Intrinsic Rotation in DIII-D

by

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for

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Intrinsic Rotation in DIII-D

Overview

- **Intrinsic rotation** = Toroidal velocity without auxiliary injected torque
  - It is commonly observed.
  - Recognized to be important for issues of stability and confinement in burning plasmas, with little auxiliary torque

- In DIII-D we have investigated intrinsic rotation in H-mode discharges,
  - Using Ohmic Heating (OH), Electron Cyclotron Heating (ECH), and
  - Using the new DIII-D co/counter Neutral Beam Injection (NBI) capability
  - NBI is an important tool to study intrinsic rotation at larger plasma $\beta$, but there must be balance in the torque profile

- A scaling for intrinsic rotation is emerging, and an initial DIII-D/C-Mod similarity experiment is encouraging

- Theories presently provide qualitative explanations
  - Neoclassical
  - Turbulence
Toroidal Intrinsic Rotation is Widely Observed In Tokamak Discharges

\[ M_\phi = \frac{V_\phi}{\bar{V}_i} \]

\[ \bar{V}_i = \sqrt{\frac{T_i}{M_i}} \]

From J.E. Rice, et al, IAEA, EX-P3-12, Chengdu 2006
Ion Velocity and Temperature Measurements in DIII–D
Require NBI: Intrinsic Measurement Limited By NBI Torque

- Only first ~ 2 ms of NBI ‘blip’ is nonperturbative; NBI torque-impulse persists.
- Move time of first NBI blip shot-to-shot to obtain time evolution.
- Long ELM-free period in D⁺ discharges with “spread” and “core” ECH deposition, with evolution of the intrinsic rotation profile.
- We have also utilized ECH H-Modes in bulk ion He²⁺ discharges, measuring the main ion velocity, as well as C⁶⁺
ECH H-modes in DIII-D Exhibit Hollow Intrinsic Rotation Profiles. The Core Rotation Can Be Reversed, to the Counter-Ip Direction

- Relatively flat intrinsic rotation profile also seen in C-Mod EDA H-modes, as in DIII-D OH H-modes.

\[ \rho = \text{normalized toroidal flux radial coordinate.} \]
ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

- OH H-mode and “spread” ECH H-mode

![Graph showing C6+ Velocity in Deuterium discharges and ECH deposition profiles.](image)
ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

- OH H-mode and “spread” ECH H-mode
- ECH H-mode with “core” deposition

ECH deposition profiles

C6+ Velocity in Deuterium discharges.

ECH-H (''spread'')

ECH-H ('core')

pECH(a.u.)

"core" (x 1/2) "spread"
ECH Deposition Profile In ECH H-modes Correlates With the Hollow Intrinsic Rotation Profile

- OH H-mode and "spread" ECH H-mode
- ECH H-mode with "core" deposition and "off-axis" deposition
- OH H-modes and "off-axis" ECH H-modes are ELMing.

ECH deposition profiles
Hollow Intrinsic Rotation Profiles Do Not Depend on Ion Species. Bulk Ion (He\textsuperscript{++}) ECH H-mode Profiles Are Also Hollow.

- Bulk ion He\textsuperscript{++} velocity profile is also hollow.
- These discharges are ELMing => ELMs do not preclude hollowness.

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**ECH-H ('core deposition')**

- **\(\omega_\phi\)(krad/sec)**
- **\(\rho\)**

**Bulk ion velocity**

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Hollow Intrinsic Rotation Profiles Do Not Depend on Ion Species. Bulk Ion (He\textsuperscript{++}) ECH H-mode Profiles Are Also Hollow.

- Bulk ion He\textsuperscript{++} velocity profile is also hollow.
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Hollow Intrinsic Rotation Profiles Do Not Depend on Ion Species. Bulk Ion (He++) ECH H-mode Profiles Are Also Hollow.

- Bulk ion He++ velocity profile is also hollow.
- These discharges are ELMing => ELMs do not preclude hollowness.

ECH-H ('core deposition')
Measuring bulk ion and impurity ion velocity allows a test of the standard neoclassical prediction for the bulk ion

- The predicted velocity for He$^{++}$ does not match the measured profile.
- The discrepancy is most likely that the poloidal velocity is not the neoclassical value. [W. Solomon, et al, PoP 13, 056116 (2006)]
- $V_{pol}$ is too small in these intrinsic discharges to measure accurately.

\[\omega \phi(krad/sec)\]

Neoclassical prediction for bulk ion velocity

\[\omega \phi_{NC}(He)\]

\[\omega \phi_{C}(He)\]

\[\omega \phi_{He}\]

Bulk ion velocity

- Intrinsic E field?
Core counter intrinsic rotation develops in time, after L->H
It is not due to an ECH-driven viscosity.

- Diffusive momentum transport alone cannot reproduce the rising counter-Ip rotation.

Averaged over the interior channels, $\rho < 0.25$

- $\bar{n}_e (10^{19}/m^3)$
- $P_{ECH} (MW)$
- $P_{NBI} (MW)$
- $D_\alpha (au)$
- $C^6+ V$elocity in Deuterium discharges.

- $\bar{\omega}_\phi_{core} (krad/sec)$

- $t (msec) = 1500, 2000, 2500$
Such Rotation Profiles Can in Principle Be Generated Without Any Total Injected Torque With Momentum Diffusion and A Pinch.


\[
\frac{\partial L}{\partial t} = \eta + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \left( V_{\text{pinch}} L + D \frac{\partial L}{\partial r} \right) \right]
\]

\[ L(a) \neq 0 \]

- ECH may cause an interior momentum “rearrangement”?

An example, D = const, U = const

\[ V_{\text{pinch}} = \frac{r U}{a} \]
Intrinsic Rotation is Reproducible in the Same Plasma Conditions

- Double ECH H-mode in the same DIII-D shot
- Same intrinsic profile measured

- Plasma resets to ~ Ohmic state in between
  Intrinsic rotation ~ quenched

- Density and temperature profiles reproduce to < 10% at the time of “first NBI blips”
There is a scaling for intrinsic rotation in DIII–D.

- John Rice’s C-Mod intrinsic rotation scaling, $\Delta V_\phi \sim \Delta W/I_p$, is observed in $V_{pk}$ in DIII-D.

Common, co-$I_p$ velocity in this region:

$$V_{pk} = V_\phi(\rho \approx 0.8)$$

**Rice scaling**

**Modified by $T_e/T_i$**

- Fits are done for $V_\phi C^{6+}$ in bulk D

There is A Scaling for Intrinsic Rotation in DIII–D

- John Rice’s C-Mod intrinsic rotation scaling\(^1\), \(\Delta V_\phi \sim \Delta W/I_p\) is observed in \(V_{pk}\) in DIII-D.

Common, co-\(I_p\) velocity in this region

\[ V_{pk} = V_\phi (\rho \approx 0.8) \]


Rice scaling

Modified by \(T_e/T_i\)

\[ V_{pk}(\text{km/sec}) \]

\[ \frac{W}{I_p}(\text{J/A}) \]

\[ \frac{[T_e(0)/T_i(0)]W}{I_p}(\text{J/A}) \]

- Fits are done for \(V_\phi\) \(C^6^+\) in bulk D

Data points for \(V_\phi\) \(He^{++}(+)\)
There is a scaling for intrinsic rotation in DIII–D:

- John Rice’s C-Mod intrinsic rotation scaling\(^1\), \(\Delta V_\phi \sim \Delta W/I_p\) is observed in \(V_{pk}\) in DIII-D.

\[ V_{pk} = V_\phi(\rho \approx 0.8) \]

**Common, co-\(I_p\) velocity in this region**


**Rice scaling**

**Modified by \(T_e/T_i\)**

- Fits are done for \(V_\phi\) C\(^{6+}\) in bulk D
- Data points for \(V_\phi\) He\(^{++}\) (+) and C\(^{6+}\) (\(\bullet\)) in bulk He fall in line.
This Common Scaling Motivated an Intrinsic Rotation Similarity Experiment Between DIII–D and C-mod

- **Dimensionless parameters**
  \[ \hat{\beta} \propto \frac{nT}{B^2} \equiv \hat{\beta} \]
  \[ \hat{\nu} \propto \frac{an}{T^2} \equiv \hat{\nu} \]
  \[ \hat{\rho} \propto \sqrt{T/aB} \equiv \hat{\rho} \]
  \[ q \propto \frac{B}{B_\theta} \equiv q_{95} \]

- **Dimensionless Velocity**
  \[ M_\phi = \frac{V_\phi}{\bar{V}_i} \]

- **Match:**
  \[ \hat{\beta} \hat{\nu} \hat{\rho} q_{95} \] (absolute parameters)
  shape ( \( \varepsilon = \frac{a}{R_0}, \kappa \ldots \) )

- **Measure:** \( M_\phi \)

- **DIII-D Target Shot**
  ELMing H-mode; \( \sim \) steady state ("off-axis" ECH H-mode) \( T_e \sim T_i \)

- **Single point \( M_\phi \) comparison, not profile

- **Assumptions required to compare:**

  \[ M_{\phi,C-Mod} \]

  \[ M_{\phi,PK} \]

  ECH specific

  \[ 0.2 \ 0.4 \ 0.6 \ 0.8 \ 1.0 \]

  \[ \rho \]

  DIII-D

  C-Mod
Initial DIII-D/C-Mod Similarity Experiment Shows a Good Match in the Intrinsic $M_\phi$

<table>
<thead>
<tr>
<th></th>
<th>DIII-D</th>
<th>C-Mod</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_T$(T)</td>
<td>1.75</td>
<td>3.75</td>
</tr>
<tr>
<td>$a$(m)</td>
<td>0.60</td>
<td>0.22</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.87</td>
<td>1.64</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>4.9</td>
<td>4.8</td>
</tr>
<tr>
<td>$\hat{\beta}$</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>$\hat{\nu}$</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>$\hat{\rho}$</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>$M_\phi$</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>$n_e(10^{19}/m^3)$</td>
<td>5.4</td>
<td>22.</td>
</tr>
<tr>
<td>$T$(keV)</td>
<td>1.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>
The Rice Scaling Motivates a Search for a Similarity Path in $\beta q$

$$W/I_p \rightarrow nT/B_\theta \rightarrow [^\wedge \beta q_{95}]^{1.25} [\nu, \rho, ..]^\delta$$

Vary $q_{95}$ and $\beta$ with product constant $C$-Mod

C-Mod match
$q_{95} = 4.8$
$B_T = 3.75$ T

DIII-D Target
$q_{95} = 6.5$
$q_{95} = 5.1$
$B_T = 5.63$ T

Minority ICRH
(H)D

$M_\phi$

$\beta q_{95}$
Intrinsic Rotation and NBI Torque: NBI Does Not Quench The Intrinsic Rotation

- Local co-directed velocity persists, with zero volume integrated torque.
- Linear variation of velocity near zero torque indicates NBI impulse is additive.
- We will also look into the details of the torque and momentum profiles.

* Data from Wayne Solomon, CO1.0006
NBI Does Not Quench Intrinsic Rotation: Confinement Time Analysis for Incremental NBI Torque-impulse

- ECH H-mode target; add NBI incremental torque

Intrinsic + NBI, ~ steady

\[ \bar{n}_e (10^{19}/m^3) \]
\[ P_{\text{ECH}} (\text{MW}) \]
\[ P_{\text{NBI}} (\text{MW}) \]

\[ D_\alpha \text{ (a.u.)} \]

\[ \omega \phi \text{ (krad/sec)} \]
\[ \rho \approx 0.15 \]
\[ \rho \approx 0.6 \]
NBI Does Not Quench Intrinsic Rotation: Confinement Time Analysis for Incremental NBI Torque-impulse

- ECH H-mode target; add NBI incremental torque

![Graph showing intrinsic + NBI, ~ steady](image)

- Confinement time analysis globally integrated:

![Graph showing time analysis](image)
NBI Does Not Quench Intrinsic Rotation: Confinement
Time Analysis for Incremental NBI Torque-impulse

• ECH H-mode target; add NBI incremental torque

Intrinsic + NBI, ~ steady

- $n_e(10^{19}/m^3)$
- $P_{ECH}(MW)$
- $P_{NBI}(MW)$
- $D_\alpha$ (a.u.)
- $\omega_\phi$(krad/sec)
- $\rho \approx 0.15$
- $\rho \approx 0.6$

- Confinement time analysis globally integrated:
  - $W_{MHD}(MJ)$
  - $L_{(Nt-m-sec)}$
  - $\Delta L/\Delta W$
  - $N/P_{NBI}$

- $N = NBI$ torque

response follows source
NBI Does Not Quench Intrinsic Rotation: Confinement Time Analysis for Incremental NBI Torque-impulse

- ECH H-mode target; add NBI incremental torque

**Intrinsic + NBI, ~ steady**

- Confinement time analysis globally integrated:
  - \( W_{MHD}(MJ) \)
  - \( L(Nt-m-sec) \)
  - \( \Delta L/\Delta W \)
  - \( N/P_{NBI} \)
  - \( N = NBI \) torque

\( \tau_\phi \sim \tau_E \)
NBI Does Not Quench Intrinsic Rotation: Confinement Time Analysis for Incremental NBI Torque-impulse

- ECH H-mode target; add NBI incremental torque

### Intrinsic + NBI, ~ steady

- \( P_{ECH}(MW) \)
- \( P_{NBI}(MW) \)
- \( D\alpha \) (a.u.)
- \( n_e(10^{19}/m^3) \)
- \( \omega_\phi \) (krad/sec)
- \( \rho \approx 0.15 \)
- \( \rho \approx 0.6 \)

### Confinement time analysis globally integrated:

- \( W_{MHD}(MJ) \)
- \( L(\text{Nt-m-sec}) \)
- \( \Delta L/\Delta W \)
- \( N/P_{NBI} \)
- \( N = \text{NBI torque} \)

\( \tau_\phi \sim \tau_E \) subtracting intrinsic momentum

If no intrinsic response follows source

\( \langle L/N \rangle_t \)

- \( \tau_\phi \)
- \( \tau_E \)
High Power Locally Balanced NBI Reveals Intrinsic Rotation

- Use new DIII-D simultaneous co/counter NBI capability

- The goal will be to push intrinsic rotation scaling to higher $\beta$ values with high power NBI.

- This shot, no ECH, add counter beam in steps.
High Power Locally Balanced NBI Reveals Intrinsic Rotation

\[ \eta (N_t m/m^3) \]
\[ 10 \times \ell (N_t m-sec/m^3) \]
\[ t = 2800 \text{ msec} \]

\[ V_\phi (\text{km/sec}) \]
\[ M_\phi \]

- \( M_\phi \) profiles
High Power Locally Balanced NBI Reveals Intrinsic Rotation

- **co-phase**
- **near-balanced**

Torque density, $\eta \approx 0$, for $\rho < 0.75$, and $\eta < 0$ outside.

- yet, plasma momentum density, $\ell > 0$, everywhere.

- $V_{pk}$ scaling describes the “intrinsic” value!

- $M_\phi$ profiles

- $W/I_p$
- $(T_e/T_i)W/I_p$
Theories predict intrinsic rotation: Extensions to Neoclassical theory

- 2nd order neoclassical theory; off-diagonal elements


- Not yet the complete story, but the predicted pedestal value cannot be ignored

\[
\nu = \frac{R_0 q V_i}{\varepsilon^{3/2} V_i}
\]
Theories predict intrinsic rotation: Turbulence

- Turbulence theories to date provide motivation, qualitative predictions.
  

  G.M. Staebler, PoP, 11 (2003) toroidal: theoretical framework in which to include turbulence stress


  B. Coppi, IAEA, Lyon (2002)


  J. Thomas and B. Coppi UP1.00072

  P. Nataf and B. Coppi UP1.00073

- As with energy confinement, we will need to measure the turbulence characteristics!
Summary

• Intrinsic rotation exists, independent of ion species. It increases in the co-Ip direction with increased plasma stored energy.

• In ECH H-modes, the details of the core profile, including a transition to counter-Ip rotation, depend upon the ECH power deposition profile.

• Intrinsic rotation is reproducible, with repeated plasma profiles.

• There is a scaling; The Rice scaling is a starting point and now we are searching for the dimensionless result.

• An initial DIII-D/C-Mod similarity experiment is encouraging; much more to do.

• It will be possible to measure intrinsic rotation using near-balanced NBI torque in DIII-D, pushing $\beta_N$ to 2, and beyond.

• Theories are coming to the point that direct comparison with experiment can be made.