Linear Stability Analysis of an EDA H-mode Edge Plasma: A Quest for the Quasi-Coherent Mode

J.R. Myra,[1] D.A. Baver,[1] and M. Umansky[2]

[1] Lodestar Research Corporation, Boulder, Colorado 80301, USA
[2] Lawrence Livermore National Laboratory, Livermore, California 94550, USA

acknowledgement: B. LaBombard (MIT)

presented at the TTF Meeting, Apr. 6 - 9, 2011, San Diego
work supported by DOE grant DE-FG02-07ER84718

Introduction

- Enhanced D-Alpha (EDA) H-modes in Alcator C-Mod are of interest
  - good energy confinement
  - quasi-steady ELM-free operation
  - see: Greenwald, et al., Phys. Plasmas **6**, 1943 (1999).
    Terry, et al., Nucl. Fusion **45**, 1321 (2005).
- EDA thought to be enabled by the quasi-coherent mode (QCM)
  - QCM is an edge oscillation with $k_\theta \sim 1 - 2\ \mathrm{cm}^{-1}$ and $f \sim$ few100′s kHz
  - may regulate the pedestal gradient and particle transport
- key question: is the QCM related to a linear unstable mode
  - weak instability ~ weak nonlinearity ⇒ quasi-coherent oscillation (?)

this poster: use the edge eigenvalue code 2DX to conduct a systematic search for candidate linear modes

The 2DX code:

- solves linearized eigenvalue equations in the R-Z plane for each toroidal n
  - discretize using finite difference ⇒ sparse matrix
  - solve using an existing eigenvalue package SLEPc
    - Krylov-Schur algorithm
    - Cayley spectral shift often employed
  - typically have 10’s to 100’s of grid-points per dimension
  - run times are 10’s of seconds to a few hours on a single processor
- uses realistic X-point/divertor geometry (edge + SOL)
  - similar capabilities to BOUT and BOUT++
- has a specialized equation parser ⇒ easy to change physics model
  - present study uses a variety of fluid-based physics models
- has been benchmarked against analytical theory and BOUT

- more 2DX info: Baver et al., Lodestar Report #LRC-10-137
  www.lodestar.com/LRCreports
- this study: use C-Mod geometry with EDA experimental plasma profiles

Physics models explored here

- RMHD = reduced resistive MHD
- RB = add e-inertia
- (RB-ES = add e-inertia but electrostatic limit $\delta_e \rightarrow \infty$)
- RBi = add ω_{*i} = ion FLR
- RBiE = add E_r shear
- RBiEK = add KH = Kelvin-Helmholtz drive
- RDBiEKM = add EM DW

Instability mechanisms included:
- curvature-driven resistive and ideal ballooning
- gradient-driven collisional and inertial drift waves
- perpendicular flow-driven Kelvin-Helmholtz

Suppression mechanisms included:
- ion diamagnetic current (FLR)
- E_r shear

Instabilities not included:
- parallel KH [Rogister NF 2004]
- current-driven peeling [see poster P25]

Equation set (optional poster)

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

$$\gamma\left(\nabla_\perp^2\delta\Phi+\overbrace{\frac{1}{n}\nabla_\perp^2 T_i\delta n}^{\text{ion FLR}}\right)=\overbrace{-\delta\mathbf{v}_E\cdot\nabla\varpi}^{\text{KH}}\overbrace{-\mathbf{v}_E\cdot\nabla\left(\nabla_\perp^2\delta\Phi+\frac{1}{n}\nabla_\perp^2 T_i\delta n\right)}^{E_r\text{ shear}}+\frac{2B}{n}C_r(T_i+T_e)\delta n+\frac{B^2}{n}\partial_\parallel\delta J+\mu_{ii}\nabla_\perp^4\delta\Phi$$

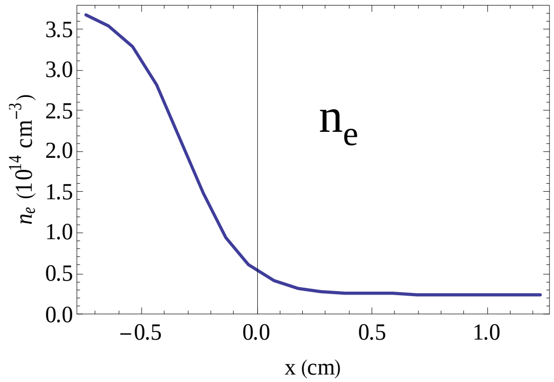
$$\gamma\delta n=\overbrace{-\mathbf{v}_E\cdot\nabla\delta n}^{E_r\text{ shear}}-\delta v_E\cdot\nabla n+\overbrace{\partial_\parallel\delta J}^{\text{DW-ES}}$$

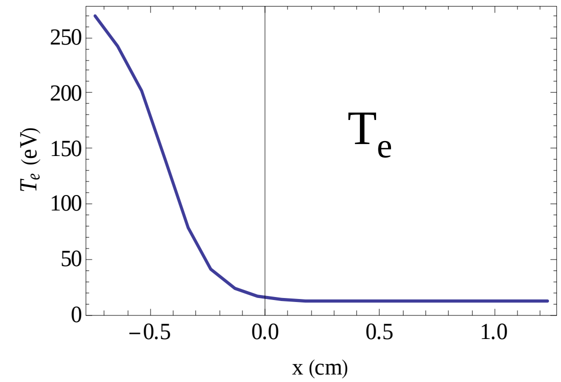
$$\gamma\left(\frac{n}{\delta_{er}^2}\overbrace{-\nabla_\perp^2}^{\text{e-inertia}}\right)\delta A=\overbrace{-\mathbf{v}_E\cdot\nabla\left(\frac{n}{\delta_{er}^2}\overbrace{-\nabla_\perp^2}^{\text{e-inertia}}\right)\delta A}^{E_r\text{ shear}}+\nu_e\nabla_\perp^2\delta A-\mu n\nabla_\parallel\delta\Phi+\overbrace{\mu T_e\nabla_\parallel\delta n}^{\text{DW-ES}}+\overbrace{T_e\mu\delta\mathbf{b}\cdot\nabla n+1.71n\mu\delta\mathbf{b}\cdot\nabla T_e}^{\text{DW-EM}}$$

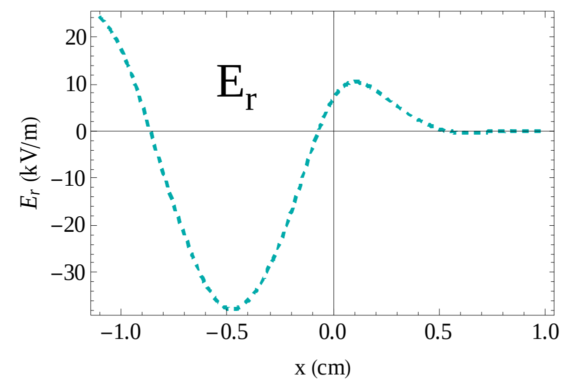
where

$$\delta J=-\nabla_\perp^2\delta A \qquad \varpi=\nabla_\perp^2\Phi+\overbrace{\frac{1}{n}\nabla_\perp^2 p_i}^{\text{ion FLR}} \qquad \delta\mathbf{b}\cdot\nabla Q=i\frac{k_b(\partial_r Q)}{\mu\delta_{er}^2 B}\delta A$$

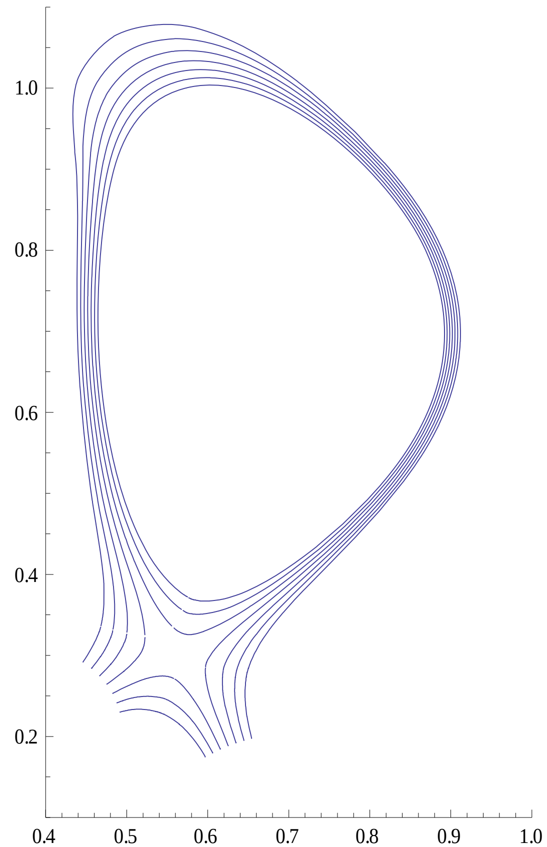
Input profiles and geometry



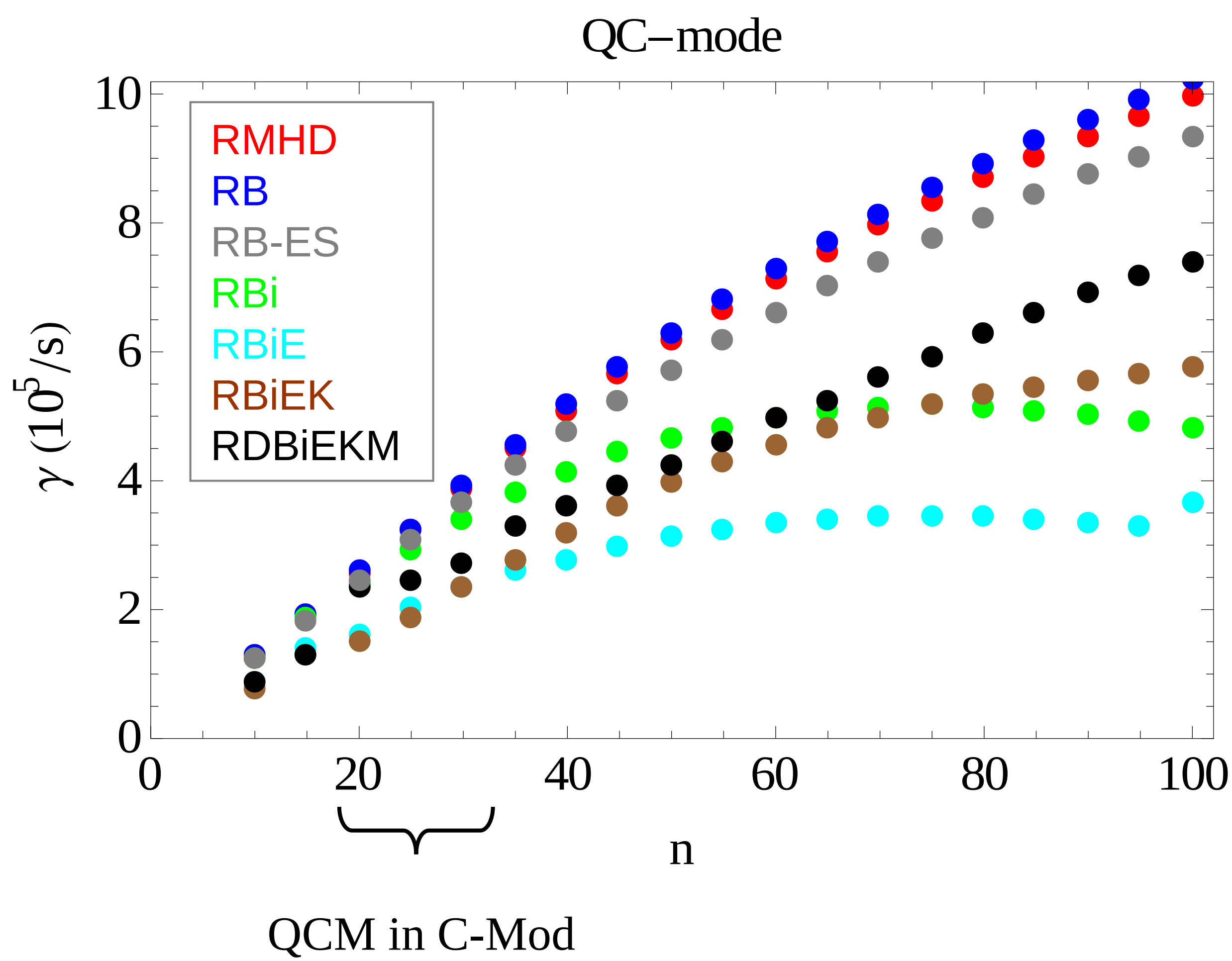




- typical C-Mod EDA discharge conditions
- E_r fit to McDermott et al. PoP 2009

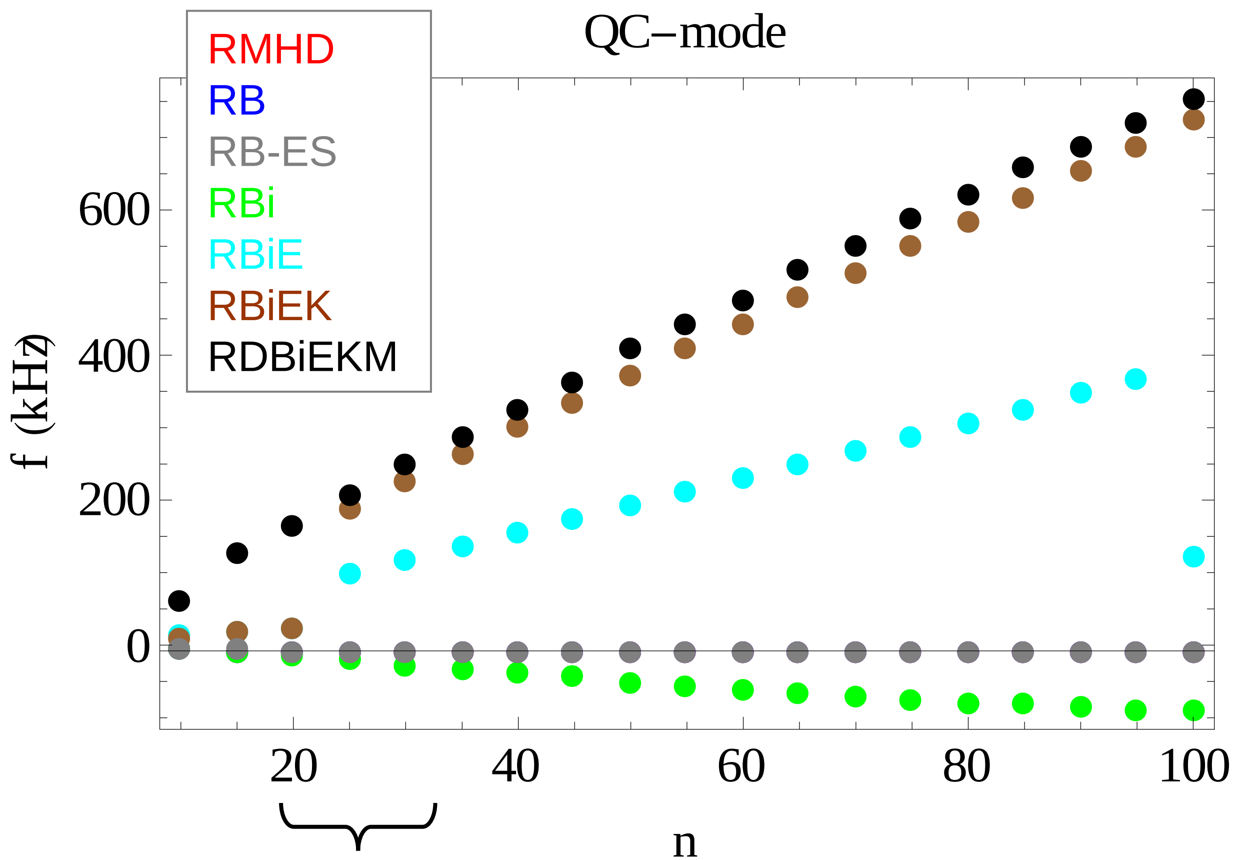


Growth rate spectra show some insensitivity to the model



- RB models show expected increase of γ with n
- ion FLR reduces growth at larger n
- spectral peak sensitive to T_i
  - see p. 10
- E_r shear further reduces γ
- KH not very significant
- DW restores nearly linear growth with n

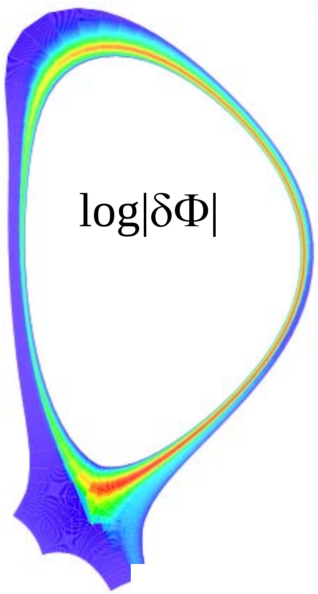
Frequency spectra are dominated by Doppler shifts

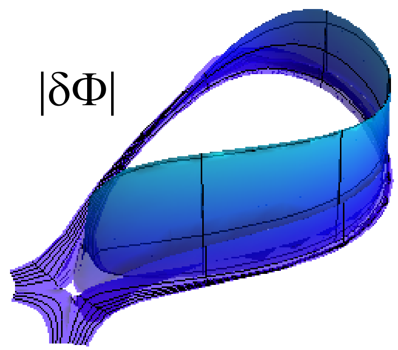


QCM in C-Mod

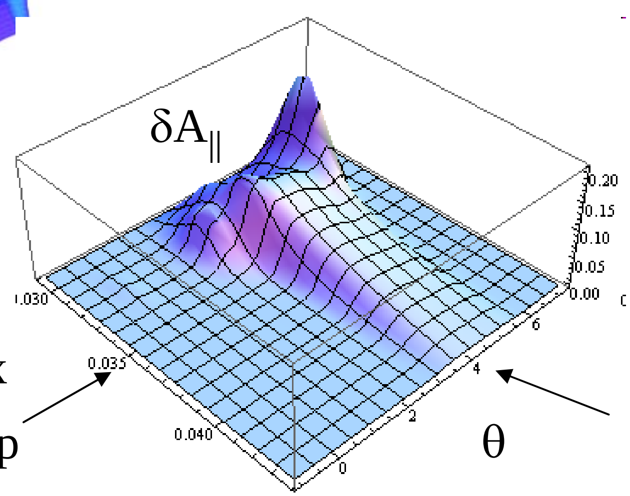
- RB models show small f as expected
- ion FLR ⇒f < 0 (ion direction)
- E_r ⇒ Doppler shift to electron direction
- DW f increases linearly with n
- freqs are comparable to C-Mod (almost trivial due to Doppler)

Typical eigenmodes are localized to outboard edge and give rise to δB





- mode structure qualitatively as observed in C-Mod

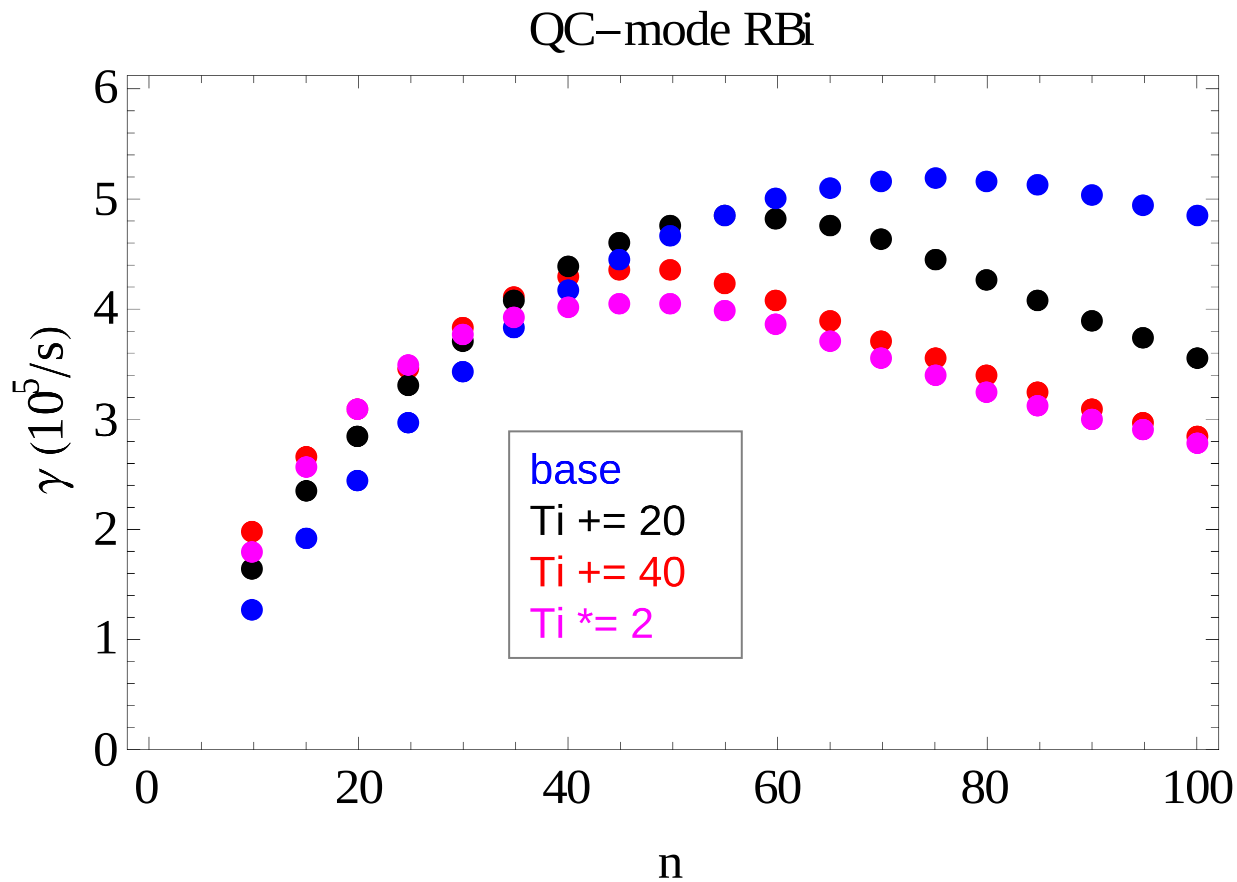


- modes (in both EM & ES models) have $\delta J_{||}$ and hence generate fluctuating δB like C-Mod observations

RBi model (qcrb13) n = 20

Best linear candidate is RBi mode

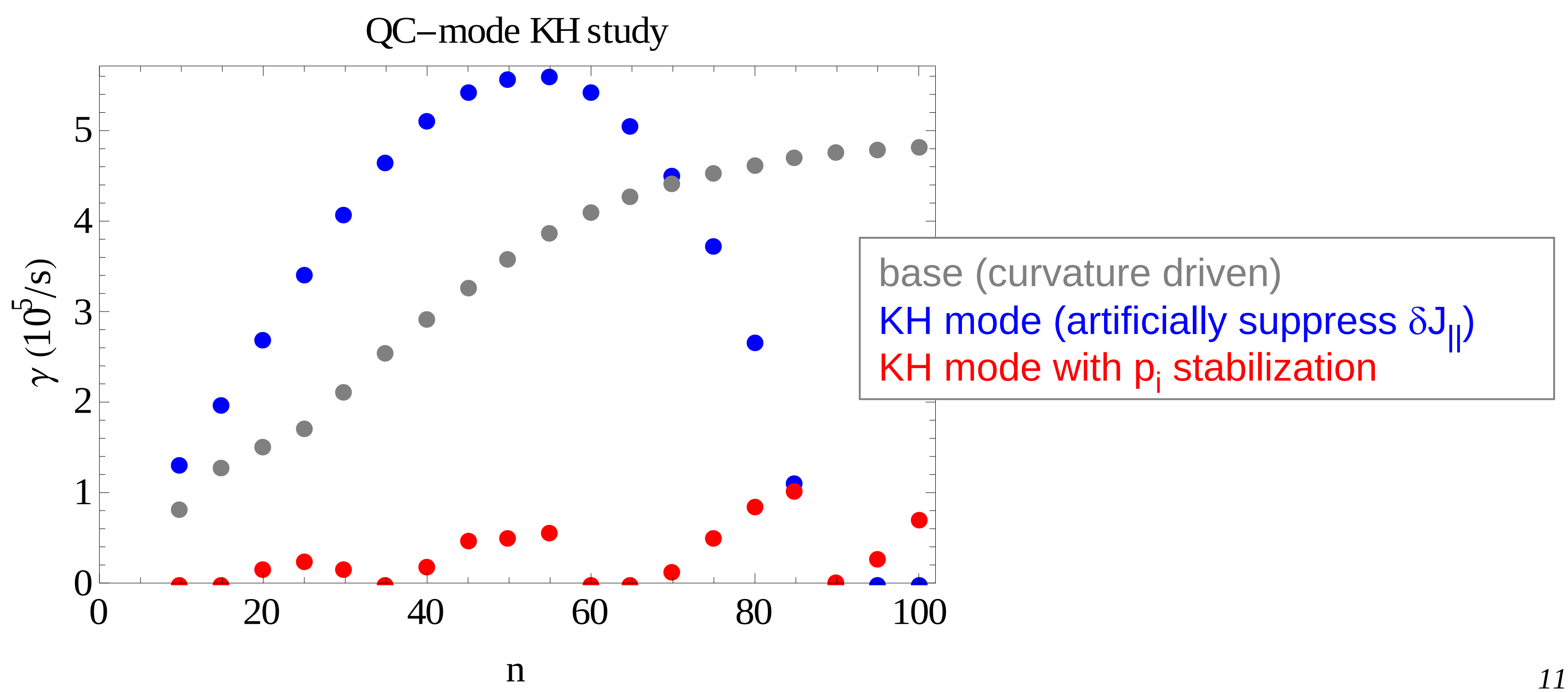
- Study T_i sensitivity for the RBi model
  - Resistive ballooning with ion diamagnetic drift



- increasing T_i increases FLR stabilization of the high-n modes
  $\Rightarrow \gamma$ peak shifts to lower n
- peak is roughly in the range of C-Mod observations;
  but, DW terms destroy the peak

KH drive is mitigated by Alfvén physics and ion diamagnetism

- similar to [Rogers and Dorland, PoP 2005], we find that since $\omega_a = v_a/qR \sim \omega_E$ shearing rate, the KH mode is stabilized
  - but here ω_a arises from geometry, not specifically magnetic shear
- artificially suppressing the $\delta J_{||}$ Alfvén physics gives a robust KH mode which is stabilized by p_i (ion diamagnetism), consistent with RD-2005.



Summary

- the unstable spectrum is not very sensitive to the physics model
- instability drives are curvature (dominant), drift (high n), KH (unimportant)
- there are no unambiguous candidates for the QCM in the models investigated, but
- resistive-ballooning model with ion diamagnetic drifts gives peak growth rates at a wavenumber close to observations
  - perhaps higher-n drift waves saturate at a low level
- present results tend to suggest a role for nonlinear effects such as the inverse cascade
  - e.g. DW modes cascade into RBi mode
  - see nonlinear reduced model by D.A. Russell et al, Sat. am, Edge-VI oral