quad S = -\eta_{NBI}$$



Intrinsic Source Approximately Equivalent to One Neutral Beam Source

- **Intrinsic source must cancel NBI torque**

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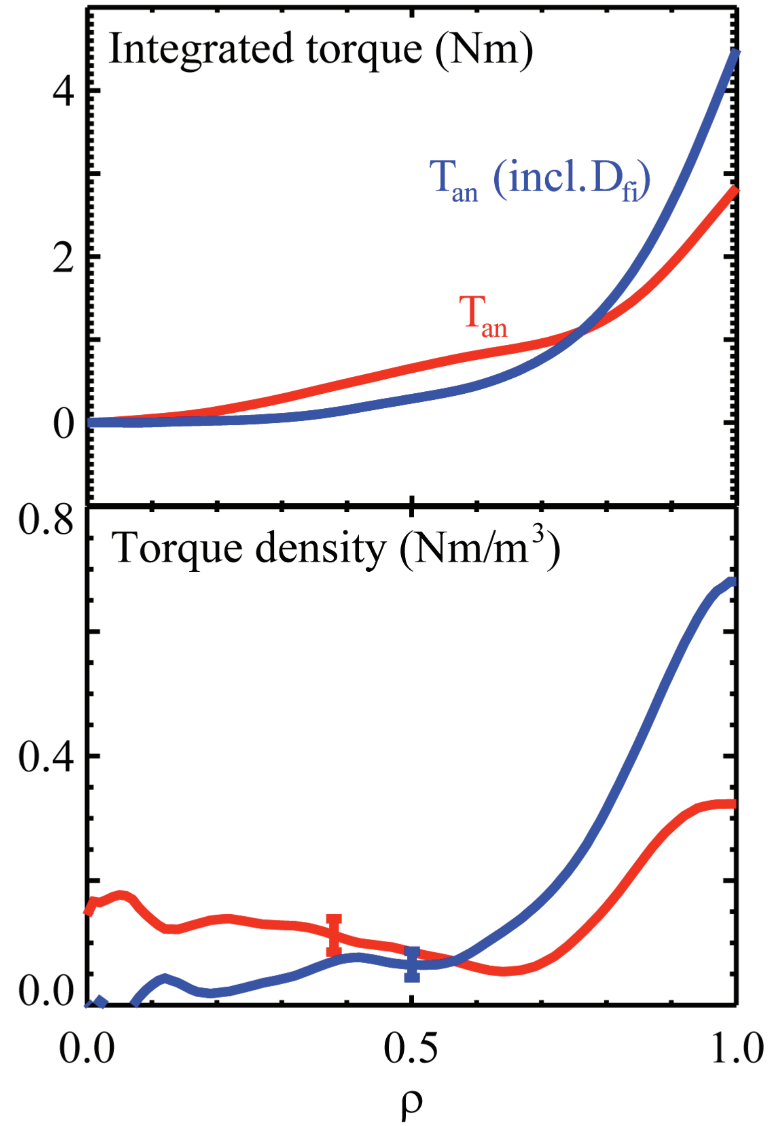
- **Additional fast ion transport alters calculated NBI torque**
  - Inferred intrinsic source becomes more peaked at edge

- **Evidence of "Residual Stress"?** [Gurcan et al PoP 2007, Dominguez and Staebler, Phys. Fluids B1993]



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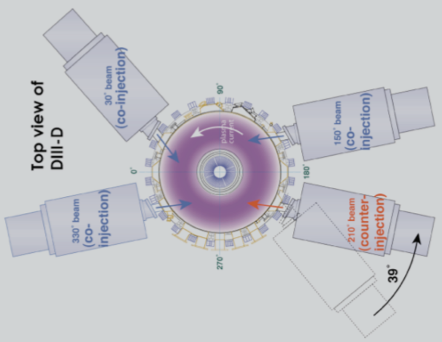

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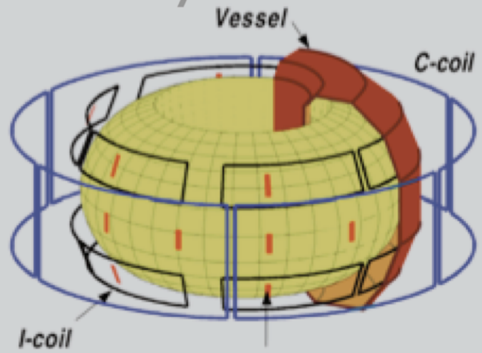

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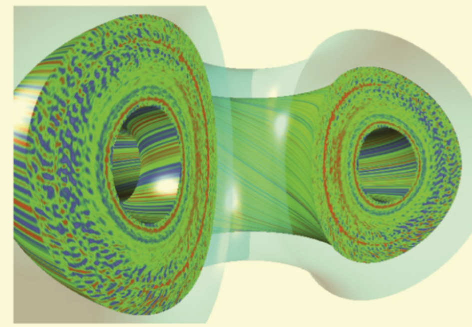


Rotation

Angular Momentum Transport Is Investigated Using Perturbative Techniques

- **Toroidal rotation evolves according to momentum balance eq.**

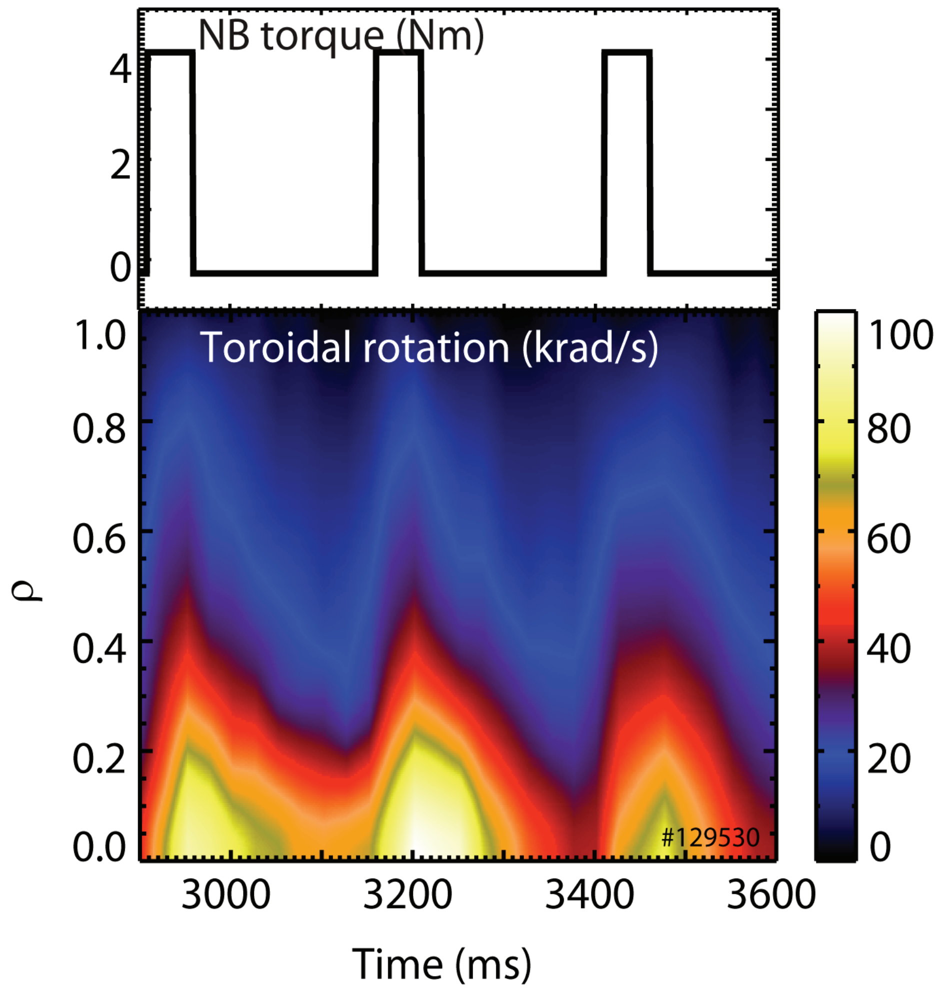
$$\underbrace{mnR\frac{\partial V_\phi}{\partial t}}_{\text{Rate of change of momentum}} = \underbrace{\sum \eta}_{\text{Momentum sources/sinks}} - \underbrace{\nabla \cdot \Gamma}_{\text{Transport}} + \underbrace{S}_{\text{"Intrinsic source"}} \quad , \quad \Gamma = -mnR\left(\underbrace{\chi_\phi \frac{\partial V_\phi}{\partial r}}_{\text{diffusion}} - \underbrace{V_\phi V_{pinch}}_{\text{pinch}}\right)$$

- **In modulated cases, equilibrium sources and sinks do not have to be known**
  - Removes many uncertainties

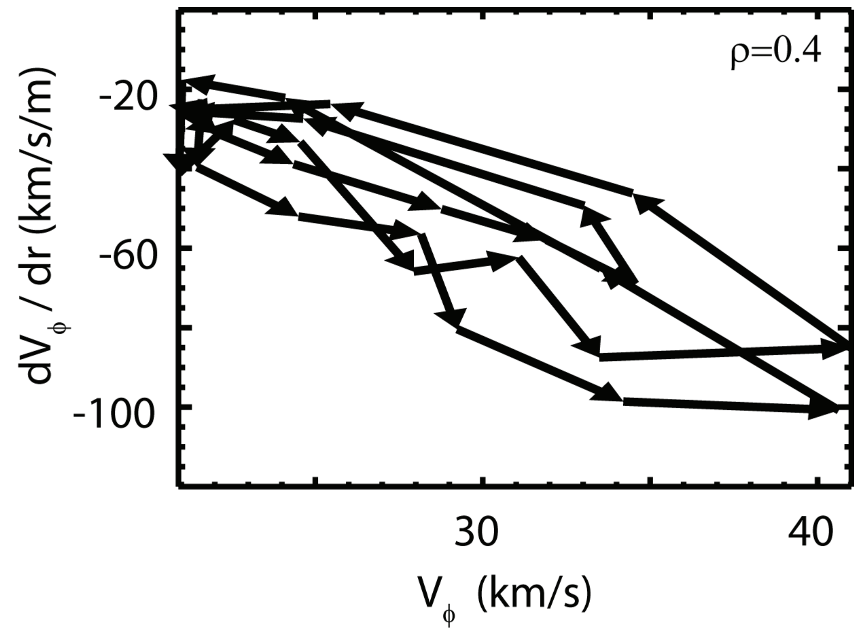
- **If one can compute perturbed sources/sinks, then Γ_ϕ is determined**

- **Model Γ_ϕ evolution to determine diffusive and convective contributions**

Neutral Beam Torque Pulses at Constant Power Are Used to Create Non-Local Rotation Perturbations

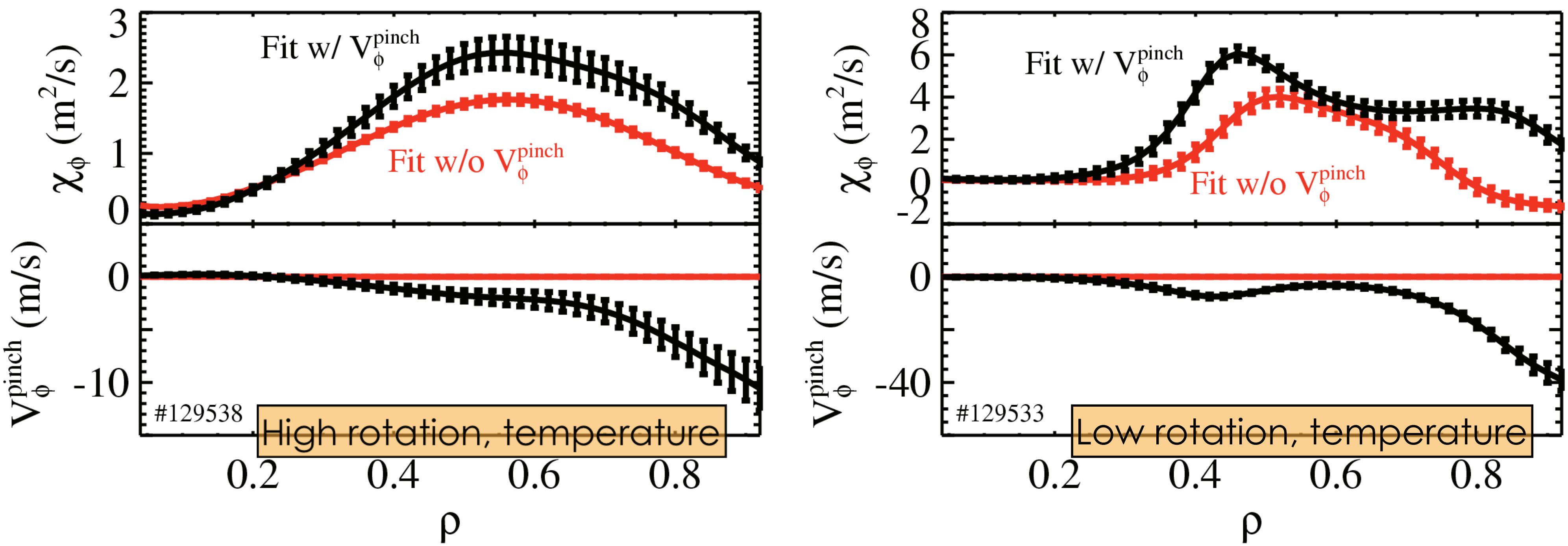


- **Clearly see effect of torque pulses in rotation measurements**
- **Must change V_ϕ independently of dV_ϕ/dr during perturbation**



Inward Pinch of Momentum Inferred From Neutral Beam Torque Perturbations

- **Inclusion of pinch in momentum improves fit to momentum flux evolution**
- **Pinch alters inference of momentum diffusivity**
  - Can exceed a factor of 2
  - Most significant when transport high (low rotation, reduced ExB shear)



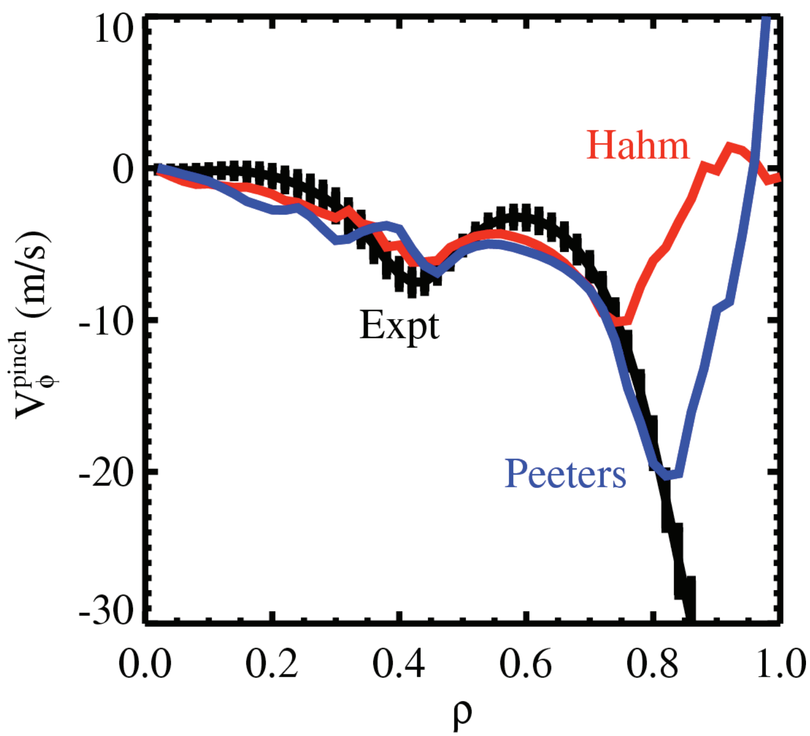
Inward momentum pinch also seen on JT-60U, JET and NSTX

Good Agreement Found Between Theoretical and Experimentally-Determined Pinch Velocity

- **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 (2006) $$V_{Hahm} = \frac{\chi_\phi}{R}[-4]$$

- **No obvious distinction between theories experimentally**
  - L_n term only appreciable in DIII-D toward the edge

- **However, results from NSTX suggest L_n term does matter** [Kaye et al, this meeting EX/3-2]



Summary

- **Non-resonant magnetic fields apply a torque to the plasma, which can result in a spin up of the plasma at low rotation**
  - Including associated improvement in confinement
- **Strong RSAE activity has been shown to modify the rotation profile, while leaving the total angular momentum content unchanged**
  - Modification of NB torque profile
- **Intrinsic source inferred directly from momentum balance**
- **Experimental observation of momentum pinch in reasonable agreement with theoretical predictions**