Measurement and Modeling of Intrinsic Torque on DIII-D

By

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In Collaboration with

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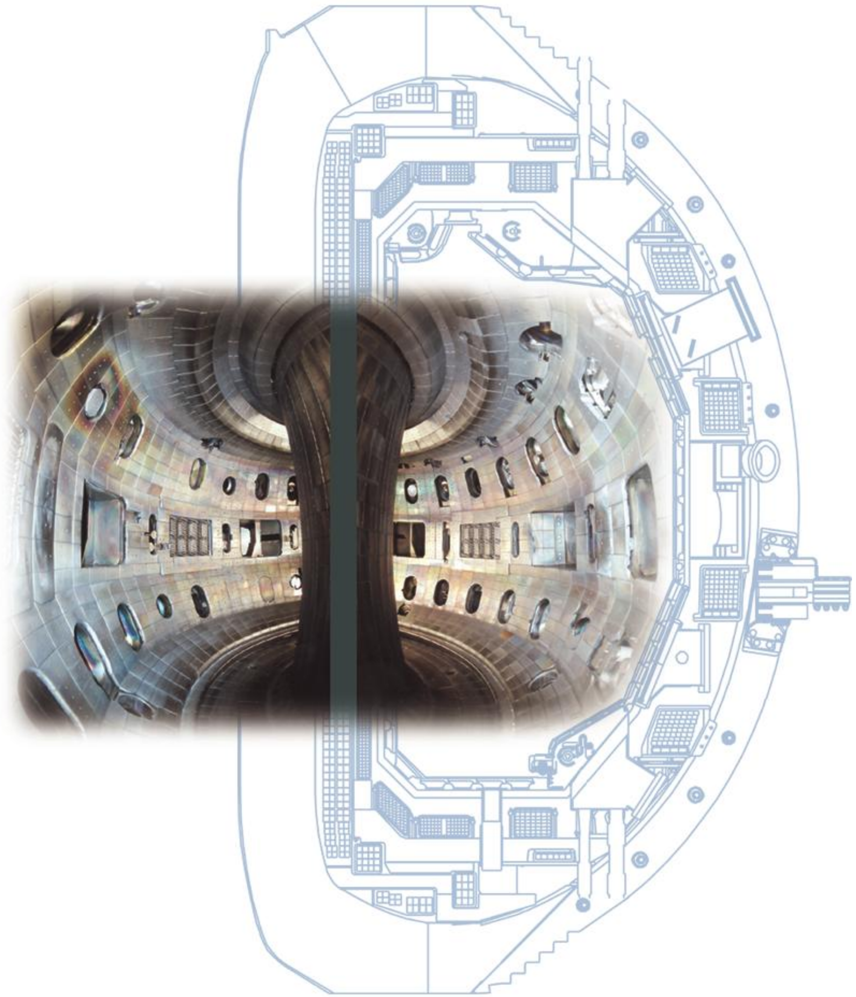

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

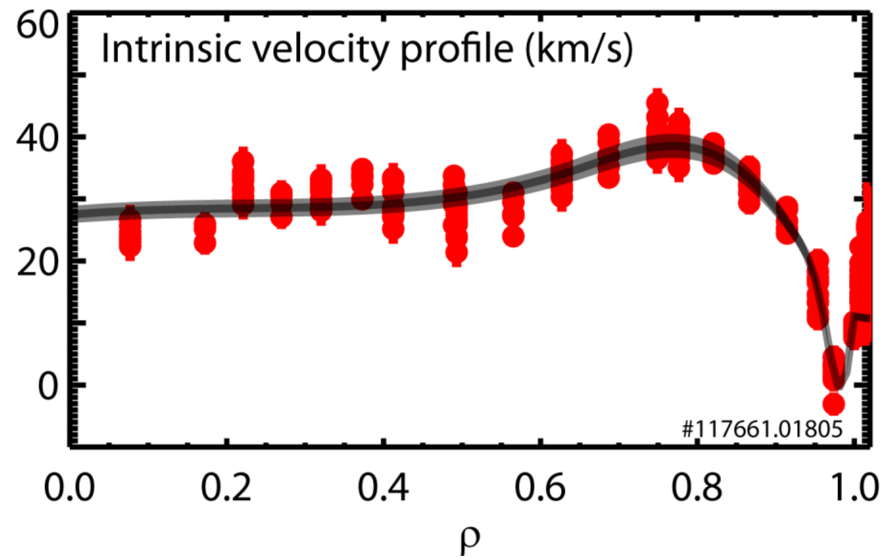
PPPL PRINCETON PLASMA PHYSICS LABORATORY

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, torque driven by beams becomes comparatively smaller relative to moment of inertia

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

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



Intrinsic drive

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

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

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

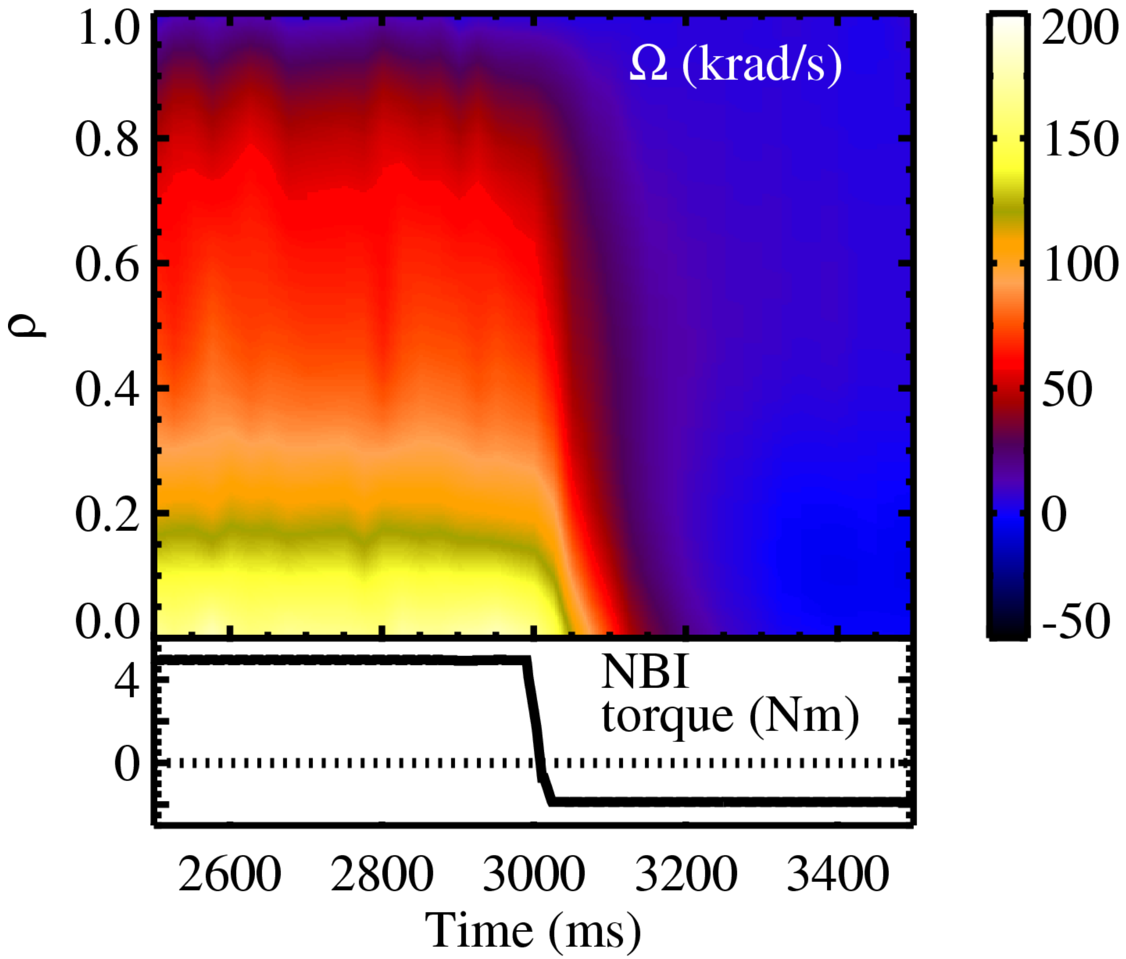
- **Other unspecified torques**

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**

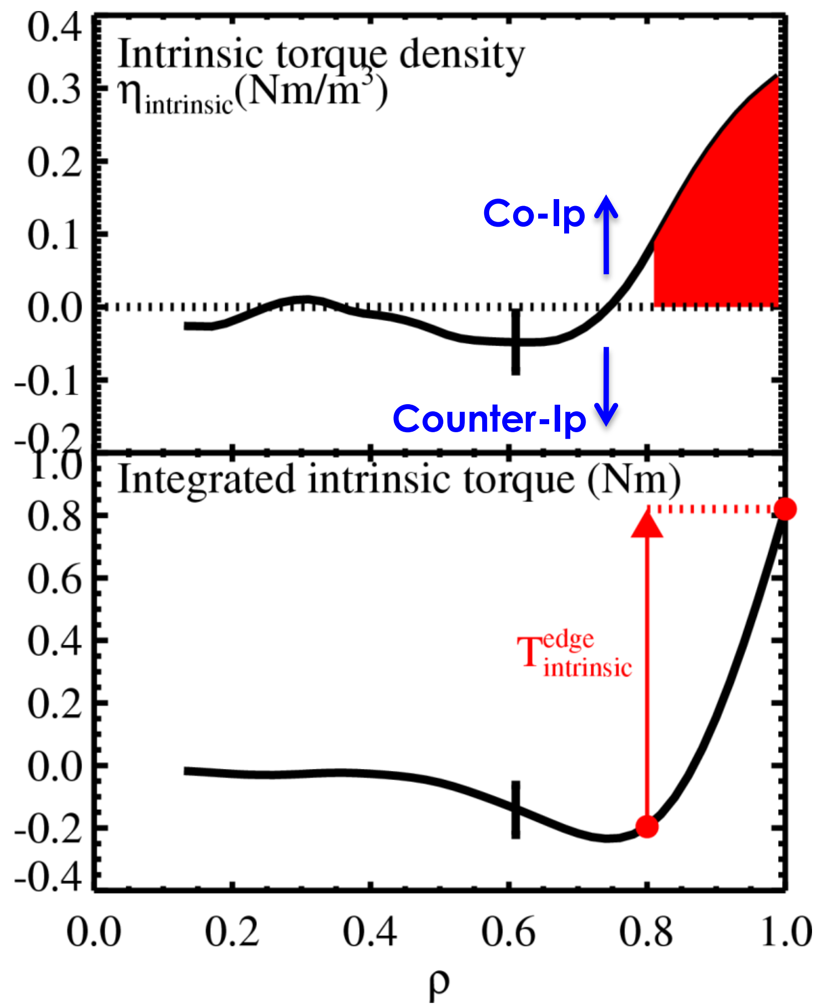
$$\eta_{NBI} + \eta_{\text{intrinsic}} = 0$$

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



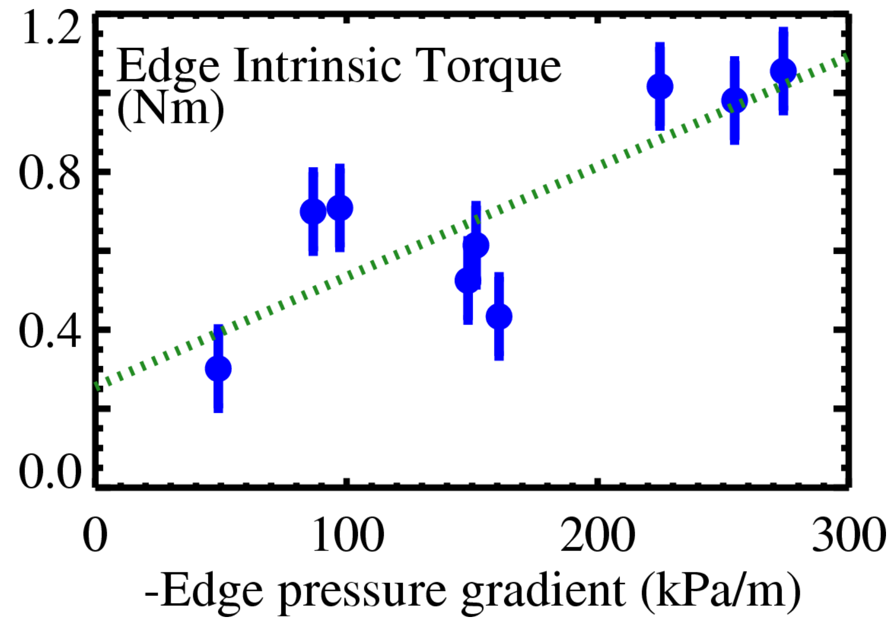
Intrinsic Torque Profile in H-Mode Plasmas Always Peaked at the Edge

- **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**
- **Empirically, what processes contribute to the intrinsic torque?**



Edge Intrinsic Torque Is Well Correlated with Pedestal Pressure Gradient

- **Data obtained from power and plasma current scans**
- **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**

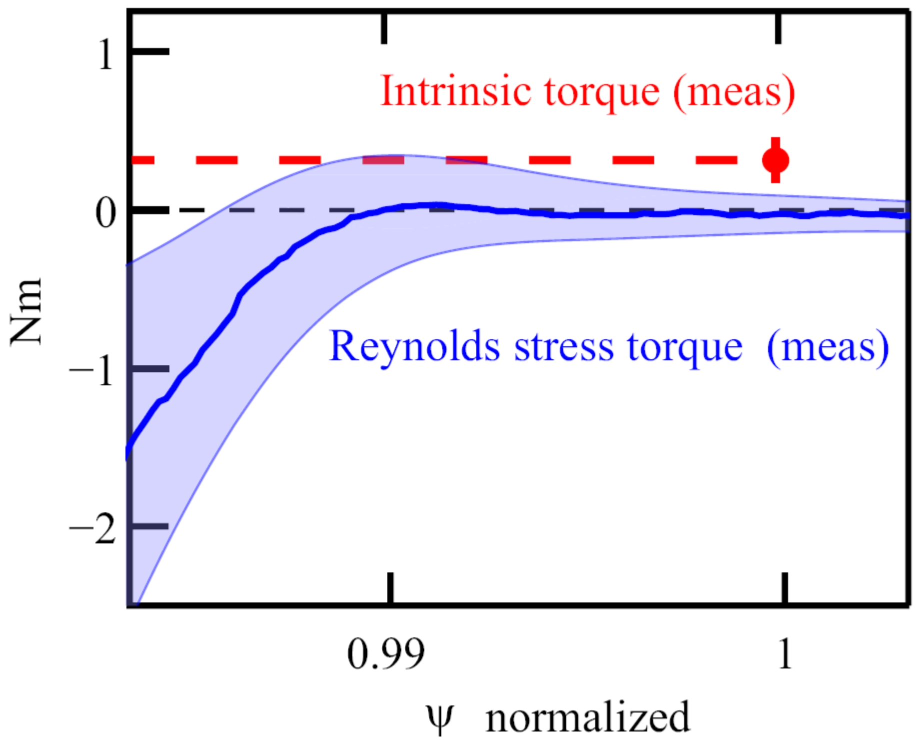


Solomon et al, PoP (2010)

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

- **Multi-tip reciprocating probe measures all terms of fluid stress tensor**
  - Mostly arises from Reynolds stress contribution

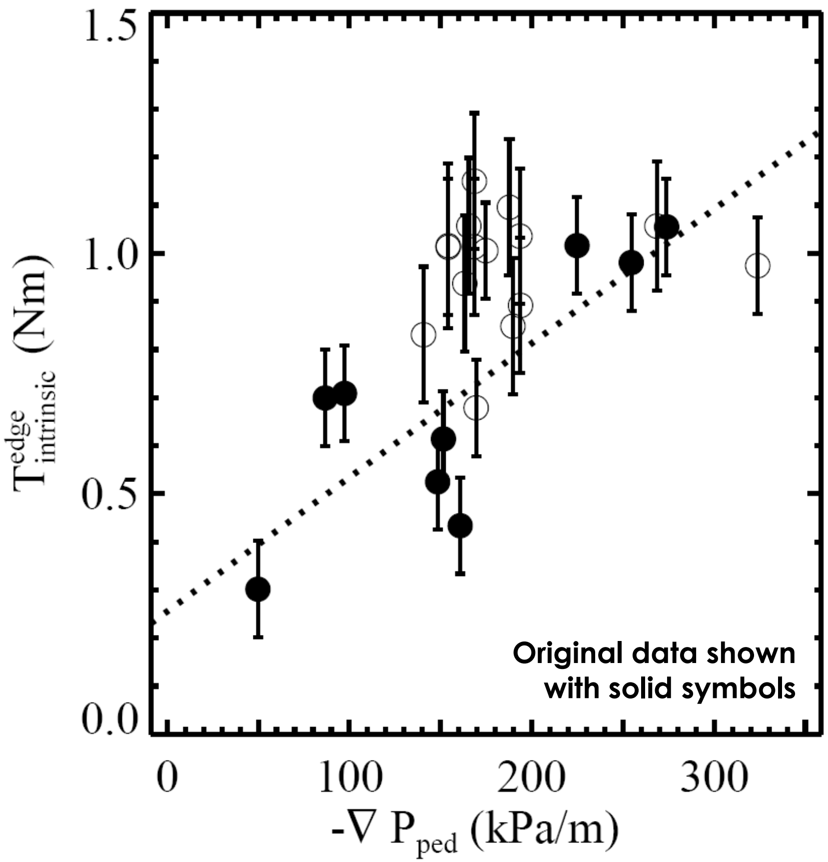
- **Discrepancy implies there are additional torques at edge contributing to intrinsic drive**



Muller et al, PRL 2011

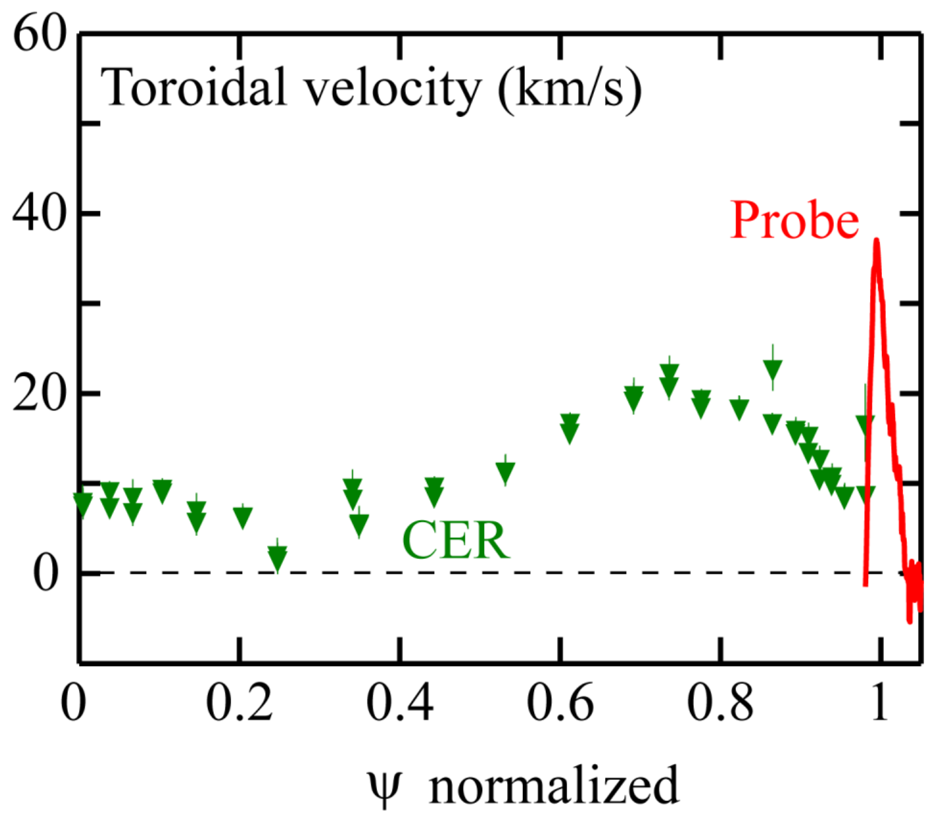
Additional Physics Is Required to Understand Edge Intrinsic Torque from Wider Data Set

- **Include QH-mode, hybrid plasmas, different shapes (USN, LSN, DN) and toroidal rotation levels**
- **Relationship between edge intrinsic torque and pressure gradient becomes much less clear**
- **Almost factor of 3 variation for fixed ∇P_{ped} ~ -160 kPa/m**



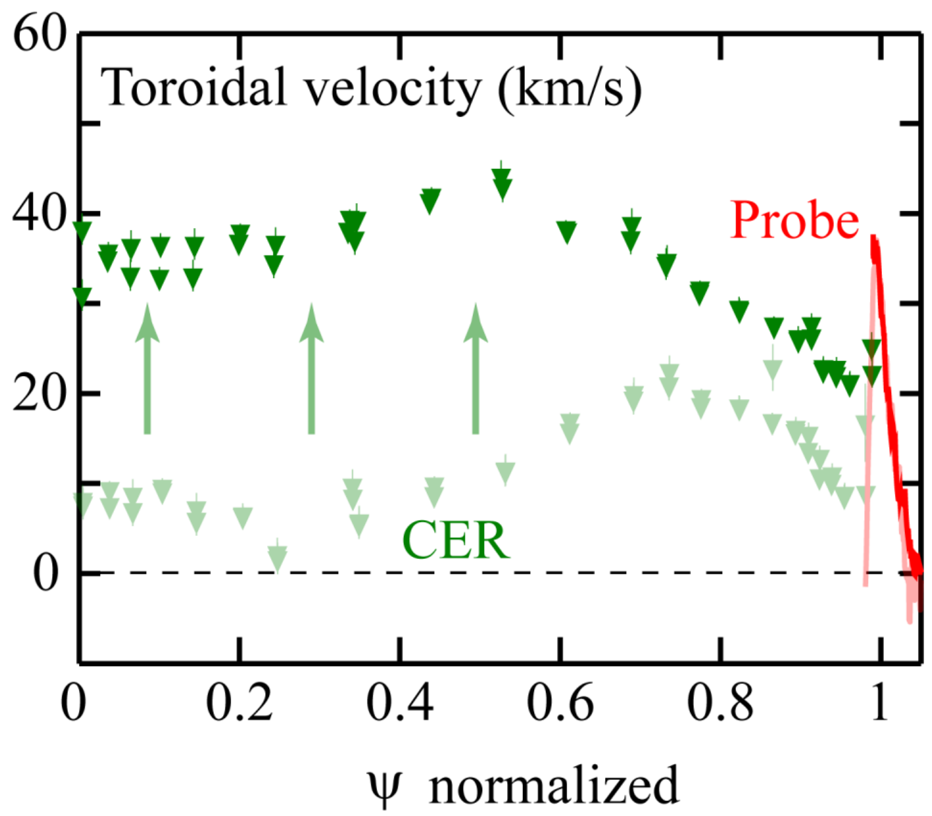
Intrinsic Drive Appears to Originate from Narrow Region at the Edge

- **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**

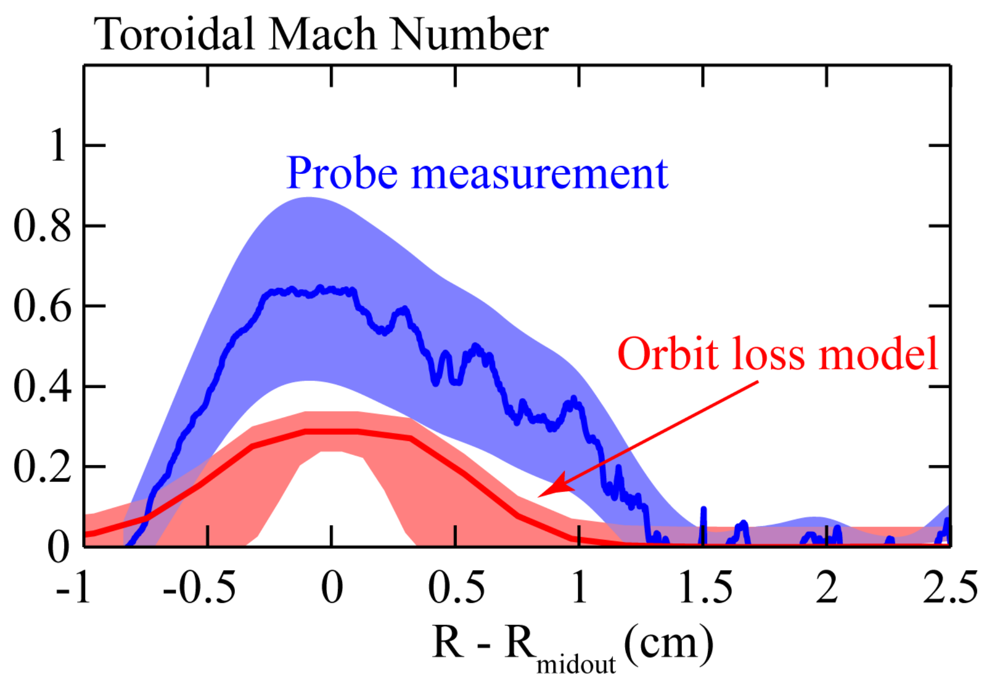


See Grierson, after lunch for details on new main ion CER measurements

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**

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



Torque from Orbit Loss Expected to Show Dependence on Edge Ion Temperature

- **Measure of orbit loss torque made estimating rate at which collisions drive empty loss cone toward Maxwellian**

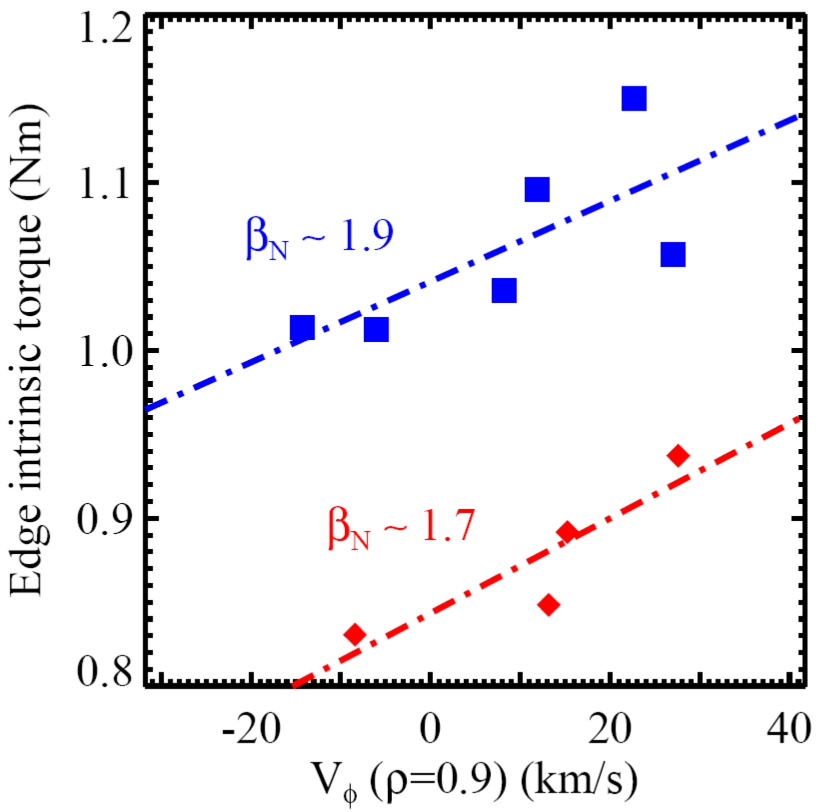
$$\eta_{O.L.} \propto \nu m n \left\langle R V_{\phi}^{\rho=1} \right\rangle$$

- **Separatrix velocity in turn dependent on**
  - Separatrix ion temperature $\sqrt{T_i^{\rho=1}}$
  - location of the x-point relative to the midplane separatrix R_x / R_{mid}

- **Empirically, add these quantities to regression analysis to understand edge intrinsic torque data set**

Intrinsic Torque Persists Even in Plasmas With Finite External Momentum Input

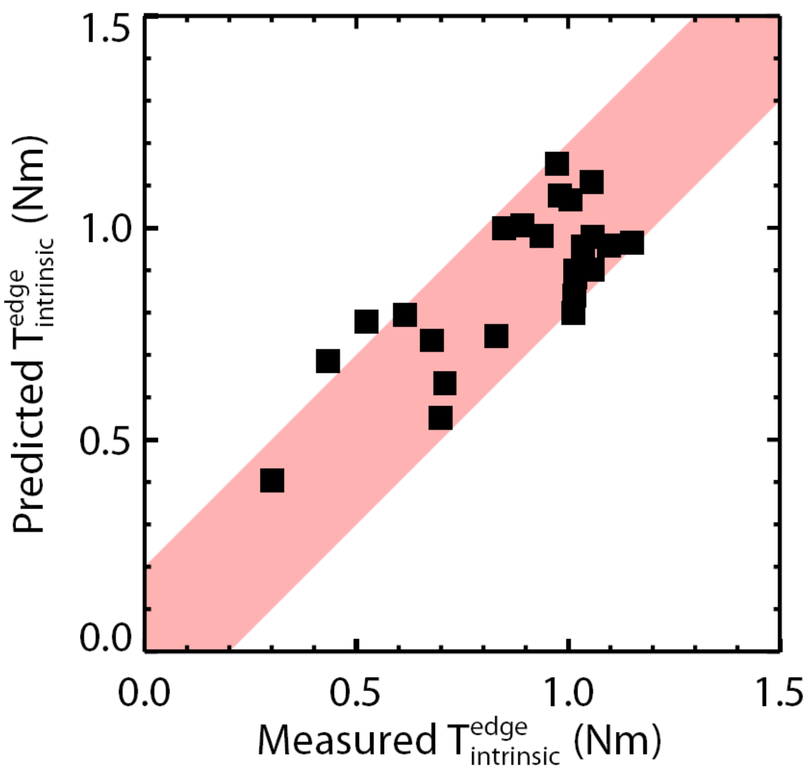
- **Weak dependence of intrinsic torque on rotation**
  - Enhanced at rapid rotation by approx 0.25 Nm per 100 km/s of velocity at top of pedestal
- **Intrinsic torque increases with β_N**
  - Partially due to changes in ∇P_{ped}



Consideration of Various Empirical Quantities Gives Excellent Predictor of Edge Intrinsic Torque

- **Pedestal pressure gradient (∇P_{ped})**
- **Orbit loss physics (T_i, R_x)**
- **Finite rotation effects (V_ϕ)**

$$T_{\text{intrinsic}}^{\text{edge}} = -2.80\times10^{-3}\nabla P_{\text{ped}}(\text{kPa/m}) + 0.38\sqrt{T_i^{\rho=1}(\text{keV})} + 0.56 V_\phi^{\rho=0.9}(100\,\text{km/s}) + 0.16\frac{R_x}{R_{mid}}$$



- **R^2>0.9 (vs 0.34 for ∇P_{ped} only fit)**
- **Intrinsic torque predicted within ~0.2 Nm**

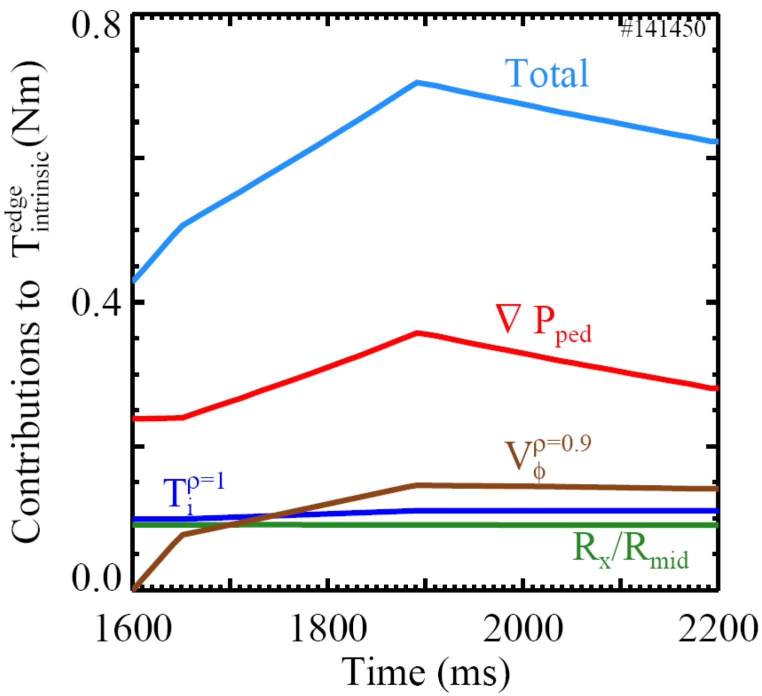
Solomon et al, NF (submitted)

Empirical Model of Intrinsic Torque Is Used to Model Intrinsic Rotation Evolution Following L-H Transition

- **Build model based on:**
  - Spatially and temporally constant χ_ϕ
  - Pinch velocity V_{pinch} calculated in TRANSP based on theoretical models
    - Previously showing reasonable agreement with experiment
  - Boundary condition V_ϕ from Mach probe measurement
  - Intrinsic torque density profile

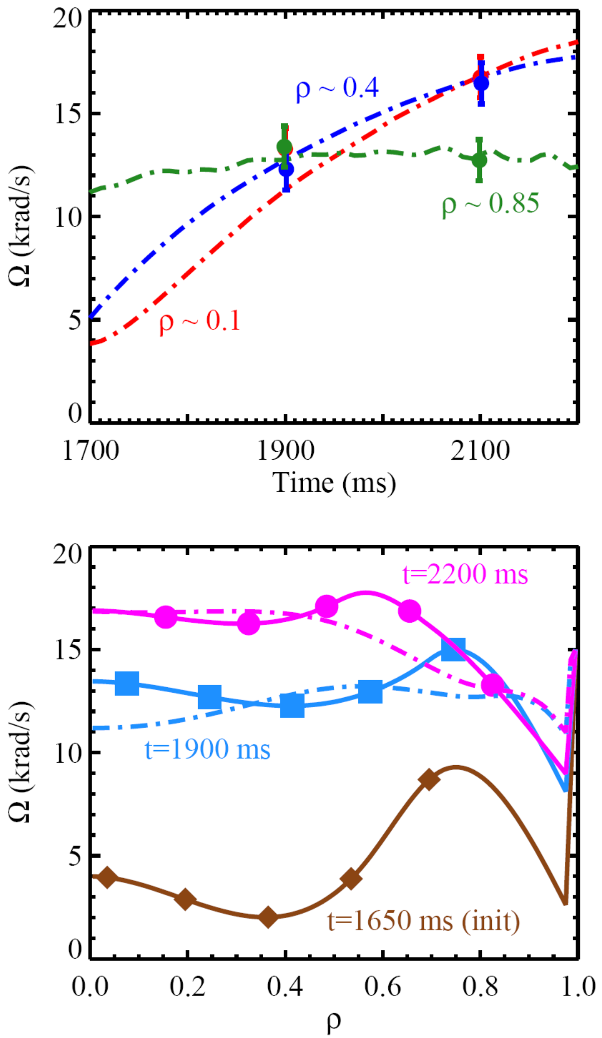
$$\eta_{intrinsic}(\rho,t) = 0 \quad \text{for } \rho < 0.8$$
$$= c(t)(\rho - 0.8) \quad \text{for } 0.8 < \rho < 0.96$$
$$= \eta_{RS}^{probe}(\rho,t) \quad \text{for } \rho > 0.96$$

with c chosen so as to match model for edge intrinsic torque



Empirical Intrinsic Torque Profile Model Plus Simple Transport Model Is Sufficient to Reproduce Rotation

- **Intrinsic rotation profile measured shot-to-shot with NBI blips at different delays**
- **Simulate intrinsic rotation evolution inside ρ<0.99**
- **Narrow rotation layer semi-quantitatively reproduced and persists in time**
  - Only possible with inclusion of intrinsic torque profile



Conclusions

- **Plasma edge capable of generating an intrinsic torque that is robustly observed in all H-modes**
- **Contributions to edge intrinsic torque include**
  - Pedestal pressure gradient (residual stress)
  - Separatrix temperature, X-point location (thermal ion orbit loss)
  - Enhancement / positive feedback with velocity
- **Empirically determined expression for edge intrinsic torque serves as excellent predictor**
- **Intrinsic rotation evolution after L-H transition consistent with modeling based on calculated intrinsic torque**