Observation and Quasilinear Modeling of Rotation Reversal Hysteresis in Alcator C-Mod Plasmas

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Introduction: The Mystery of the LOC/SOC Transition and the Intrinsic Rotation Reversal

- The **LOC/SOC transition** is a universally observed break in slope of confinement time on tokamaks
  - Thought to be caused by a transition in underlying turbulence, possibly involving TEM and ITG, e.g. (Camenen PPCF 2017)
- **Intrinsic Rotation Reversal** has been found to correlate with the LOC/SOC transition on many machines (AUG, JET, etc...)
  - Intrinsic rotation must be from an internal torque source, which results from turbulent Reynolds stress (Diamond NF 2013)
Motivation: Hysteresis Experiments Provide Controlled Experiment of a Turbulent Transition

- How do we characterize the link between the LOC/SOC transition, rotation reversals, and changes in turbulence?
- Reversals exhibit **hysteresis**, so the same plasma parameters manifest different rotation states.
- **This Work**: Compare turbulence at the same input plasma parameters but differing rotation within a single shot.
Different Rotation but Nearly Indistinguishable Density and Temperature Profiles

- Mean profiles are shown here for 5.4 T, 0.8 MA LOC (t=0.96 s) and SOC (t=0.6 s)
- Electron profiles from same shot; error rigorously estimated with GPR [Chilenski NF 2017]
- Ion profiles from different but matched shots.
Hysteresis is a Reproducible Phenomenon Observed Across Multiple Shots

Even with LBO!
Linear Gyrokinetic Simulations Confirm Mode Stability Unchanged across LOC/SOC Transition

- Linear CGYRO runs at four different times were performed in the rotation reversal region for 0.8 MA
  - Matched profiles from LOC and SOC
  - ±10% scan from SOC, shown in gray
- Dominant linearly unstable mode does not change in the rotation reversal region!
  - Consistent with previous work looking at Alcator C-Mod plasmas [Sung NF 2013, White PoP 2013]
- $k_y \rho_s \gtrsim 1.0$ modes marginally stable

![Graph showing $\omega_R [c_s/a]$ and $\gamma [c_s/a]$ vs $k_y \rho_s$]
Fluctuation Measurements Change Across Transition Despite Similar Linear Stability

- Reflectometry spectra $\sim \langle |\frac{\tilde{n}_e}{n_0}|^2 \rangle$
  - changes from LOC to SOC
  - Data from 88 GHz reflectometer; sensitive to $k_\perp$ up to 10 cm$^{-1}$ [Lin PPCF 2001]

- Interpretation is unclear – effect of Doppler shift vs. change in turbulence?

![](image.png)
Separation of Linear and Nonlinear Physics: Quasilinear Transport Approximation (QLTA)

- In mQLTA, flux is given by the sum over modes of a quasilinear weight (*linear mode structure*) with mode intensity (*nonlinear saturation*)
  \[ Q_{i,\text{anom}} = \sum_k W_{Q_i,k} \left\langle \phi_k^2 \right\rangle \]

- Weights used in mQLTA match weights from fully nonlinear simulation [Waltz PoP 2009]; cross-phases match experiment [White PoP 2010, Freethy APS-DPP 2017]
Mixed Mode Picture – Plasma Behavior not Determined by Single Mode

- Separate Modes into families:
  I. Low-\(k\), \(\omega\) ion-directed; separated into (a) and (b) based on particle flux
  II. \(k_y \rho_s \gtrsim 1\), hybrid mode; strong inward particle pinch
  III. High-\(k\), electron-direction; exhausts mostly \(Q_e\)

- E.g. Ion Flux given by:
  \[ \dot{Q}_i = W_{Qi,\text{Ia}} \cdot \left\langle \phi^2 \right\rangle_{\text{Ia}} \]
  \[ + W_{Qi,\text{Ib}} \cdot \left\langle \phi^2 \right\rangle_{\text{Ib}} \]
  \[ + W_{Qi,\text{II}} \cdot \left\langle \phi^2 \right\rangle_{\text{II}} \]
  \[ + W_{Qi,\text{III}} \cdot \left\langle \phi^2 \right\rangle_{\text{III}} = 0 \]
Experimental Fluxes Provide a Constraint on Nonlinear Mode Saturation Levels

\[ \text{Flux} = \sum_k \text{weight} \cdot \text{intensity} \]

- Anomalous fluxes calculated using TRANSP and NEO
- Qualitatively different \textit{mixed} saturation levels lead to the observed transport!
  - Narrower-k, higher-k ITGs active – suggestive of SOC
  - Wider-k, hybrid modes active – suggestive of LOC
Momentum Transport Not Captured by Local Gyrokinetic Model

• CGYRO predicts down-gradient momentum fluxes
  • Global effects (e.g. density profile curvature) expected to be important, see [Hornsby NF 2018; Grierson PRL 2017]

QL Weights [GB units]

\[
t=0.6 \quad (\text{SOC})
\]

\[
t=0.96 \quad (\text{LOC})
\]
What are the underlying Physics? Possibilities for Intrinsic Torque Generation

- Diagnose importance of global effects by examining mode structure:
  - $k_r = n(\theta_* - \theta_0)q' \Rightarrow $ Small $\Delta \theta$ leads to large $\Delta r$ (radial envelope)

![Graph showing $f_{\text{rot}}$ vs $r/a$ and $k_y\rho_s$ for different families.](image)

$k_y\rho_s = 0.8$
- Family Ib
- More active in "SOC"
- Steeper $u'$

$k_y\rho_s = 0.1$
- Family Ia
- More active in "LOC"
- Shallow $u'$
Mode Ia, Low-k ITG; SOC vs LOC vs No Shear

- All $k_y\rho_s = 0.2$ – shear really changes response
Mode Ib, High-k ITG; SOC vs LOC vs No Shear

- All \( k_y \rho_s = 0.8 \) – different parallel response
Mode II, High-k ITG; SOC vs LOC vs No Shear

- All $k_y \rho_s = 1.4$ – different parallel response
Flow Shear Affects Growth Rates of \( k_y \rho_s \sim 1 \) Marginal Modes

- Performed scans reducing mean ExB and Mach flow shear (color scale on plot to the right)
- Marginal modes with large enough \( k_y \rho_s \) strongly affected by flow shear, while dominant modes relatively unchanged
- Provides possible mechanism for bifurcation (increasing flow shear -> changed mode population -> increasing flow shear)
Momentum Transport Predicted is Primarily Diffusive
1.1 MA Ohmic – **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...

(Ti profiles WIP due to instrumental effects, but emissivity-averaged Ti changes ~50eV)
Hysteresis used to probe turbulence with same local plasma parameters

- Phase Contrast Imaging (PCI) measures line-integrated $\tilde{n}_e$, $k_R < 30$ cm$^{-1}$
  - $+k_R$ goes from LFS to HFS, aligned with electron diamagnetic drift direction at top
  - $\vec{k} \parallel \vec{B} \times \vec{k}_0$ PCI selection rule
  - $\pm k_R$ asymmetry $<>$ up/down asymmetry
- High-$k$ ($k_R \rho_s = 1\sim10$) “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, different PCI spectra
0.8 MA Ohmic – different toroidal rotation, same local profiles, same PCI spectra

Counter-current -15 km/s

Co-current +5 km/s
0.8 MA +ICRF – different toroidal rotation, same local profiles, different PCI spectra!
Reflectometry Provides Local Fluctuation Measurements

- These data are collected from the 87.5 GHz and 88.5 GHz channels of the C-Mod O-Mode baseband reflectometer.

- 2D scattering effects (e.g. scattering, diffraction, sidebands) complicate the analysis of the returned signal.

- Can be sensitive to $k_\perp$ up to 10 cm$^{-1}$ (see Lin PPCF 2001).
0.8 MA Reflectometer power spectra show differences
0.8 MA + ICRF reflectometer power spectra also show differences
Conclusions and Future Work

• Rotation reversal hysteresis demonstrates that nearly identical n, T profiles can lead to different momentum transport and turbulent fluctuations
  • A change in the most linearly unstable mode alone is unable to explain the rotation reversal and LOC/SOC transition in Alcator C-Mod

• Multi-Mode Quasilinear Transport Approximation suggests that a change in mix of mode saturation levels (e.g. a “population collapse”) could be consistent with observed bistability of turbulence

• Future work: Comparisons needed against nonlinear and global simulations to answer questions raised by mQLTA model:
  • Is turbulence bistability actually observed in nonlinear simulation?
  • What is the global structure of the modes, and do they provide a viable mechanism for the required intrinsic torque generation?
References


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Extra Slides
Nonlinear Heat Flux Spectra Possibly Consistent with mQLTA Prediction

Heat flux spectra at r/a=0.8

FIG. 14. Time averaged heat flux spectra on $k_y\rho_s$ in the “ion heat flux matched” runs (a) main ion heat flux spectrum in the LOC discharge (shot 1120626023) and (b) electron heat flux spectrum in the LOC discharge (c) main ion heat flux spectrum in the SOC discharge (shot 1120626028) and (d) electron heat flux spectrum in the SOC discharge.