Developments in Predictive Understanding of Plasma Rotation on DIII-D

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Performance of Future Devices Influenced by Attained Rotation Profile

Sources:
Neutral beam, intrinsic ...

Sinks:
Non-axisymmetric fields

Transport:
Diffusivity, Pinch...

Rotation

Turbulence Control
Improved confinement

Modify NTM/RWM stability

Error field thresholds
Locked mode avoidance
n=3 Non-Resonant Magnetic Fields (NRMF) Applied to Slowly Rotating Plasma Leads to Rotation Spin Up

- NBI power and torque constant during time range shown
- Rotation acceleration happens at all minor radii
- Simultaneous improvement in energy confinement

Garofalo, PRL (accepted)
Application of NRMF Drags Plasma Rotation to Neoclassical Offset Rotation

- Neoclassical theory predicts a non-zero “offset rotation” [Cole et al PRL 2007]

\[ T_{\text{NRMF}} \sim B^2 (V_\phi - V_0^{0,\text{NC}}) \]

\[ V_0^{0,\text{NC}} \approx \frac{k}{Z_i e B_\theta} \frac{dT_i}{dr} \]

- Offset rotation in counter \( I_p \) direction

- Measured torque exhibits offset linear relationship

\[ \beta_N \sim 1.9 \pm 13\% \]

\[ n_e \sim 4.1 \times 10^{19} \text{ m}^{-3} \pm 5\% \]

Garofalo, PRL (accepted)
Effect of NRMF on Plasma Rotation Can Be Adequately Modeled Throughout the Discharge

- Evolve rotation using momentum balance in TRANSP

\[ mnR \frac{\partial V_\phi}{\partial t} = \sum \eta + \nabla \cdot \left( mnR \chi_\phi^{\text{eff}} \frac{\partial V_\phi}{\partial r} \right) \]

- Vary NRMF torque according to I-coil waveform \( B^2 \) and velocity relative to offset

\[ \eta_{\text{NRMF}} \sim B^2 (V_\phi - V_\phi^0) \]

- Allow only slow, linear variation of momentum diffusivity \( \chi_\phi^{\text{eff}} \)
Toroidal Rotation Can Be Modified by Strong Reverse Shear Alfvén Eigenmode (RSAE) Activity

- Central rotation almost 2x greater with RSAE activity suppressed
- However, total angular momentum content comparable
- Suggestive of redistribution of fast ions rather than complete loss
  - Change in rotation due to changes in torque profile?

See Van Zeeland EX/6-2 on RSAE's
Torque Profile is Significantly Modified by RSAE-Induced Fast Ion Transport

- Assume change in rotation due to modification of source, rather than changes in momentum transport.

- Use ad hoc anomalous fast ion diffusion in TRANSP to account for effect of RSAE’s on fast ion transport.

- 40% central NB torque reduction required to match rotation.

- Inferred RSAE-induced fast ion transport consistent with:
  - Reduction in neutron rate
  - Reduced fast ion density.

![Graph showing torque density vs. \( \rho \)](image-url)
Intrinsic Rotation Plays a Role in Determining Total Plasma Rotation, Even with Neutral Beam Injection

- **Intrinsic rotation** = rotation without auxiliary torque
  - Observed on C-Mod, JET, JT-60U, Tore Supra…

- On DIII-D, torque scans performed at constant $\beta_N \sim 1.7 \pm 10\%$ to investigate intrinsic + NBI

- Large rotation observed across profile, even with net zero torque from NB
  - Persists even with significant counter injection
Near-Zero Rotation Profile With Finite Neutral Beam Torque Suggests an Intrinsic Torque Source

- From momentum balance equation

\[
m_n R \frac{\partial V_\phi}{\partial t} = \sum \eta - \nabla \cdot \Gamma + S,
\]

where

- \( \sum \eta \) is the sum of momentum sources and sinks,
- \( \nabla \cdot \Gamma \) is the transport term,
- \( S \) is the source term,
- \( \Gamma = -m_n R \left( \chi_\phi \frac{\partial V_\phi}{\partial r} - V_\phi V_{\text{pinch}} \right) \)

This equation represents the rate of change of momentum, with momentum sources and sinks, transport, and intrinsic torque contributions. The intrinsic torque term is particularly emphasized.
Near-Zero Rotation Profile With Finite Neutral Beam Torque Suggests an Intrinsic Torque Source

- From momentum balance equation
  \[ mnR \frac{\partial V_\phi}{\partial t} = \sum \eta - \nabla \cdot \Gamma + S, \quad \Gamma = -mnR \left( \chi_\phi \frac{\partial V_\phi}{\partial r} - V_\phi \frac{\partial \phi}{\partial r} \right) \]

- If \( V_\phi \) zero and constant, then net torque to plasma must be zero

- Situation essentially realized here
  - Despite one net counter NB source
  - Direct evidence of intrinsic source

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

\[ T_{NBI} \sim 5 \text{ Nm} \quad (3 \text{ co} + 0 \text{ ctr NB}) \]

\[ T_{NBI} \sim -2.5 \text{ Nm} \quad (1 \text{ co} + 2 \text{ ctr NB}) \]
Intrinsic Source Approximately Equivalent to One Neutral Beam Source

- Intrinsic source must cancel NBI torque

\[ \eta_{NBI} + S = 0 \quad \rightarrow \quad S = -\eta_{NBI} \]
Intrinsic Source Approximately Equivalent to One Neutral Beam Source

- Intrinsic source must cancel NBI torque
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- Additional fast ion transport alters calculated NBI torque
  - Inferred intrinsic source becomes more peaked at edge

- Evidence of “Residual Stress”?  
Angular Momentum Transport Is Investigated Using Perturbative Techniques

- Toroidal rotation evolves according to momentum balance eq.

\[ mnR \frac{\partial V_\phi}{\partial t} = \sum \eta - \nabla \cdot \Gamma + S, \quad \Gamma = -mnR \left( \chi_\phi \frac{\partial V_\phi}{\partial r} - V_\phi V_{\text{pinch}} \right) \]

  - Rate of change of momentum
  - Momentum sources/sinks
  - Transport
  - "Intrinsic source"
  - Diffusion
  - Pinch

- In modulated cases, equilibrium sources and sinks do not have to be known
  - Removes many uncertainties

- If one can compute perturbed sources/sinks, then \( \Gamma_\phi \) is determined

- Model \( \Gamma_\phi \) evolution to determine diffusive and convective contributions
Neutral Beam Torque Pulses at Constant Power Are Used to Create Non-Local Rotation Perturbations

- Clearly see effect of torque pulses in rotation measurements
- Must change $V_\phi$ independently of $\frac{dV_\phi}{dr}$ during perturbation
Inward Pinch of Momentum Inferred From Neutral Beam Torque Perturbations

- Inclusion of pinch in momentum improves fit to momentum flux evolution
- Pinch alters inference of momentum diffusivity
  - Can exceed a factor of 2
  - Most significant when transport high (low rotation, reduced ExB shear)

Inward momentum pinch also seen on JT-60U, JET and NSTX
Good Agreement Found Between Theoretical and Experimentally-Determined Pinch Velocity

- Theory predicts drive of momentum pinch through low-\(k\) turbulence
  - Peeters et al. PRL (2007) 
  \[ V_{\text{Peeters}} = \frac{\chi \phi}{R} \left[ -4 - \frac{R}{L_n} \right] \]
  \[ V_{\text{Hahm}} = \frac{\chi \phi}{R} [-4] \]

- No obvious distinction between theories experimentally
  - \(L_n\) term only appreciable in DIII-D toward the edge

- However, results from NSTX suggest \(L_n\) term does matter
  [Kaye et al, this meeting EX/3-2]
Summary

- Non-resonant magnetic fields apply a torque to the plasma, which can result in a spin up of the plasma at low rotation
  - Including associated improvement in confinement

- Strong RSAE activity has been shown to modify the rotation profile, while leaving the total angular momentum content unchanged
  - Modification of NB torque profile

- Intrinsic source inferred directly from momentum balance

- Experimental observation of momentum pinch in reasonable agreement with theoretical predictions
Application of NRMF Drags Plasma Rotation to Neoclassical Offset Rotation

- Neoclassical theory predicts a non-zero "offset rotation" [Cole et al PRL 2007]
  \[ T_{NRMF} \sim B^2 (V_\phi - V_{\phi,NC}^0) \]
  \[ V_{\phi,NC}^0 \approx \frac{k}{Z_i e B_\theta} \frac{dT_i}{dr} \]

- Offset rotation in counter I_p direction

- Measured torque exhibits offset linear relationship

Garofalo, PRL (accepted)
Magnitude and Radial Dependence of Offset Rotation in Semi-Quantitative Agreement with Theory

- Neoclassical model gives offset rotation of form
  \[ V^0_{\varphi,NC} \equiv \left( k_c / Z_i e B_\theta \right) \left( dT_i / dr \right) \]
  with \( k_c \) depending on collisionality regime

- Values of \( k_c(\rho) \) fall within theoretical limits for \( \nu \) and \( 1/\nu \) regimes
  - Apparently highly non-linear connection between regimes

Garofalo, PRL (accepted)
Modeling of NRMF Torque At Low Rotation Must Consider Role of Intrinsic Rotation

- Evolve measured NRMF torque profile from initial step according to $B^2(V_\phi - V_\phi^0)$
- Assume intrinsic source constant in time
- Scale $\tau_\phi$ with $\tau_E$
- For each $\rho$, solve for intrinsic source giving best fit to integrated angular momentum evolution

$$\frac{dL}{dt} = -\frac{L(t)}{\tau_\phi(t)} + T_{\text{NBI}}(t) + T_{\text{NRMF}}(t) + T_{\text{intrinsic}}$$
At Low NBI Torque, Modeling of NRMF Torque Is Consistent With Expectations for Intrinsic Rotation

- Intrinsic source profile similar to previous results

\[
\frac{dL}{dt} = -\frac{L(t)}{\tau_\phi(t)} + T_{\text{NBI}}(t) + T_{\text{NRMF}}(t) + T_{\text{intrinsic}}
\]
Both Becoulet’s $1/\nu$ Regime and Park’s “General” Formula Predict Very Large NRMF Torques in ITER

- ITER (Scenario 2) with ELM suppression fields
  - $\tau_{\text{dam}} \sim 10 \text{ ms (} 1/\nu \text{ regime)}$
  - [Becoulet, et al., IAEA (2008)]
- NRMF Torque is very large compared to NBI torque
  - $\tau_L \sim \tau_E = 3.7 \text{ s}$
  - $T_{\text{NRMF}}/T_{\text{NBI}} = \tau_L/\tau_{\text{dam}} \sim 370$

- ITER (Scenario 2) with ELM suppression fields
  - $\tau_{\text{dam}} \sim 10\text{-}100 \text{ ms (general formula)}$
  - [Park, et al., IAEA (2008)]
- Still, NRMF Torque is very large compared to NBI torque
  - $T_{\text{NRMF}}/T_{\text{NBI}} = \tau_L/\tau_{\text{dam}} \sim 37\text{-}370$
Calculated Neutral Beam Torque Profile May be Questionable in the Presence of Alfvén Eigenmodes

- Neutral Beams are Primary Source of Angular Momentum on Most Large Tokamaks

- Torque profile deposited by neutral beams typically calculated by codes like TRANSP
  - Classical transport of fast ions included

- Most DIII-D plasmas exhibit various Alfvén Eigenmode
  - Redistribute fast ions, non-classical transport
ECH has been Used as a Means of Controlling Reverse Shear Alfvén Eigenmode (RSAE) Activity

- **ECH near $\rho(q_{\text{min}})$**
  - RSAEs suppressed
- **ECH near axis**
  - RSAEs present

See Van Zeeland poster JP8.00087
Analysis of Momentum Transport Gives Estimate of Anomalous Fast Ion Diffusion Driven by RSAEs

- Assuming classical fast ion (FI) transport
  - Local diffusivity $\chi^\text{eff}_\phi$ is notably larger for $\rho<0.7$ for shot with RSAE’s (wrong source profile)
Analysis of Momentum Transport Gives Estimate of Anomalous Fast Ion Diffusion Driven by RSAEs

- **Assuming classical fast ion (FI) transport**
  - Local diffusivity $\chi_{\phi}^{\text{eff}}$ is notably larger for $\rho<0.7$ for shot with RSAE's (wrong source profile)

- **If use $D_{fi}=0.3\rightarrow0$ m$^2$/s profile**
  - Better match for $\chi_{\phi}^{\text{eff}}$ for $\rho<0.7$

- **Torque profile altered by inferred RSAE-induced fast ion transport**
  - 50% reduction in core
Deduced Anomalous Diffusion Consistent with Fast Ion Measurements

- Classically, discharge with RSAE’s expected to have slightly greater fast ion pressure.
- Measurement of fast ion profiles (FIDA) shows it has lower pressure.
- Anomalous fast ion diffusivity also consistent with change in measured neutron rate.
Anomalous FI Diffusion Deduced from Momentum Transport Accounts for RSAE Neutron Deficit

- Large deficit in neutron rate compared with classical computation
  - Enhanced when RSAEs present

- Neutron rate recalculated based on deduced anomalous fast ion diffusion profile

- Additional neutron deficit associated with case with RSAE’s accounted for
Significant Alfvén Eigenmode Activity in These Discharges Again Has Visible Effect on Fast Ions

- TRANSP over-predicts neutrons by 20–30%.
- TRANSP total stored energy high compared with kinetic EFIT.
- Assuming other kinetic profiles are correct, suggests fast ions not behaving classically.
Anomalous Fast Ion Diffusion Can Bring Neutron Rate and Stored Energy Into Agreement

- Anomalous diffusion $D_{fi} \sim 2 \text{ m}^2/\text{s}$ brings neutron rate down to measured value
- Central fast ion pressure reduced $> 30\%$
- Central torque density reduced $> 50\%$
Different Response of Angular Momentum to Torque Observed in Hybrid Scenario

- $q_{95} \sim 4.5$, $\beta_N \sim 2.5$

- Still have significant angular momentum at zero NB torque

- Scan does not get to zero angular momentum
  - 3/2 mode slows and locks
  - Can’t estimate anomalous torque

- Can still get incremental momentum confinement time
  - Shows improvement with increasing rotation

![Graph showing the relationship between torque and confinement time.]
For Hybrids, Relative Importance of ExB Shear Diminished as Rotation Reduced

- Uses measured density, toroidal rotation, and current profiles
- At high rotation, ExB shear essential to reproduce measured temperature profiles
- At low rotation, ExB shear (not surprisingly) plays little role
ExB Shear Appears To Be Much Less Important in the Previous H-mode plasmas

- Agreement of temperature profiles is not dramatically improved by including ExB shearing
- Underlying degradation of momentum confinement with torque can be masked by strong ExB shear.
Non-Axisymmetric Magnetic Fields Apply a Torque to the Plasma

- Non-axisymmetric fields practically unavoidable, and may be deliberately applied (e.g., ELM suppression)
- Both resonant and non-resonant fields affect plasma rotation

**Resonant braking** \[ T \propto \frac{1}{V_\phi} \]

**Non-Resonant braking** \[ T \propto V_\phi \]

[Graphs showing the relationship between I-coil current and toroidal velocity over time, with labeled regions for different time periods and shading for specific cases.]
However, Correlation is Not Always Seen Even at DIII-D Aspect Ratio

- Momentum and ion thermal diffusivities comparable at large rotation
  - Standard result
- But, diffusivities show different dependence on rotation
- Important to correct for intrinsic rotation at low torque
- Momentum diffusivity increases with rotation esp. for $\rho \geq 0.5$
- Including momentum pinch may restore correlation between both quantities

Solomon PPCF 2007
Total Mechanical Angular Momentum Reveals Non-Linear Response to Total Neutral Beam Torque

- Suggests momentum confinement time is dependent on torque
  \[ \tau_\phi \sim \frac{L}{T} \]

- Simple quadratic fits data
  \[ L - L_0 = AT - BT^2 \]
  \[ L_0 \equiv \text{Intrinsic angular momentum} \]

- Need to include torque associated with intrinsic rotation
  - If \( L \) doesn’t go to zero with \( T \), then \( \tau_\phi \) blows up
  - If \( L \) positive when \( T \) negative, get negative \( \tau_\phi \)
Momentum Confinement Shows Improvement as the Neutral Beam Torque is Reduced

- Momentum confinement time recomputed allowing for intrinsic torque
  \[ \tau_\phi \sim \frac{L}{(T_{\text{NBI}} + T_{\text{intrinsic}})} \]

- Find same improvement at low torque when analyze dynamic behavior
  \[ \frac{dL}{dt} = T(t) - \frac{L(t)}{\tau_\phi^{\text{relax}}} \]

![Graph showing relationship between \( T_{\text{NBI}} + T_{\text{intrinsic}} \) and \( \tau_\phi \)]

- Steady state
- Transient
Including Momentum Pinch Improves Fit to Momentum Flux Evolution

- Non linear least squares fit of $\chi_\phi$, $V_\phi^{\text{pinch}}$ profiles
  - Assumed constant in time
- Inclusion of pinch improves reconstruction of momentum flux at some radii on NSTX
  - Still not perfect $\rightarrow$ Other off-diagonal terms? $\chi_\phi$, $V_\phi^{\text{pinch}}$ changing...?
• Rotation plays an important role in fusion plasmas
  – Turbulence suppression
  – RWM and NTM stabilization

• Therefore, performance of future devices depends on attained rotation profile

• Achieving predictive understanding of rotation and exploiting this knowledge to generate optimal rotation profile will result in significant payoff for fusion

• Problem can be broken down into three key areas
  – Sources (Neutral beam, intrinsic …)
  – Sinks (Resonant and non-resonant magnetic fields…)
  – Momentum transport (confinement, diffusivity, pinch…)

WM Solomon/IAEA/Oct2008