Theoretical investigation of the quasi-coherent mode

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Introduction

• The quasi-coherent (QC) mode is thought to be an essential ingredient for obtaining EDA operation on Alcator C-Mod.
  – $k_0 \sim 1 \text{ cm}^{-1}$, $f \sim 100 \text{ kHz}$
  – may regulate pedestal gradient and particle transport.
• Quasi-coherency of the mode suggests weak nonlinear processes, and the possibility of an underlying linear mode.
• Previous talk (Russell et al.) employed SOLT code to model edge and SOL turbulence in EDA operation.
  – nonlinear electrostatic fluid model
  – simplified geometry (2D in plane perpendicular to B)
  – SOLT-QC mode emerges, but not associated with $\gamma_{\text{max}}$
• Present work takes a complementary approach using a new tool, the 2DX code.
  – linear fluid models
  – realistic divertor X-pt geometry

Conduct a systematic search for candidate linear modes.
The 2DX edge linear eigenvalue code:


- Solves linearized eigenvalue problem in R-Z plane for each toroidal mode number n.
- Inputs experimental magnetic divertor geometry for edge and SOL
  - here, an Alcator C-Mod EDA shot 1080321020.01200 [analyzed for the FY11 FES Joint Research Target in pedestal physics]
  - also inputs experimental profiles of $n_e$, $T_e$, $T_i$ and $E_r$
- Sparse matrix package SLEPc enables high resolution.
- 2DX has a specialized equation parser to input the physics model
  - employed here to study a variety of fluid-based models
- 2DX has been benchmarked against analytical theory, BOUT++, ELITE, …
A variety of physics models were studied

- 3-field fluid models for vorticity (potential), density, parallel current
  - RMHD = reduced resistive MHD
  - RB = resistive ballooning with e-inertia
  - RBi = RB including ion FLR
  - RBiEK = also including Er shear and Kelvin-Helmholtz drives
  - RDBiEK = also including drift wave physics
- Instability mechanisms modeled:
  - curvature driven resistive and ideal ballooning
  - gradient driven collisional and inertial drift waves
  - flow-driven KH modes
- Suppression mechanisms modeled:
  - ion diamagnetic currents (FLR)
  - $E_r$ shear
X-pt geometry supports two RB branches

- 2 fastest resistive ballooning branches are nearly degenerate
- \( n = 20 \) mode is in experimental range
  - C-Mod: \( n \sim 17 \) to 21
  - spatially confined by X-pts (outboard side)
- BUT no spectral peak near \( n = 20 \)
Ion diamagnetism plateaus growth rates for \( n > 15 \)

- BUT still no strong spectral peak near \( n = 20 \)
  - strength of peak is somewhat sensitive to \( n \) vs. \( T_i \) profile (including SOL)
- \( f_{n=20} \approx -15 \) kHz (ion direction) in plasma frame
- only fastest modes shown

- C-Mod data:
  - \( f \approx 55 \) to 70 kHz, e-direction (lab frame), possibly i-direction (plasma frame)
  - \( n \approx 17 \) to 21
n = 20 RBi mode characteristics:

- Separatrix spanning
  - interesting for pedestal gradient regulation and transport across LCFS
- Mainly electrostatic but has magnetic perturbation $\delta A_||$
  - experimental magnetic signature seen (compare $\delta A_||/\delta \Phi$ with 2DX)
Drift wave physics: complex spectrum with $\gamma \propto n$

- RDBiEK = more complete model including resistive ballooning, ion diamagnetism, drift waves, sheared $E_r$, and KH physics
- 2 fastest modes shown
- No spectral peak near $n = 20$
- $f_{n=20} \sim 200+$ kHz (electron direction) in lab frame
  - probably sensitive to profile uncertainties

No linear modes with strong peak growth rates in the relevant range of wave-numbers have emerged yet.
Toy model suggests QC-state could arise from nonlinear wave-wave coupling

\[
\frac{dA_k}{dt} = \gamma_k A_k + \sum_{k=k'+k''} C_{k,k',k''} A_{k'} A_{k''}
\]

- 1D model for vorticity advection nonlinearity \((A_k = \Phi_k) \Rightarrow C_{k,k',k''} = -k'k''\)
- Parabolic growth rate spectrum \(\Rightarrow 2\) free parameters
- Some parameter choices \(\Rightarrow\) QC state

Key ingredients:
- Resonant three-wave interactions
- Mode coupling to low \(k >\) peak linear growth at high \(k\)
- Phase-locking
Summary

• The main instability drives in the EDA edge plasma are curvature (dominant), drift (high n)
• The QC mode cannot be identified with a strong linear peak $\gamma$ in the models investigated so far.
• Caveat: Future work should include the parallel KH and peeling drives, as well as additional study of EM effects
  – EDA $v_{||}$ profile across the separatrix needed
  – preliminary: peeling doesn’t change the qualitative picture
• The resistive-ballooning model with ion diamagnetic drifts (RBi) captures some qualitative features of C-Mod observations.
• Present 2DX results and those of SOLT (Russell et al.) suggest a role for nonlinear effects such as the inverse cascade
  – e.g. DW modes cascade into RBi mode
Smoothed experimental profiles for Alcator C-Mod EDA shot 1080321020.01200

\[ n_e \, (\text{cm}^{-3}) \]

\[ T_e \, (\text{eV}) \]

\[ E_r \, (\text{V/cm}) \]

\[ n = 40 \Rightarrow k_{\perp \rho_{i, \text{sep}}} \sim 0.1 \]
Physics models

- 3-field model for vorticity (electrostatic potential), density, and parallel vector potential (parallel current)

\[
\gamma \left( \nabla_{\perp}^2 \delta \Phi + \frac{1}{n} \nabla_{\perp}^2 T_i \delta n \right) = -\delta v_E \cdot \nabla \omega - v_E \cdot \nabla \left( \nabla_{\perp}^2 \delta \Phi + \frac{1}{n} \nabla_{\perp}^2 T_i \delta n \right) + \frac{2B}{n} C_r (T_i + T_e) \delta n + \frac{B^2}{n} \partial_{||} \delta J + \frac{B^2}{n} \delta b \cdot \nabla ||J + \mu_{ii} \nabla_{\perp}^4 \delta \Phi
\]

\[
\gamma \delta n = -v_E \cdot \nabla \delta n - v_E \cdot \nabla n + \partial_{||} \delta J
\]

\[
\gamma \left( \frac{n}{\delta_{er}^2} - \nabla_{\perp}^2 \right) \delta A = -v_E \cdot \nabla \left( \frac{n}{\delta_{er}^2} - \nabla_{\perp}^2 \right) \delta A + v_e \nabla_{\perp}^2 \delta A - \mu_n \nabla || \delta \Phi + \mu_T e \nabla || \delta n + T_e \mu \delta b \cdot \nabla n + 1.71 n \mu \delta b \cdot \nabla T_e
\]

where

\[
\delta J = -\nabla_{\perp}^2 \delta A
\]

\[
\omega = \nabla_{\perp}^2 \Phi + \frac{1}{n} \nabla_{\perp}^2 p_i
\]

\[
\delta b \cdot \nabla Q = i \frac{k_b (\partial_r Q)}{\mu \delta_{er}^2 B} \delta A
\]

Lodestar
Effect of peeling drive

**RPMHD model**
- (reduced resistive MHD with peeling terms -- EM model)
- base case and with ad-hoc current multiplier = 2

**Conclusion**
- for the base $J_\parallel$ profile, there is little effect on growth rates
  - the peeling mode is below threshold
- for larger currents, the peeling mode emerges and is robustly unstable
2DX has been cross-benchmarked

Ideal ELM (Peeling-ballooning) stability