Validation of Theoretical Models of Intrinsic Torque in DIII-D and Projection to ITER by Dimensionless Scaling

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Experiments on DIII-D have Advanced the Predictive Capability for Intrinsic Rotation in ITER

- Toroidal rotation in ITER is expected to be strongly influenced by intrinsic sources.
- Empirical dimensionless scalings provide extrapolation from multi-machine databases.
- First-principles based predictions require momentum diffusion, pinch and residual fluxes plus boundary condition.
Prediction of Toroidal Rotation Required to Assess Stability, Transport, ELM Suppression for ITER

- Can we predict overall angular momentum?
- Can we predict the core gradients and structure?
- What is the role of the boundary condition?

- Overall rotation for MHD stability, W transport
- Core rotation gradients for $E_r$ shear and confinement improvement
- Rotation and $E_r$ in the pedestal for RMP ELM suppression$^1$ and access to QH-mode

DIII-D ITER Baseline Electron Heating$^2$

153523.03700

$\rho_N$

Peaking  Hollowing  Notch

Impurity $\Omega$ (kRad/s)

$^1$C. Paz-Soldan EX/1-2
$^2$C. Holland TH/6-1
Outline

• Dimensionless scaling of intrinsic torque

• Testing physics based models of core intrinsic rotation profile

• Dependence of Edge Flow on Geometry
Joint Experiment\(^1\) with JET and ASDEX-U Tests \(q^*\) Scaling of Intrinsic Torque

- \(q^*\) for DIII-D, JET, ITER 0.01, 0.004, 0.002 (÷2.5, ÷2.0)

- Dimensionless parameter scan used to match conditions\(^2\)

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\(^1\)T. Tala (EPS 2016)
Joint Experiment\(^1\) with JET and ASDEX-U Tests $q^*$

**Scaling of Intrinsic Torque**

- $q^*$ for DIII-D, JET, ITER
  0.01, 0.004, 0.002 (÷2.5, ÷2.0)

- Dimensionless parameter scan used to match conditions\(^2\)

- Torque perturbation method used to extract intrinsic torque\(^3\)

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\(^1\)T. Tala (EPS 2016)


Dimensionless Match Obtained on DIII-D for Factor of 1.4 Variation in $q^*$

- ELMy H-mode conditions
  - Low $q^*$ 2.2 T (Un-Scaled)
  - High $q^*$ 1.4 T (scaled)

- $I_p$ scaled with $B_T$, $n \sim B_T^{4/3}$, $T \sim B_T^{2/3}$
  same $\beta_N$, $q_{95}$

- Good confinement $H_{98(y,2)} \sim 1.0$
Intrinsic Torque Dominantly in Outer Region and Increases When Reducing $\rho^*$

- Higher torque at low $\rho^*$ projects favorably to ITER
- Shape consistent with previous studies of intrinsic torque\(^1\)
- Measurement cross-validated with zero rotation technique\(^2\)

\(^1\)W.M. Solomon, *Nucl. Fusion* 51 073010 (2011)
Projecting the DIII-D Intrinsic Torque to ITER Yields Approximately 45 Nm of Intrinsic Torque — More than NBI Torque

- ITER has 33 Nm of available neutral beam torque
- Intrinsic torque is near available torque from NBI
- Projection to ITER scaled using $T_i$ to dimensionalize
- Predicted\(^1\) toroidal rotation from $\tau_{NBI} + \tau_{int}$
  $\langle \Omega \rangle \approx 12$ kRad/s
  - 1% of Alfven speed, marginal for RWM stability

\[
\tau_{ITER} = \frac{\tau_{DIII-D}}{T_i,DIII-D} \left( \frac{\rho_{ITER}^*}{\rho_{DIII-D}^*} \right)^{-1.5} T_i,ITER
\]

\(^1\)C. Chrystal Phys. Plasmas (submitted)
Multi-machine Intrinsic Torque Scaling Confirms DIII-D Results and Normalization

- Similar experiments executed on JET and ASDEX-U\(^1\)
- Scaling with ion temperature best organizes data set\(^1,2\)
- Projection to ITER with multiple parameters in progress\(^2\)

We Project Relatively Low Toroidal Rotation
→ Finite performance improvement for ITER\(^2\)
→ Details of the rotation profile matter

\(^1\)T. Tala (EPS 2016)
\(^2\)C. Chrystal (APS 2016)
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Electron Heating Causes a Rotation Reversal and Global NL GTS Simulation Captures both Shape and Magnitude

- Rotation reversal occurs because of turbulence residual stress
- Validation of residual stress required to predict ITER rotation
- Simulations indicate low-k ITG with zonal flow $E \times B$ and global effects responsible¹

¹W.X. Wang TH/P3-12
Rotation Profile Reversal Correlates with Onset of Temperature Profile Resilience and Confinement Degradation

- **Density** $\langle n_e \rangle$
  $2.5-3.0 \times 10^{19} \text{m}^{-3}$ and no NBI promotes $T_e \sim T_i$

- **Direct electron heating** raises both temperatures

- **Between 0.5→1.0 MW** power degradation sets in
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Rotation Profile from Main-ion CER Show Rotation Reversal When Power Degradation Sets In

- On DIII-D direct measurements of the main-ion (D) toroidal flow available\(^1\)
  - Other machines use impurities
- Deuterium carries energy, momentum fluxes
- Location where rotation gradient changes indicates non-diffusive flux
  - Not necessarily the sign (+/-) of rotation velocity

\(^1\)Grierson et. al. Phys. Plasmas (2014)
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At Onset of Power Degradation Plasma Becomes Linearly Unstable to ITG at Radius where Rotation Gradient Increases

- Direct electron heating raises both $T_e, T_i$ with clear increase of $a/L_{T_i}$ at mid-radius

- TGLF$^1$ indicates excitation of ITG$^2$ turbulence

\[ \partial_{\rho}^2 \Omega^\varphi(k\text{Rad/s}) \]

\[ T_e(\text{keV}) \]

\[ T_i(\text{keV}) \]


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Global Nonlinear Gyrokinetic Simulation Shows Rotation Profile is Balance of Residual Stress and Diffusion

- **Momentum flux** decomposed by series of simulations\(^1\)
  - Three simulations produce \(\Pi_{\text{resid}}, V_p, \chi_\phi\)

- **Residual stress** balanced by momentum diffusion\(^2\)
  - Momentum pinch small

- **Spatial integration of** \(\Pi_\phi\equiv0 + \text{B.C. predicts intrinsic rotation profile}\

\[
\Pi_\phi = -m_in_i\langle R^2 | \nabla \rho | \rangle \left( \chi_\phi \frac{d\Omega}{d\rho} - V_p \Omega_\phi \right) + \Pi_{\text{Resid.}}
\]

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\(^1\)W.X. Wang Phys. Plasmas 13 (2006)

\(^2\)W.X. Wang APS (2016)
Prediction of Intrinsic Rotation Profile from Electrostatic Turbulence Matches Both Shape and Magnitude of Experiment

- Prandtl number used to relate energy and momentum flux
  - Rotation profile and $\chi_\phi$ is not available in \textit{ab. initio.} prediction
  - Experiment and theory $Pr = \chi_\phi/\chi_i \approx 0.7$
- Qualitative shape and quantitative magnitude in agreement with experiment

**Global Nonlinear GTS Simulation can Predict Intrinsic Rotation Profile from Electrostatic Fluctuation-Induced Residual Stress**
• Dimensionless scaling of intrinsic torque

• Testing physics based models of core intrinsic rotation profile

• Dependence of Edge Flow on Geometry
Edge Velocity “Layer” Exhibits Novel Dependence on Boundary Shape - Maximized for ITER Configuration

- Edge velocity w/pinch possible source of intrinsic co-current angular momentum
- Inverting plasma shape test orbit-loss mechanism
- Find $V_{||}$ always co-$I_p$ and maximized for LSN, favorable $\nabla B$
  - Same as ITER configuration

Boedo et al. Phys. Plasmas accepted (2016)
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- Core rotation correlates with edge rotation layer$^{1,2}$

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$^{1}$Boedo et. al. Phys. Plasmas accepted (2016)
$^{2}$S.R.Haksey APS-DPP (2016)
Rotation Experiments on DIII-D Are Producing Scalings and First-principles-based Validation of Momentum Transport for ITER

- Scaling of increased intrinsic torque towards ITER $\Psi^*$ observed on DIII-D and projects twice as much torque from NBI only.
- Successful capture of hollow intrinsic rotation demonstrates ability to predict rotation profile self-organization.
- Edge rotation where intrinsic torque is maximized correlates with core rotation.
Predicted Intrinsic Rotation Improves ITER Performance via Direct $E \times B$ and Indirect Multi-Channel Effect (Density Peaking)

Flat Density
No $E \times B \Rightarrow Q=5$
Flat Density
$+E \times B \Rightarrow Q=8$
+Density Evolved
$+E \times B \Rightarrow Q=11$

C. Chrystal APS-DPP (2016) Invited Talk
How Does an Intrinsic Rotation Gradient Appear?

• Need a mechanism to break the toroidal symmetry
  - mean E×B shear, ZF E×B shear, up/down asymmetry, profile and turbulence intensity variation

• Intrinsic torque generated by residual stress $\Pi_{\text{resid.}}$
  - Low-k turbulence in the presence of symmetry breaking

• Both diffusion and pinch can balance residual stress
  - here $\Omega$ adjusts with local rotation gradient creating $\Pi_{\text{diff.}}$ until total $\Pi = 0$

Residual stress and momentum diffusion balance

$\eta = -\nabla \cdot \Pi$

$\Pi_{\text{resid.}}$

$\Pi_{\text{diff.}}$

B.C.
Balance of Residual Stress and Momentum Diffusion Responsible for Steady-State Experimental Rotation Profile

- Qualitative balance residual stress and momentum diffusion producing a rotation “hollowing” is realized in GTS simulation

- But quantitative, first-principles prediction of rotation profile requires additional information
  - Cannot use experimental rotation profile to derive diffusive flux, needs Pr

\[ \Pi_{\text{resid}} / \Pi_{\text{norm}} \]

\[ \eta = -\nabla \cdot \Pi \]

Residual stress and momentum diffusion balance