Predicting the Rotation Profile in ITER

by
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in collaboration with

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Rotation Is Important for Determining Stability and Performance in Tokamaks, Affects Predictions of ITER Performance

- Rotation is important for determining ExB shear, MHD stability, transport of high-Z particles
  - All key for determining fusion power output

- Also key for ITER is affect of pedestal rotation on access to ELM free H-mode via QH-mode\(^1\) and RMP ELM suppression\(^2\)
  - Scaling arguments offer favorable prospect of RMP ELM suppression

ITER modeling has shown a doubling of fusion power when taking rotation into account due to ExB shear suppression of turbulence

\[\omega_0 (\text{krad/s})\]

Determining Rotation in ITER Is Difficult Due to the Presence of Many Similar Size Momentum Sources

- Momentum source in many current tokamaks dominated by NBI
- ITER’s larger moment of inertia means non-NBI sources need to be well understood because NBI torque will not be dominant

- Intrinsic rotation profiles display features caused by many physical effects that may be present in ITER
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Co-current LCFS feature:
- Orbit loss
- Co/counter current transport
- Residual stress
- Neutral particles
- Fast-ion loss
- Field ripple/NTV
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Core gradient:
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- Beam torque
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H-mode Intrinsic Rotation Examples

Deuterium $V_g$ (km/s)

$\rho$

DIII-D
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Evaluating 3D field torques requires rotation profile, subject of future work after “initial condition” is laid down

H-mode Intrinsic Rotation Examples
Outline

• DIII-D investigation of LCFS co-current feature in intrinsic rotation plasmas
  – Fast-ion effects on $\rho_*$ scaling
  – Neutral particle effects on intrinsic momentum transport

• ITER prediction based on co-current feature and core NBI

• Implications for RMP ELM suppression and conclusion
Scaling of Intrinsic Co-current Rotation Feature Is Key for Predicting ITER Rotation Boundary Condition

- Low $\rho_*$ operating regime of ITER cannot be achieved in current tokamaks
- Robust co-current rotation near LCFS is a boundary condition, investigated by: empirical scaling$^{1,2}$, dimensionless parameters scans$^3$, reduced physics models$^{4,5}$

- Similar predictions: 4-10 krad/s, but discrepancy exists between databases ($M \sim \rho_*$) and dimensionless parameter scan ($M \sim \rho^{-1}_*$)
  - Databases vary $\rho_*$ more widely, dimensionless parameter scan varies $\rho_*$ alone but had significant fast-ion population
- Dimensionless parameter scan (intrinsic torque) results need to be verified in intrinsic rotation conditions

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Measured Scaling of Intrinsic Rotation in ECH H-modes Has Smaller Discrepancy and Increases Confidence in ITER Prediction

- No significant scaling of intrinsic Mach number measured with in dimensionless parameter scan, defying both possible expectations
  - Fundamentally different from observing variation with Mach number in a database

- Expectation was $M \sim \rho^{-1.0 \pm 0.9}$, new result not quite within error bar, perhaps edge plasma factors or $Z_{\text{eff}}$ changes are the cause of variation in results
  - Other dimensionless parameters matched

- Adjust previous intrinsic torque based ITER prediction of $\sim 10$ krad/s: result is 3 krad/s, very near the previous predictions (4-10 krad/s)
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- Adjust previous intrinsic torque based ITER prediction of ~10 krad/s: result is 3 krad/s, very near the previous predictions (4-10 krad/s)

- Intrinsic rotation predictions are consistent enough for ITER prediction

- Are there boundary effects influencing attempts to measure the $\rho_*$ scaling?
Momentum Transport from Neutrals in Pedestal Is a Hidden Variable that May Affect Current Tokamaks Much More than ITER

- Neutral particles in pedestal are a hidden variable for most current experiments because they are rarely measured, may be corrupting ITER predictions
- Experiment in DIII-D made proxy investigation: change neutrals particles significantly through SOL conditions, observe intrinsic rotation

\[ M_{\text{ped}} \sim f \left( \frac{n_{\text{nuet}}}{n_e}, \frac{n_{\text{neut}}}{a \nabla n_{\text{neut}}} \right) \]

- Basic idea: neutrals affect rotation via charge exchange and ionization, effect is much reduced in ITER due to decreased neutral penetration into plasma

![Graph showing integrated momentum flux](Image)
Proxy Investigation Uses Divertor Closure to Change Neutral Trapping, Effect Shown by SOLPS Modeling

- DIII-D upper divertor can be made significantly more closed than lower divertor
- Create similar intrinsic rotation discharges (ECH H-modes) in these two configurations
  - Measure main-ion rotation from core to LCFS with main-ion CER
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Across Database of Open/Closed Plasmas, Pedestal Top Rotation Constant While Midplane Neutral Emission Changes

- Pedestal top intrinsic rotation (carbon) gives basic indication of changes in edge/pedestal rotation
- For the parameters varied in these discharges, main trend is expected to be with $T_i$

- Neutrals appear to have little effect because rotation data sets essentially the same while midplane neutral emission clearly increase for open cases
DIII-D Intrinsic Rotation in Open/Closed Divertors Do Not Change Significantly with Changes in Pedestal Fueling

- Divertor closure affects amount of neutral fueling near LCFS as seen by SOLPS modeling and density profile results, even when other parameters are the same
  - Density profiles changes are significant given the same $I_p$, $\beta$, etc.

- Main-ion intrinsic rotation is largely unaffected compared to normal experimental variation

- Edge neutrals have no significant effect on intrinsic rotation
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- Main-ion intrinsic rotation is largely unaffected compared to normal experimental variation.

- Edge neutrals have no significant effect on intrinsic rotation.

- Intrinsic rotation predictions are consistent enough for ITER prediction.
- No significant contamination of intrinsic rotation experiment from neutral particles.
- With increased confidence in boundary condition for ITER, we proceed with prediction.
Initial ITER Modeling Done Without Rotation Is Baseline for Evaluating Effect of Rotation

- Predictive TRANSP determines sources
  - ITER baseline scenario (15 MA), EPED pedestal
  - 35 N•m and 33 MW NBI, 10 MW ICRF, 6 MW ECCD (at q=3/2, 2 surfaces)

- Core solution with TGYRO with TGLF+NEO transport

- Next, use edge rotation boundary condition and also solve transport in momentum channel with NBI
  - TGLF momentum transport worked well in DIII-D\textsuperscript{1} at lower collisionality and q

\begin{align*}
\text{T}e (\text{keV}) & \approx 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
\text{T}i (\text{keV}) & \approx 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
\omega (\text{krad/s}) & \approx 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \\
\text{ne (10}^{19}/\text{m}^3) & \approx 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0
\end{align*}

Core Rotation Shear in ITER Is Predicted to Significantly Improve Fusion Performance

- Rotation boundary condition of 4 krad/s is used, relatively modest value within 3-10 krad/s range of predictions
- Core rotation determined from TGLF momentum flux and 35 N•m source
- Deuterium Mach numbers are modest: $M_{\text{core}} \approx 0.2$, $M_{\text{ped}} \approx 0.04$
  - Significant for heavy impurity transport
- $Q_{\text{fus}}$ approximately doubles due to density peaking and increased temperatures caused by rotation shear
  - Grains of salt: Q values are idiosyncratic to the impurities and radiated power, there are nonlinearities and initial condition is important, residual stress not included in core (see Grierson EX/P6-3 this afternoon)
Performance Improvement From Rotation Shear Is Due to Reduction of Low-k Turbulence and Increase in Density Peaking

• In simulation with rotation, low-k turbulence => outward particle flux, intermediate-k => inward particle flux

• Without ExB shear, total flux would be outward, force TGYRO to flatten density profile

• ExB shear suppresses low-k turbulence more strongly, so flux is balanced even with a peaked density profile

• Increased Te due to reduced transport further destabilizes intermediate-k turbulence, increasing inward particle flux, as seen in similar studies\(^1\)

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\[ \text{Total Flux: +0.045} \]
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Simple Scaling Relation Offers Favorable Prospect of Achieving RMP ELM Suppression in ITER

• Low rotation RMP ELM suppression is hard to achieve, hypothesized to be a result of inward movement of $E_r=0$¹
  – $\omega_{\perp,e}$ also hypothesized², movement is typically correlated with $E_r=0$ movement

• Relation for $E_r=0$, divergence free flow:

$$V = k(\psi)B + \omega(\psi)R\hat{\phi} \Rightarrow -\frac{\nabla P}{nZe} = \omega RB_\theta$$

• ITER needs less rotation because of:
  – Larger gradient scale length (larger size)
  – Larger poloidal field

• 5-9 krad/s of pedestal top rotation is lower limit for suppression in DIII-D, translates to 0.2-0.5 krad/s for ITER, <3 krad/s prediction
  – Effect of RMP field on rotation prediction still needed to fully answer this question

[1] Paz-Soldan, Nucl. Fusion (in review)
Conclusions

• Edge rotation prediction for ITER is made with increased confidence: 3-10 krad/s
  – Fast-ion effect on results is relatively small while reducing discrepancies between predictions
  – Neutral particle induced transport found to be small

• ITER, though large and with relatively small NBI torque, will still have significant enough ExB to decrease turbulent transport
  – Prospect of RMP ELM suppression is good

• These rotation predictions must now be integrated with effects from intrinsic and applied 3D fields
Intrinsic Rotation Does Not Vary with Gross Change in Neutrals Associated with Divertor Detachment

- Detached divertors have higher neutral particle pressures
- These conditions were created with significant main-chamber gas fueling in order to increase plasma density
- These changes are expected to increase neutral densities inside the confined plasma, but this causes no significant change to the intrinsic rotation
  – So long as $T_i$ does not begin to drop
- This result supports conclusions drawn from open/closed divertor comparisons
Dimensionless Parameter Scan Executed in ECH H-modes in DIII-D Achieved Desired Variation in $\rho_*$

- $\rho_*$ was decreased by ~30%, the expected range achievable in DIII-D with limitations on field variation due to ECH absorption.

- Change in $Z_{\text{eff}}$ is likely due to a change in carbon source due to a hard to control change in boundary conditions.
  - This is a potential confounding factor for the results, though previous work has not seen causal changes in intrinsic rotation with $Z_{\text{eff}}$. 

![Graphs showing variation in $\rho_*$, $\beta$, $\nu_*$, and $Z_{\text{eff}}$]
Simple Scaling Relation Offers Favorable Prospect of Achieving RMP ELM Suppression in ITER

- RMP ELM Suppression at low rotation is thought to be difficult due to the movement of the $E_r=0$ crossing to lower minor radius
- Using the divergence-free form of velocity:
  \[ V = k(\psi)B + \omega(\psi)R\hat{\phi} \]
  a relation for $E_r=0$ can be made into scaling requirement for Mach number
  \[ -\frac{\nabla P}{nZe} = \omega RB_\theta \Rightarrow -\frac{\nabla P}{nZe} = \omega RB_\theta \left(\frac{R\sqrt{T/m/B/a}}{R\sqrt{T/m/B/a}}\right) \]
  \[ M\epsilon = -\rho_q(\lambda_T^{-1} + \lambda_n^{-1}) \]
  - $\omega$ is the toroidal rotation frequency if poloidal rotation is zero, B approximated as toroidal field to make factor of $q$
  - We will assume the normalized gradient scale lengths will NOT change in ITER
- 5-9 krad/s of pedestal top rotation is current lower limit for RMP ELM suppression in DIII-D, yields a lower limit of 0.2-0.5 krad/s for ITER, <3 krad/s prediction
  - Effect of RMP ELM suppression on rotation prediction still needed to fully answer this question