Non-curvature Driven Modes in the H-mode Edge Pedestal

B. Rogers

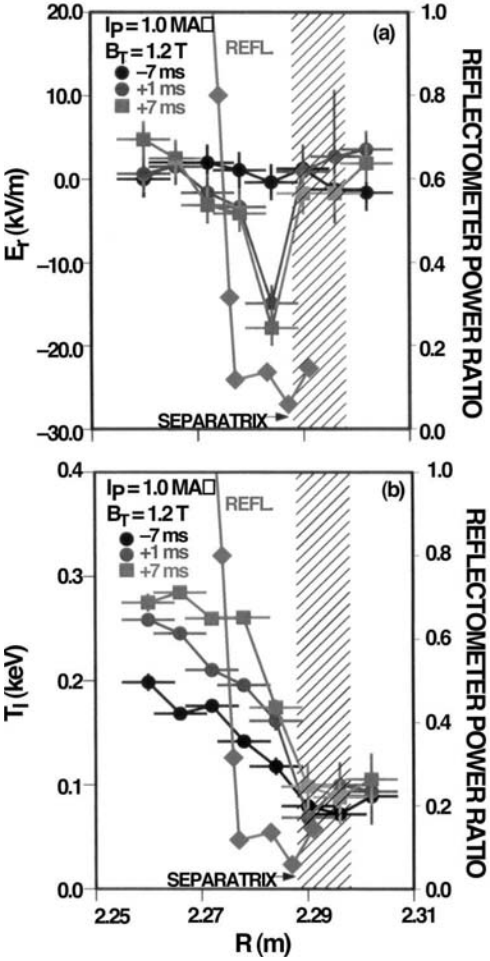
Dartmouth College, Hanover, NH

W. Dorland

University of Maryland, College Park, MD

- **What controls the height and width of the H-mode edge pedestal?**
- **What linear instabilities are potentially important in the pedestal?**
- **Is the contribution of the $E \times B$ shear always stabilizing?**

H-mode Edge E_r profile in DIIID (K Burrell, PoP 1999)



- E_r **"well" near steepest plasma gradients with** $V_E \sim V_{*e} \sim -V_{*i}$
- **Typical pedestal widths** $\Delta \sim (10-20)\rho_i$

E_r Profile can be Destabilizing

- **The stabilizing effect of $E \times B$ shear is well known, however:**

  Even if magnetic curvature is neglected, there are at least three linear instabilities at pedestal-relevant parameters that are potentially *destabilized* by typical profiles of $E \times B$ shear and plasma gradients.

- **These modes all *require* finite curvature in the V_E and/or plasma gradient profiles to be unstable**

- **Not present in simulations with spatially constant plasma gradients and/or spatially constant $E \times B$ shear (*ie* local simulations)**

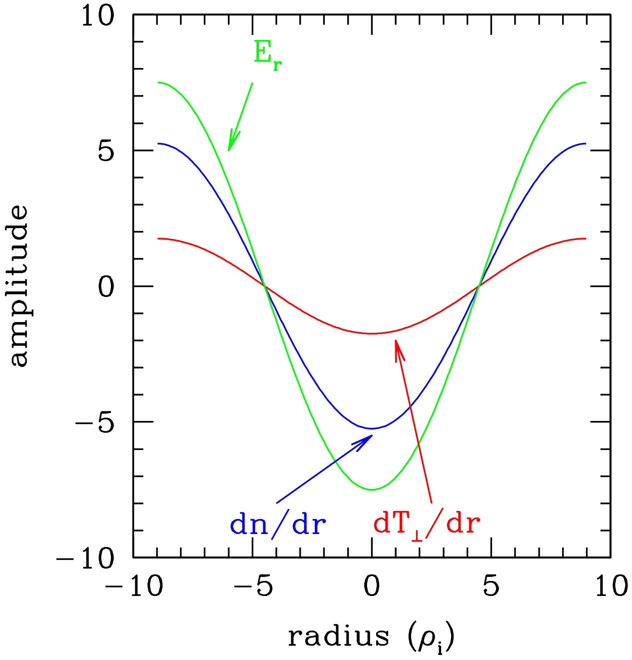
Our Analysis

- Gyrokinetic GS2 simulations and analytic calculations of a simple slab model of the H-mode pedestal that includes:
  - Spatially varying $E \times B$ shear and plasma gradients with typical pedestal magnitudes and spatial scales
  - Magnetic shear
  - Electromagnetic effects
  - Kinetic effects (eg Landau damping, FLR)

  but excludes

  - Magnetic curvature
  - Poloidal variation and other toroidal geometry effects
  - Parallel flows

GS2 simulations



- **Sheared slab geometry with no magnetic curvature**
- **Radially periodic BC's**
- **Simple (eg sinusoidal) background profiles of** V_E, n', T_i', T_e'
- **Comparable magnitudes of** $V_E \sim V_{*e} \sim -V_{*i}$ **at typical H-mode levels**

Analytic calculations

- **Electromagnetic Gyrofluid model (Snyder and Hammett, 1999)**

- **Periodic and non-periodic (eg, tanh) sheared slab profiles of n, T, etc (Periodic and non-periodic cases yield similar results)**

- **Electron model is isothermal and includes a simple approximation to electron Landau damping:**

$$\nabla_{\|} T_e = 0 \ , \qquad \alpha \partial_t \psi - \nabla_{\|}(\phi - n) = (\mu d_t + \nu + \lambda |k_{\|}|) J$$

- **Identical results (for $k_\perp^2 \rho_i^2 \ll 1$) obtained from an isothermal Braginskii model**

Limitations

- **GS2 simulations and analytic calculations are based on the standard "flux-tube" ordering:**
  - **Order-unity variations of background plasma** *gradients* **n', T' etc are OK**
  - **But, assumes mode is radially localized to a region over which the deviations in the** *absolute* **levels of n, T etc are small**

  For one of the modes of interest - the KH mode - the radial envelope is comparable to the entire pedestal width. Fully non-local simulations are needed to go further.

- **Lack of realistic toroidal geometry effects**

Summary: Three Main Modes

1. Kelvin-Helmholz Instability

– **Driven by shear in $E \times B$ velocity V_E**

– $k_\perp \sim 1/\Delta$

– **Magnetic shear and V_{*i} are stabilizing**

Near marginal stability for narrow H-mode pedestal parameters. Probably stable for wide pedestals.

2. "Tertiary Mode"

– **An adiabatic, electrostatic mode arising at high-$k_\parallel$ and $k_\perp > 1/\Delta$**

– **Driven mainly by T_i'**

– **Stable for vanishing or constant $E \times B$ shear**

– **Insensitive to magnetic shear**

– **FLR effects stabilizing**

Near marginal stability for narrow H-mode pedestals. Possibly unstable for wider pedestals.

Summary: Three Main Modes (II)

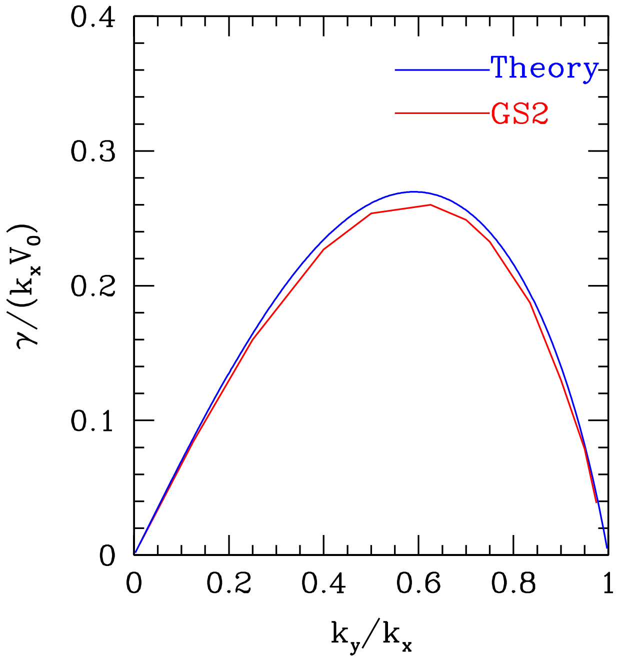
3. Linear Driftwave Instability

Aside from $E \times B$ shear, similar to the mode that was discussed in the literature decades ago.

- **Driven by plasma gradients and (for typical H-mode parameters) electron Landau damping**
- $k_\perp \sim (0.2 - 5)/\rho_s$ **and** $k_\| \sim \sqrt{\beta} k \rho_s / \Delta$
- *Requires* **spatial variations in the** $E \times B$ **shear or plasma gradients (like those typical of the edge pedestal) to be linearly unstable in the presence of magnetic shear**
- **Electromagnetic effects important (stabilizing)**

Unstable for all parameters we have checked. Strong candidate for driving transport in the H-mode edge of toroidal or linear devices

KH Mode Basics



- **In the most unstable case ($\hat{s} = 0$ and no diamagnetic effects), for either *tanh* or *cos* profiles:**
  - $\gamma_{max} \simeq 0.25 V'_{E,max}$ **for** $k \sim 1/\Delta$
  - $\omega \sim \gamma_{max}$ **or less (profile dependent)**
  - **Linear eigenfunction varies radially on pedestal scale**

KH Mode and Magnetic Shear

- **Can be stabilized by magnetic shear:**

  $\vec{B} = B_0 \left(\hat{e}_z + \frac{x}{L_s} \hat{e}_y \right)$, $k_\parallel = k_z + k_y x / L_s$

  Stable if:

  $L_s \lesssim C_A / V'_{E,max}$

  or assuming $L_s = qR/\hat{s}$ **and** $V'_{E,max} = 2V_E/\Delta$ **(**Δ**=full pedestal width):**

  $\Delta \gtrsim 1.6 \rho_i \left(\frac{qR}{d_i \hat{s}} \frac{V_E}{V_{*i0}} \right)^{1/2}$ **(stable)**

Sample H-mode Edge Parameters

- **DIIID:**

  $R \simeq 168\ cm$

  $n \sim 2 \times 10^{13}\ cm^{-3}$

  $T_e \sim T_i \sim 350 eV$

  $B \sim 2T$

  $m_i = 2m_p$

  $\hat{s} \sim 2\ ,\ q \sim 3.5$

  $\beta_e \sim 7.1 \times 10^{-4}$

- **Alcator CMOD:**

  $R \simeq 68\ cm$

  $n \sim 1.5 \times 10^{14}\ cm^{-3}$

  $T_e \sim T_i \sim 250 eV$

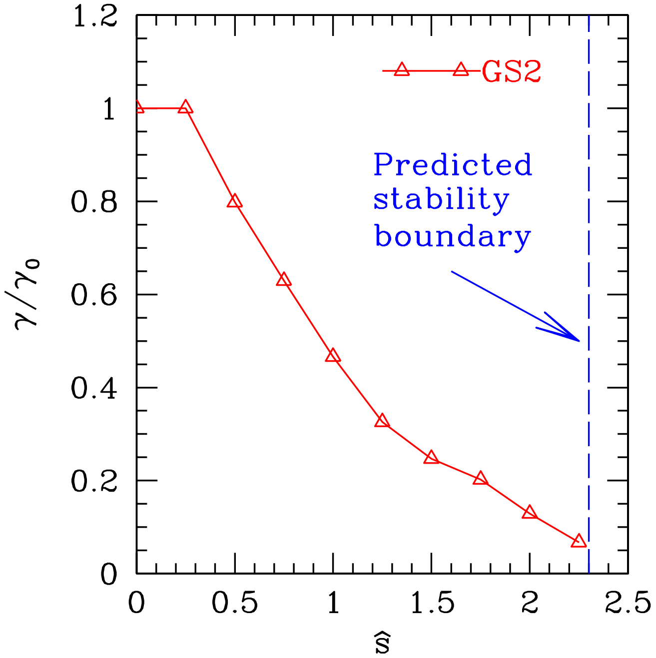
  $B \sim 5.3T$

  $m_i = 2m_p$

  $\hat{s} \sim 2\ ,\ q \sim 3.5$

  $\beta_e \sim 5.4 \times 10^{-4}$

KH Mode and Magnetic Shear (II)

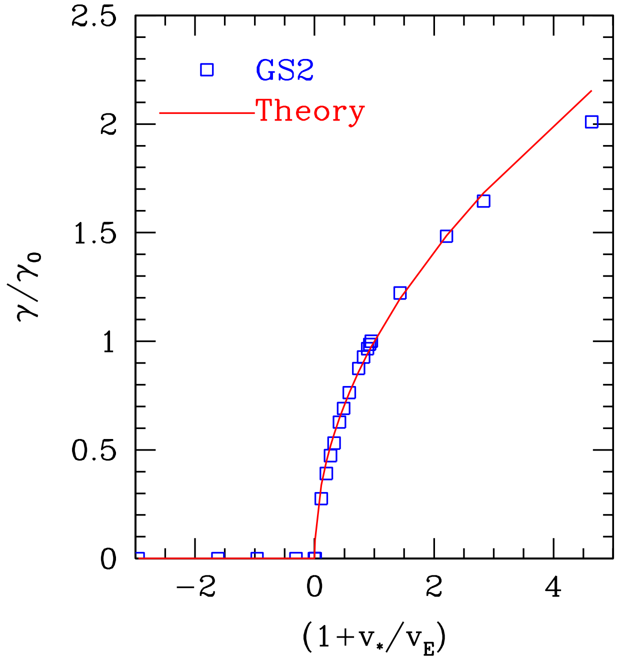


- **Evaluating shear stability condition for sample parameters and assuming $V_E \sim V_{*i0}$:**

$$\Delta/\rho_i \gtrsim 1.6 \left(\frac{qR}{d_i \hat{s}} \frac{V_E}{V_{*i0}}\right)^{1/2} \simeq 12 \ \textbf{(DIIID)},\ 10 \ \textbf{(CMOD)}$$

Suggests narrow pedestals are close to marginal due to shear alone

KH Mode and Ion Diamagnetic Effects



- **But, ion diamagnetic effects are also stabilizing:**

A necessary condition for instability is $V_E\,(V_E + V_{*i}) > 0$ **or**

$(1 + V_{*i}/V_E) > 0$ **(unstable)**

In typical (?) pedestals $V_{*i}/V_E \sim -1$ **(the marginal case)**

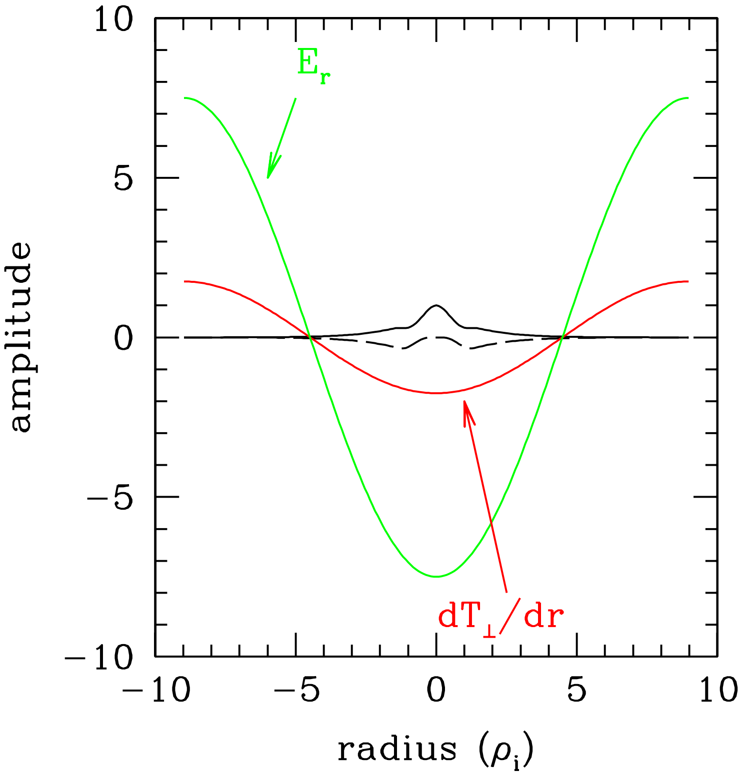
KH Mode

- **Narrow pedestals are close to marginal stability**

  Is this a coincidence?

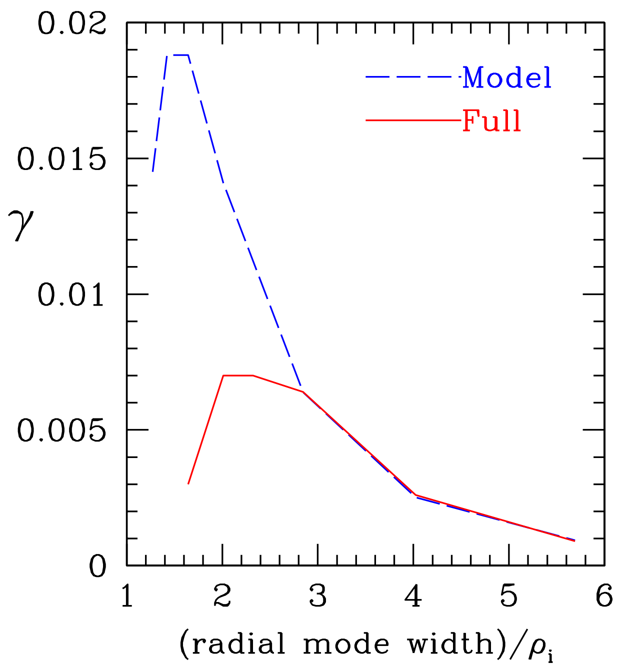
  Need a more detailed study, including realistic geometry and ion diamagnetic effects, to determine role.

Tertiary Mode



- Predominantly adiabatic and electrostatic
- Driven mainly by T_i' and localized by $E \times B$ shear
- Insensitive to magnetic shear

Tertiary Mode (II)



- **Growth rate and frequency:**

  $\gamma \sim \sqrt{\frac{\rho_s}{\Delta}} V_E/\Delta$, $\omega \simeq k_y V_E$ **(weaker than KH by factor of** $\sqrt{\rho_s/\Delta}$**)**
- **Stabilized by FLR effects (?) when** $\Delta \sim (5-10)\rho_i$

Probably unstable except for narrow pedestals but difficult to judge based on simple model. Work in progress.

Driftwave Mode

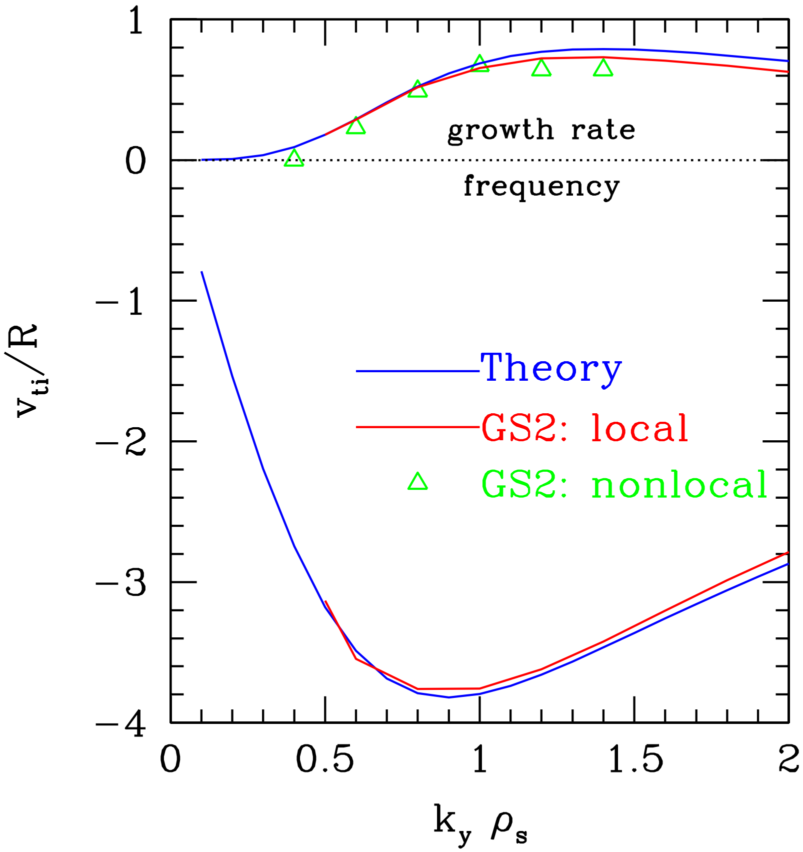
- An electron drift wave that (for typical H-mode β's) is predominantly destabilized by electron Landau damping with secondary contributions from electron inertia and/or resistivity

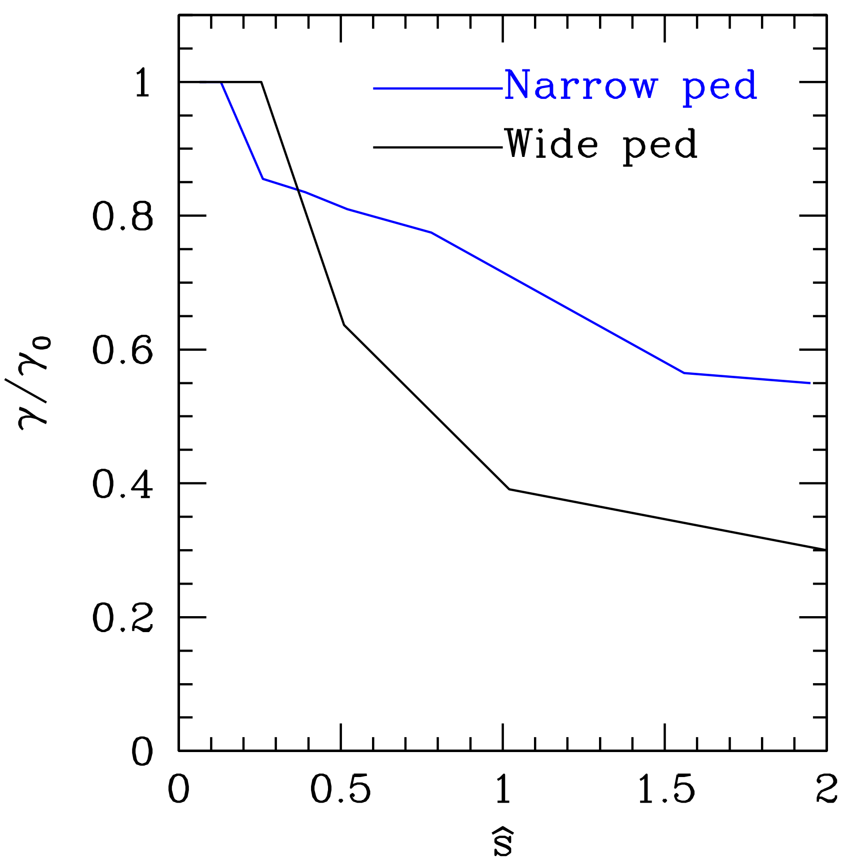
- Radially localized by the curvature of either the $V_E \propto \phi'$ or n' profiles:
  - For $k\Delta \gg 1$, eigenfunction is Gaussian with (radial) mode width $\delta_d \sim \sqrt{\Delta/k} < \Delta$

- Typically $\gamma_{max} \sim (0.1 - 0.2)\omega_{*e,n}$ for $k_\| \sim \sqrt{\beta} k \rho_s/\Delta$

- Magnetic shear is moderately stabilizing for typical parameters (consistent with analytic results since $k_\| > k\delta_d/L_s$)

Driftwave Mode (II)

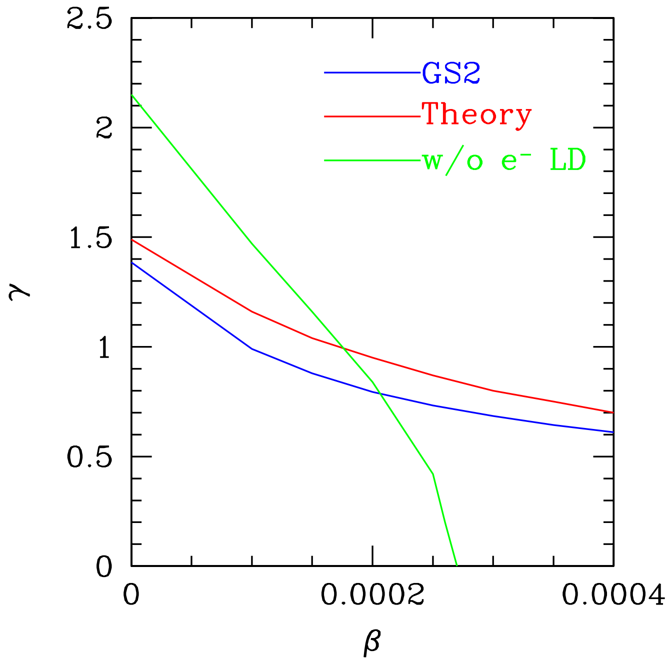


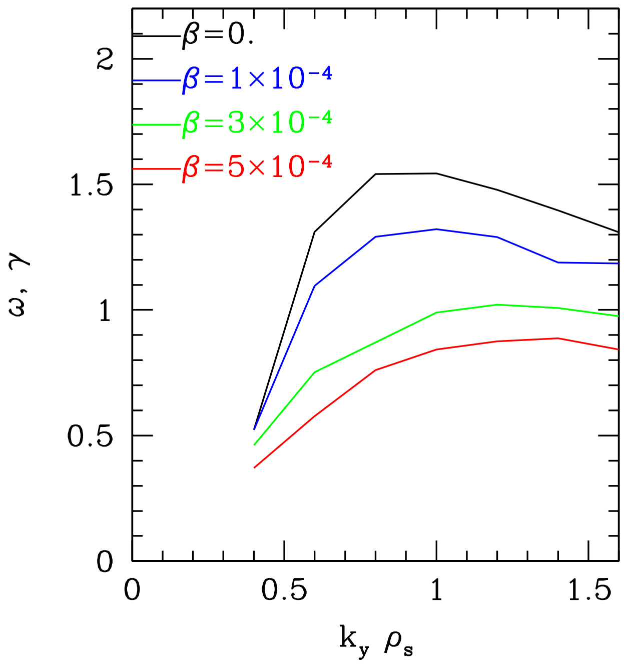


- **In analytic calculations, γ is given by a cubic DR:**

$$\bar{\gamma}\bar{\gamma}_i\left[\alpha\bar{\gamma}_e+\left(\mu\bar{\gamma}+\nu+\lambda|k_\parallel|\right)k_y^2\right]=-k_\parallel^2\left[\bar{\gamma}_e+k_y^2\rho_s^2(\bar{\gamma}_i+\tau\bar{\gamma}_e)\right]$$

Driftwave Mode (III)





- **For typical β values, electron LD is destabilizing**
- **Finite β is stabilizing**

Summary

- Neglecting magnetic curvature and parallel flows, but including $E \times B$ shear, magnetic shear, and profile variation, we find three linear instabilities that are potentially relevant to H-mode pedestals:
  - KH mode

    Near marginal stability due to magnetic shear and ion diamagnetic effects, but is potentially unstable for narrower pedestals.
  - Tertiary mode

    Potentially stabilized by FLR effects in narrower pedestals. Possibly unstable for wide pedestals.
  - Nonlocal driftwave mode

    Unstable for all parameters we have checked. Electron Landau damping and EM effects important. A potentially important driver of transport in either toroidal or linear machines.

- **Even if only the driftwave mode is important, an accurate simulation model would need to include:**
  - **Nonlocal profile effects and $E \times B$ shear**
  - **EM effects**
  - **Kinetic effects (electron Landau damping)**