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

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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

\[ mR \frac{\partial n V_\phi}{\partial t} = \sum \eta - \nabla \cdot \Pi_\phi + \ldots \]

Rate of change of angular momentum density

\[ \Pi_\phi = -mnR \left( \chi_\phi \frac{\partial V_\phi}{\partial r} - V_\phi V_{pinch} \right) + \Pi_{RS} \]

• Turbulence driven
• Independent of velocity

\[ \sum \eta = \eta_{NBI} + \ldots? \]

• Other unspecified torques

Intrinsic velocity profile (km/s)
Intrinsic Torque Profile Can Be Measured With Beams By Zeroing Out Rotation Profile

- With co-current NBI torque, rotation is also co-$l_p$

- 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 < \( \rho \) < 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 $E \times B$ 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

![Graph of toroidal velocity (km/s) vs. psi normalized showing edge rotation layer and core rotation development.](image)
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

\[ \frac{dL(\rho)}{dt} = T_{\text{NBI}}(\rho) + T_{\text{intrinsic}}(\rho) - \frac{L(\rho)}{\tau_\phi(\rho)} \]

with \( L(\rho) = \int_0^\rho nmRV_\phi \ dV \)

- At each \( \rho \), solve for two unknowns \( T_{\text{intrinsic}}(\rho) \) 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 $\nabla P$
- 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-$I_p$ 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