Observations of Rotation Reversal and Fluctuation Hysteresis in Alcator C-Mod Plasmas

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Motivation: Hysteresis Experiments Provide Careful Probe of LOC/SOC Transition

- Toroidal rotation reversals are correlated with LOC/SOC transition from density ramps [Rice NF 2013]
  - Question: What changes in turbulence are seen across the rotation reversal and LOC/SOC transition?
- Reversals exhibit hysteresis, so the same plasma parameters manifest different rotation states
  - Approach: Compare turbulence physics at the same plasma parameters but differing rotation within a single shot
Different Rotation but Nearly Indistinguishable Density and Temperature Profiles

- 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.
Linear Gyrokinetic Simulations Confirm Mode Stability Unchanged across LOC/SOC Transition

- Linear CGYRO runs at four different times were run in the rotation reversal region
  - 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
Fluctuation Measurements Change Across Transition Despite Similar Linear Stability

- Reflectometry spectra \( \sim \left( \frac{\bar{n}_e}{n_0} \right)^2 \) changes inconsistent with pure Doppler shift from LOC to SOC
  - Data from 88 GHz reflectometer; sensitive to \( k_\perp \) up to 10 cm\(^{-1}\) [Lin PPCF 2001]
- Rotation and fluctuation spectra robust to perturbation – bistability cannot be explained through linear stability alone in Alcator C-Mod
Separation of Linear and Nonlinear Physics: Quasilinear Transport Approximation (QLTA)

- In mQLTA, flux is given by the sum over modes of a quasilinear weight \((\text{linear mode structure})\) with mode intensity \((\text{nonlinear saturation})\)

\[
Q_{i,\text{anom}} = \sum_{k} W_{Q_i,k} \langle \bar{\phi}_k^2 \rangle
\]

- Weights used in mQLTA match weights from fully nonlinear simulation [Waltz PoP 2009]; cross-phases match experiment [White PoP 2010]
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:
  
  \[
  Q_i = W_{Qi, Ia} \cdot \langle \phi^2 \rangle_{Ia} + W_{Qi, Ib} \cdot \langle \phi^2 \rangle_{Ib} + W_{Qi, II} \cdot \langle \phi^2 \rangle_{II} + W_{Qi, III} \cdot \langle \phi^2 \rangle_{III} = 0
  \]
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 mixed saturation levels lead to the observed transport!
    - Narrower-k: suggestive of SOC reflectometer spectra
    - Wider-k: suggestive of LOC reflectometer spectra
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 turbulent fluctuations and momentum transport

• Future work: extend predictions of mQLTA to momentum fluxes, and compare against nonlinear simulation
References

Extra Slides
What about momentum?

• Don’t expect many intrinsic stress sources to be captured by local linear runs

• [Grierson PRL 2017] Turbulent momentum diffusion balances with intrinsic stress generation
Hysteresis Observed Robustly in Multiple Plasma Conditions

- Hysteresis is observed at multiple currents, and survives perturbation from LBO.

- Low-power ICRF heating ramps also lead to hysteresis, with similar
Radial Dependence of Parameters – Global versus Local Transition?

- Electron-direction quasilinear response is different at different radii.
- Turbulence Spreading may be responsible for excitation of marginally stable modes, leading to “global” transition rather than “local” transition
  - Plays well with “population collapse” theory
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 $k_r \rho_s$ 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 LOC discharge.
0.8 MA Reflectometer power spectra show differences
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)