Observations of Intrinsic Rotation Reversal Hysteresis in Alcator C-Mod Plasmas

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Motivation: In L-mode, Intrinsic Rotation Correlates with Ohmic Confinement Scaling

- Toroidal rotation observed in L-mode plasmas with no external torque
  - In C-mod, rotation profiles of Ar16+ are measured with HiReX-SR
- Rotation can reverse, and in ohmic plasmas is correlated with LOC/SOC transition [Rice NF 2013]
- Theory suggests need for residual stress term to generate intrinsic torque – do changes in turbulent state unify reversals and the LOC/SOC transition?

[Rice NF 2011]
Overview: Rotation reversal hysteresis observed in response to density ramps

• Reversals demonstrate hysteresis, so the same plasma parameters can lead to multiple rotation states

• Hysteresis response to up/down ramps is demonstrated at multiple currents

• Can compare turbulence at the same plasma parameters but differing rotation state within a single shot
Hysteresis loops show clearly separated co-counter-current transition densities

USN 5.4 T \( T_{e0} \approx 2.7 \text{ keV} \) \( q_{95} = 4.7 \)
0.8 MA \( T_{i0} \approx 1.3 \text{ keV} \) \( v_{\text{min}}^* \approx 0.4-0.5 \)
Qualitatively similar hysteresis observed at multiple currents

<table>
<thead>
<tr>
<th>Current</th>
<th>$T_e0 \approx$</th>
<th>$q_{95} = $</th>
<th>$n_e [10^{20}/m^3]$</th>
<th>$v^{*}_{min} \approx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 MA</td>
<td>1.9 keV</td>
<td>4.7</td>
<td>0.70 - 1.00</td>
<td>0.4 - 0.5</td>
</tr>
<tr>
<td>1.1 MA</td>
<td>1.7 keV</td>
<td>3.5</td>
<td>1.0 - 1.6</td>
<td>0.4 - 0.5</td>
</tr>
</tbody>
</table>
Hysteresis used to probe PCI spectra with same local plasma parameters

• Phase Contrast Imaging (PCI) measures line-integrated $\tilde{n}_e$, $k_R < 30 \text{ cm}^{-1}$
  • $+k_R$ goes from LFS to HFS, aligned with electron diamagnetic drift direction at top
  • $\pm k_R$ asymmetry $<>$ up/down asymmetry

• High-$k$ ($k_R \rho_s = 0.1\sim1.0$) “wings” are observed in co-current 1.1 MA ohmic plasmas, but not co-current 0.8 MA ohmic plasmas [Rice NF 2013]
1.1 MA Ohmic – **different** toroidal rotation, **same** local profiles...

\[
\begin{align*}
\text{Co-current} &+20 \text{ km/s} \\
\text{Counter-current} &-7 \text{ km/s}
\end{align*}
\]

\[n_e\] [10^{20} \text{ m}^{-3}] \\
\[a/L_{n_e}\] [-] \\
\[T_e\] [keV] \\
\[a/L_{T_e}\] [-]

\(r/a\)

(Ti profiles WIP due to instrumental effects, but emissivity-averaged Ti changes ~50eV)
1.1 MA Ohmic – different toroidal rotation, same local profiles, different PCI spectra
0.8 MA Ohmic – different toroidal rotation, same local profiles...

(Ti profiles WIP due to instrumental effects, but emissivity-averaged Ti changes ~50eV)
0.8 MA Ohmic – different toroidal rotation, same local profiles, same PCI spectra
Hysteresis also observed in response to ICRF heating ramps

- Introduced **ICRF heating ramp** (0.2-1.2 MW) to 0.8 MA plasma held at fixed density
  - Compare: 0.95 MW $P_{\text{ohm}}$ @ 0.8 MA, 1.45 MW $P_{\text{ohm}}$ @ 1.1 MA

![ICRF Power](attachment:image1)

**USN 5.4 T**
- $T_{e0} \approx 2.4$ keV
- $T_{i0} \approx 1.7$ keV
- $q_{95} = 4.7$
- $v^*_\text{min} \approx 0.4$-$0.5$

![Graph](attachment:image2)
0.8 MA +ICRF – different toroidal rotation, same local profiles...

(Ti profiles WIP due to instrumental effects, but emissivity-averaged Ti changes ~50eV)
0.8 MA +ICRF — different toroidal rotation, same local profiles, different PCI spectra!

Frequency [kHz]

Counter-current -10 km/s  Co-current +30 km/s

![Graph showing frequency vs. kR for both current directions]
Addition of ICRF breaks “wing”/current correlation

1.1 MA Ohmic, Co-Current +20km/s

0.8 MA +ICRF, Co-Current +30km/s
Up/down asymmetries modified by rotation state when “wings” present

- Compare integrated power of PCI fluctuations $2 \text{ cm}^{-1} < \pm k_{R} < 10 \text{ cm}^{-1}$
  - High: $300 \text{ kHz} < f < 700 \text{ kHz}$
  - Low: $50 \text{ kHz} < f < 200 \text{ kHz}$

- Steady co-current rotation has more power in fluctuations with $+v_{ph,R}$ (lab frame, LFS to HFS) when “wings” are also present

\[
\frac{(P_{+k_{R}} - P_{-k_{R}})}{\bar{P}}
\]
Conclusions

• Intrinsic Rotation in L-mode displays robust hysteresis at multiple currents in response to density ramps

• Nearly identical electron density and temperature profiles from the same shot can lead to different rotation profiles

• Addition of ICRF heating to 0.8 MA plasmas can cause “wings” ($k_R \rho_s = 0.1 \sim 1.0$), previously observed in 1.1 MA plasmas, to appear in PCI spectra

• Changes in ion-scale turbulence measured by PCI are observed if “wings” are present, but these are not a necessary condition for a rotation reversal