Investigation of Intrinsic Rotation Dependencies in Alcator C-Mod

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Introduction

- **Intrinsic rotation reversals** have been observed in multiple tokamaks and ohmic L-mode reversals remain difficult to explain [Rice 1997, 2004, 2007, 2008].

- Correlations between rotation reversals and turbulence parameters (n and T gradients, collisionality, dominant linear instability) have been found in some experiments but not others [Angioni 2011, McDermott 2014, Rice 2011, Rice 2012, Sung 2013, McDermott 2011].

- Conversely, it has also been suggested that neoclassical effects, rather than linear turbulence drive, causes rotation reversals [Hillesheim 2015].

- Using a large set of 80+ C-Mod intrinsic rotation profiles, little correlation has been found between reversals and gradients, dominant turbulent regime, and neoclassical corrections.
Intrinsic rotation can benefit tokamak plasma stability and confinement

- **Plasma rotation** contributes in **stabilizing various MHD instabilities** and flow shear **suppresses turbulence** [Hahm 1994, Burrell 1997, Strait 1994].

- **Intrinsic rotation**, toroidal plasma rotation without external momentum input, was observed in multiple devices i.e. C-Mod, JET, AUG, TCV, DIII-D, and KSTAR. [Rice 2007, Shi 2013].

- Motivation for studying intrinsic rotation is two-fold:
  - Helps in **preventing locked modes** in low-torque plasmas and **turbulence suppression** in ITER
  - Studying intrinsic rotation can provide better understanding of momentum transport.

- One interesting intrinsic rotation phenomenon is the **rotation reversal**.
Rotation reversals and what drives it is an ongoing debate

- Rotation reversals, spontaneous change in toroidal rotation direction without significant effects global plasma parameters, also observed in various devices [Rice 2005, Bortolon 2006, McDermott 2011].
  - However, different theories have been proposed concerning the primary drivers of reversals.

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Rice, J.E. et al 2011 Nucl. Fusion 51 083005
Studies seek to identify key dependencies to understand the driving mechanism behind rotation reversals and intrinsic rotation

- Many studies have focused on the **residual stress term**, driven by turbulent transport, as the analytical driver of reversals [Diamond 2013].

- The residual stress term is a **collection of momentum flux mechanisms** that are not directly convective or diffusive.
  - If one or more of these terms **dominate the rest and change sign**, it could lead to a rotation reversal.

- Previous studies have focused on looking for experimental correlations to identify a primary term:
  1) The **electron density gradient** [Angioni 2011, McDermott 2014].
  2) The **dominant turbulence regime (TEM/ITG transition)** [Rice 2011, McDermott 2011].

- Other studies suggest **3) neoclassical corrections** modify the turbulent transport [Barnes 2013, Hillesheim 2015].
Large number of Alcator C-Mod shots are used to test the various hypotheses

- 80+ ohmic L-mode intrinsic rotation/reversal shots from C-Mod are used.
  - Rotation reversals are created using electron density and current ramps.

- Toroidal rotation velocity profiles are measured using C-Mod’s HiResolution X-ray spectrometer with Spatial Resolution (HIRESR), a passive, non-momentum injecting diagnostic system [Reinke 2012].
  - Velocity is calibrated using locked modes, assuming \( V_\phi = 0 \).

- C-Mod data is analyzed and compared to results from previous work (R/Lne, TEM/ITG, neoclassical intrinsic rotation model).

- The normalized rotation gradient \( u' \equiv -(R^2/v_{thi})(d\Omega/dr) \) is used as the key rotation variable, as done in previous work.
1) **Local Profile Gradient Hypothesis** identifies the local electron density gradient as the primary parameter for determining strength and sign of the residual stress term [Angioni 2011, McDermott 2014].

- Other terms, R/L_{Te} and R/L_{Ti}, showed weak correlations.

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McDermott, R. M. et al 2014 *Nucl. Fusion* 54 043009
However, strong gradient correlations are not found in C-Mod

- Within $R/L_{ne} < 4$, a strong correlation between $u'$ and $R/L_{ne}$ is not found in C-Mod analysis at $\rho = 0.35$, 0.5, and 0.7.

- No noticeable correlation found between $u'$ and temperature gradients.

“Double reversal” in rotation observed in ASDEX Upgrade with increasing collisionality [Angioni 2011, McDermott 2014].

- $v_{\text{eff}} = v_{ei} / (c_s/R) = 0.00279 \times (15.94 - 0.5 \log \frac{n_e}{T_e^2}) \times \frac{n_e}{T_e^2} R \sqrt{m_A Z_{\text{eff}}}$

- **Weak correlation** found in C-Mod but no double reversal.

2) Dominant Turbulence Regime Hypothesis states that the dominant linear instability is the primary driver of reversals [McDermott 2011, Rice 2011].

- Observed reversals simultaneously with change in global confinement regime.
- Global confinement regime believed to occur with change in dominant turbulence regime (TEM to ITG).
- Mode change causes change in mode propagation direction and sign of residual stress term.

Rice, J.E. et al 2012 Phys. Plasmas 19 056106
However, linear stability analysis using GYRO show that the most unstable mode does not change with rotation in C-Mod

- C-Mod data show both co-current and counter-current shots remain **ITG-dominated** at $\rho = 0.35$, $0.5$, and $0.7$

- Consistent with Choongki Sung's results for C-Mod [Sung 2013].

- For AUG ($\rho = 0.5$ and $k_\theta \rho_s = 0.3$), both types of shots remain **TEM-dominated** [Angioni 2011, McDermott 2014].

- Linear stability results suggest that the **TEM/ITG dominance is not the primary parameter**.
Some suggest that neoclassical effects rather than linear turbulence drive causes reversals by modifying turbulent transport

- **3) Neoclassical Correction Hypothesis** suggests that neoclassical corrections, dependent on collisionality, are the primary drivers [Barnes 2013].

- One specific study created a **1-D intrinsic rotation model** to test this hypothesis with results from MAST [Hillesheim 2015].
  - As normalized collisionality $\nu_\star$ crosses threshold $\nu_c \sim 1$, rotation reverses:

$$\nu_\star = \frac{qR_\psi \nu_{ii}}{(v_{ti}\epsilon^{3/2})} = 10^{-3} Z_i^4 n_i \frac{Rq}{T_i^2 \epsilon^{1.5}}$$

$$u' = -\frac{q}{2} \left( \frac{R}{L_{Ti}} \right)^2 \frac{\rho_i}{r} \frac{\chi_i}{\chi \phi} \tilde{\Pi}(\nu_\star)$$

$$\tilde{\Pi}(\nu_\star) = \frac{\tilde{\Pi}_0 (\nu_\star/\nu_c - 1)}{1 + (\nu_\star/\nu_c)(\tilde{\Pi}_0/\tilde{\Pi}_\infty)}$$
However, initial results from C-Mod and AUG do not agree with the 1-D intrinsic rotation model predictions of rotation gradients.

- **Rotation gradient** calculated from C-Mod and AUG experimental data compared with those calculated from the 1-D model.

- **C-Mod and AUG results do not agree** with those predicted by the 1-D model at \( \rho = 0.3, 0.5, \) and 0.7 – still ongoing work.

Courtesy of C. Angioni and R.M. McDermott at ASDEX Upgrade
A large set of 80+ ohmic L-mode intrinsic rotation profiles in C-Mod were used to test three hypotheses regarding the primary dependencies of rotation reversals.

A strong correlation between $u'$ and $R/L_{ne}$ was not found in C-Mod. But a weak correlation found between $u'$ and $\nu_{eff}$ – consistent with AUG results.

No correlation between reversals and TEM/ITG transition was found in C-Mod – inconsistent with earlier results. Both co-current and counter-current shots were ITG-dominated.

C-Mod and AUG experimental data inconsistent with the 1-D neoclassical intrinsic rotation model.
Summary

• **Intrinsic rotation reversals** have been observed in multiple tokamaks and ohmic L-mode reversals remain difficult to explain [Rice 1997, 2004, 2007, 2008].

- Correlations between rotation reversals and turbulence parameters (gradients, collisionality, dominant linear instability) have been found in some experiments but not others [Angioni 2011, McDermott 2014, Rice 2011, Rice 2012, Sung 2013].

- Conversely, it has also been suggested that **neoclassical effects**, rather than linear turbulence drive, causes rotation reversals [Hillesheim 2015].

- Using a large set of 80+ C-Mod intrinsic rotation profiles, **little correlation has been found between reversals and gradients, dominant turbulent regime, and neoclassical corrections.**
Future Work

- Additional testing of the three hypotheses
  - Analysis with larger data sets
  - Regression analysis of C-Mod data
  - Use of shots with larger temperature and density gradients
  - Use of more accurate profile fitting routines
  - Determining electron/ion diamagnetic direction experimentally
  - Calculation of input constants for Barnes/Hillesheim 1-D model
  - Further testing of the full intrinsic rotation theory model
    - **Currently being done using GKW with NEO in AUG**
  - Calculation and use of device scalings to normalize parameters

- Identifying other potential dependencies
  - Use of non-linear gyrokinetic simulations
  - Regression analysis on C-Mod results
  - Considering effects of up/down asymmetry and non-local transport
This study aims to achieve four goals involving intrinsic rotation

- Provide further evidence for/against the hypotheses
  - Analyze 60+ C-Mod rotation profiles etc. to test conflicting viewpoints i.e. TEM/ITG, density gradient, etc.

- Perform study with error and sensitivity analysis
  - Calculate effect of measurement and analysis errors on results – something previous work lacks

- Form database for future work
  - Create collection of C-Mod rotation data for further analysis

- Identify new possible dependencies of rotation reversals
  - Use C-Mod data to find other possible drivers
The methodology focuses on a streamlined analysis workflow

**Database**
- Identify high-quality Ohmic L and H-mode intrinsic rotation and rotation reversal shots and steady-state time ranges for analysis
- Categorize and list shot numbers into shot database

**Process Stream**
- Time-average data for steady-state period delimited by the time range
- **Fit density, temperature, and toroidal velocity profiles** using fitting tools and estimate fitting errors Save all parameters for each shot into C-Mod database
- Perform **linear stability analysis using GYRO**

**Quality Check**

**Data Analysis**
- **Compares results** to key parameters identified in the three hypotheses
- Perform **regression analysis** to identify primary drivers of rotation reversals
The analysis workflow utilizes many C-Mod routines and tools

C-Mod Shot Database

EFIT

Analysis Workflow

*All IDL routines and modifications made will be listed in the Appendix
Where does Residual Stress fit into all of this?

**Figure 1.** Diagram of essential elements of the toroidal momentum transport.
Observations of Double Reversal at AUG

McDermott, R. M. *et al* 2014 *Nucl. Fusion* 54 043009
C-Mod Linear Stability Results (Density Gradient vs. Real Frequency)

\[ \omega_r @ \rho_\phi = 0.35 \]

McDermott, R. M. et al 2014 *Nucl. Fusion* 54 043009
C-Mod Linear Stability Results (Density Gradient vs. Real Frequency)

AUG

C-Mod

$k_\theta \rho_s = 0.3$

C-Mod Linear Stability Results (u’ vs. Real Frequency)

\[ k_\theta \rho_s = 0.3 \]

\[ \omega_r (c_s/a) @ \rho_\Phi = 0.35 \]

\[ \omega_r (c_s/a) @ \rho_\Phi = 0.5 \]
C-Mod Linear Stability Results (u’ vs. Real Frequency)

C-Mod

\[
u' @ \rho_\Phi = 0.35
\]

\[
\omega_r (c_s/a) @ \rho_\Phi = 0.35
\]

ITG
TEM

\[
u' @ \rho_\Phi = 0.5
\]

\[
\omega_r (c_s/a) @ \rho_\Phi = 0.5
\]

k_0 \rho_s = 0.5
C-Mod Linear Stability Results (u' vs. Real Frequency)

\[ \omega_r \left( \frac{c_s}{a} \right) @ \rho_\Phi = 0.35 \]

\[ \omega_r \left( \frac{c_s}{a} \right) @ \rho_\Phi = 0.5 \]

\[ k_\theta \rho_s = 0.7 \]
Additional Hillesheim comparisons

J. C. Hillesheim et al 2015 *Nucl. Fusion* **55** 032003
Additional Hillesheim comparisons – ASDEX Upgrade

$\rho_\phi = 0.35$

$\rho_\phi = 0.7$

Courtesy of C. Angioni and R.M. McDermott at ASDEX Upgrade