Micro-Instabilities of Tokamak Edge Pedestal

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中科院等离子体研究所，合肥 2011. 12

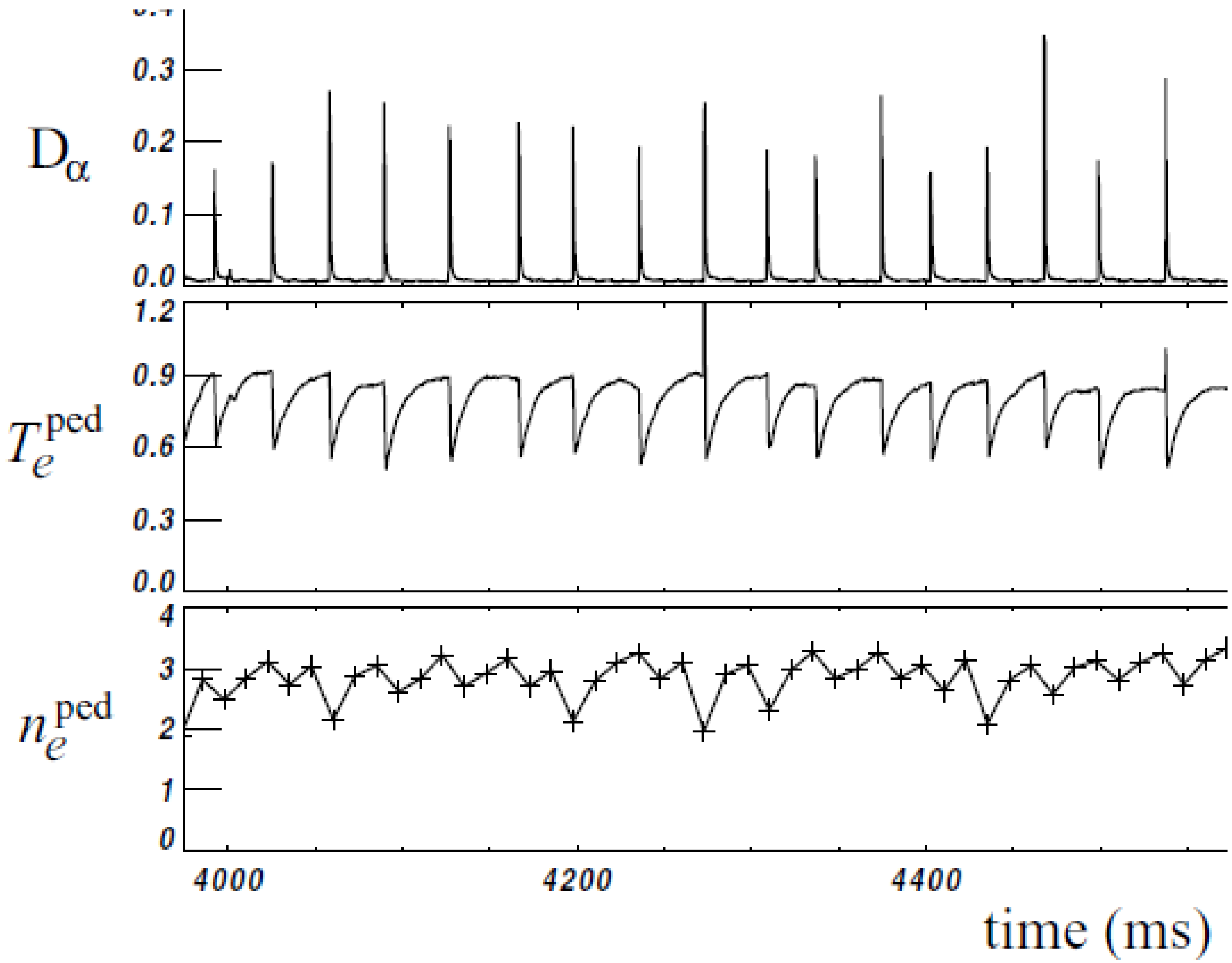
Outline

- What is the dominant linear micro-instability of edge pedestal?
  - Three DIII-D experimental profiles.
  - Global gyrokinetic particle simulations.
- **A high n, low frequency mode** caused mostly by electron temperature gradient.
  - Agrees with our and other flux tube simulations.
  - NOT expected Kinetic Ballooning Mode
- **A low n, high frequency mode** caused mostly by density gradient.
  - Only seen in global simulations.
  - Likey to be peeling-ballooning mode.

Edge pedestal evolution between ELMs

After an ELM cycle, pedestal density builds up within *10* ms.

[Callen *et al.*, Nucl. Fusion (2010.)]

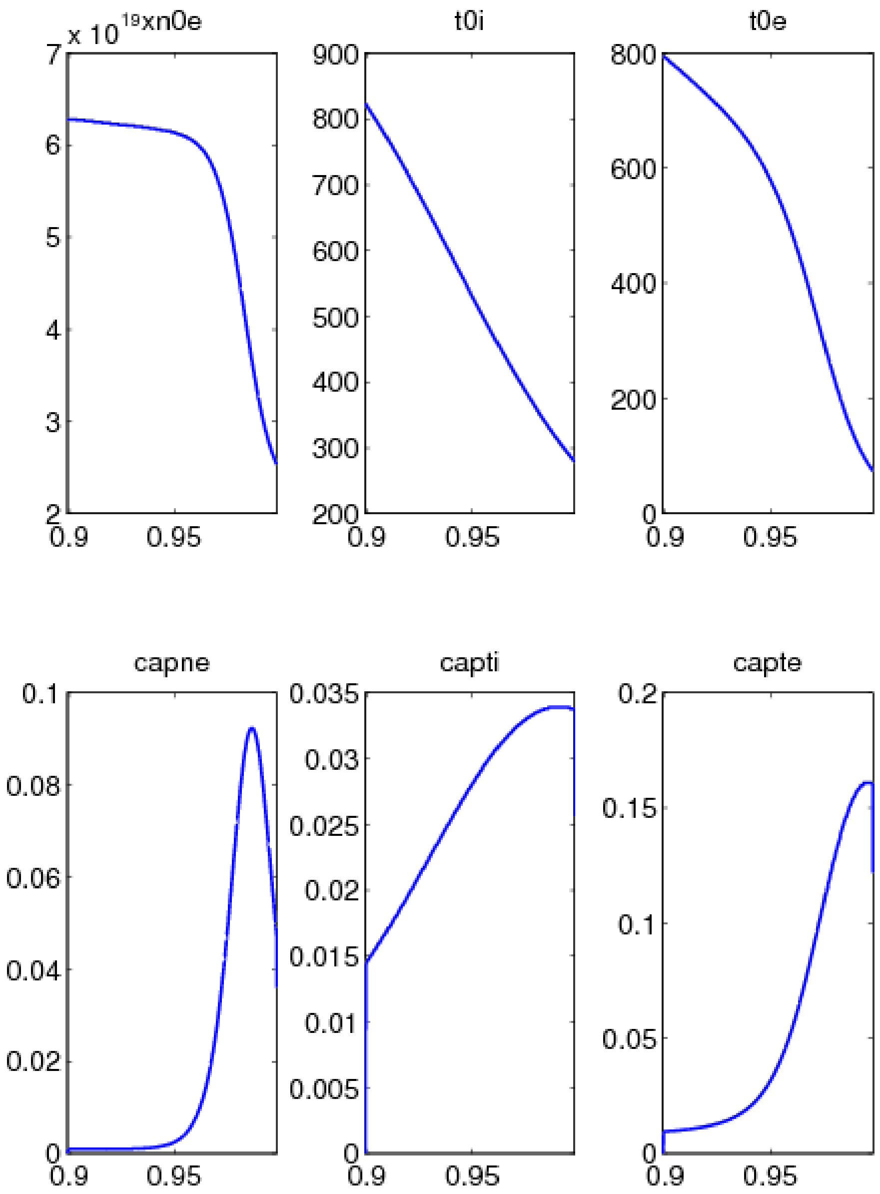


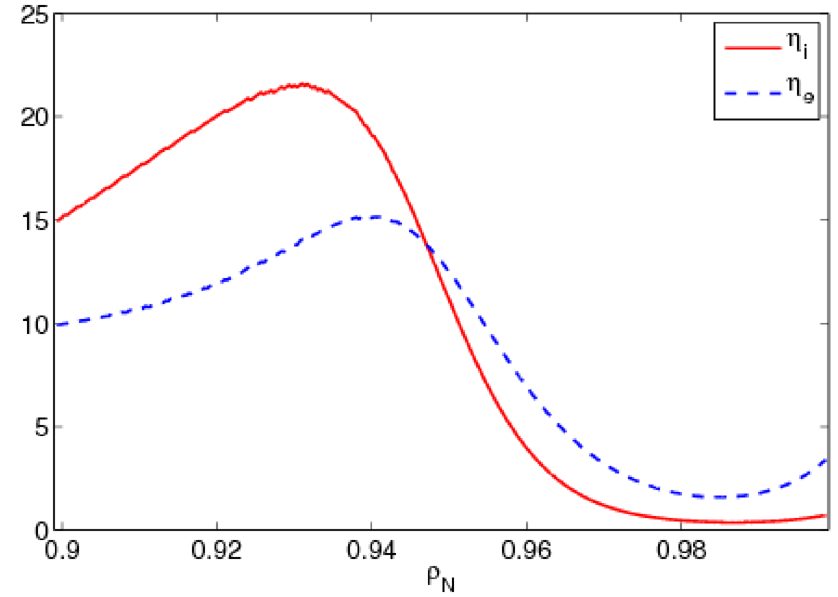
Two questions:

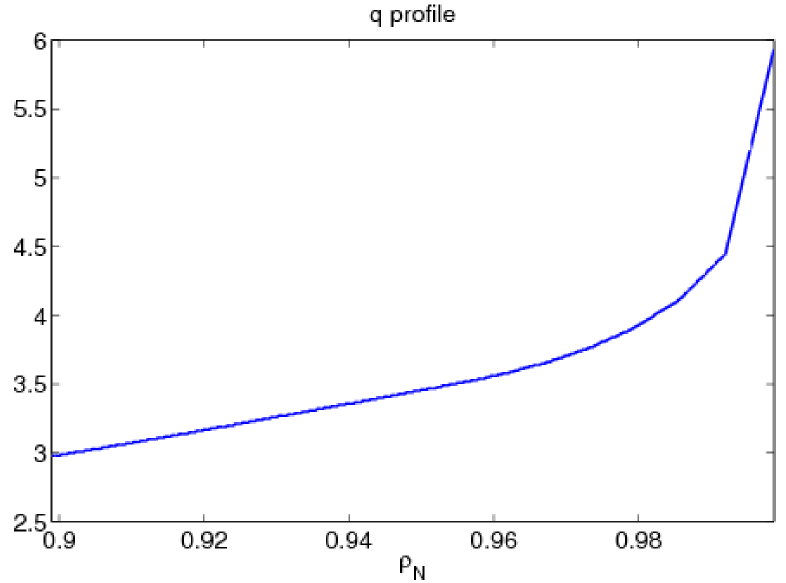
1. How does the pedestal build up?

2. When does the pedestal collapse?

A typical DIII-D shot (131997) profile







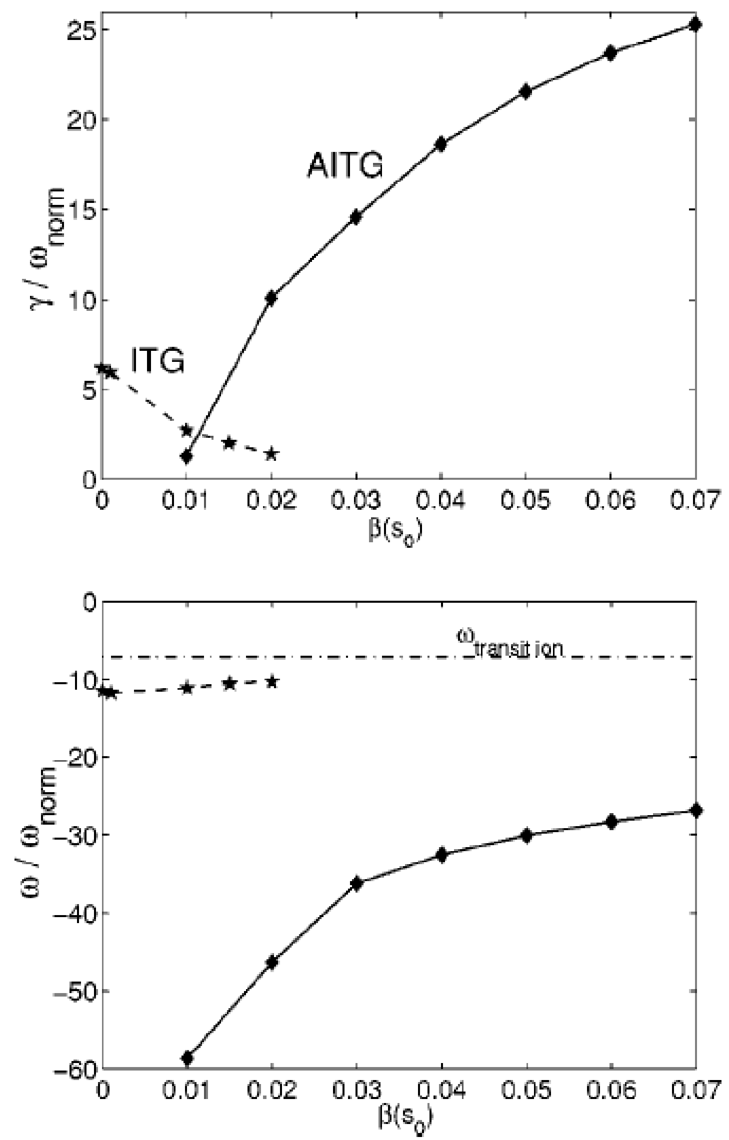
Predicting the pedestal: the EPED1 model

- Pedestal height and width rise together until an ELM is triggered.
- **EPED1 model**: P. Snyder *et al*. PoP **16**, 056118 (2009)
- **Pedestal height: peeling-ballooning stability**
  - Well studied with MHD
  - Accurately reproduce the observed pedestal height at a given pedestal width.
- **Pedestal width: kinetic ballooning mode (KBM)?**
  - Used in EPED1 model, but not confirmed by experiments and simulations yet.
  - Requires electromagnetic kinetic simulations.

Looking for kinetic ballooning mode...

- Driven by ion temperature gradient
- Long wave length, intermediate n
- Electromagnetic
- Sudden change of real frequency
- Propagates in ion diamagnetic direction
- Even parity electrostatic potential in the ballooning structure.

1432 Phys. Plasmas, Vol. 10, No. 5, May 2003



Falchetto 2003, GK simulation at core.

KBM @ DIII-D edge: experimental clues

- **DIII-D H-mode**: Z. Yan et al. PoP 18, 056117 (2011)
  - A high frequency electron mode
  - A low frequency ion mode
    - Seems to be driven by electron pressure and density gradient
- **DIII-D quiescent H-mode**: Z. Yan et al. PRL 107, 055404 (2011)
  - An ion mode dominates
    - Low frequency
    - Intermediate n
    - Long wave length
    - high decorrelation rates
    - Driven by pressure gradient
    - Very likely to be KBM

GENE Simlations of ASDEX Upgrade Edge

- Fluxtube simulations
  - No Er
  - Sees the dominant linear instability
- Top: ITG and ETG
- Steep gradient region: micro-tearing, ITG and ETG
- Finite kx observed.
- No KBM found.

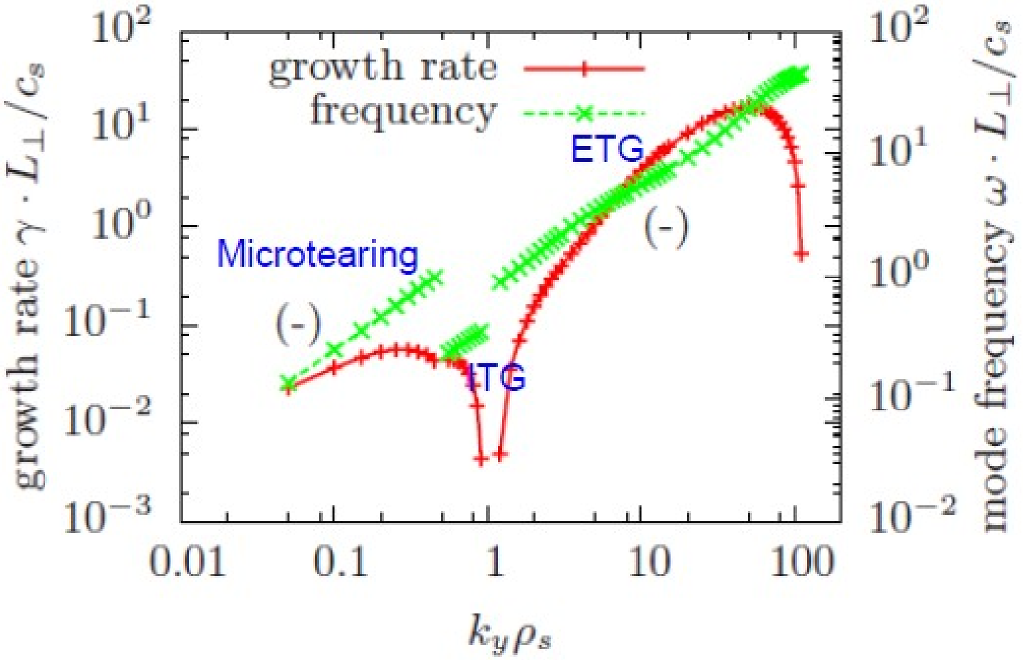
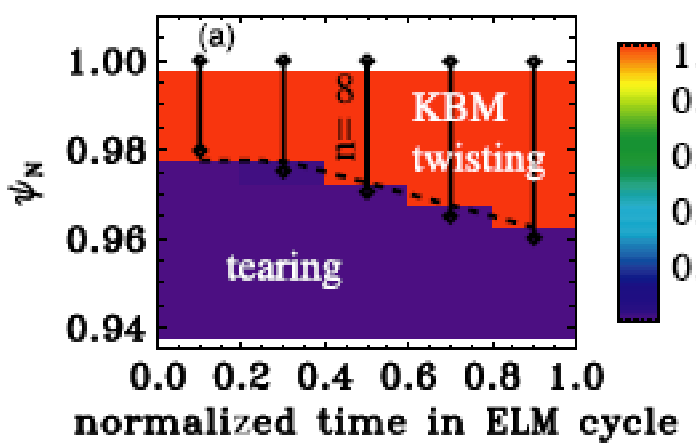


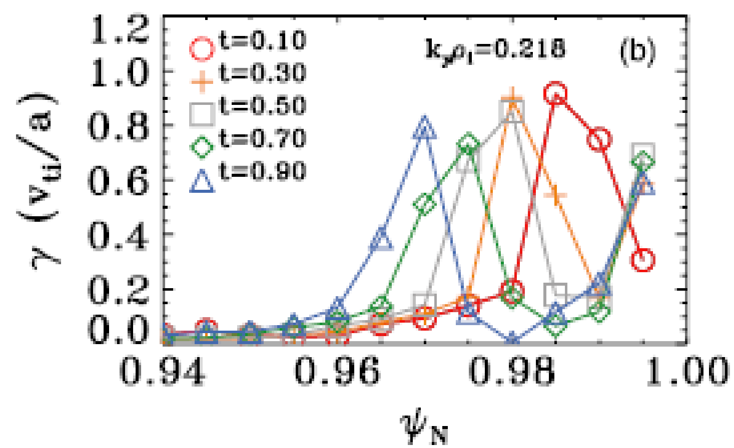
FIG. 6. (Color online) Growth rate and frequency spectra at ϱ_{pol}=0.93. Negative frequencies are indicated by (−).

D. Told et al., PoP 15, 102306 (2008)

GS2 Simulations of the MAST Edge

- Dickinson et al. PPCF 53, 115 010 (2011)
- Dickinson et al. submitted to PRL
- Top: likely micrto-tearing mode, but high k
- Steep gradient region: likely KBM
- Instabilities are distinguished by parity.

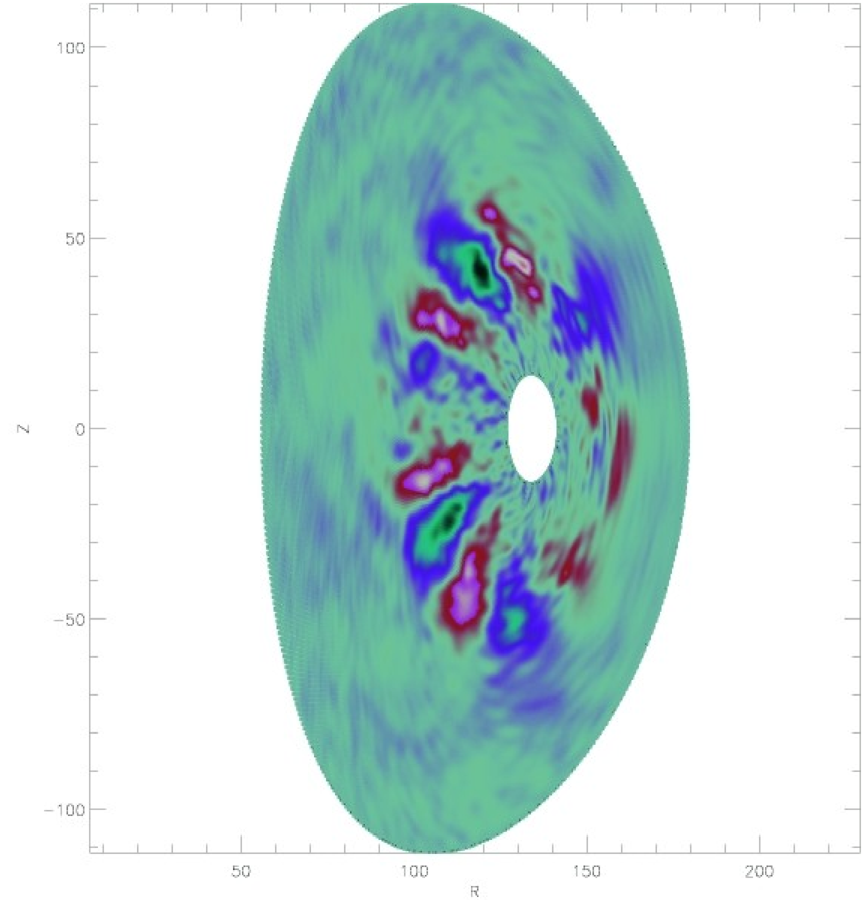




What about DIII-D H-mode simulations?

GEM is a comprehensive GK turbulence code

- The GEM Code
  - Gyrokinetic, particle-in-cell, electromagnetic, with drift-kinetic electrons, coarse-graining procedure
  - Radially global with Miller equilibrium, ITERDB
  - δf
  - Multiple-ion species
- This simulation
  - Global and flux tube
  - Collisionless and collisional
  - Edge: r/a=[0.899, 0.999]

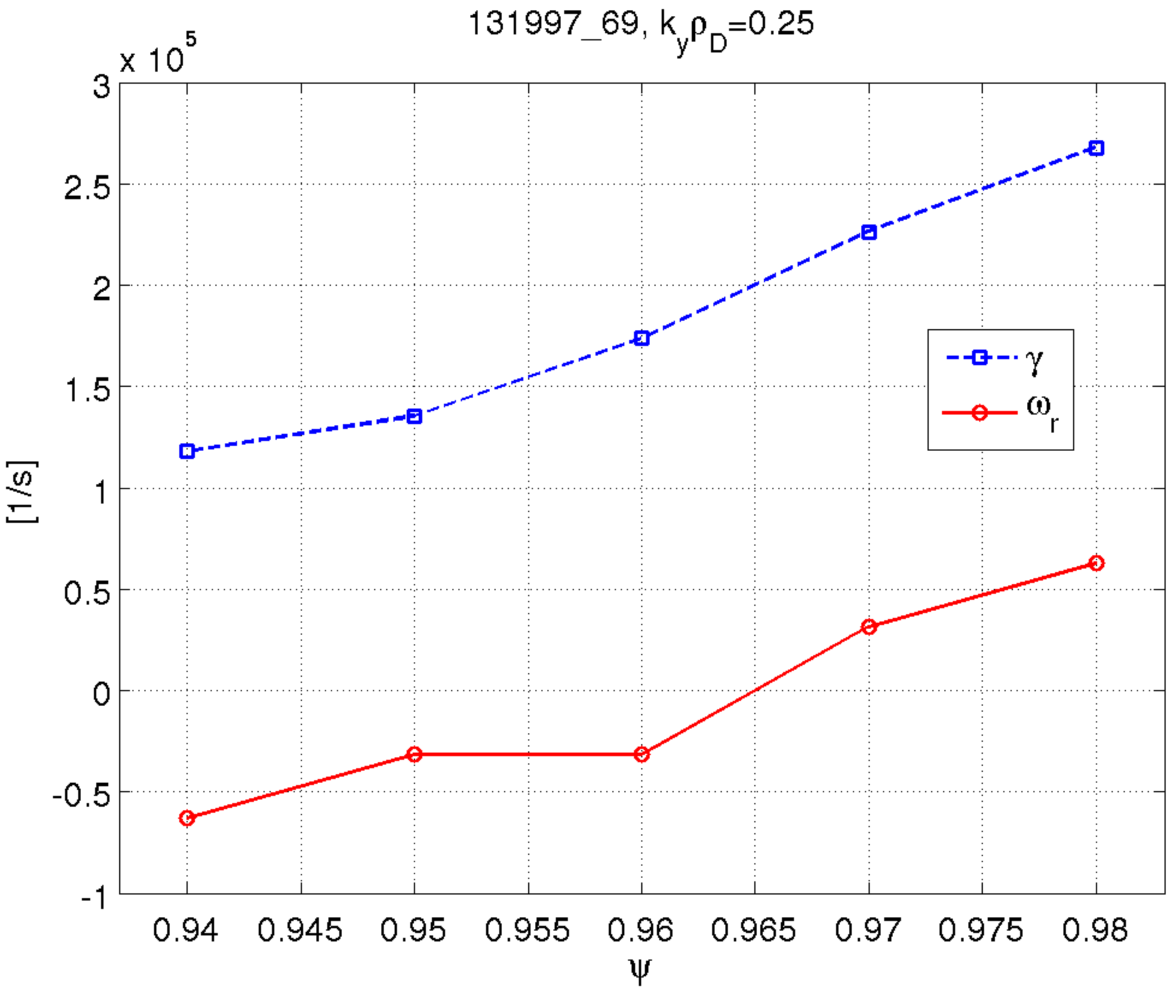


[Y. Chen et al, J. Comput. Phys., **220**, 839 (2007)].
[Y. Chen et al, J. Comput. Phys., **189**, 463 (2003)].

I. flux tube simulation

- Local density, temperature and q, keep the gradients
- With or without E_r
- Periodic BC in r
- Electromagnetic (with experimental β) and electrostatic (with low β) runs

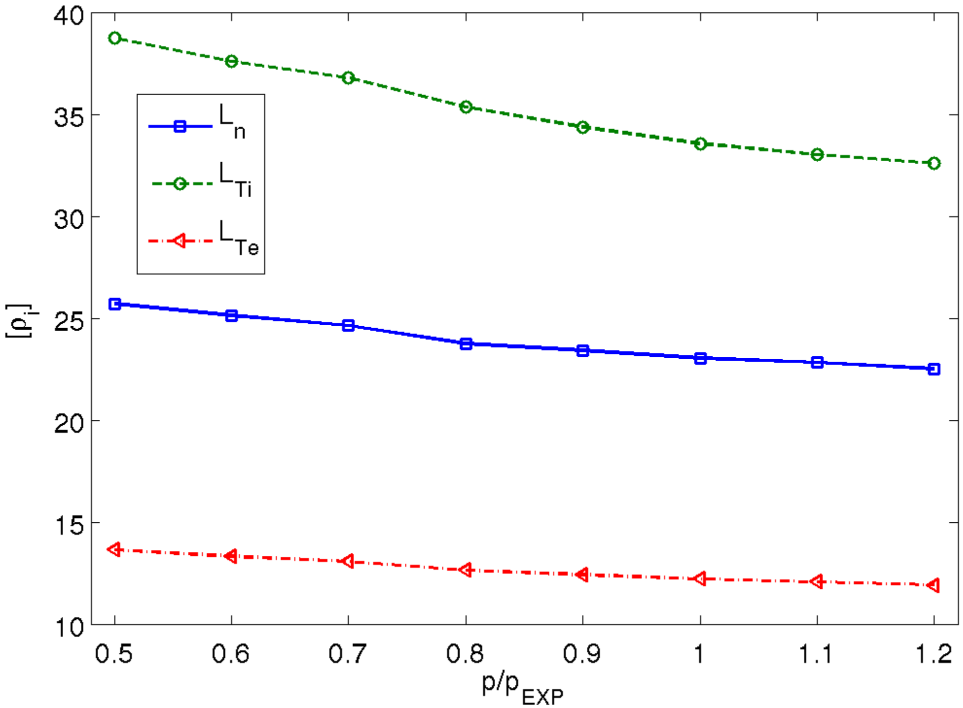
A radial scan with $k_y\rho_i$=0.25 shows the steep gradient region is more unstable



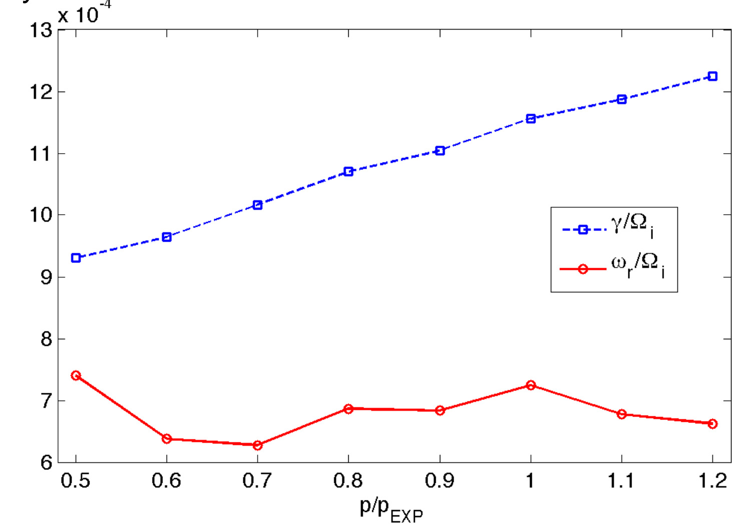
Higher pressure gradient, higher growth rate

Simulations at ψ_N=0.98

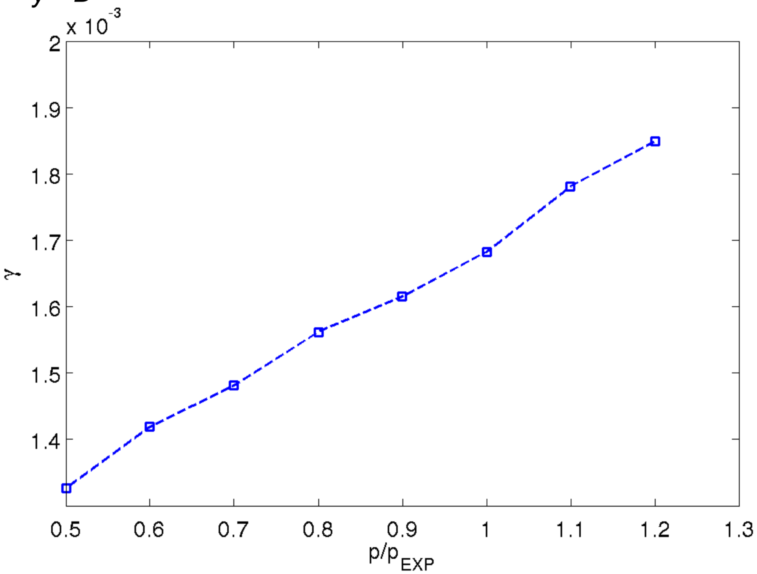
A set of 8 equilibria, all from DIII-D shot 131997 time 3011



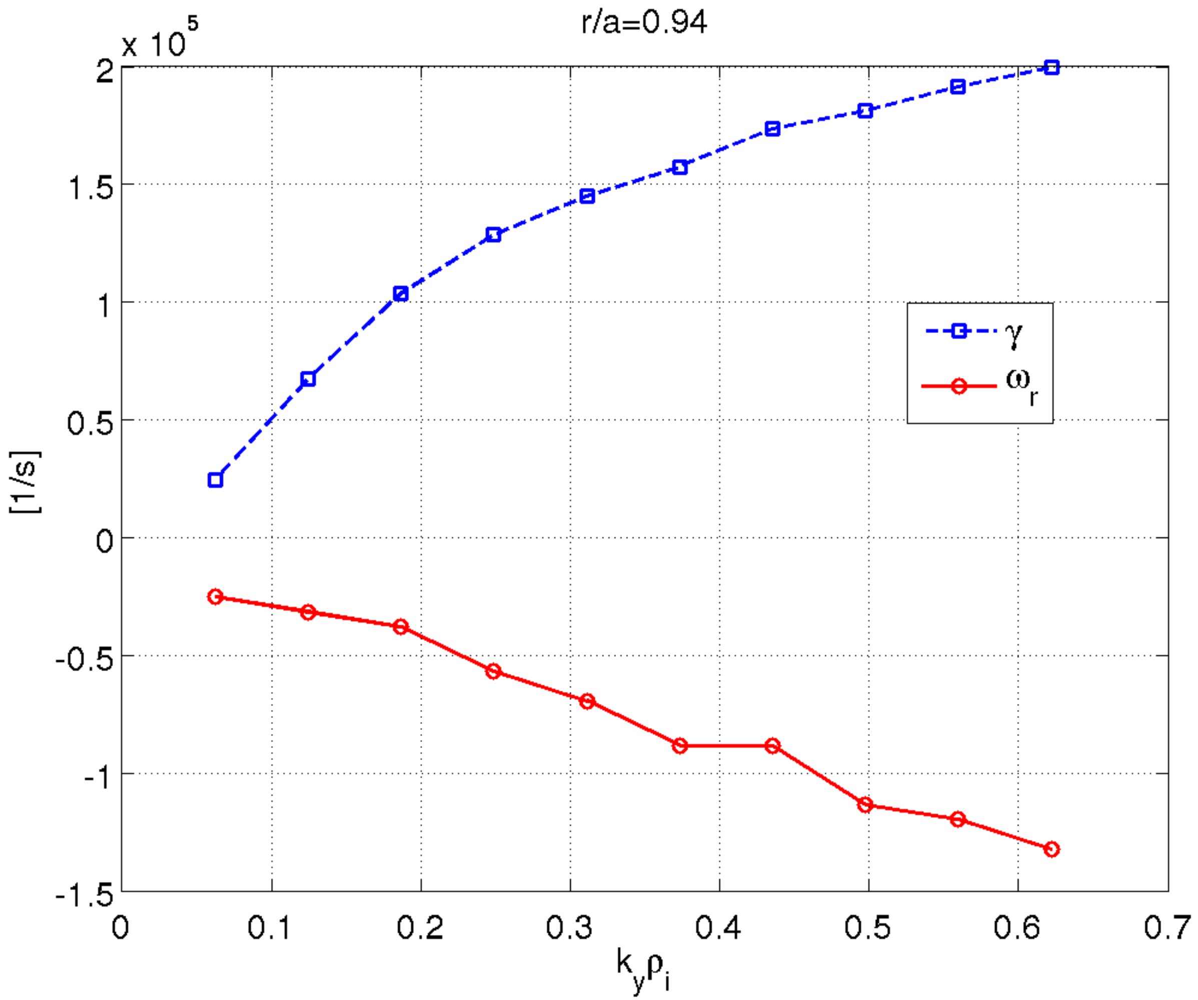
$k_y\rho_D$=0.3



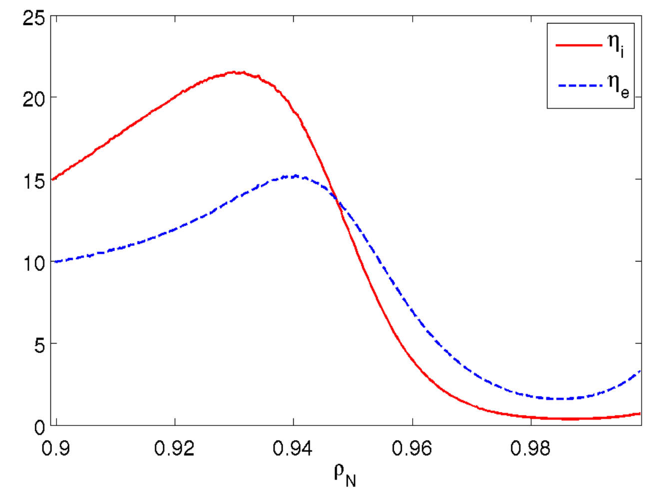
$k_y\rho_D$=0.53



(1). Pedestal top ρ_N=0.94: ITG

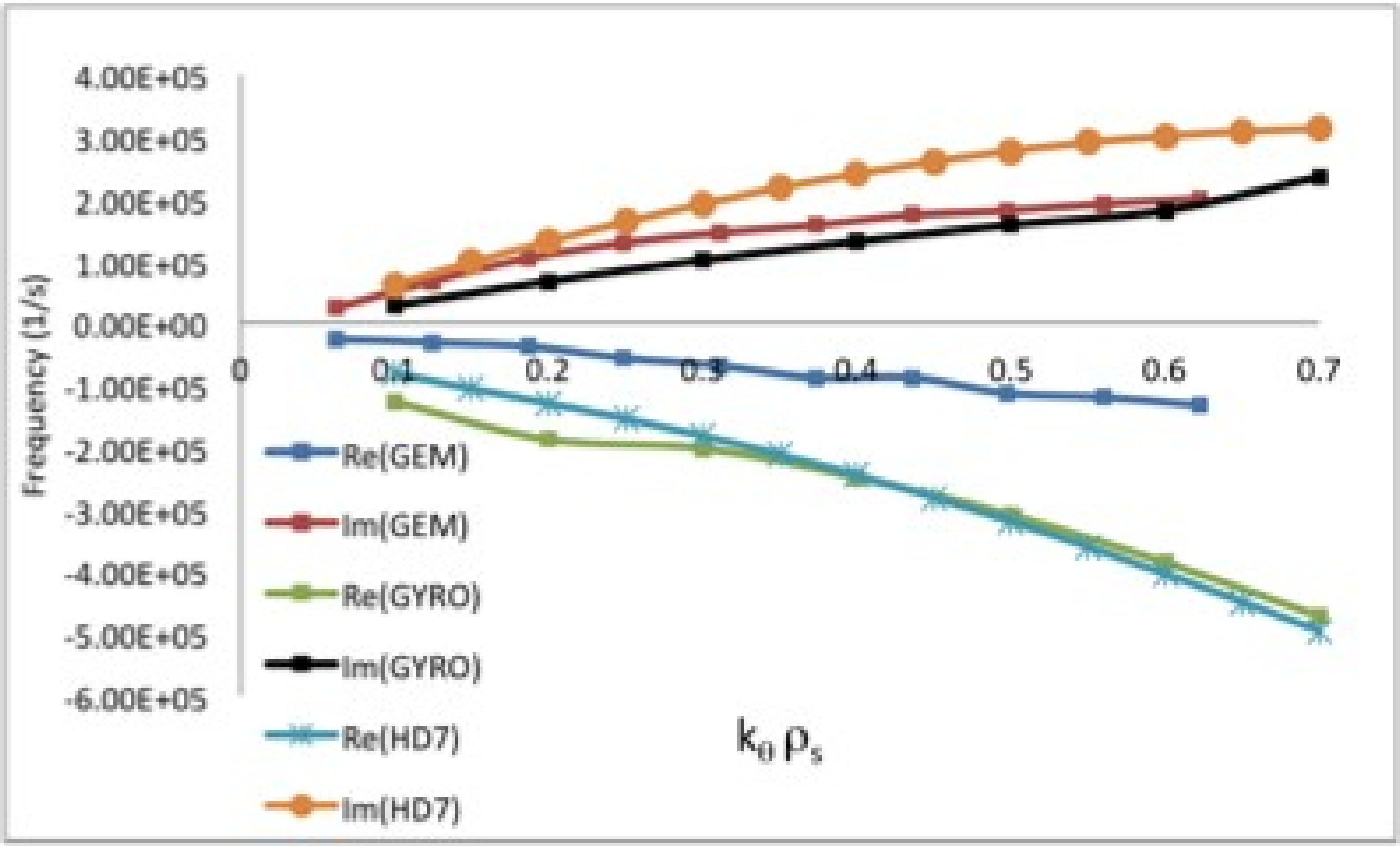


- Electrostatic.
- The linear mode propagates in the ion diamagnetic direction.
- A finite k_x ballooning mode structure
- $\eta_i > \eta_e$ in this region



GEM and GYRO have good agreement of growth rate in this region

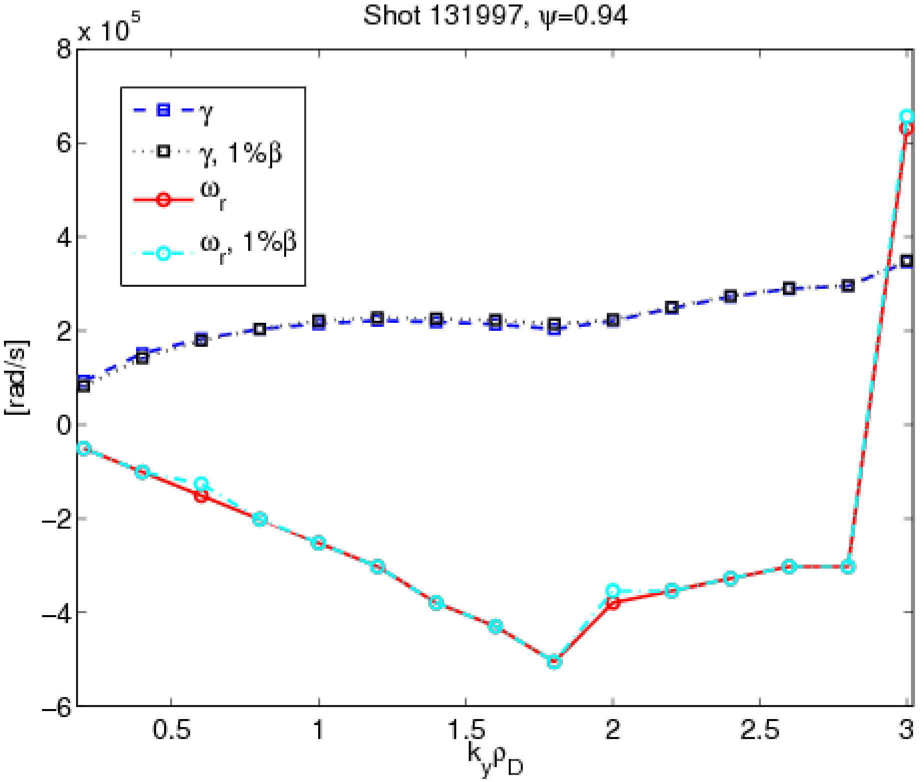
Top of pedestal



Results for GEM, GYRO (eigen solver) and HD7 (eigen solver) linear calculations

A high k_y study of pedestal top

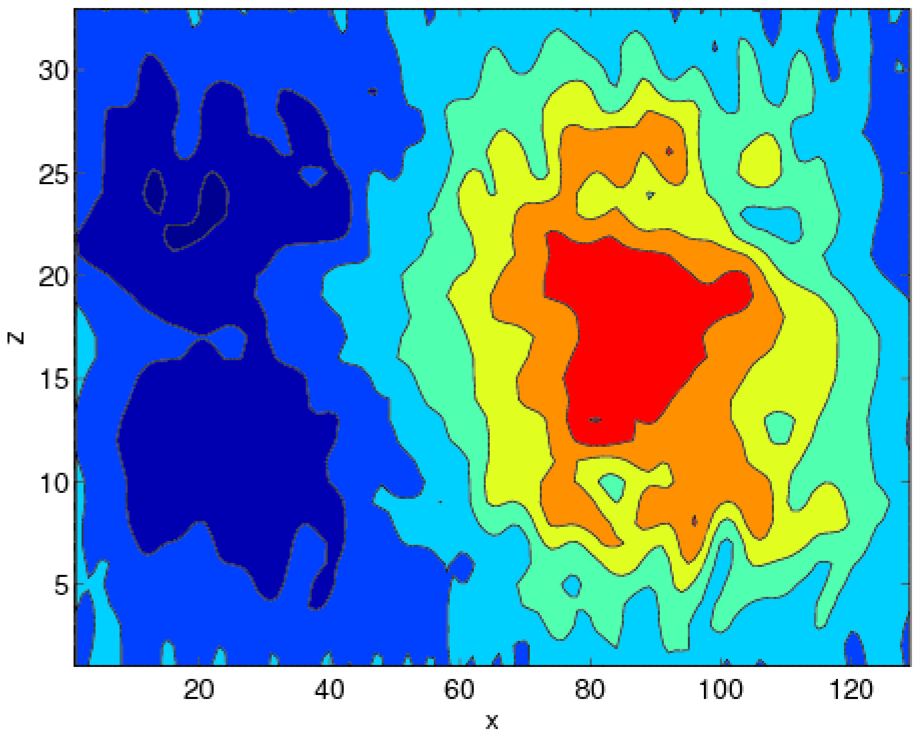
Ψ=0.94, r/a=0.9334

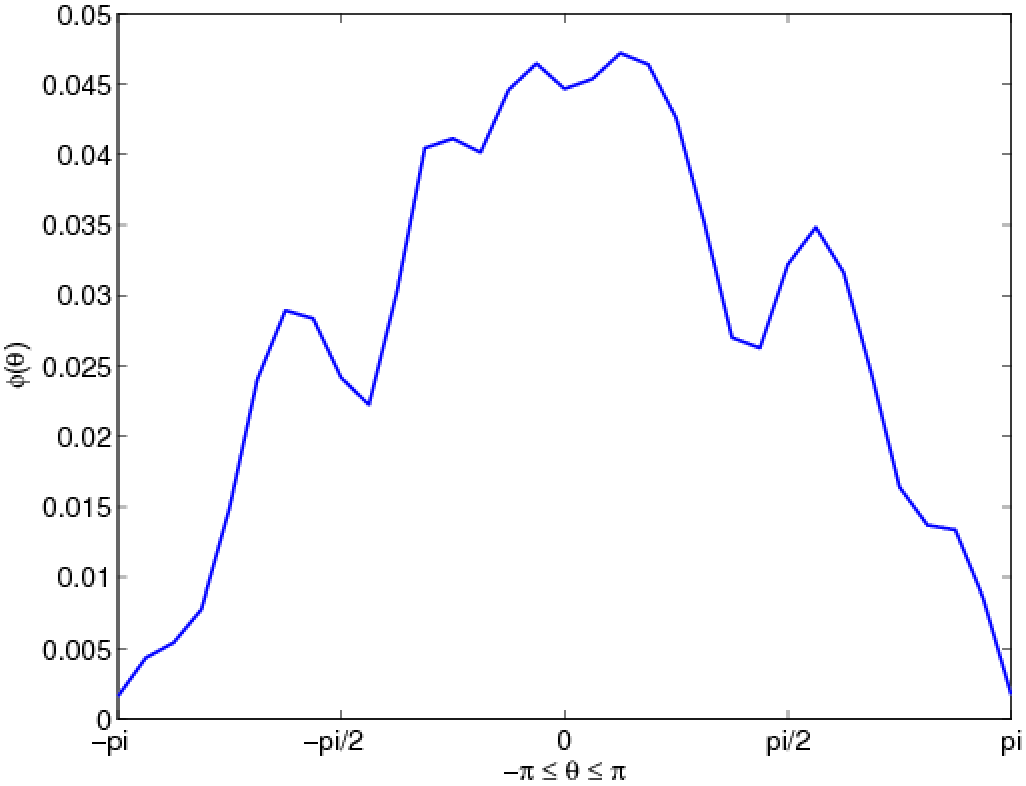


- The mode remains electrostatic even for large k_y.
  - Not micro-tearing mode
  - ETG?
- Linear growth rate becomes higher for higher k_y, but higher k_y mode may saturate nonlinearly, not known yet.
- Into the limit of GK simulation.
  - Convergence test done with smaller L_x.

$\Phi(x,z)$ remains even parity in z, like ITG/KBM

$k_y\rho_D$=0.2, ψ=0.94

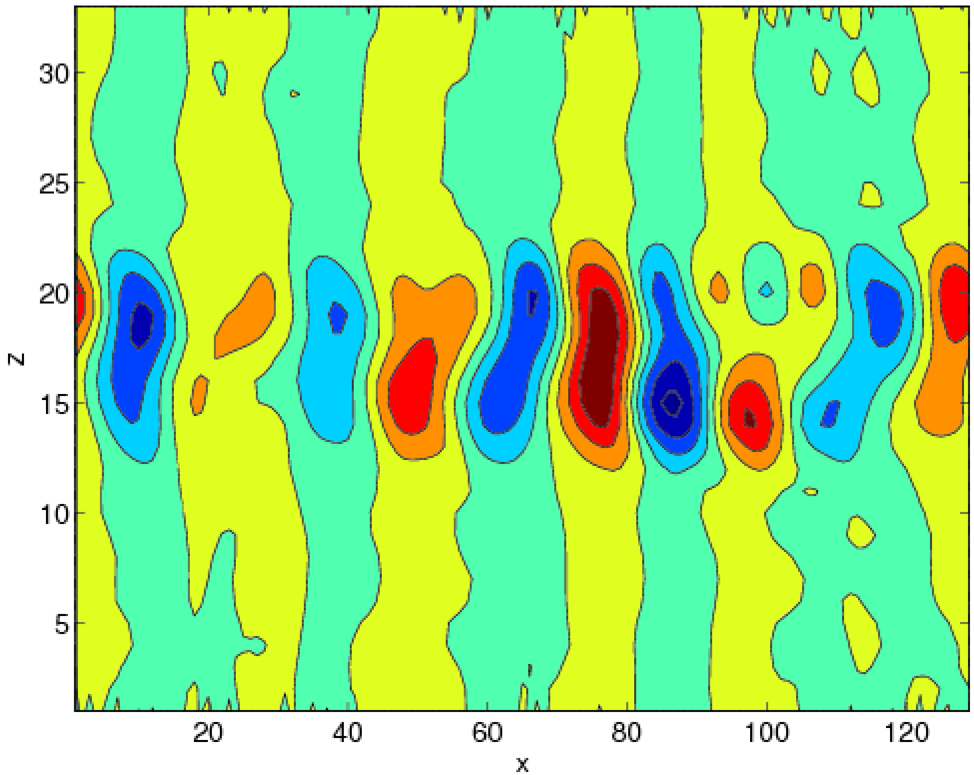


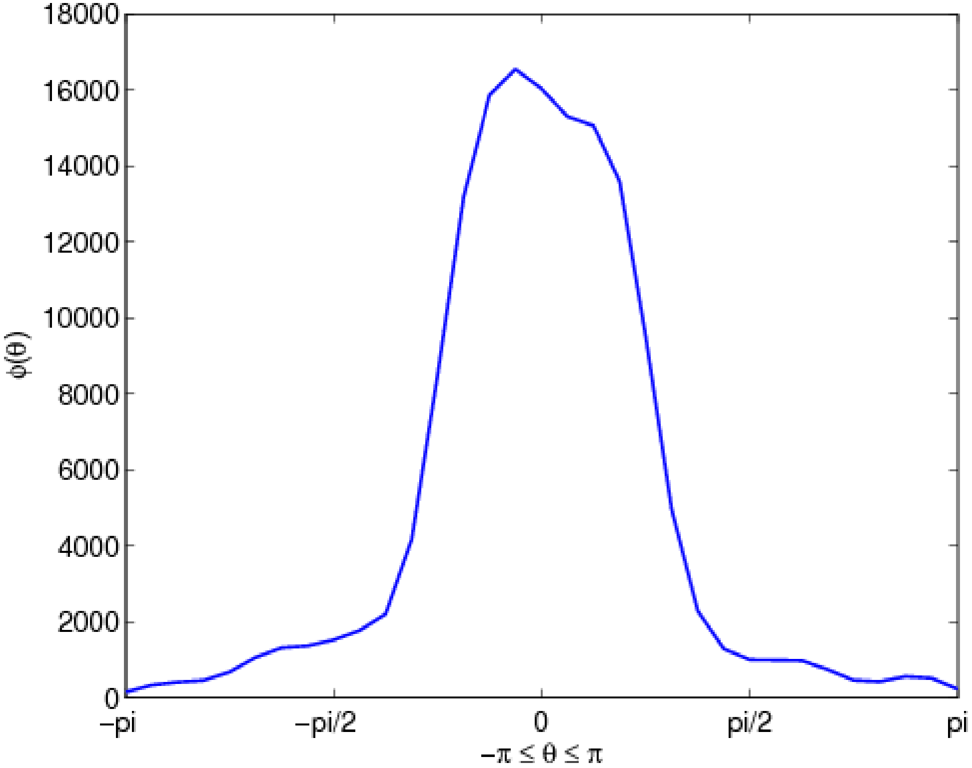


$z = q_0 R_{maj}\theta$

… even for high k

$K_y \rho_D = 2.$, $\psi = 0.94$

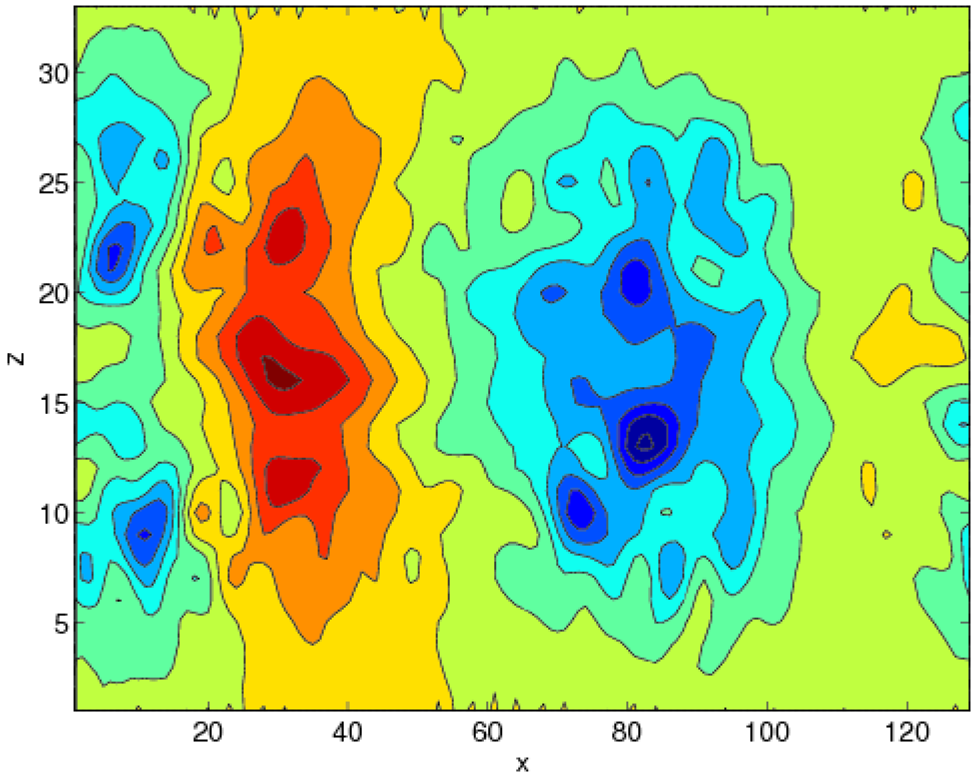


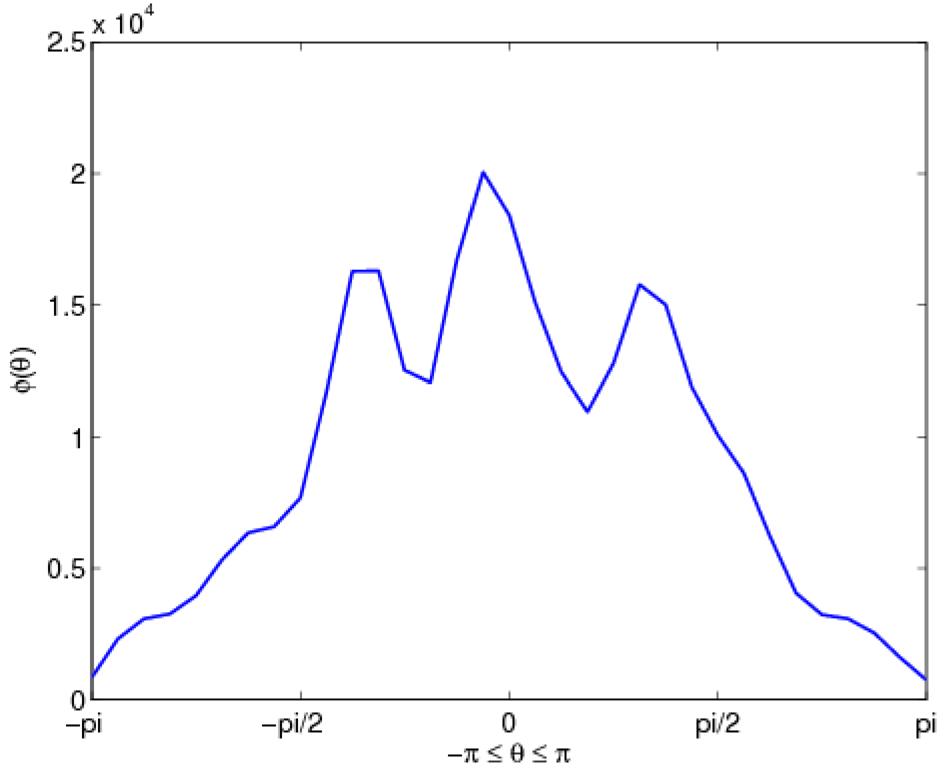


And k_x gets bigger too.

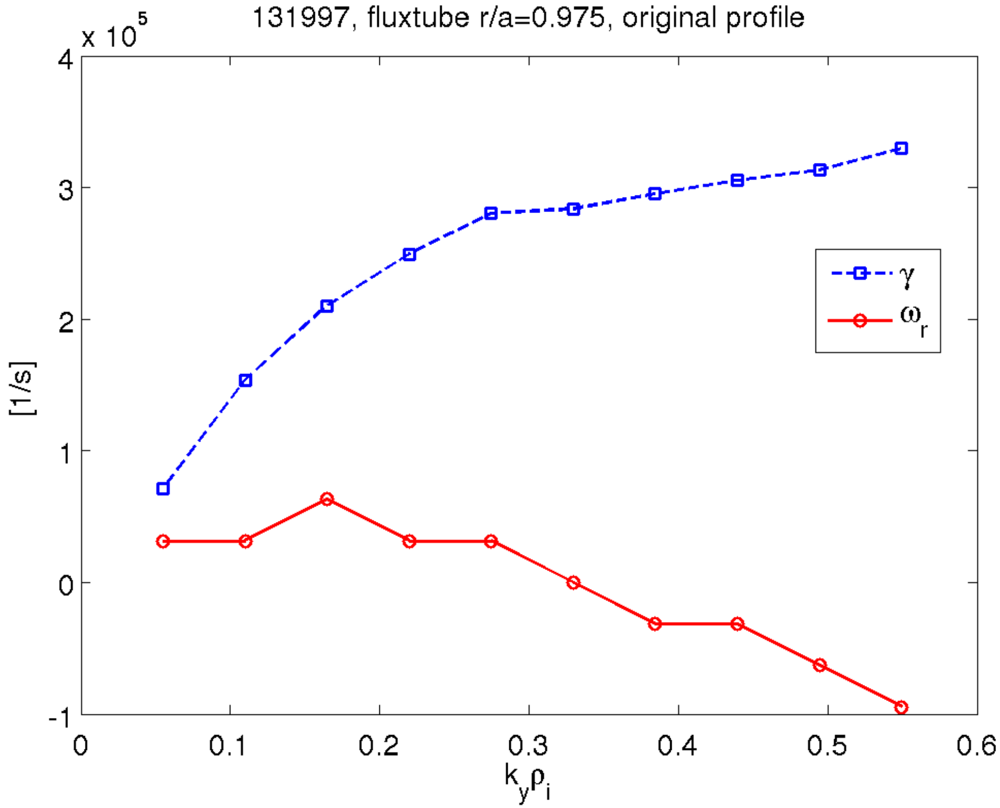
… and in the steep gradient region

$k_y\rho_D=0.2$, $\psi=0.98$





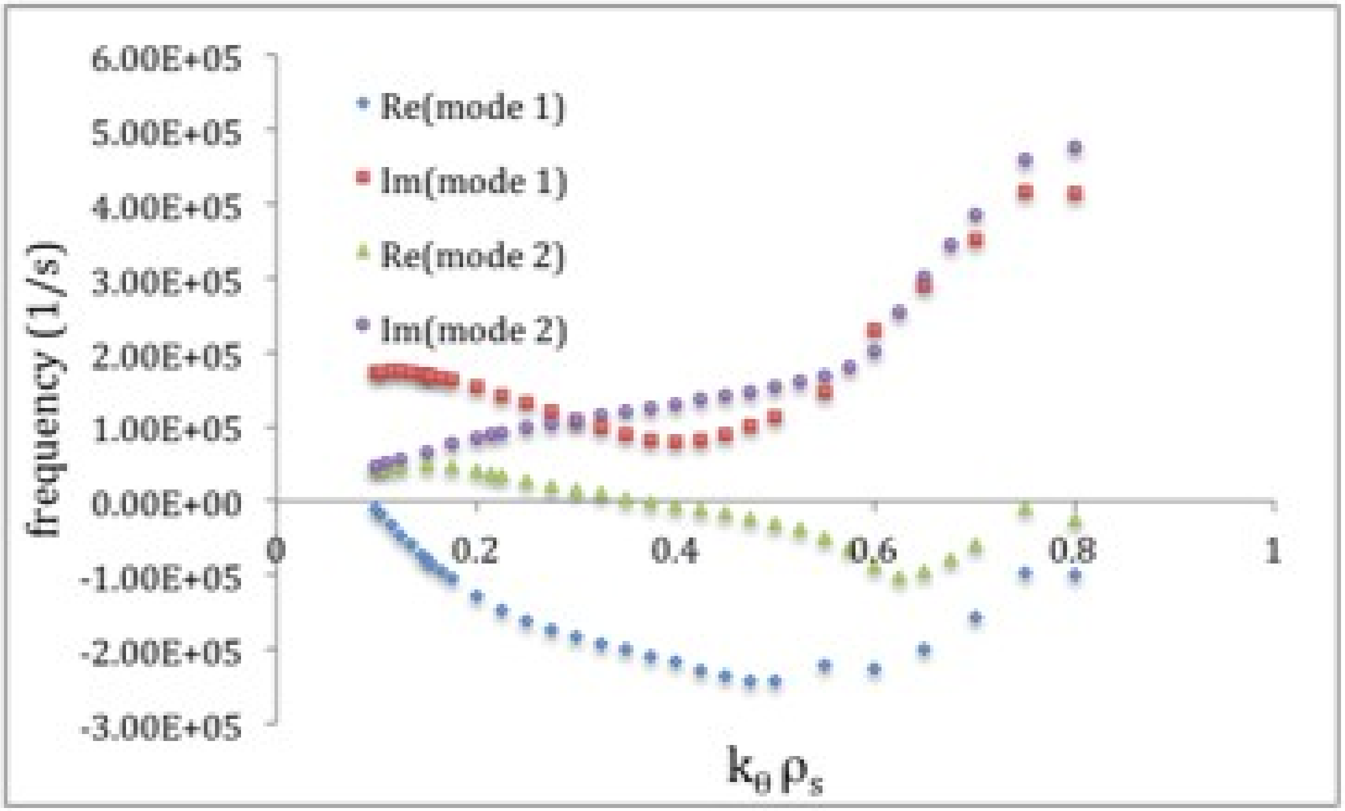
(2). Steep gradient region ρ_N=0.975: an electron mode



- High k mode may propagates in the ion diamagnetic direction without ExB drift
  - ExB drift makes all modes go in electron direction
- The mode is significantly destabilized by electron temperature gradient
  - ion temperature gradient has little effect.

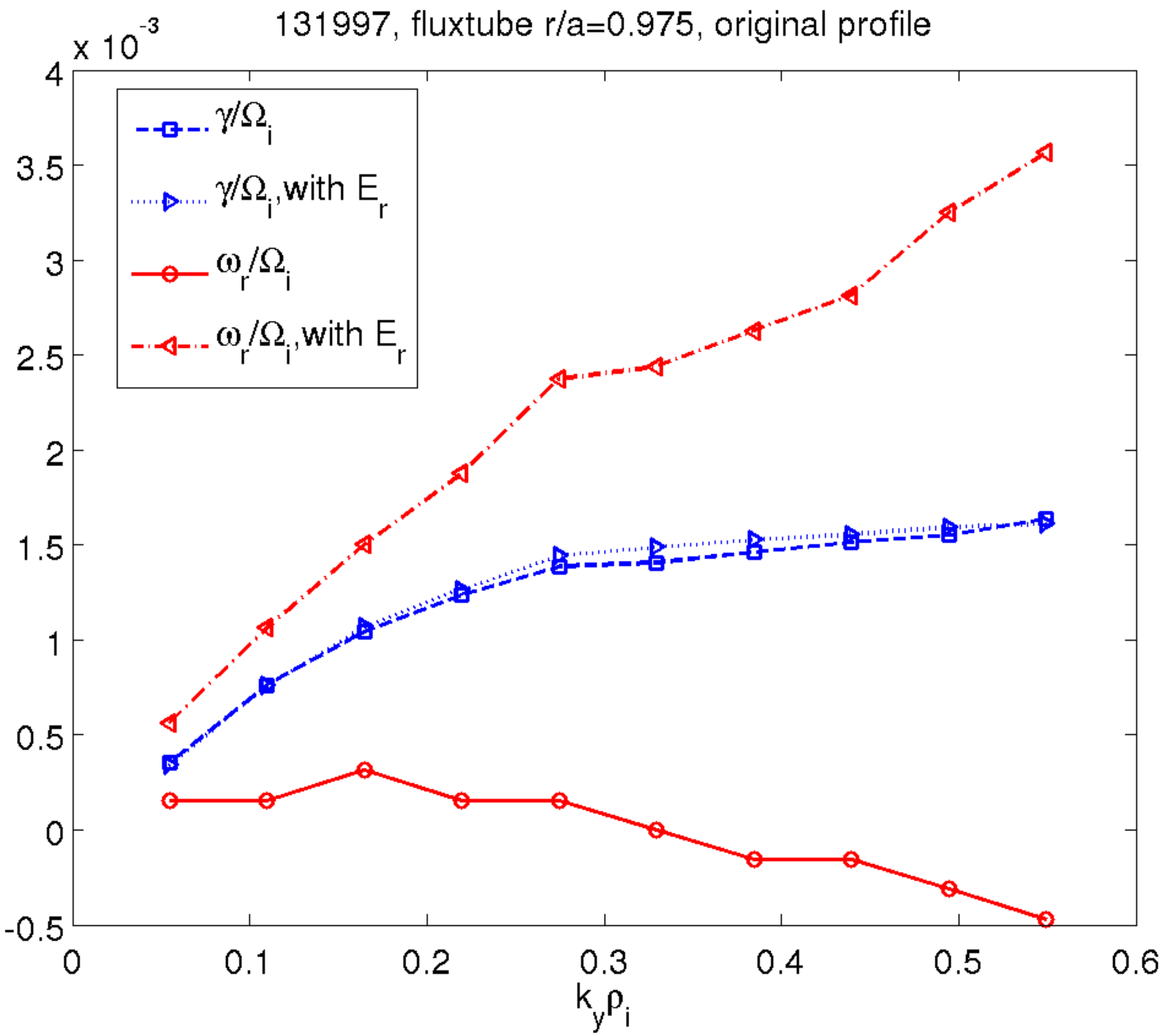
GEM and GYRO have some agreement in this region too

Results from GYRO, eigenmode calculations



Mode 2 here are comparable with GEM.

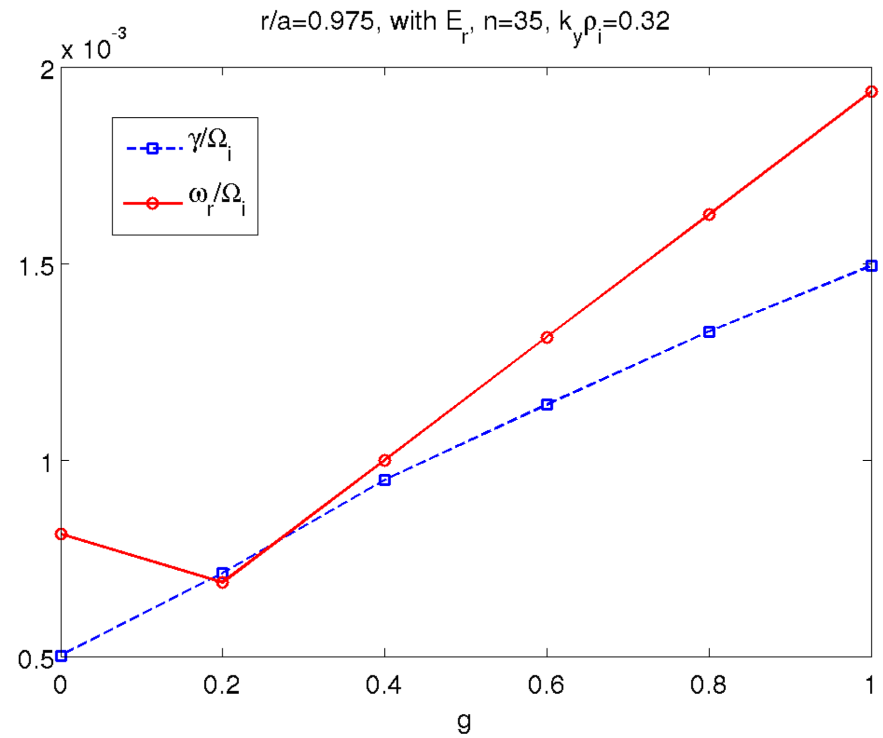
E_r makes a Doppler shift of real frequency



Little effect on the growth rate.

The mode is driven by density and electron temperature gradients

- A test of pressure gradients.
- Keep density, temperatures, and density gradient.
- Keep total pressure gradient.



$$\nabla T_{e1} = g \nabla T_e$$

$$\nabla T_{i1} = \nabla T_i + (1-g) \nabla T_e$$

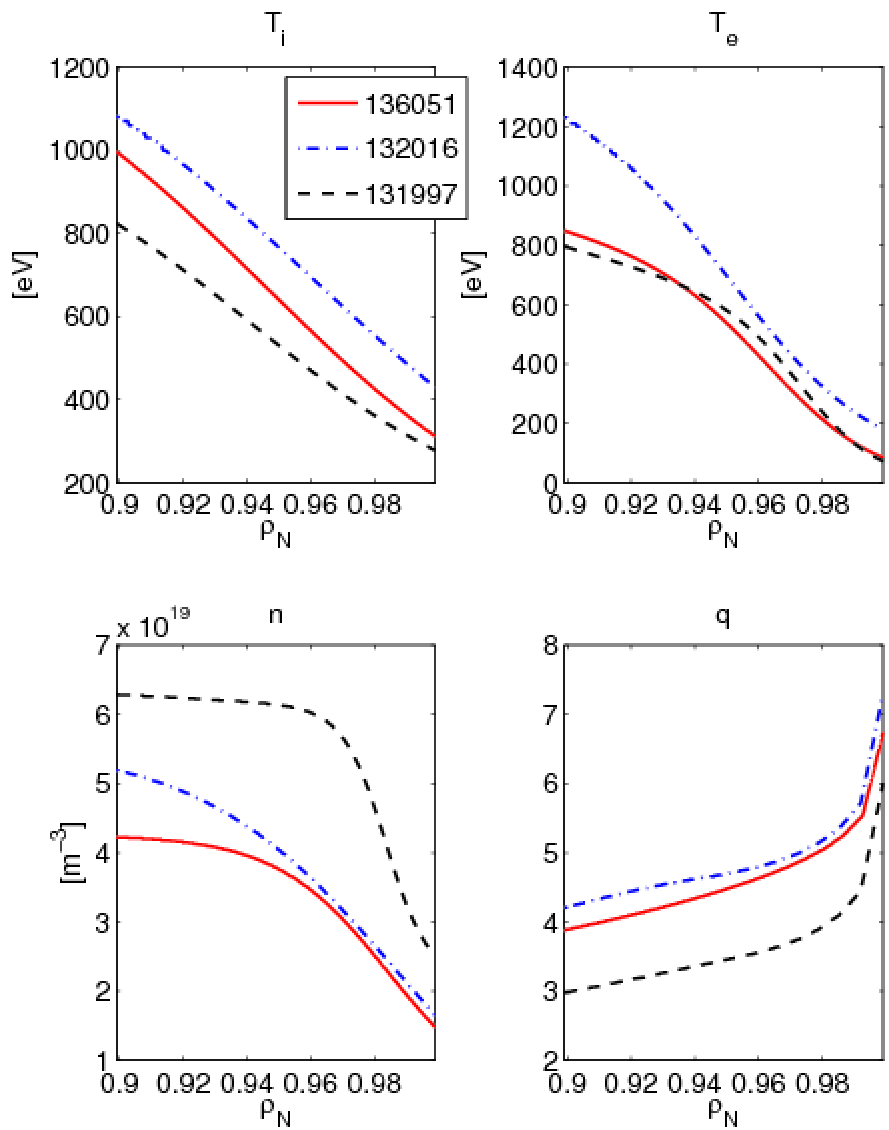
- Electron temperature gradient is more effective than ion temperature gradient.
- Density gradient is also important.

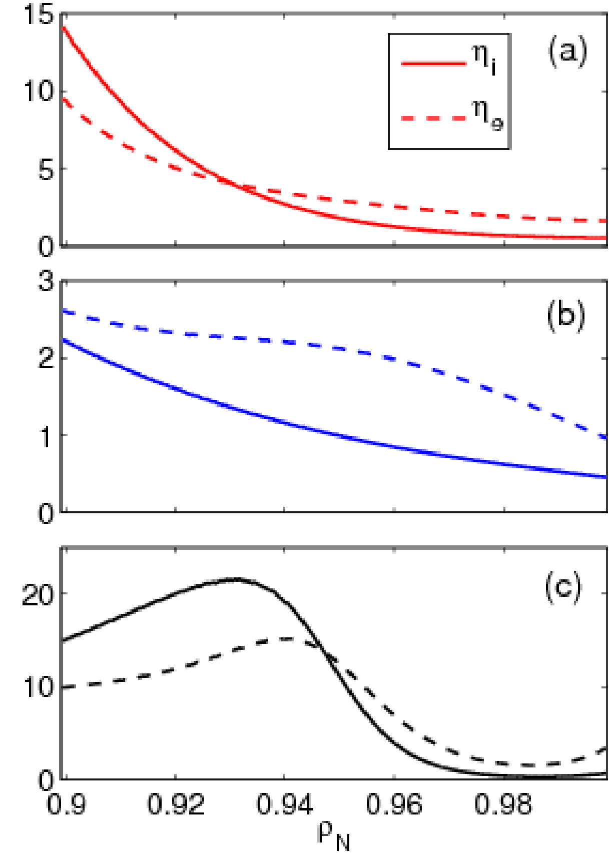
Flux tube conclusions

- Pedestal top:
  - Low k_y: ITG
  - Finite k_x
  - High k_y: micro-tearing? ETG?
- Steep gradient region:
  - Electrostatic
  - Even parity for Φ
  - Propagates in the electron direction for low k and in the ion direction for high k_y
  - Driven by density and electron temperature gradients.
- Results agree well with GYRO.

II. Global Simulations

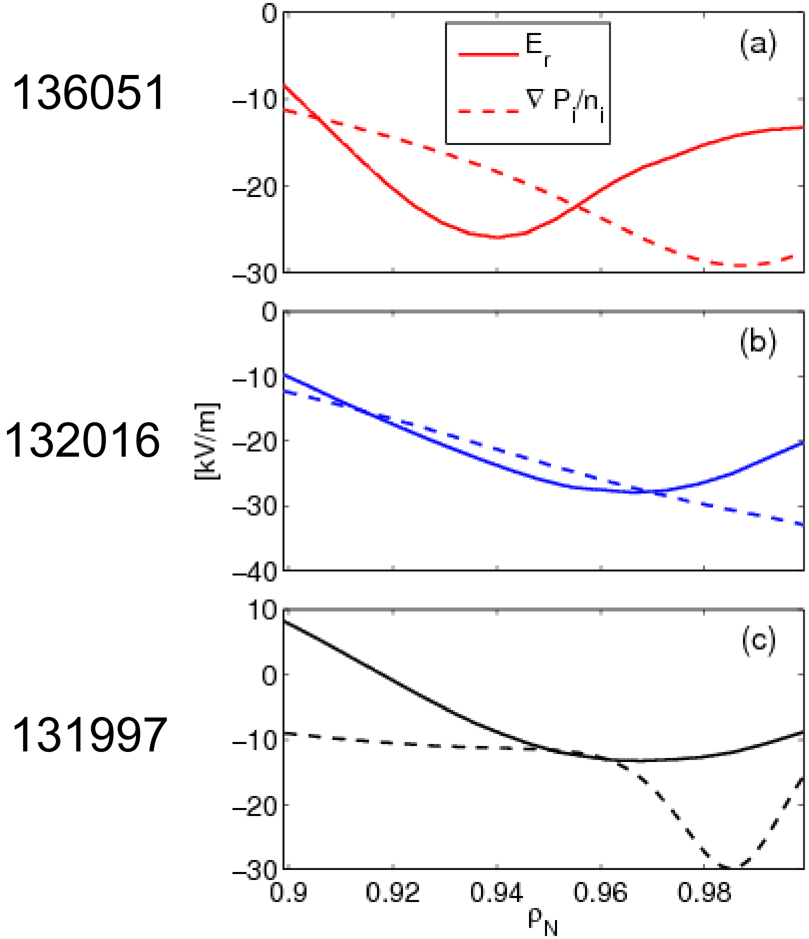
Three very different DIII-D profiles



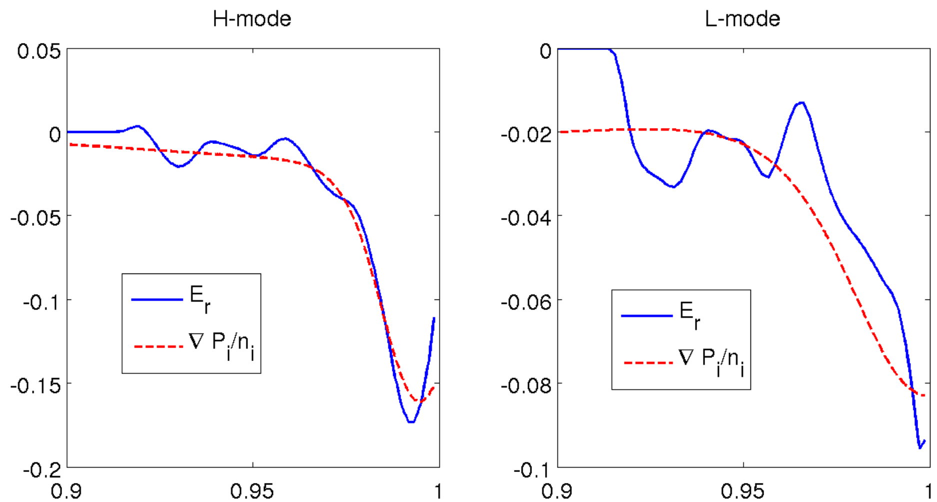


Er NOT necessarily balances grad *P*

Experimental data



XGC0 simulation results



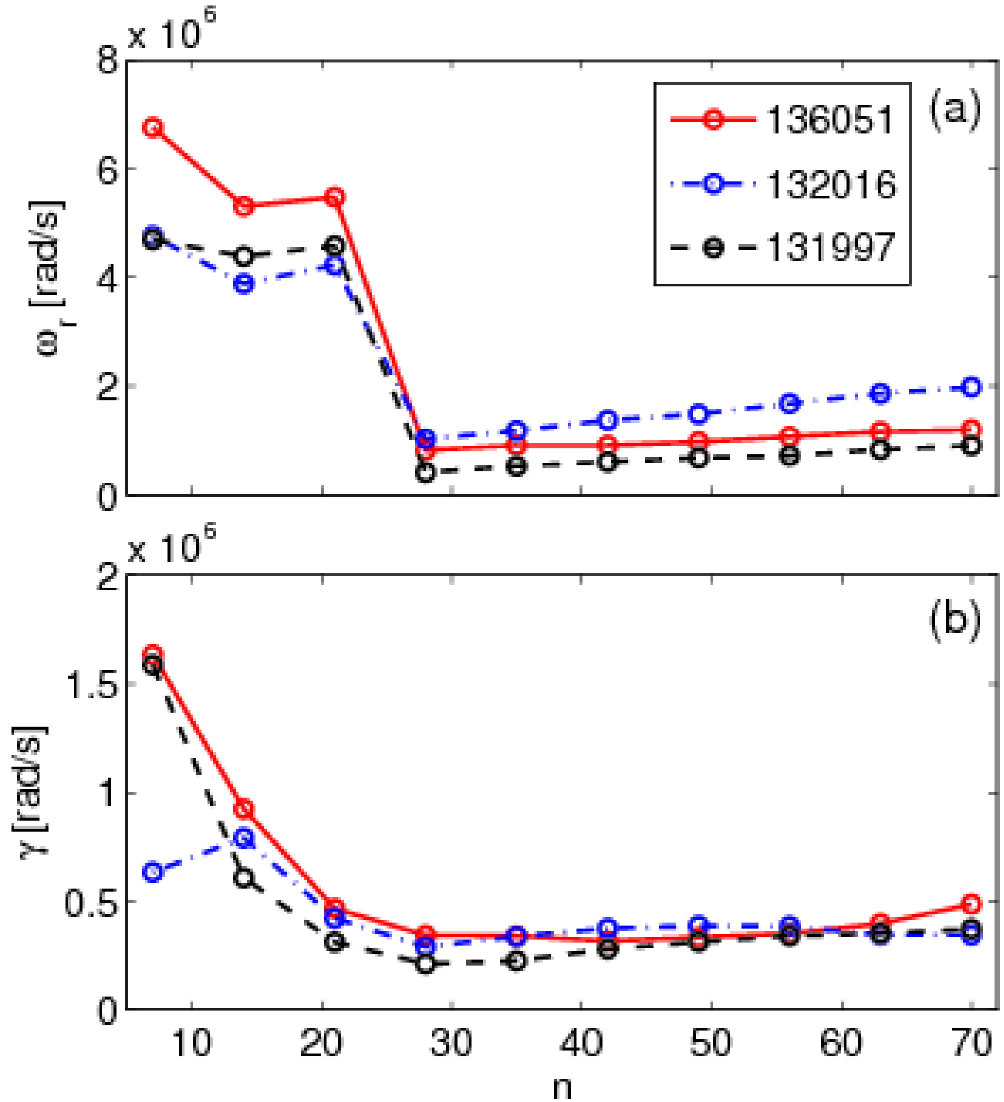
E_r may balance grad P in full-f neoclassical GK simulations

$$E_r = \frac{1}{en_i}\frac{\partial}{\partial r}P_i + (u \times B)_r$$

Two kinds of instabilities

A low n, high frequency mode

$\omega_r \sim \omega_A$

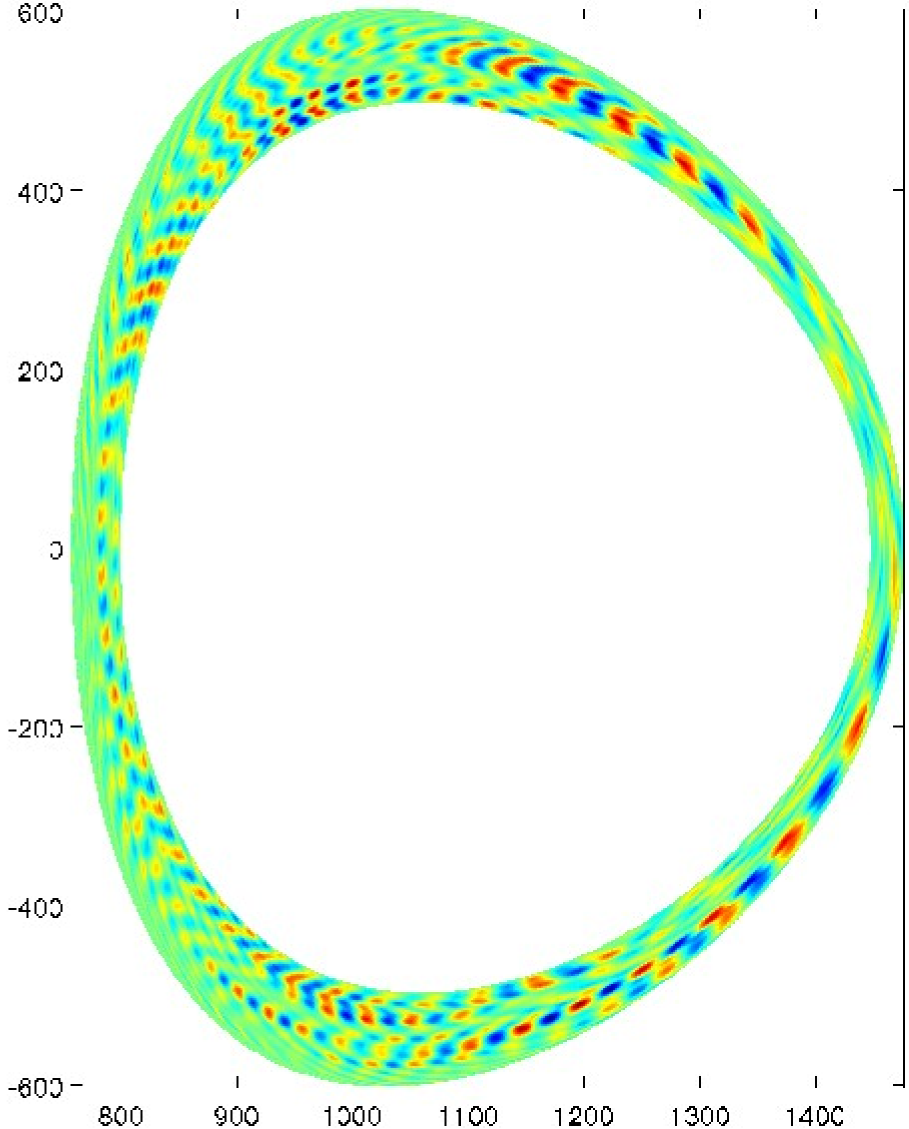


A high n, low frequency mode

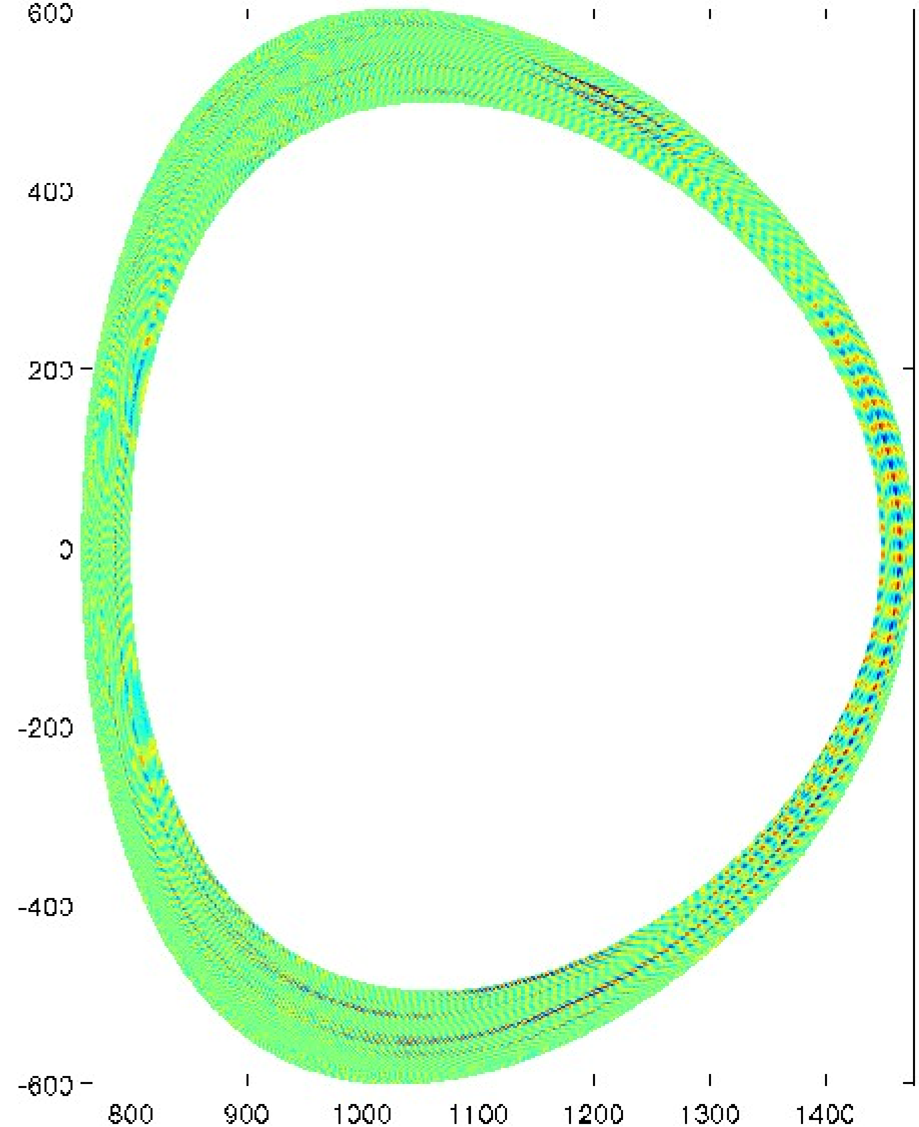
$\omega_r \ll \omega * ¿$

The global cross sections of the two modes

n=10



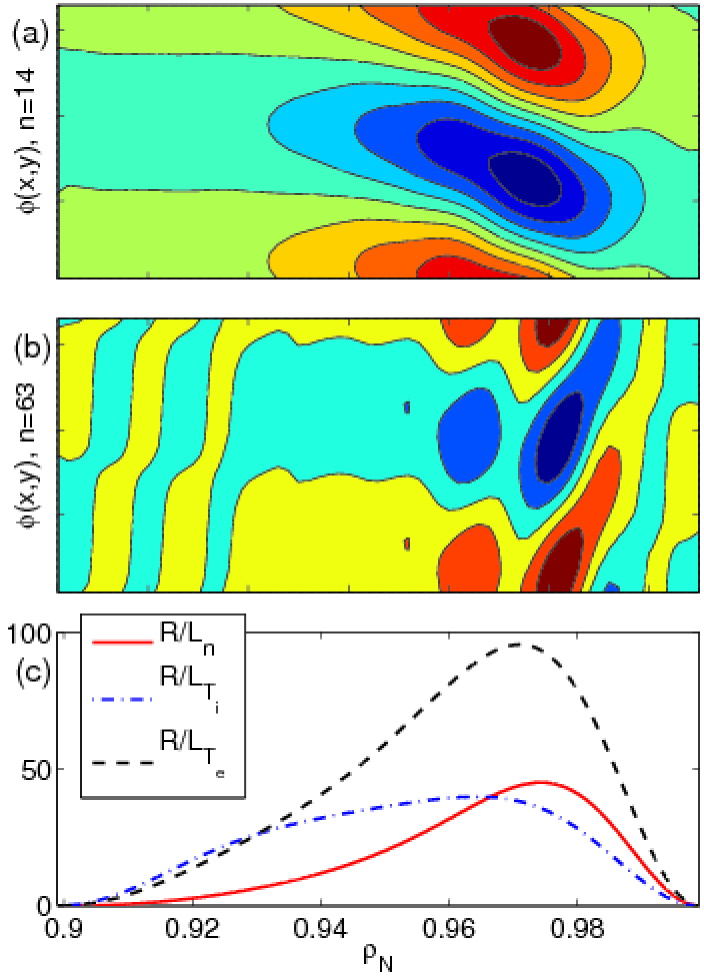
n=63



Both appear at the steep gradient region

low n

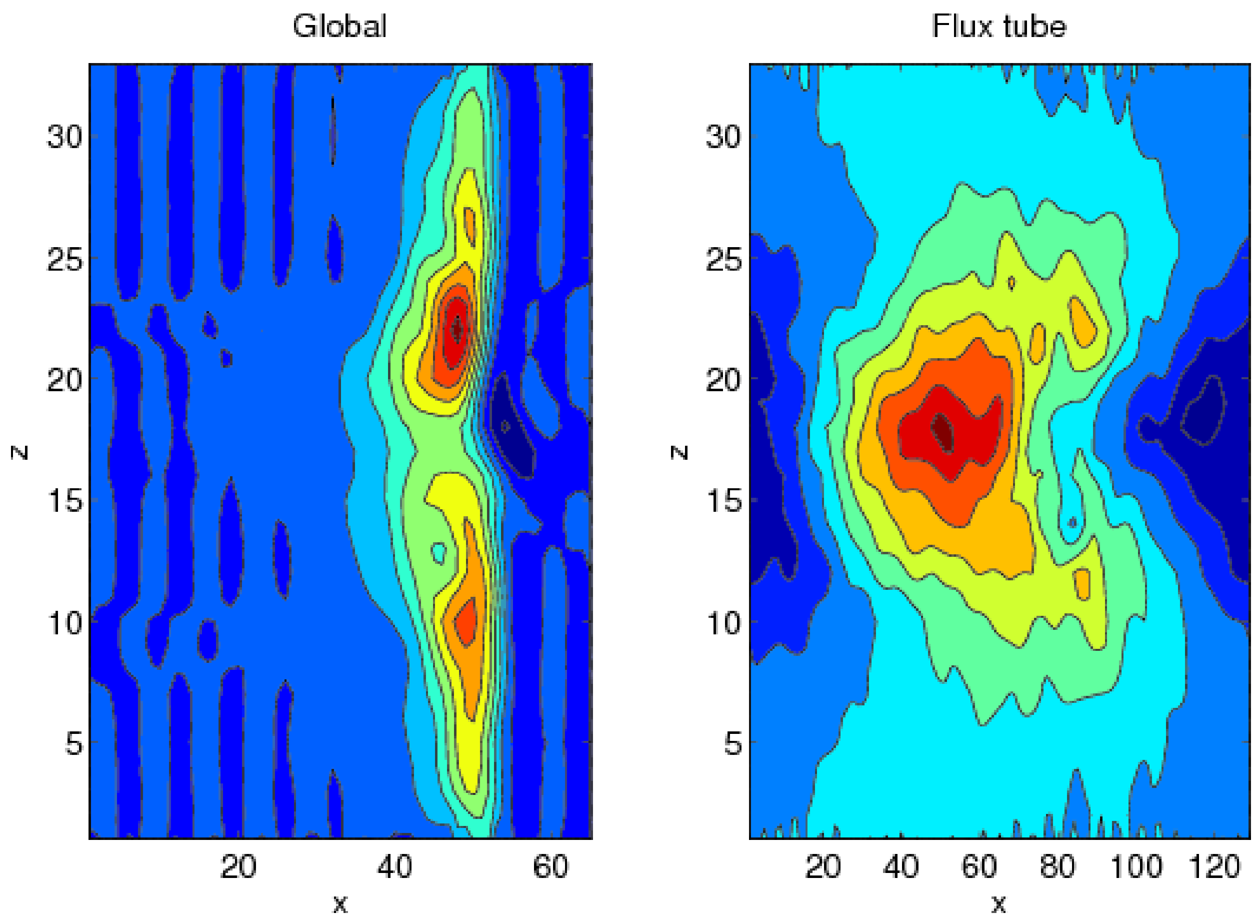
high n



- Density and temperature profiles smoothed at the boundary.
- The E_r shear and magnetic shear also affect the peak of turbulence.
- The high n mode has finite l_x structure.
- Preliminary nonlinear runs show similar phenomenon.

The ballooning structure

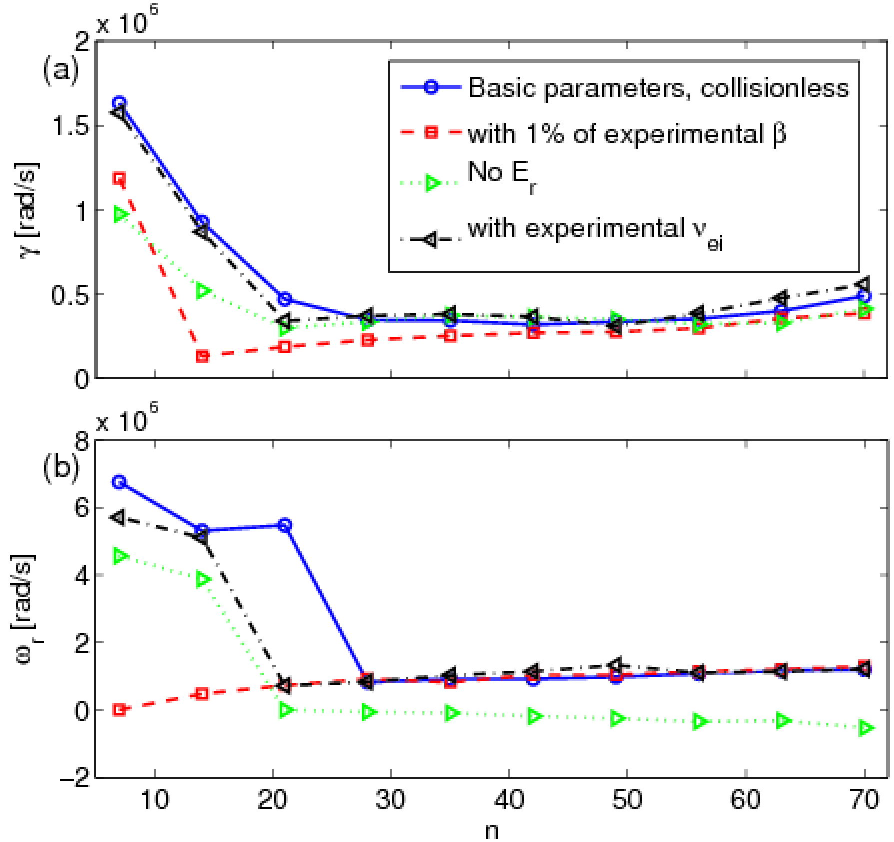
Shot 131997, n=56



$z = q_0 R_{maj} \theta$

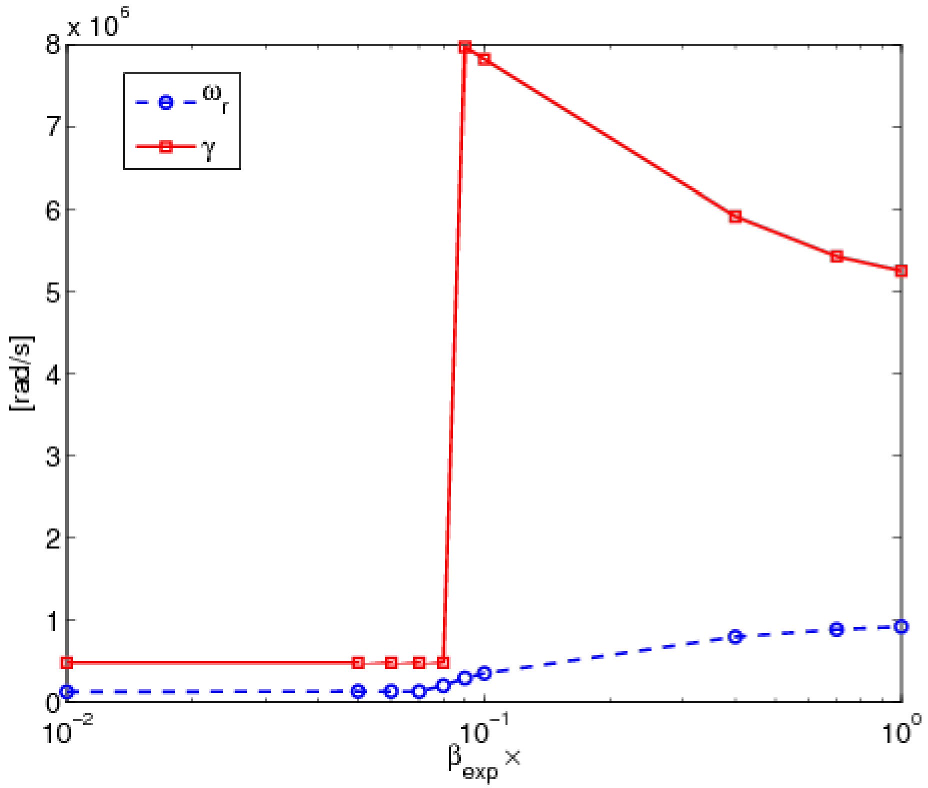
- A clear even parity Φ ballooning structure.
- Finite k_x for high n modes
- Seen in both global and flux tube runs.

Effects of E_r, β, and collision



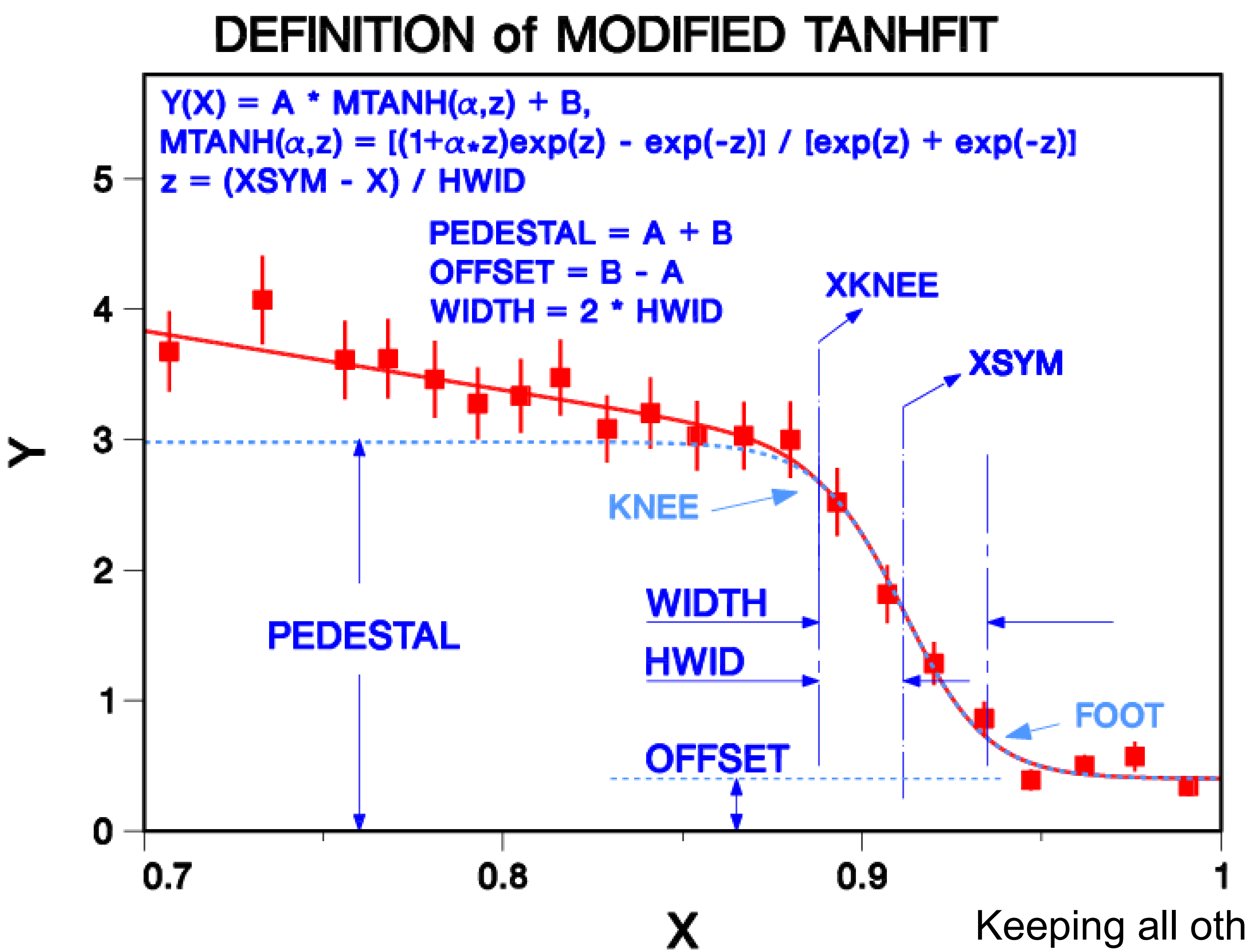
- The low n mode is electromagnetic, the high n mode is electrostatic.
- E_r causes a Doppler shift of the real frequency towards the electron diamagnetic drift direction.
- Collision has little effect for the high n mode but may bring the low n mode down to low frequency.

The high frequency mode has a β threshold



- A critical β exists as a threshold for the low n mode, for both frequency and growth rate.
- A phenomenon looks like KBM, except the mode propagates in the electron diamagnetic drift direction.

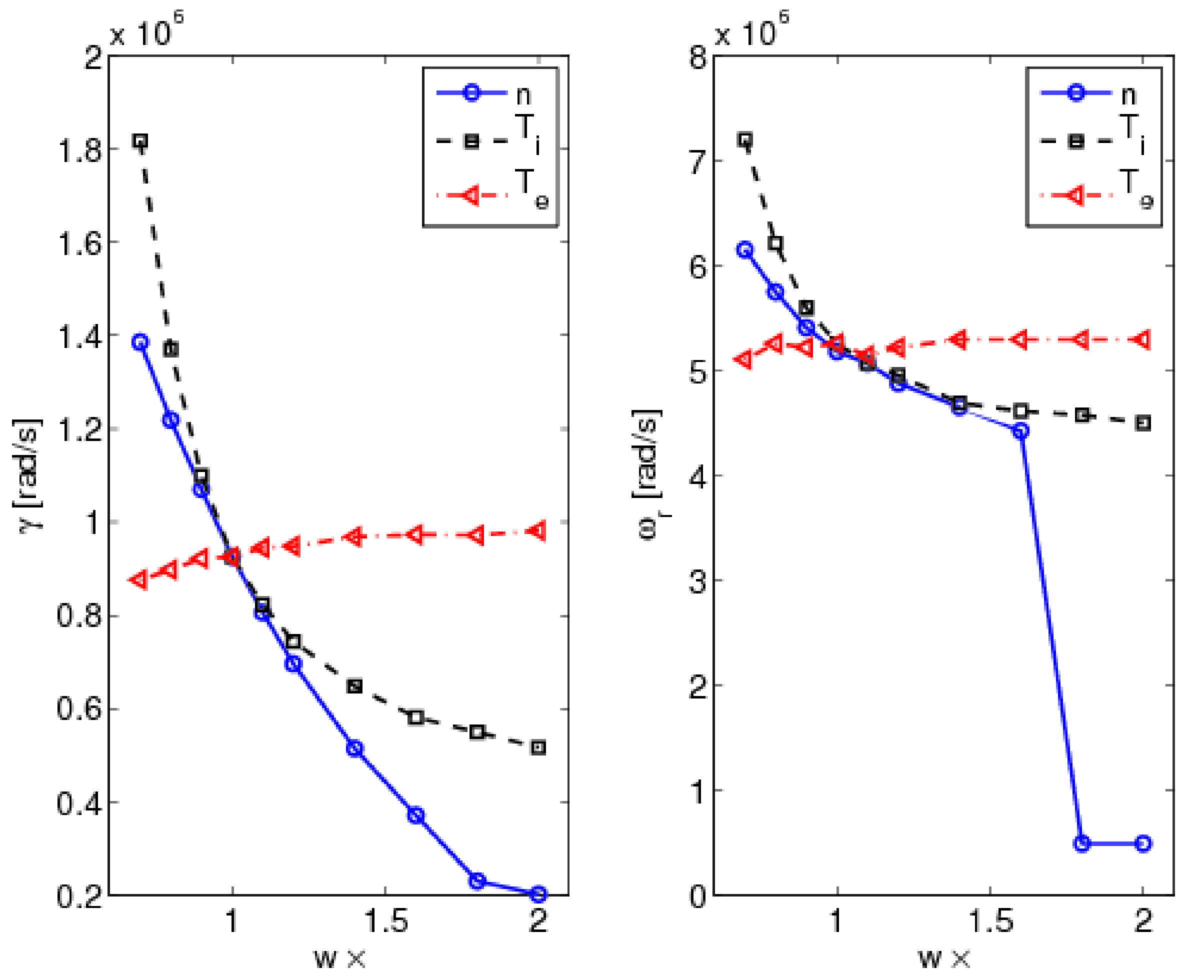
A pressure gradient scan of the two modes



Keeping all other parameters, we multiply the **width** of the density and temperature profiles by a factor.

The low n, high frequency mode is mostly destabilized by density gradient

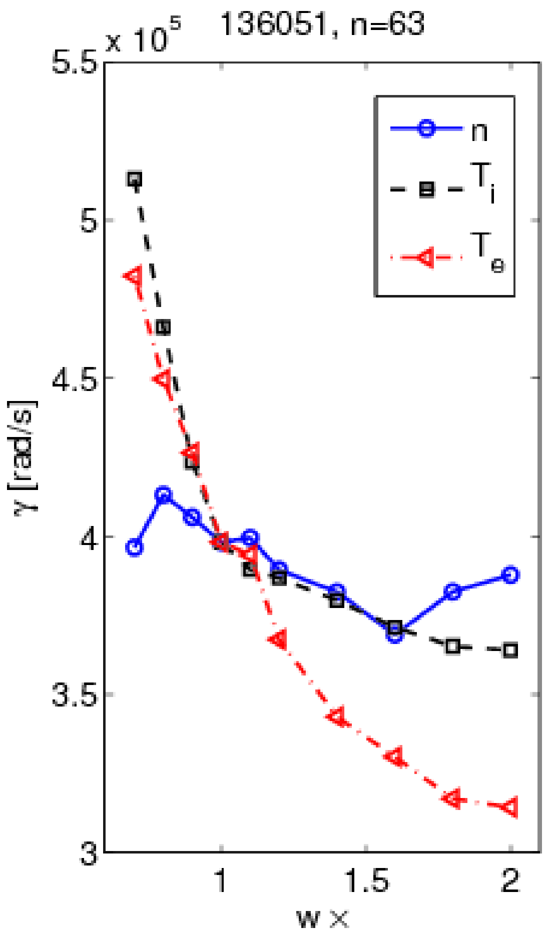
For Shot 136051

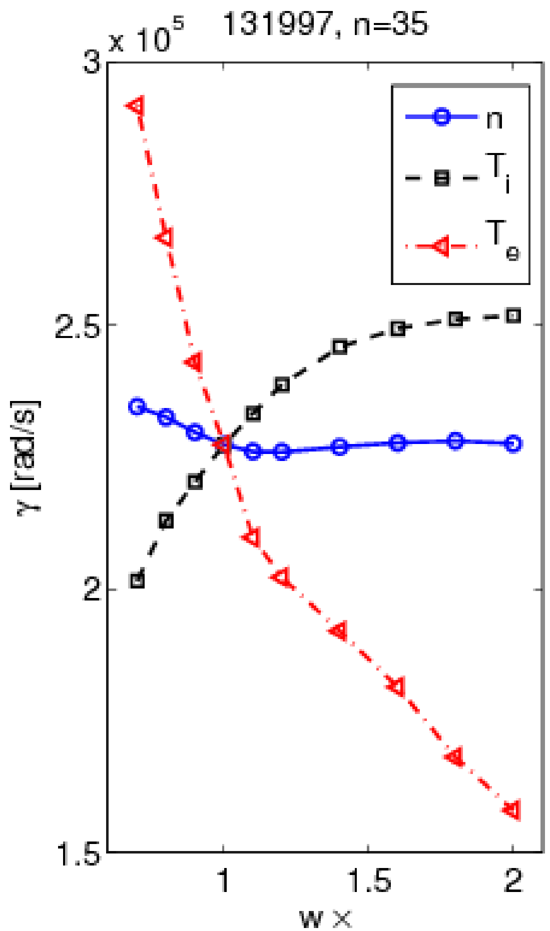


Real frequency drops down to the “high n mode” level when density gradient is small enough.

Same trend seen for all three shots.

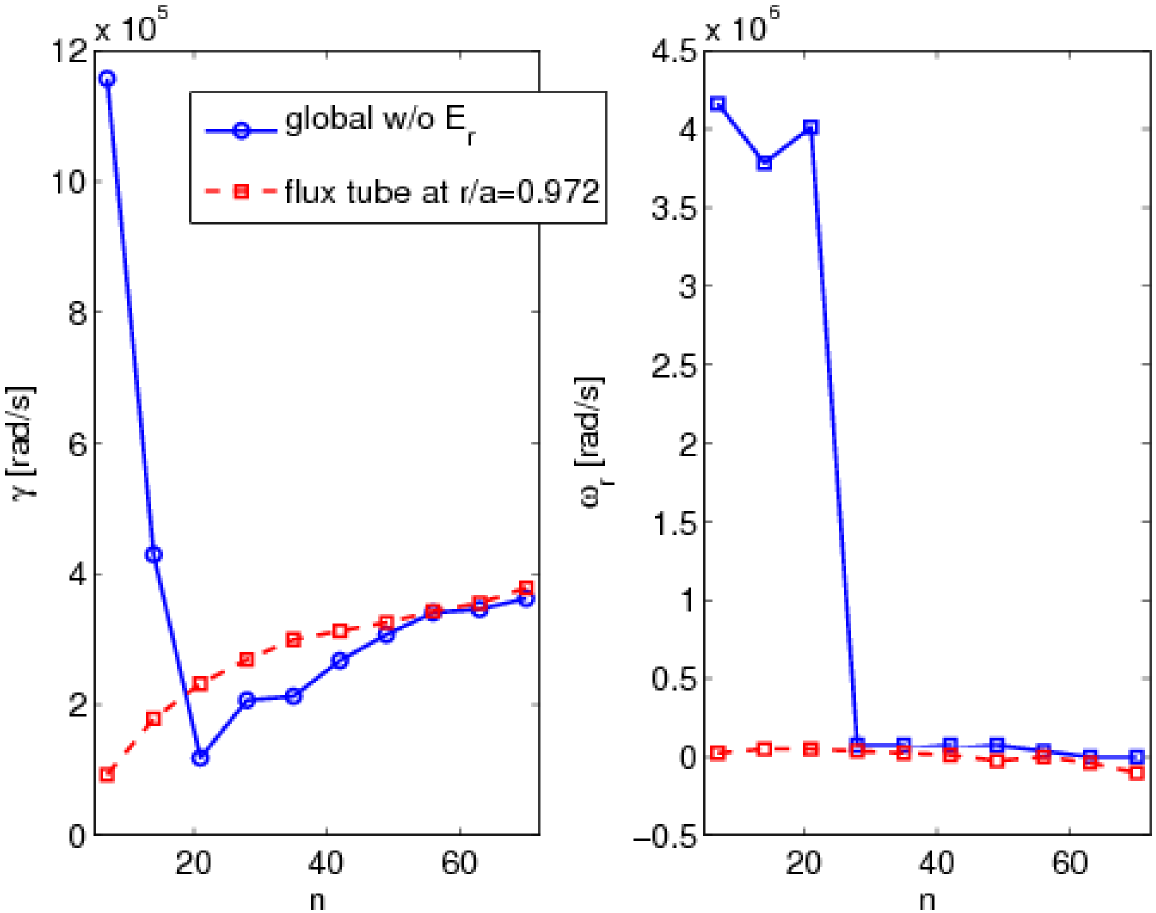
The high n, low frequency mode is mostly destabilized by electron temperature gradient





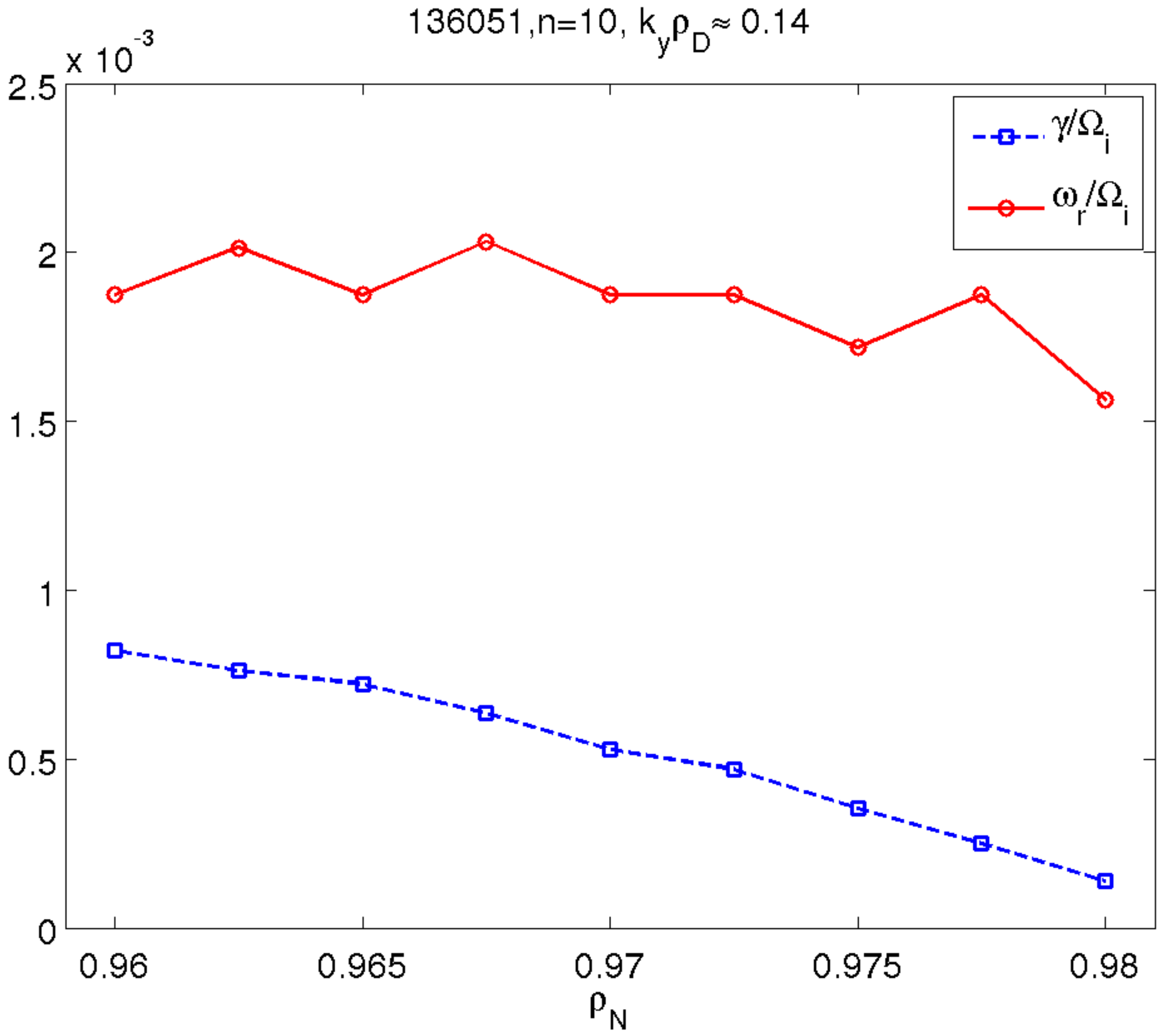
- Electron temperature gradient is the strongest drive in all three shots.
- The effects of density and temperature gradients vary for different shots.

Compare to flux tube simulations



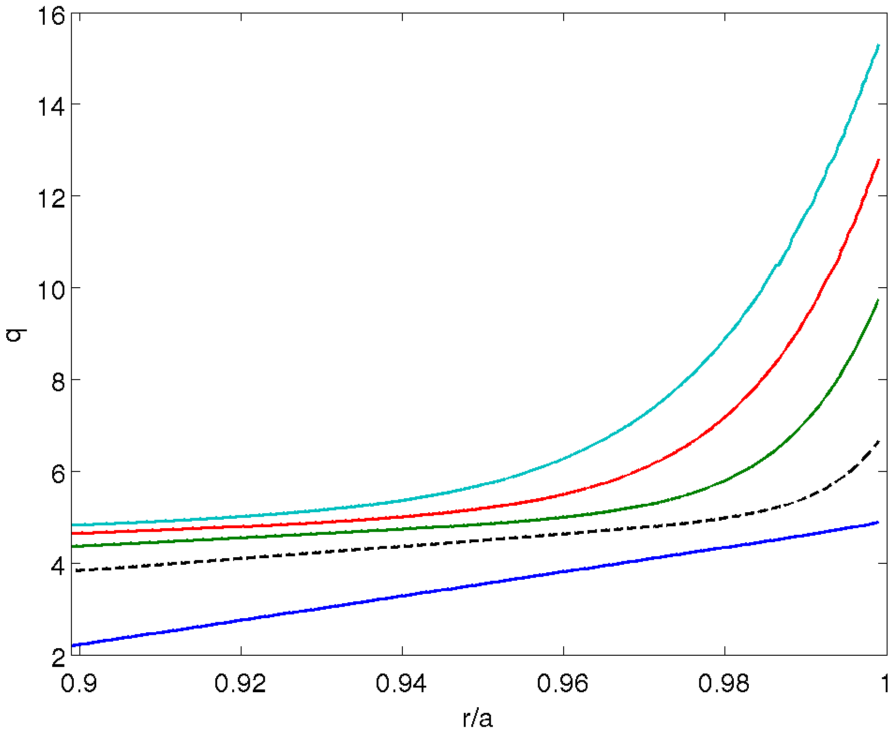
- The global results agree well with flux tube for the high n mode.
  - And our flux tube results agree well with GYRO (see the other poster of us in the same session.)
- The low n mode is only found in global simulations.

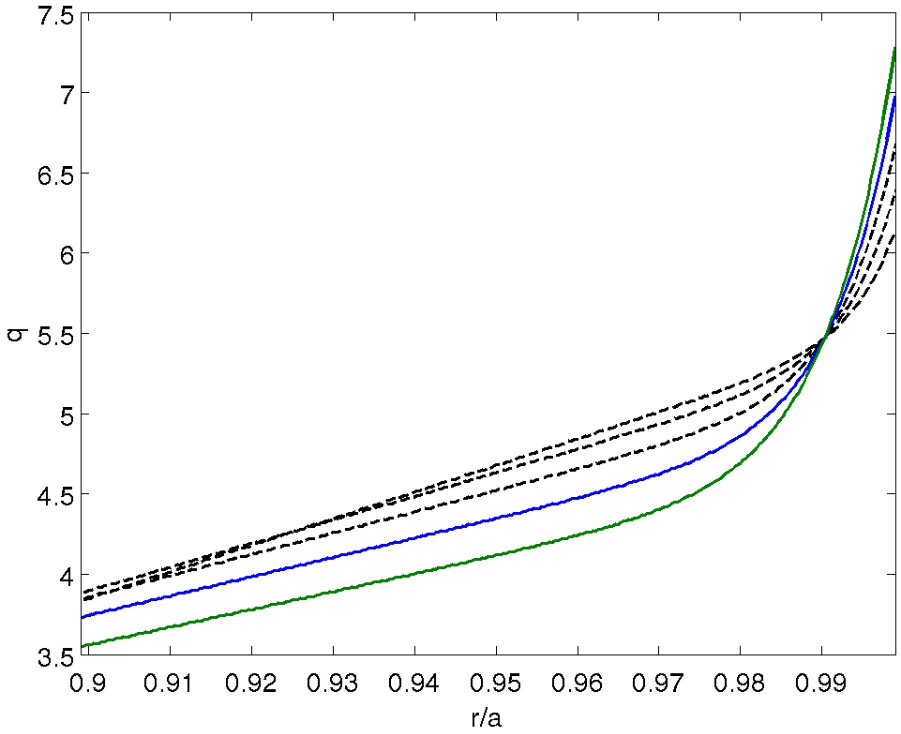
Flux tube simulation of the low n mode sees a much lower growth rate



The low n mode is very sensitive to *q*

We fit an analytical *q* profile and vary the “width” of it near the turning point.





High frequency modes only found in the *q* profiles in black dashed lines.
==> it is caused by the sudden change of magnetic shear.

Conclusions

- In global gyrokinetic particle simulations, two kinds of modes are found with different experimental H-mode profiles.
- The high-n, low frequency mode
  - Mostly destabilized by electron temperature gradient.
  - Agrees well with flux tube simulations.
  - Electrostatic
- The low-n, high frequency mode
  - Mostly destabilized by density gradient.
  - Electromagnetic.
  - Only seen in global simulations.
  - Caused by the sudden change of magnetic shear.