# Characterization of the Effective Torque Profile Associated With Driving Intrinsic Rotation on DIII-D


By

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In Collaboration with

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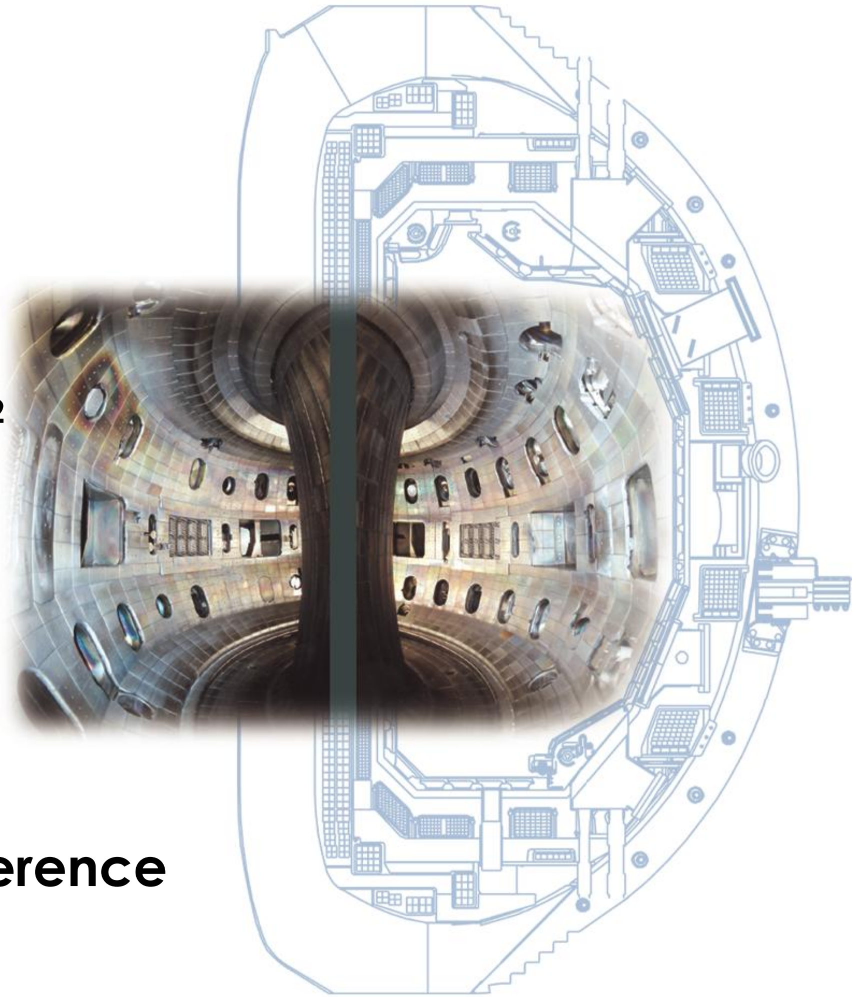

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

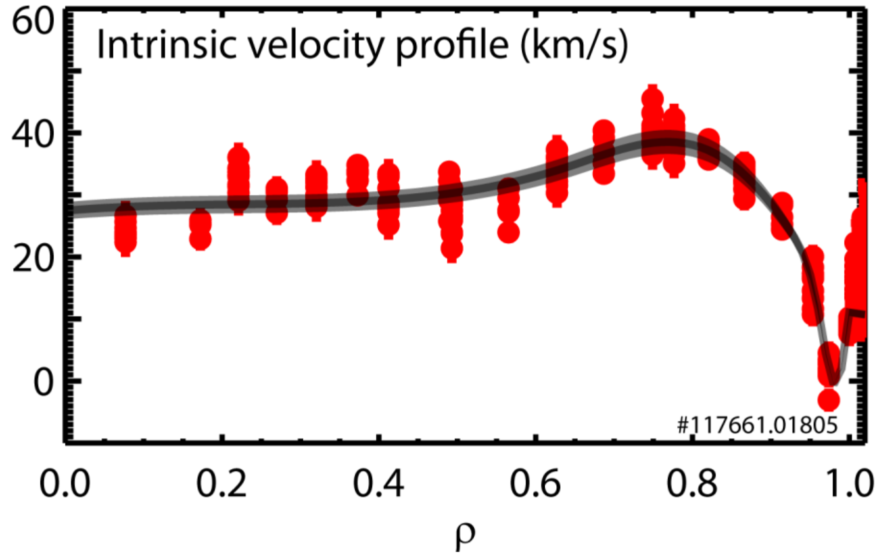
PPPL PRINCETON PLASMA PHYSICS LABORATORY

# Motivation

- **Toroidal rotation can enhance fusion performance through improvements in stability and confinement**
- **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**
- **Ultimately want to answer whether intrinsic drive is sufficient to provide significant levels of rotation for ITER**

# Intrinsic Rotation Must Manifest Itself From Terms in Toroidal Angular Momentum Balance Equation

$$\underbrace{mR\frac{\partial nV_\phi}{\partial t}}_{\text{Rate of change of angular momentum density}} = \underbrace{\sum\eta}_{\text{Torque densities}} \underbrace{-\nabla\cdot\Pi_\phi}_{\text{Transport}} + \ldots$$




Torque densities → **Intrinsic drive** ← Transport

$$\Pi_\phi = -mnR\left(\underbrace{\chi_\phi\frac{\partial V_\phi}{\partial r}}_{\text{diffusion}} \underbrace{-V_\phi V_{pinch}}_{\text{pinch}}\right) + \underbrace{\Pi_{RS}}_{\text{Residual stress}}$$

$$\sum\eta = \eta_{NBI} + \ldots ?$$

- **Turbulence driven**
- **Independent of velocity**

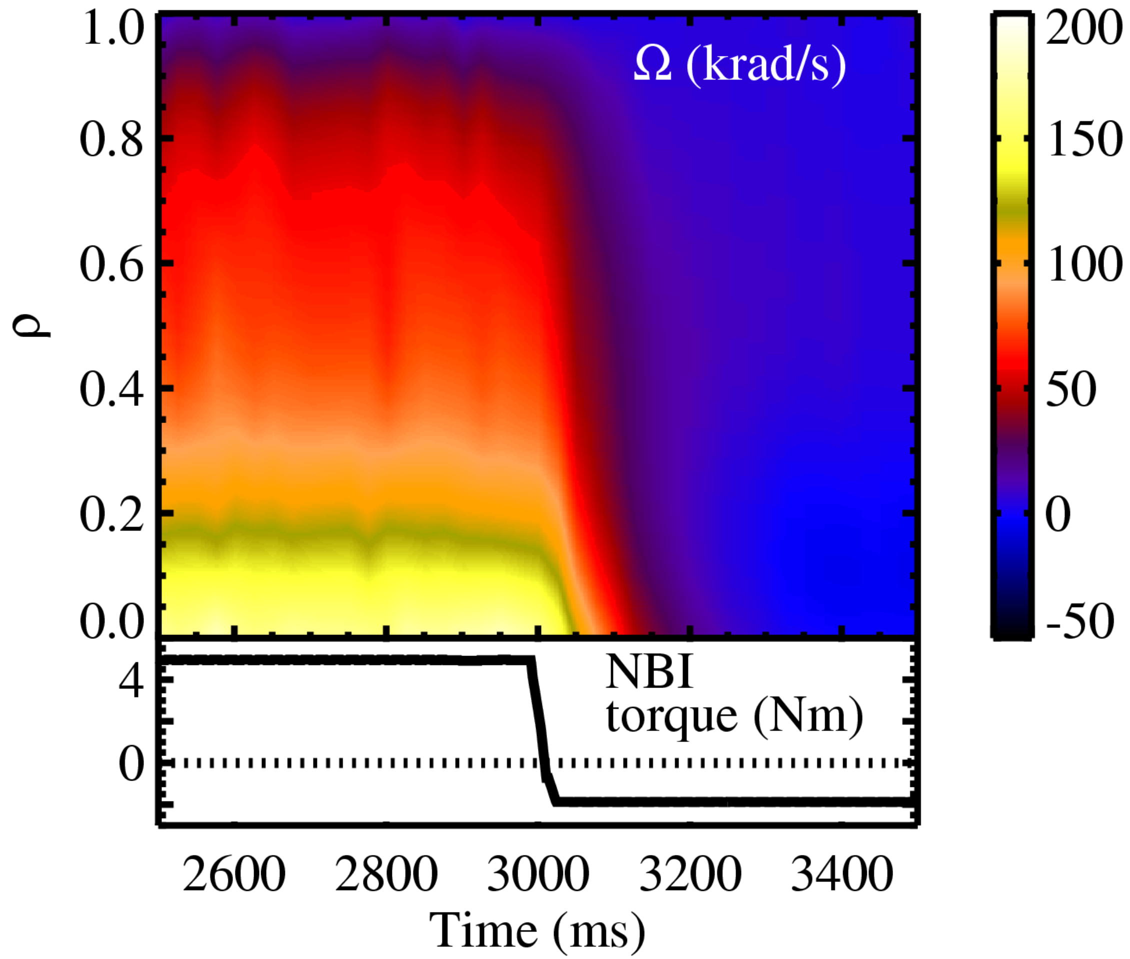
- **Other unspecified torques**

# Intrinsic Torque Profile Can Be Measured With Beams By Zeroing Out Rotation Profile

- **With co-current NBI torque, rotation is also co-$I_p$**
- **By adjusting torque slightly counter, rotation is essentially zero across profile**
- **Intrinsic torque balanced by beam torque**

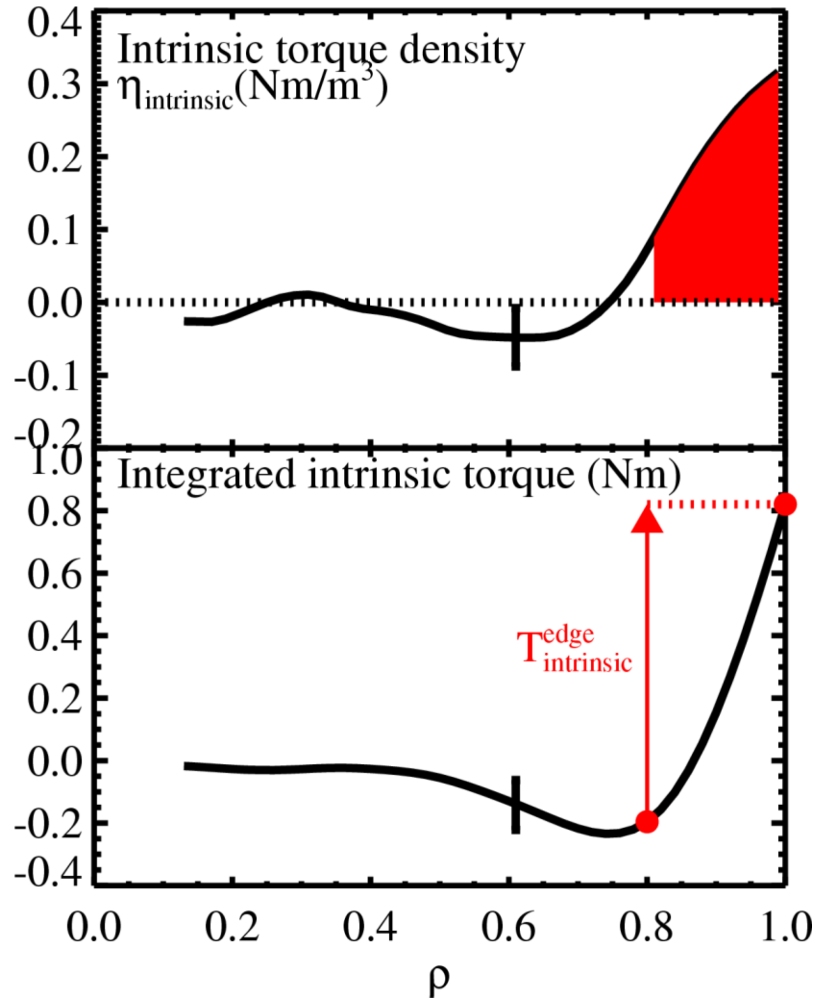
$$\eta_{NBI} + \eta_{\text{intrinsic}} = 0$$

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



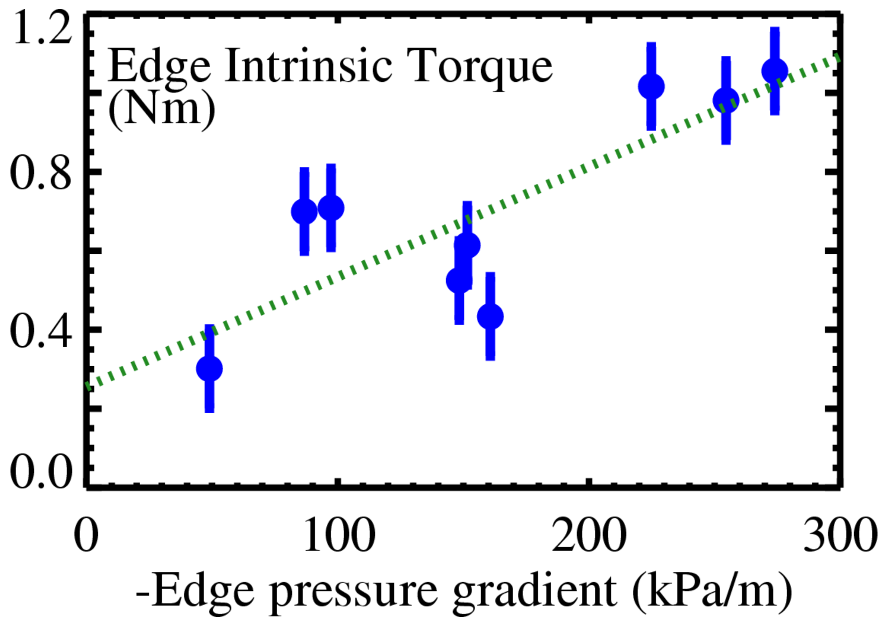
# Intrinsic Torque Profile in H-Mode Plasmas Always Peaked at the Edge

- **Intrinsic torque at the edge (0.8 < ρ < 1) found to be**
  - Always co-current directed
  - Typically comparable to between 0.5-1 NB source
- **Torque inside of mid-radius typically negligible by comparison**



# Edge Intrinsic Torque Is Well Correlated with Edge Pressure Gradient

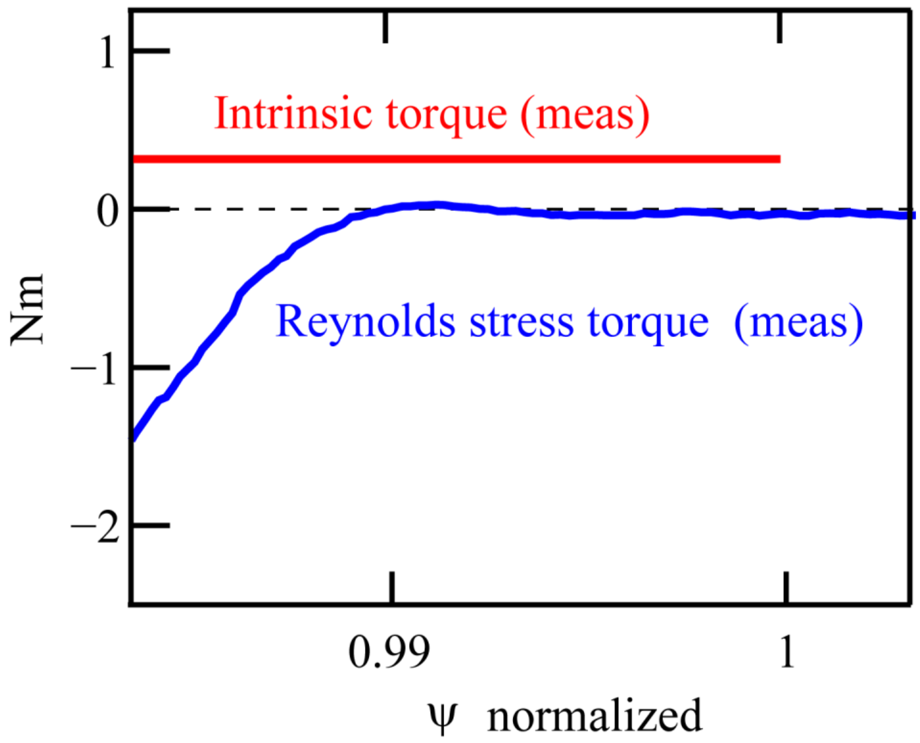
- **Qualitatively suggestive of turbulence driven stress generating intrinsic rotation**
  - Turbulent residual stress can be driven via *ExB* shear or other profile shear
- **Shear in H-mode pedestal may provide mechanism to drive intrinsic rotation in future devices**




Solomon et al, PoP (2010)

# But… Probe Measurements Find Turbulent Stress Does Not Match Intrinsic Torque

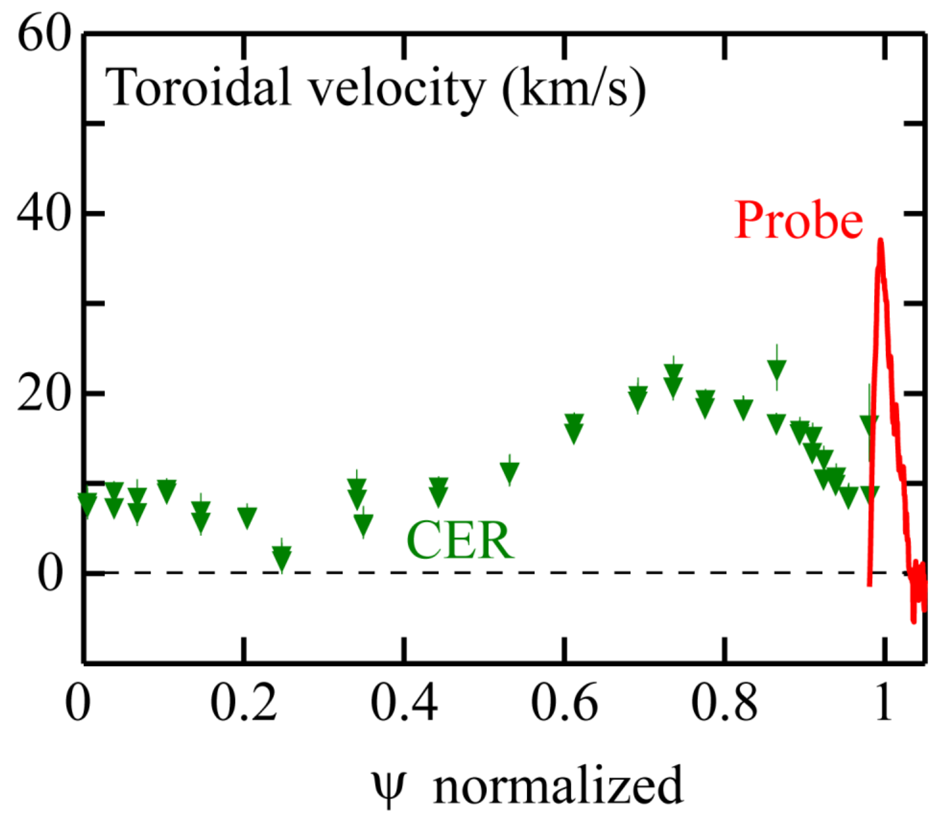
- **Conclude there are additional torques at edge contributing to intrinsic drive**




Muller et al, to be published

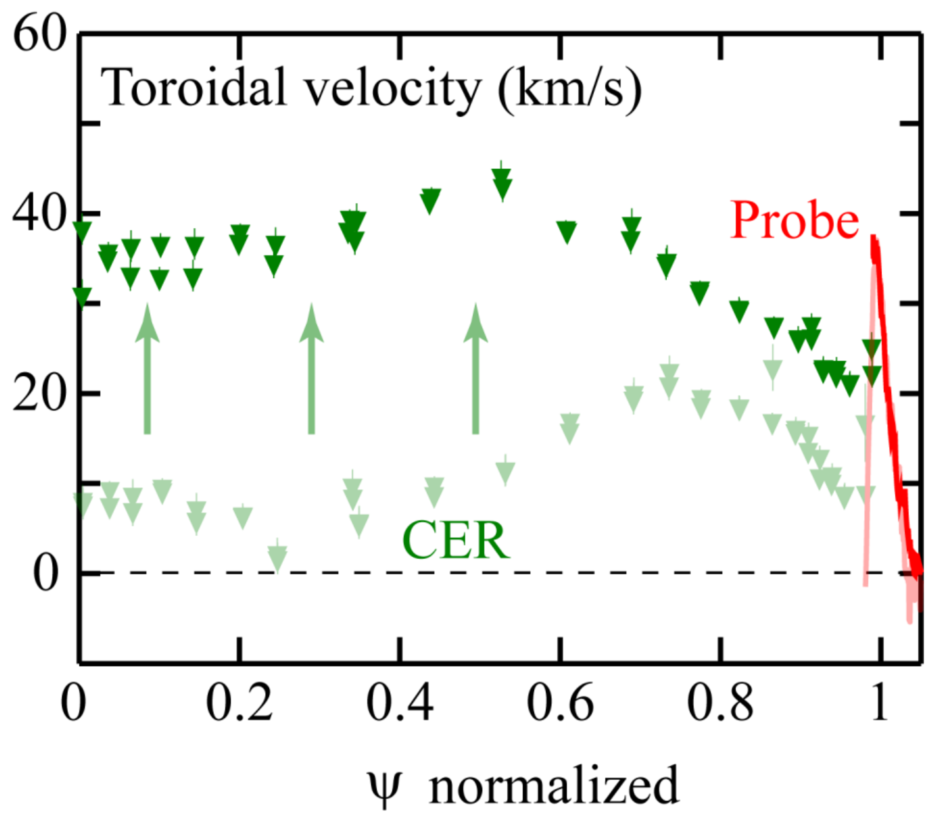
# Intrinsic Drive Appears to Originate from Narrow Region at the Edge

- **Edge rotation layer observed within 50 ms of L-H transition**
  - At time when core rotation remains low



# Intrinsic Drive Appears to Originate from Narrow Region at the Edge

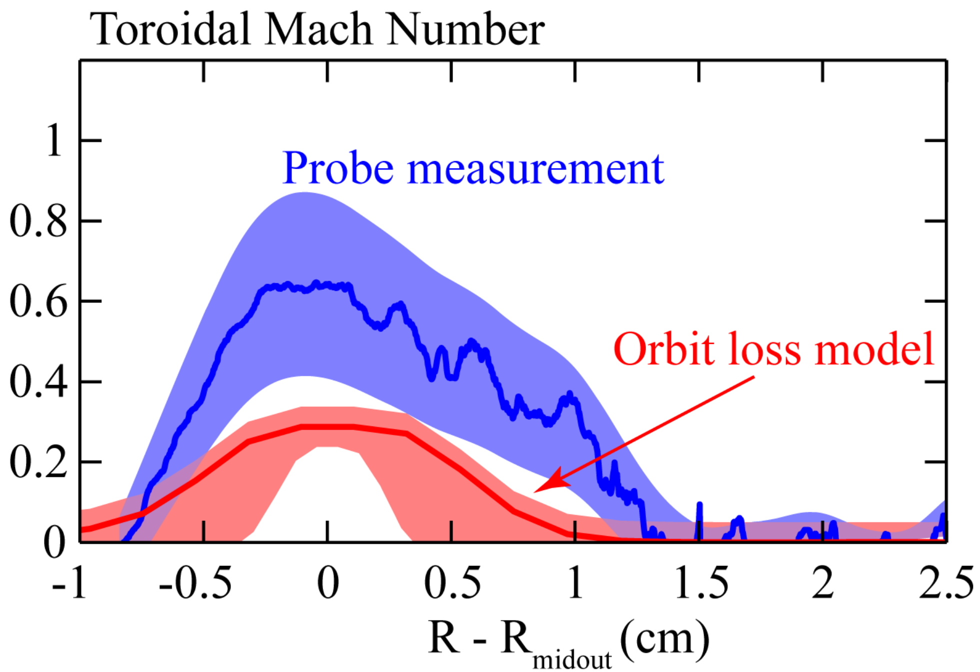
- **Edge rotation layer observed within 50 ms of L-H transition**
  - At time when core rotation remains low
- **Core intrinsic rotation develops over time**
- **Therefore, edge layer may contribute "seed" to core intrinsic rotation**



# Simple Model of Thermal Ion Orbit Loss Qualitatively Reproduces Edge Rotation Layer

- **Estimate velocity resulting from loss cone of counter-going thermal ions whose orbits are lost to divertor** [deGrassie et al, NF 2009]

- **Thermal ion orbit loss may help explain missing torque**



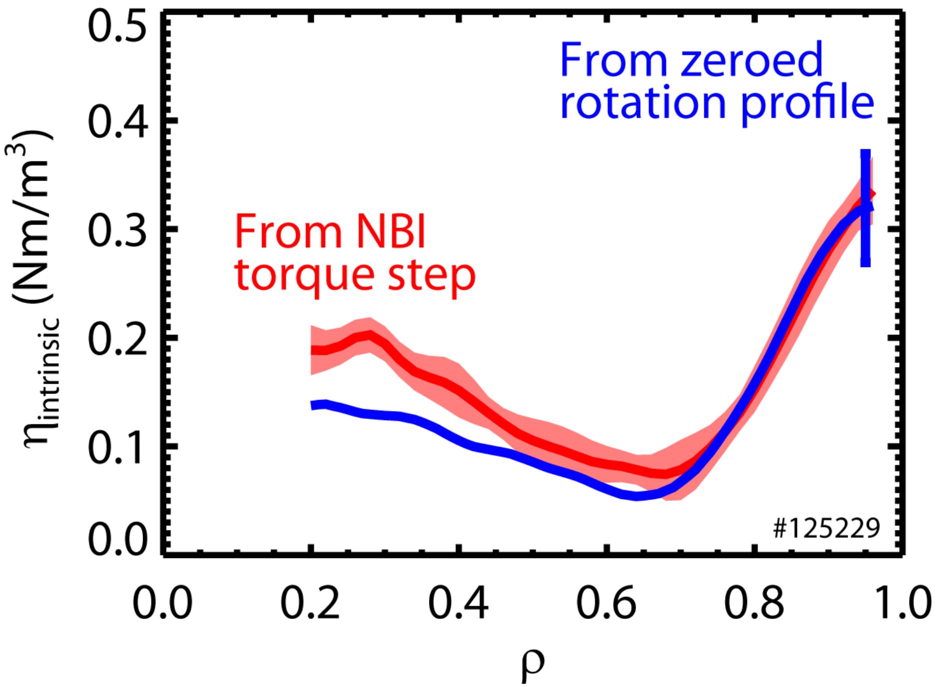
# Intrinsic Torque Profile Can Also Be Measured in Plasmas With Finite Rotation

- **Apply torque step and measure evolution of angular momentum**

$$\frac{dL(\rho)}{dt} = T_{\mathrm{NBI}}(\rho) + T_{\mathrm{intrinsic}}(\rho) - \frac{L(\rho)}{\tau_\phi(\rho)} \quad \text{with} \quad L(\rho) = \int_0^\rho nmRV_\phi \ \mathrm{dV}$$

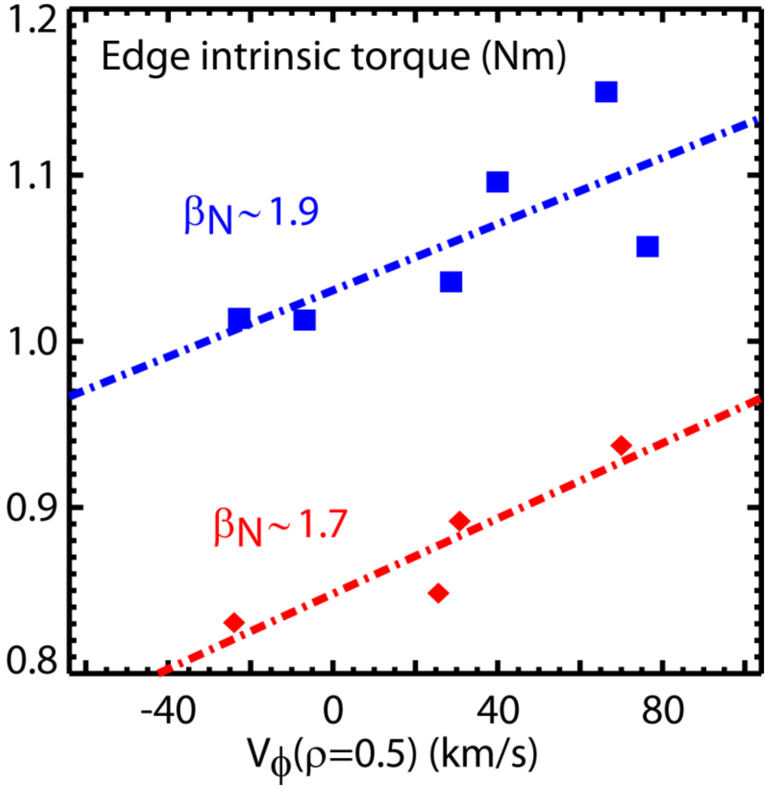
- **At each $\rho$, solve for two unknowns $T_{intrinsic}(\rho)$ and $\tau_\phi(\rho)$ from time history of data**
  - Highly over-determined

- **Gives quantitatively similar result to measurement obtained by zeroing rotation**



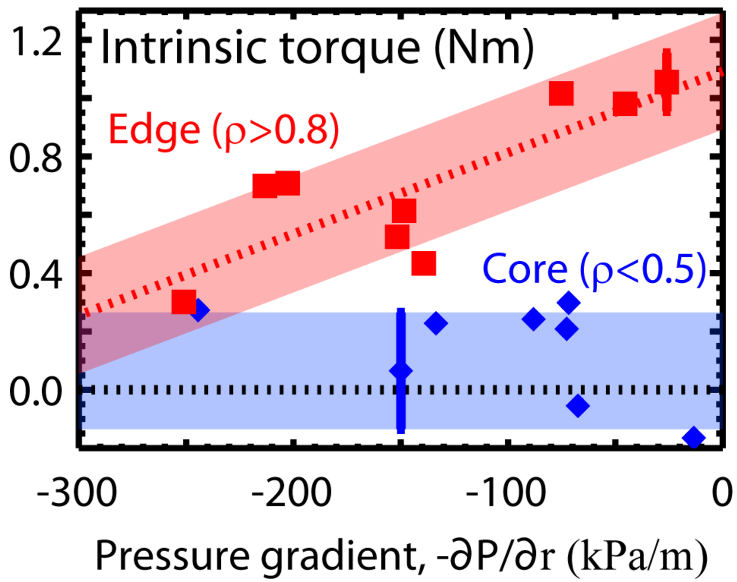
# Intrinsic Torque Persists Even in Plasmas With Finite External Momentum Input

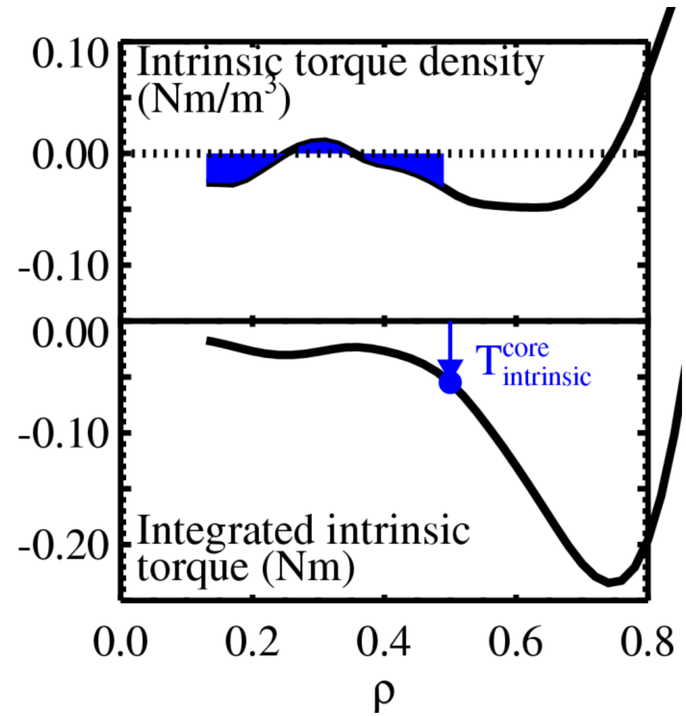
- **In fact, intrinsic torque is enhanced at rapid rotation**
  - Approx 0.1 Nm per 100 km/s of (mid-radius) rotation
- **Intrinsic torque increases with $\beta_N$**
  - Result of larger $\nabla P$ at the edge



# Intrinsic Torque Inside of Mid-Radius Tends to Be Relatively Small

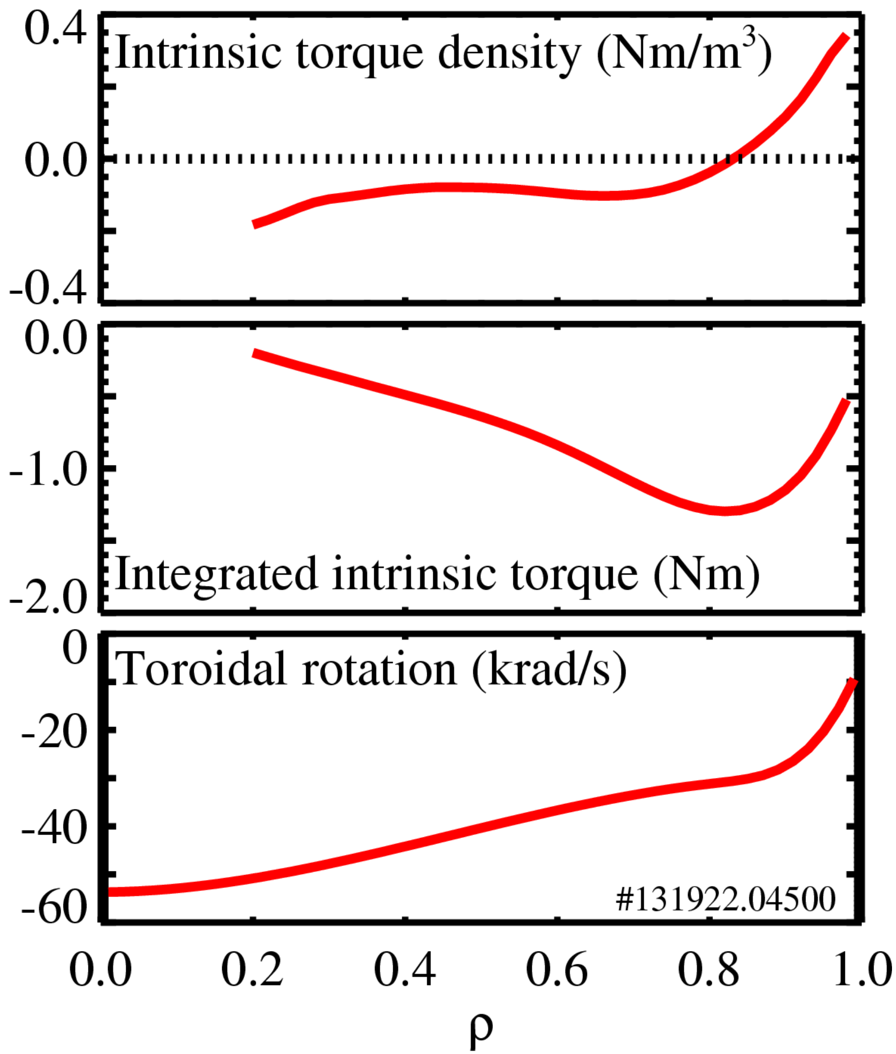
- **Much weaker compared with edge, even for similar ∇P**
- **But, certain conditions have been found where core intrinsic torque can be large enough to affect rotation profile**
- **Might core intrinsic drive be exploited to control ITER rotation?**



# QH-Mode Plasmas Exhibit Significant Counter Intrinsic Drive in Core

- **QH-mode plasmas have edge intrinsic torque compatible with standard H-mode**
- **However, a significant counter-$I_p$ intrinsic drive is found through the bulk of the plasma**
- **Torques from two regions are opposing**
  - Net result is actually slightly counter-Ip directed
  - Helps sustain large counter rotation of QH-mode plasmas

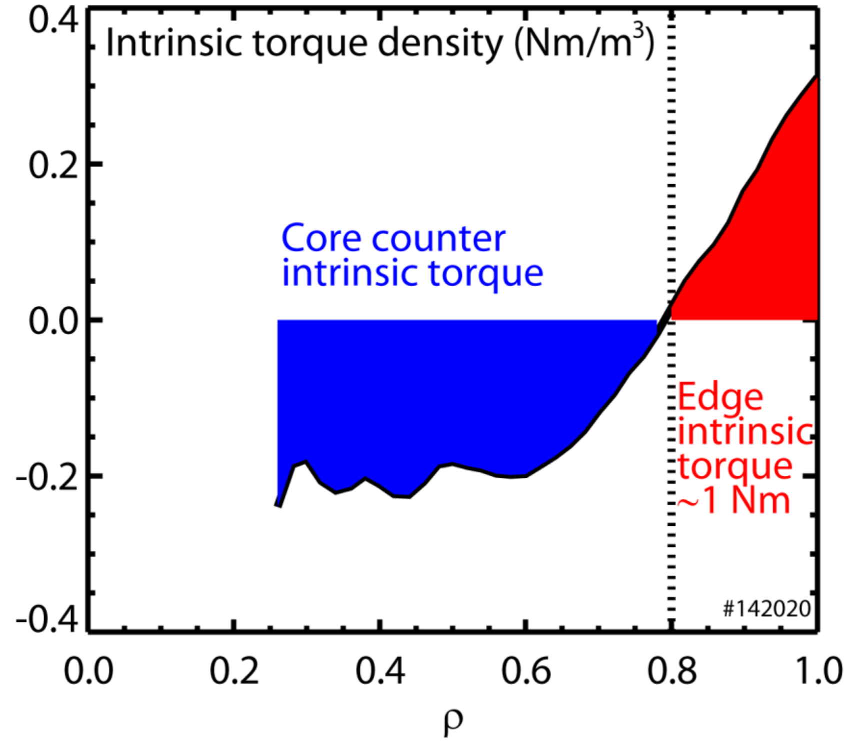


# Core Intrinsic Torque Might Be Exploited to Generate Highly Sheared Rotation Profiles

- **Intrinsic torque profile in hybrids qualitatively similar to that seen in some QH-modes**

- **In burning plasma with limited external momentum input, such an intrinsic torque profile would naturally produce a sheared rotation profile**

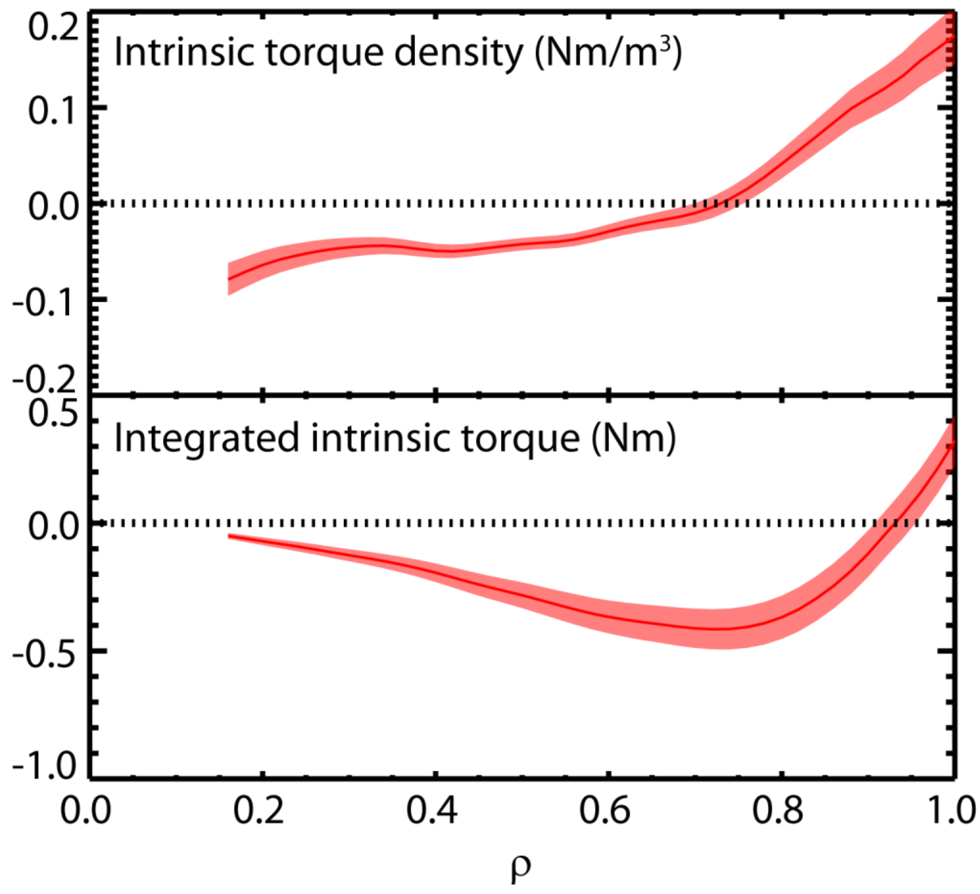
- **Very different torque profile than most present-day scenarios with NBI**



# Electron Cyclotron Heating May Provide Tool for Modifying Intrinsic Drive in the Core

- **ECH H-mode plasmas often show hollow intrinsic rotation profiles**
  [e.g. deGrassie PoP 2007]
  - Suggests possible counter drive in core from ECH

- **Measurements confirm that application of ECH to conventional H-mode produces counter intrinsic torque in the core**



# Conclusions

- **Edge pedestal capable of generating an intrinsic torque that is robustly observed in all H-modes**
  - Evidence exists that both residual stress and thermal ion orbit loss may contribute to the edge intrinsic torque

- **Additional intrinsic drive is sometimes observed in the core, which may be beneficial in enhancing core rotation shear**