Gyrokinetic Simulation of Tokamak Core and Pedestal Plasmas

Siye Ding[1], Eric Wang[2], Xueqiao Xu[2],
J. Candy[3], R. J. Groebner[3], P. B. Snyder[3] and Guosheng Xu[1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China.
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[3]General Atomics, San Diego, CA 92121, USA

54th Annual Meeting of the APS Division of Plasma Physics
Providence, Rhode Island
Oct 29-Nov 2, 2012

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and is supported by the National Magnetic Confinement Fusion Science Program of China under Contracts No. 2011GB107001, No. 2010GB104001 and 2012GB101000, the National Natural Science Foundation of China under Contracts No. 11075181, No. 11021565, No. 10990212, No. 10725523. LLNL-PRES-598012

Outline

- Introduction
- Linear comparison of a new DIII-D pedestal case and previous work with reduced current in pedestal plasma
- Linear gyrokinetic simulation with full physics in DIII-D pedestal plasma
- Linear global gyrokinetic simulation in DIII-D pedestal plasma
- Linear and nonlinear gyrokinetic simulation in EAST core plasma
- Summary

Introduction

- Gyrokinetic simulation has already been widely used in tokamak plasma core region to analyze the micro-turbulence behavior
- Recently, some endeavor was dedicated to apply gyrokinetic simulations in tokamak pedestal plasma, which has larger GK expansion parameter ρ_i/L_{eq} than core plasma
- Previous gyrokinetic analysis with reduced current and reduced physics model in DIII-D pedestal plasma showed ITG and MT mode are dominant at the top of pedestal, while an unnamed group of drift wave are found to be most unstable in the peak gradient region of the pedestal. KBM is present but subdominant in this region
- In this work, the results of gyrokinetic analysis for DIII-D pedestal plasma with full current, full physics models and global effect are presented, along with EAST core plasma linear and nonlinear simulations
- All gyrokinetic simulations in this work are using GYRO code

Recent advances in GYRO code

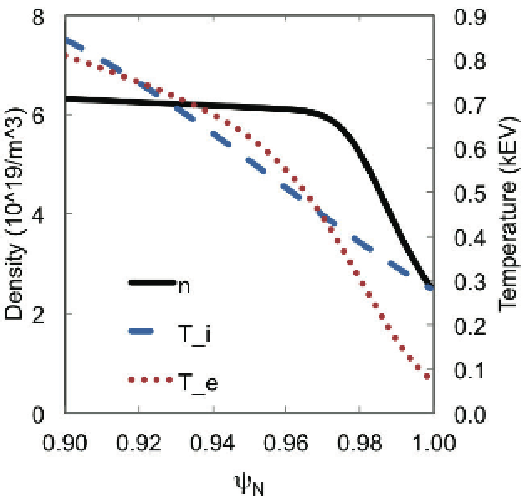
Recent advances in GYRO allow simulations to map out the linear stability of many eigen-values and eigen-vectors of the gyro-kinetic equation (as opposed to only the most unstable) at low computational cost

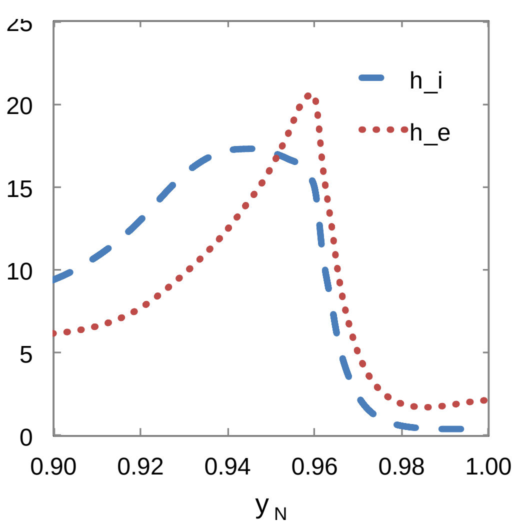
GYRO linear eigenvalue solver

- Exact solution, no Courant condition for collisons
- Can find all unstable modes in the system
- Flux tube, periodic boundary conditions ignore toroidal flow and shear
- Capable of including kinetic electrons, electromagnetic effects and pitch-angle collisions

Similar results have been obtained for full current of DIII-D shot# 145781 to previous shot w/ reduced current (reduced phys)

DIII-D shot# 131997
Previous work





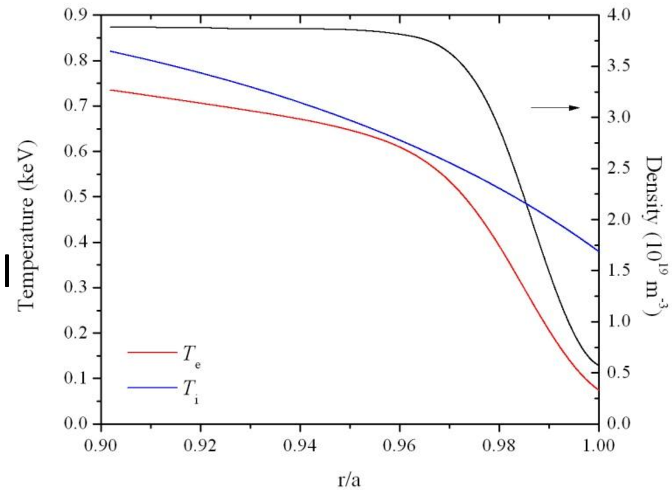
E. Wang, et al., NF, 52(2012)103015

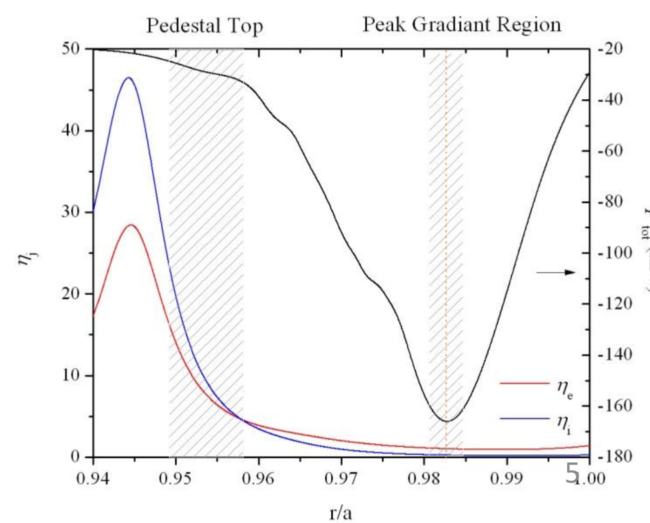
Highlight of previous results:

- Use reduced pedestal current and reduced physics model
- ITG and MT mode are dominant at the top of pedestal
- An unnamed group of drift wave are found to be most unstable in the peak gradient region
- KBM is present but subdominant in peak gradient region

There are some difference in the profiles between these two shots

DIII-D shot# 145781
Present work



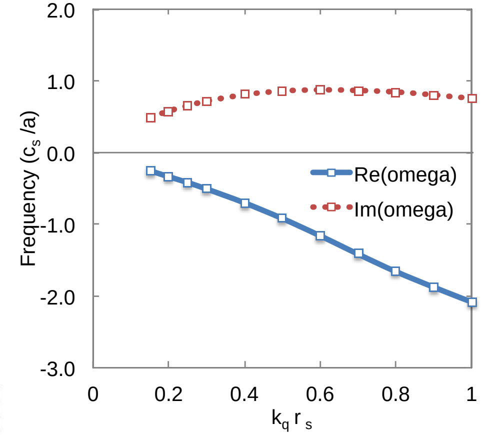


ITG dominant in pedestal top (reduced physics)

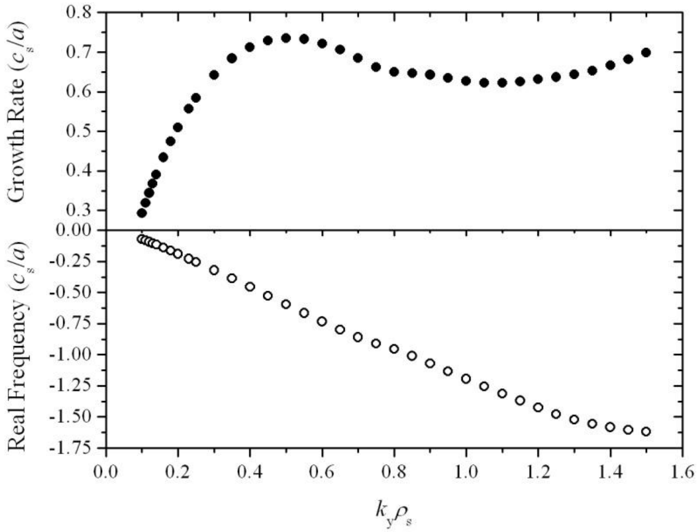
Previous work

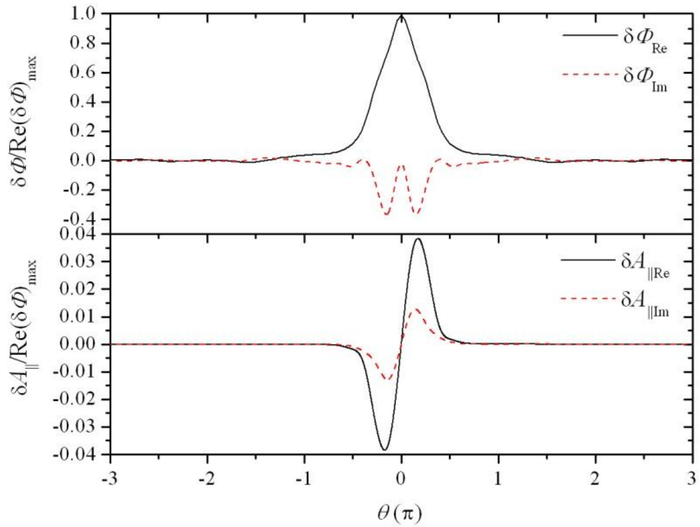
Reduced physics model (cf. previous work):

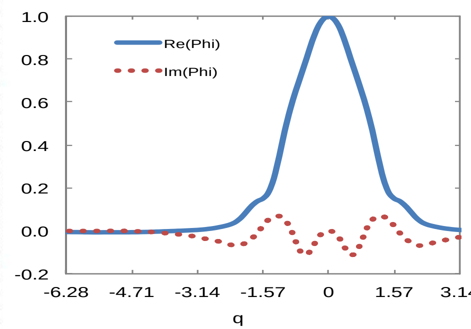
- full gyrokinetic species (ion+electron)
- EM ($\delta\Phi$, $\delta A_{||}$)
- Miller geo
- not rotation
- not collision

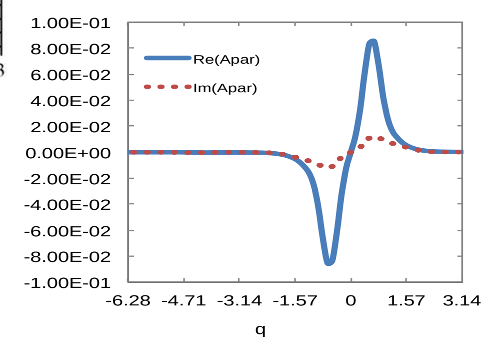


Eigen functions





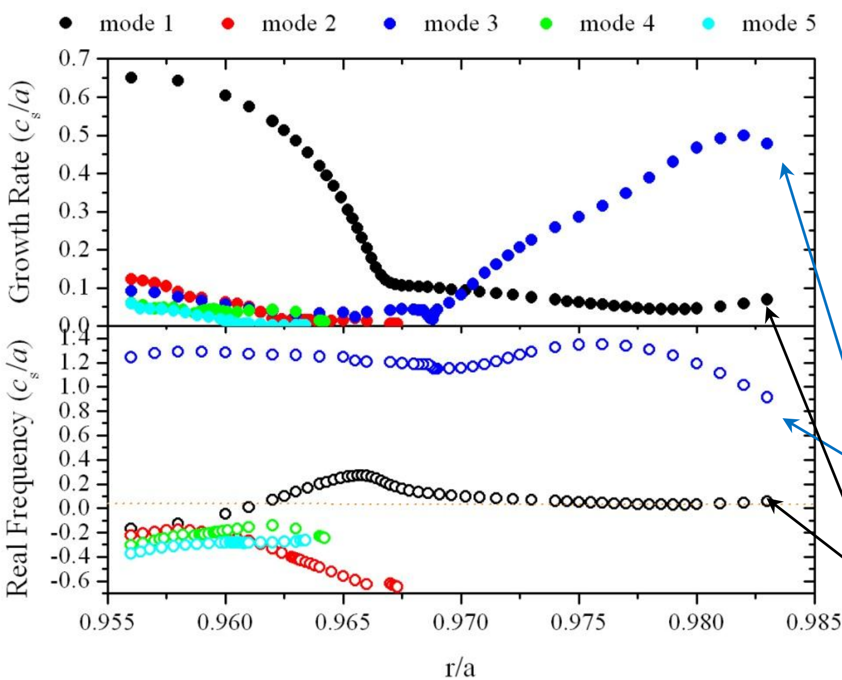




In GYRO, negative value in real frequency is defined as ion diamagnetic direction

Radial scan: mode evolution from pedestal top to peak gradient region (PGR)

$k_y\rho_s$=0.25

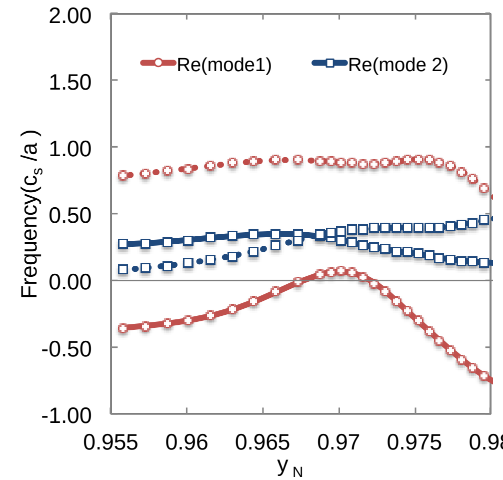


- Some modes detected in pedestal top are stabilized in the evolution from top to PGR
- Two modes which are still active there have MT and ITG parity

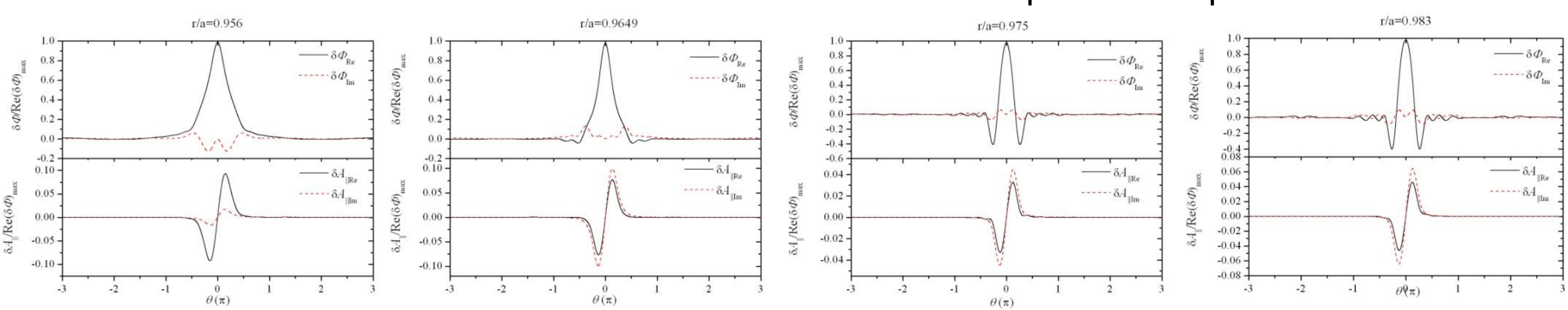
MT parity

ITG parity

Previous work

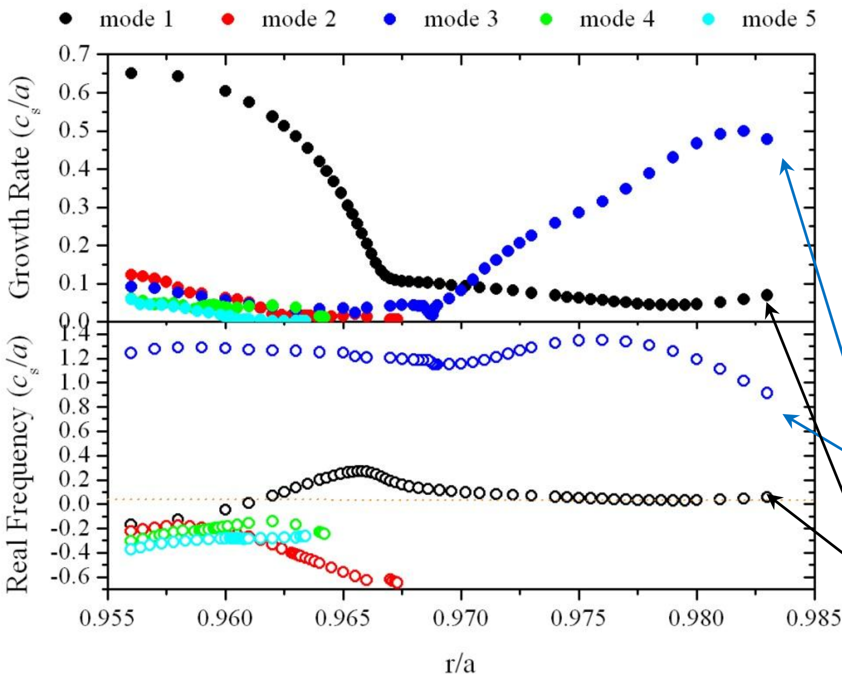


Mode structure evolution from pedestal top to PGR



Radial scan: mode evolution from pedestal top to peak gradient region (PGR)

$k_y\rho_s$=0.25

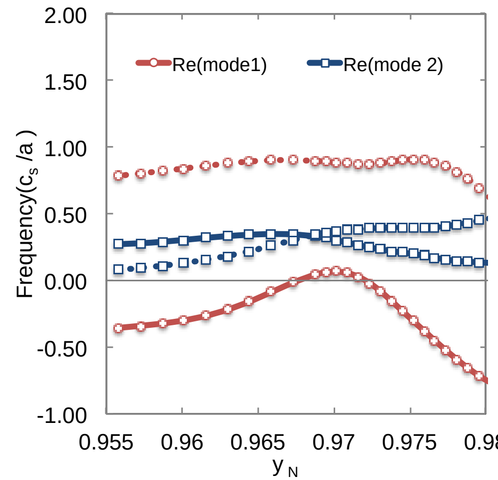


- Some modes detected in pedestal top are stabilized in the evolution from top to PGR
- Two modes which are still active there have MT and ITG parity

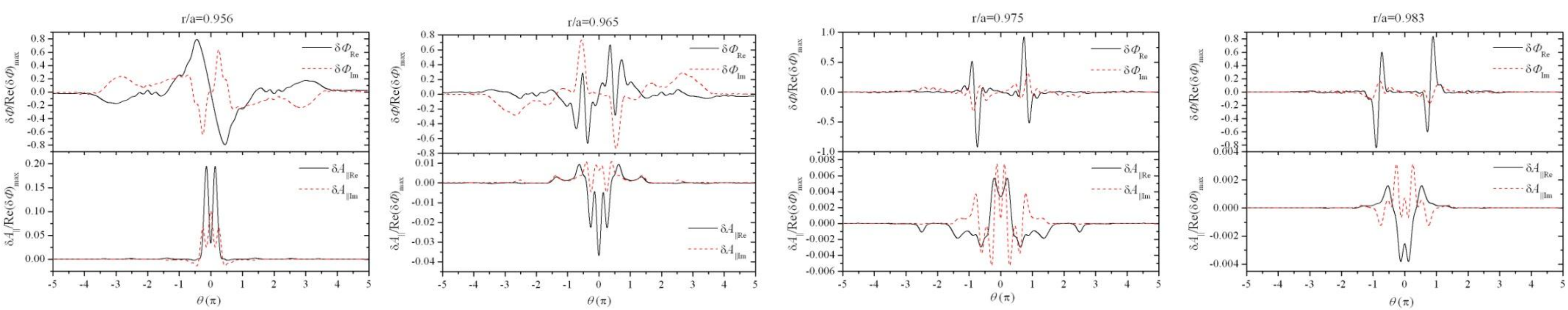
MT parity

ITG parity

Previous work

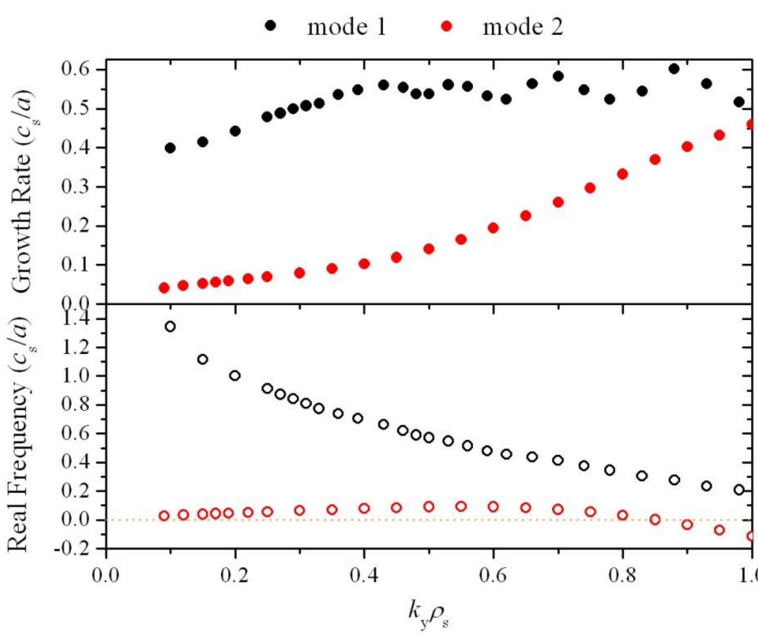


Mode structure evolution from pedestal top to PGR

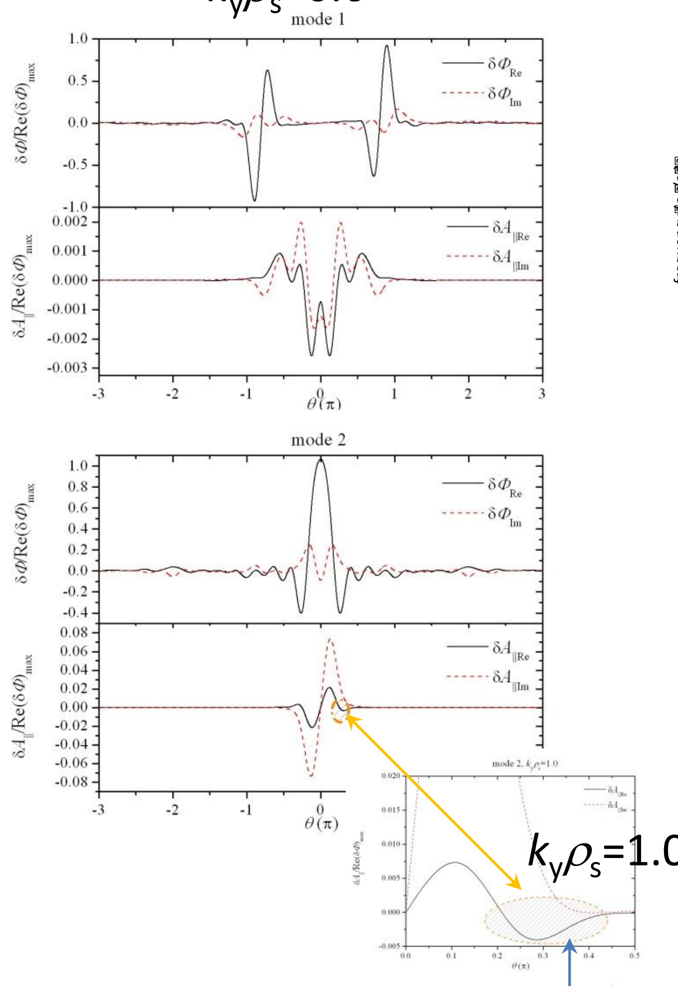


Modes in peak gradient region (PGR) w/ reduced physics model

- Two active modes in PGR w/ MT and ITG parity
- Mode 2 are traced from ITG in pedestal shoulder
- Growth Rates of two modes are getting closer, when kyrhos is about 1
- Mode 2 has a trend that changing from pure ITG parity to “hybrid”

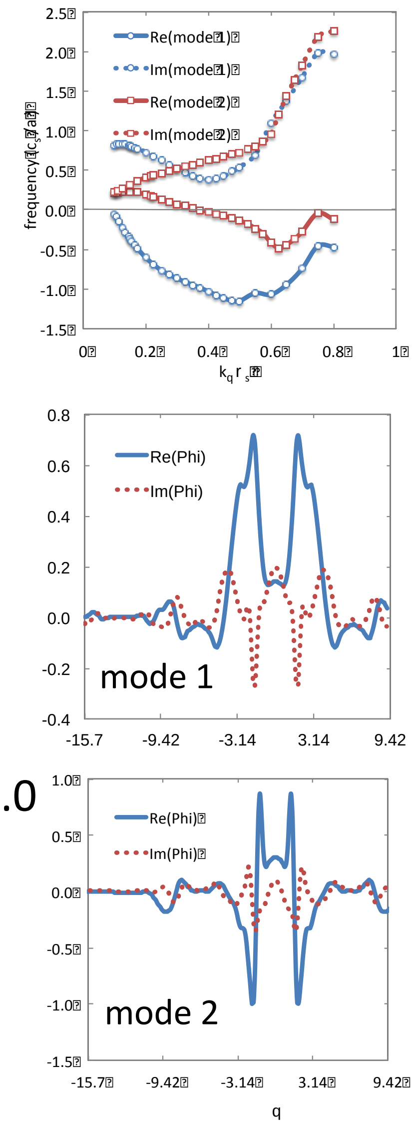


$k_y\rho_s$=0.6



When $k_y\rho_s$ becomes larger, this part will going down → from ITG parity to “hybrid”

Previous work



Conclusion of reduced physics study and work in progress

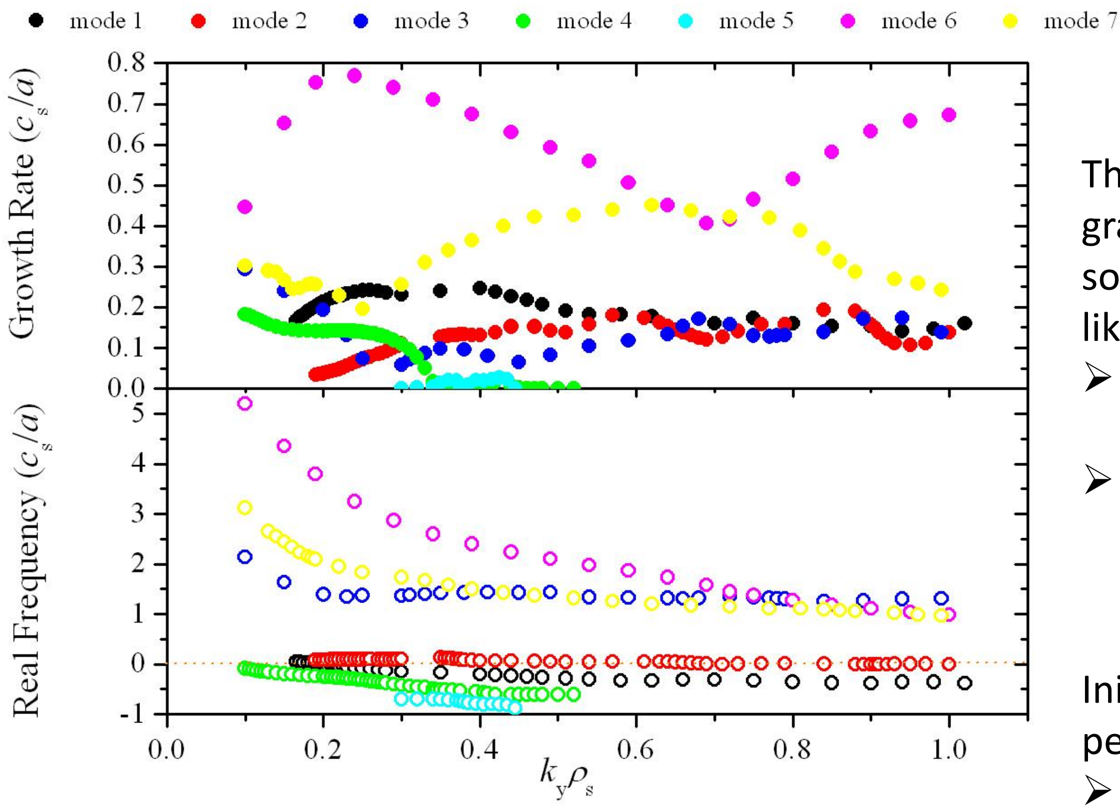
In the reduced physics study:

- Although there are some difference in profiles, major similar results are obtained (cf. previous work E. Wang, NF, 52(2012)103015)
  - ✓ ITG dominant in pedestal top
  - ✓ Modes are stabilized in radial scan from pedestal top to peak gradient region
  - ✓ Two active modes are detected in peak gradient region
- Difference between presented and previous work
  - ✓ Two active modes in peak gradient region have MT and ITG parity in eigen function
  - ✓ Two modes are basically in electron diamagnetic direction

Work in progress:

- Setting up global simulations
  - ✓ Profile variation
  - ✓ Nonlocal effects
- Characterize and identify instabilities in unmodified pedestal, using physics previously ignored
  - ✓ $\delta B_{||}$
  - ✓ Rotation
  - ✓ Full geometry
  - ✓ Collisions
  - ✓ Profile variation

Full physics simulation in PRG part I – w/ $\delta B_{||}$, rotation, full geo, w/o collision



Calculated by GYRO eigenvalue solver

In this simulations, n_{orb}=16, i.e. 60 mesh points along an orbit in velocity grids

The EPED model predicts the pressure gradient is constrained by KBM fluctuations, so that experimental pedestal profiles are likely near the KBM stability threshold.

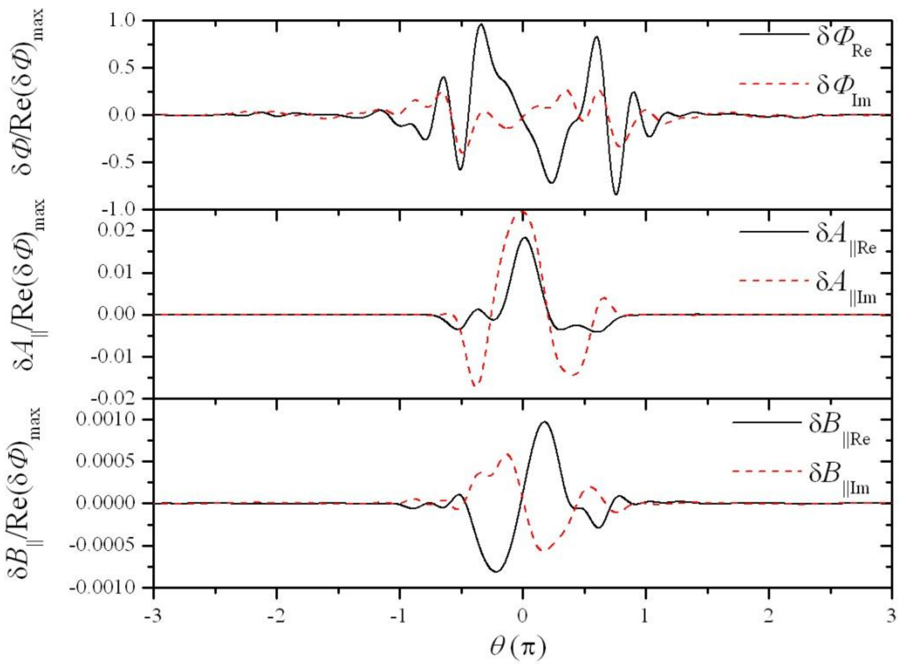
- In the absence of the KBM, what instabilities determines transport levels?
- Where in the pedestal will the most unstable mode appear?

Initial studies of this new discharge in the peak gradient region demonstrates:

- A large number of modes present
- The most unstable of which is in the electron diamagnetic direction, near Alfvenic frequencies

Full physics simulation in PRG part I – w/ $\delta B_{||}$, rotation, full geo, w/o collision

Mode 6, $k_y\rho_s$=0.39, eigen functions:



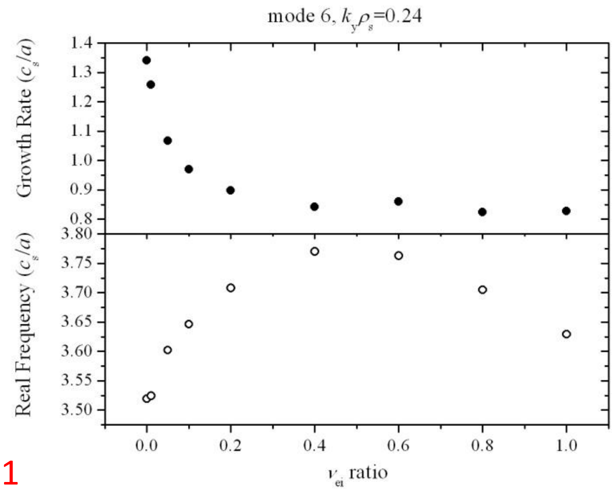
- Mode structure of electron modes oscillates on grid scale
- With different grid size
  - ✓ Structure changes
  - ✓ Sometimes frequency changes with different resolution, sometimes not

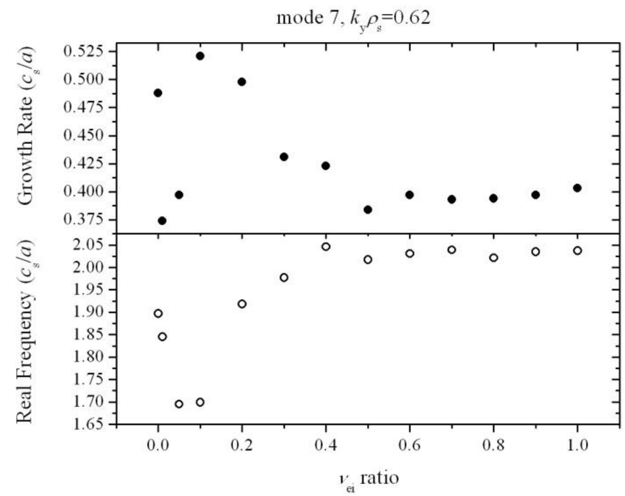
Are these modes physical or numerical?

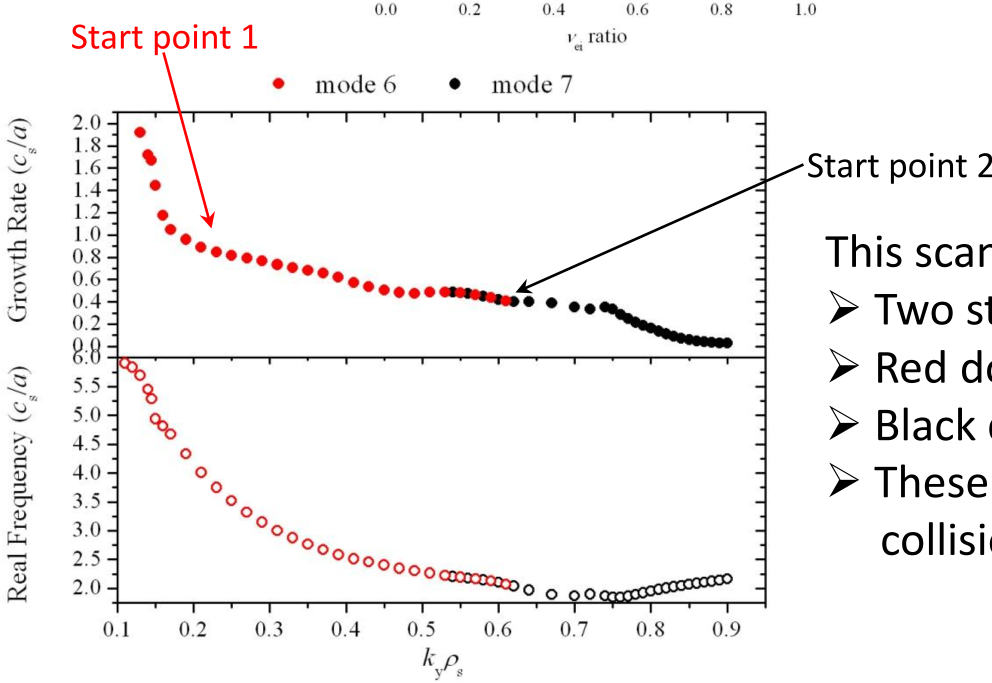
Full physics simulation in PRG part II – w/ $\delta B_{||}$, rotation, full geo and collision

Attempt to scan from no collision case (previous scan) to collisional case

n_{orb}=12







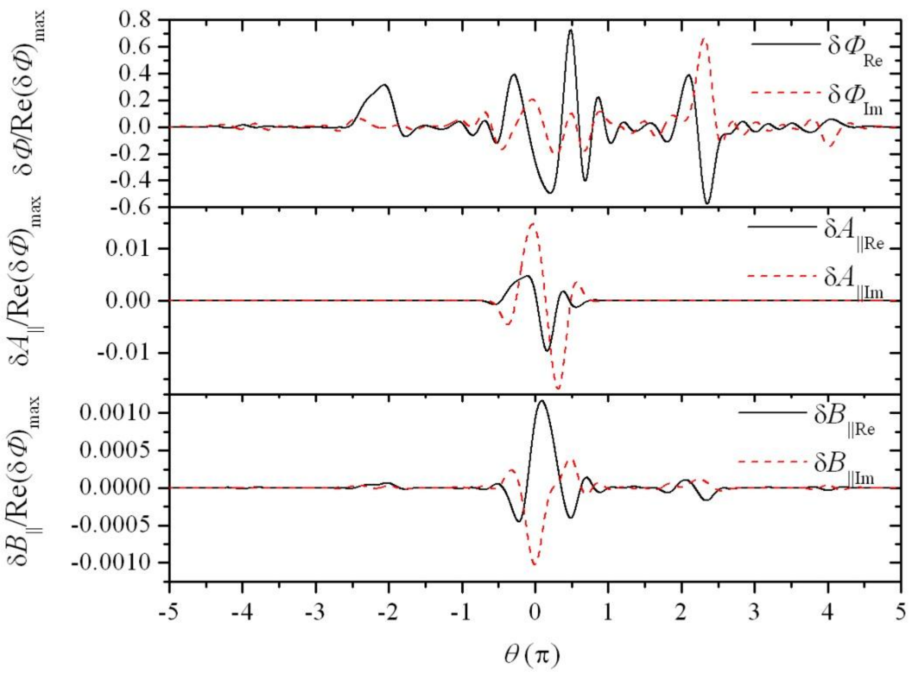
ν_{ei}=1.23 in c_s/a

This scan:

- Two start points from two modes showed above
- Red dots start from $k_y\rho_s$=0.24 (mode 6)
- Black dots start from $k_y\rho_s$=0.62 (mode 7)
- These two modes appear to merge together, when collision term is present

Full physics simulation in PRG part II – w/ $\delta B_{||}$, rotation, full geo and collision

Eigen function of previous scan @ $k_y\rho_s$=0.6



- It seems to be a little under-resolved
- This mode can not be identified simply by examining eigen functions
- Further study (various scans on β_e , etc.) will be carried on

Constraints of global simulations of pedestal profiles

Using flux tubes (constant profile gradients) in the pedestal is likely to be inaccurate, as the sharp pedestal gradients cause profile variation on length scales comparable to the flux tube size. Global simulations (which allow for profile variation) would be able to quantify how reasonable the flux tube limit is to employ.

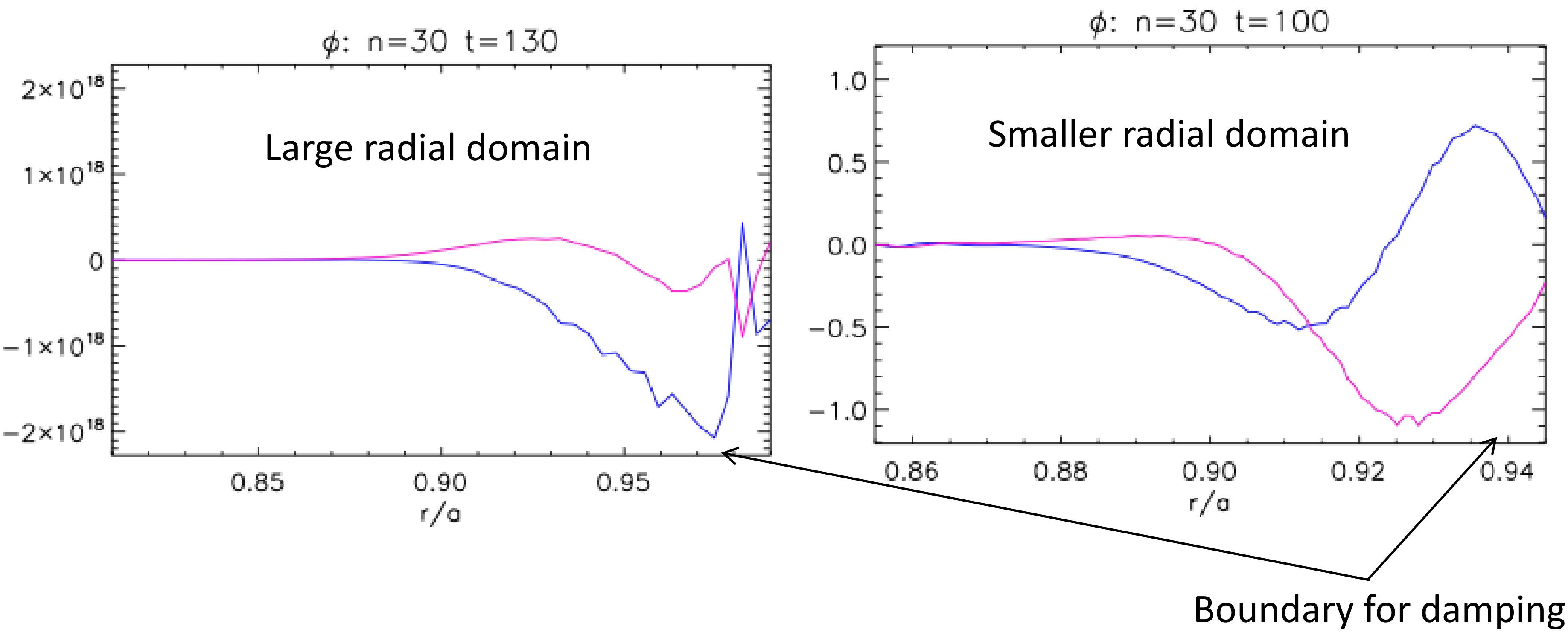
Two constraints exist with running GYRO as a global simulation

1) The radial domain cannot exceed the last closed flux surface
    a) Choose center r_0, toroidal mode number n
    b) Choose radial length, typically multiple of rational surface length.
    c) If the center of the radial domain is near the top of the pedestal, this allows for around 4 rational lengths to fit.

2) There must exist a damping region to inhibit long radial wavelength growth at both ends of the radial domain. Empirical experience indicates this region should be at least $8^*\rho_s$ wide.

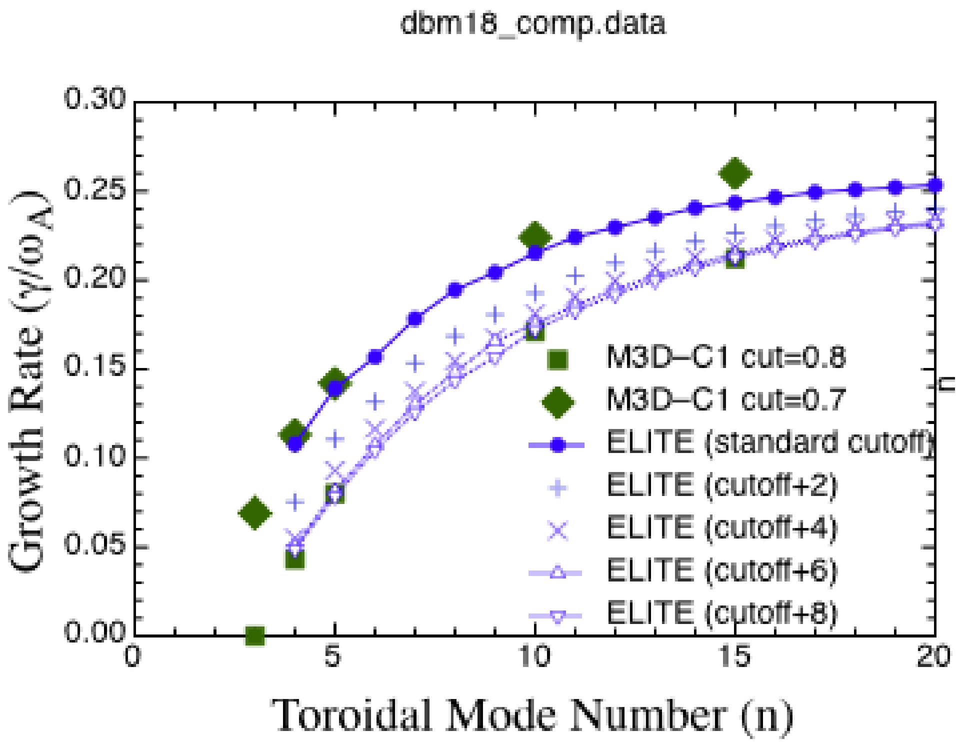
    Problem: right boundary MUST be before last closed flux surface. Peak gradient lies at r/a=0.987 and $8^*\rho_s/a$~0.138

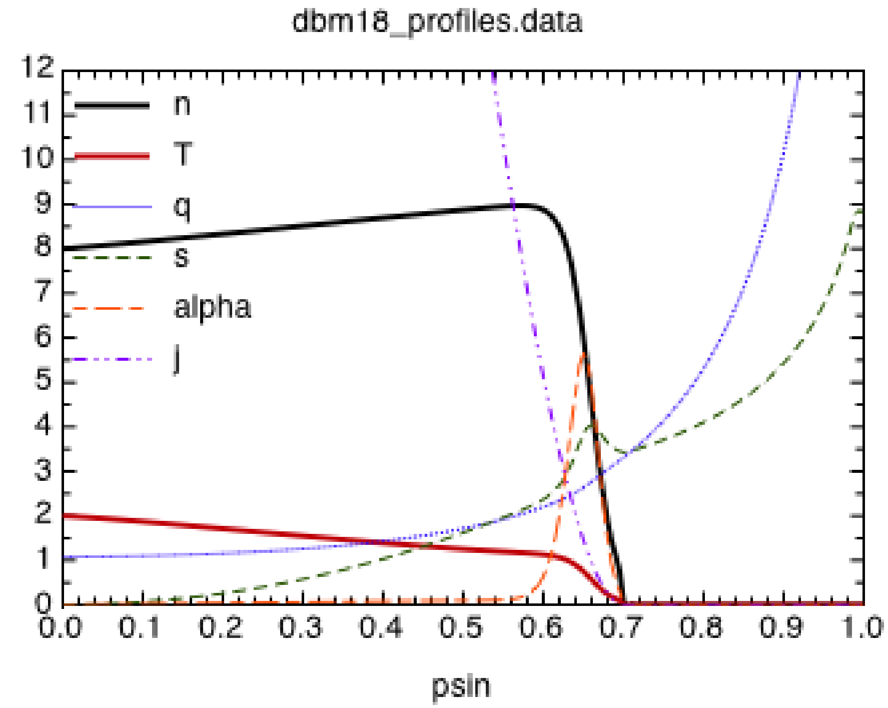
Global simulations in the pedestal peak in the damping region



Problem arises from mode peaking at or near the edge of the buffer region! This is likely due to the peak gradient of the pedestal lying within the damping region of the global simulation. We cannot extend the radial domain beyond the last closed flux surface so…

MHD calculations create shifted profile to allow buffer adequate length



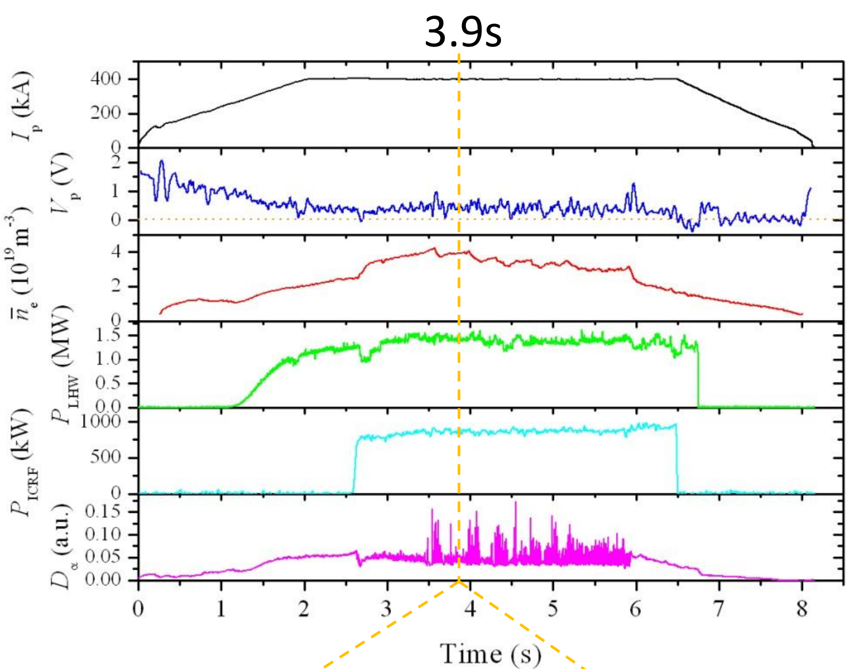


NEXT STEP:

Take the modified profiles MHD calculations use to quantify the significance of profile variation within the simulation.

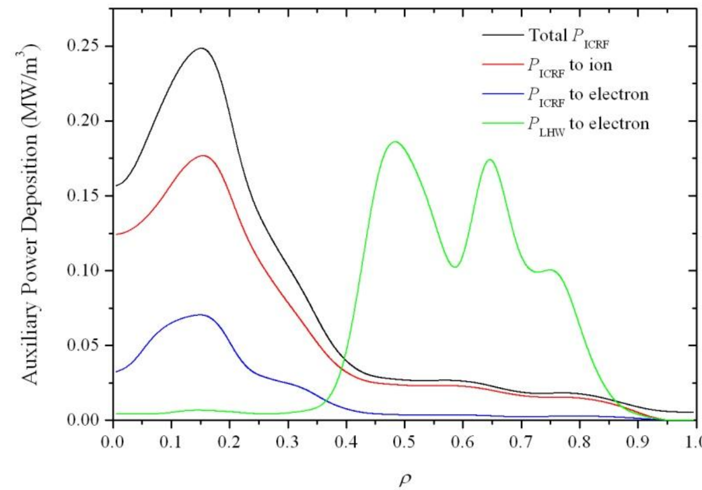
Caveat, cannot let the pressure go to zero, so may require a finite upshift in pressure in the 'tail' region

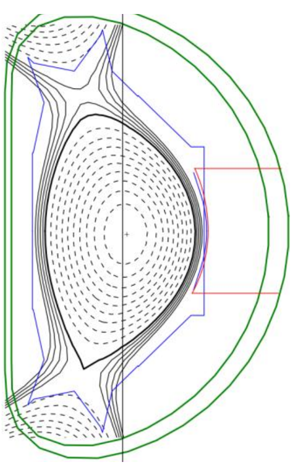
Basic info and TRANSP analysis for EAST shot# 38300

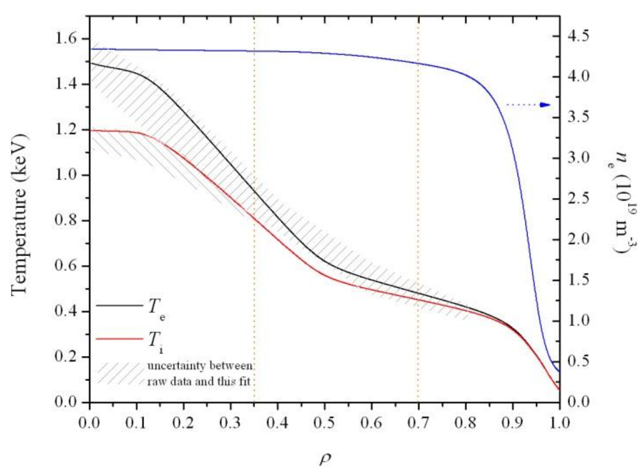


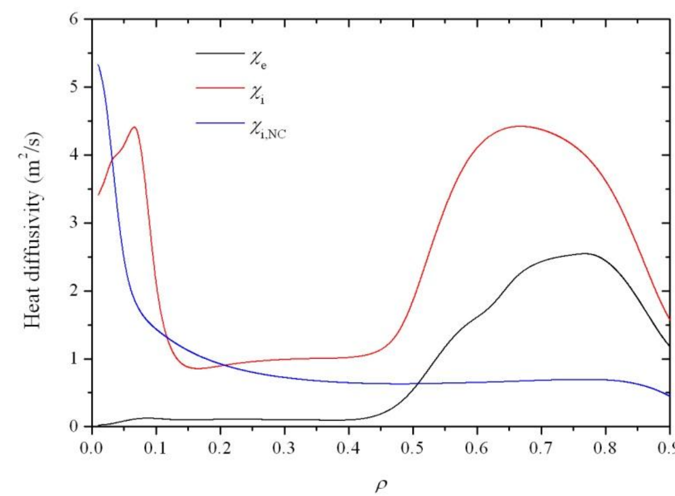
Caveat:
This fit was chosen to be the most steep fit that can test gyrokinetic analysis on low and high transport level

TRANSP power balance analysis for one time slice (3.9s)

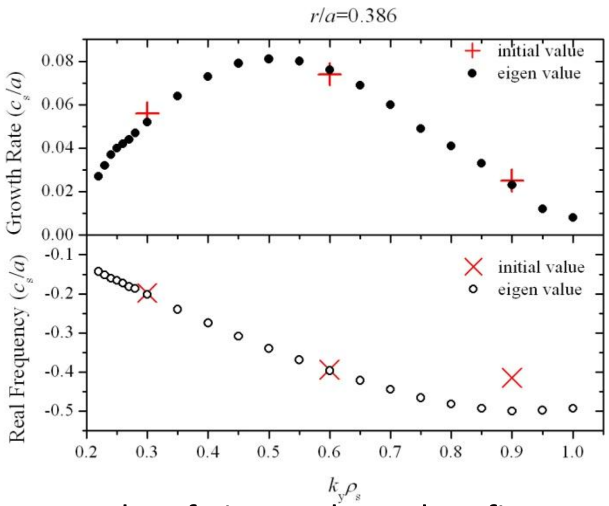






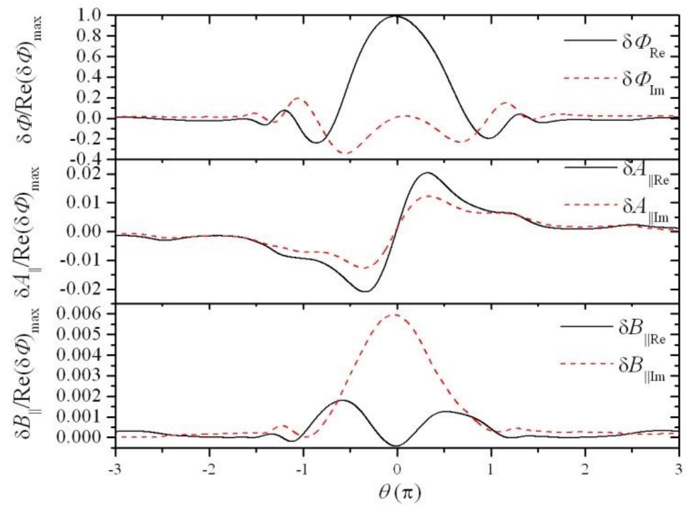


ITG: the dominant unstable mode at r/a=0.386

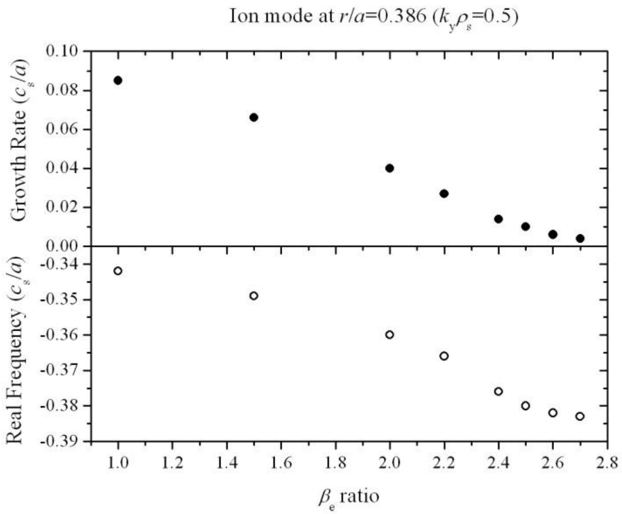


Results of eigen value solver fit
Well against that of initiall value

Eigen functions:



- Simulations using EAST exp data w/ full physics terms in GYRO
  - ✓ General geo
  - ✓ Full GK
  - ✓ Full EM effect
  - ✓ Rotation
  - ✓ Collision



β_e scan shows this mode is stabilized by β_e

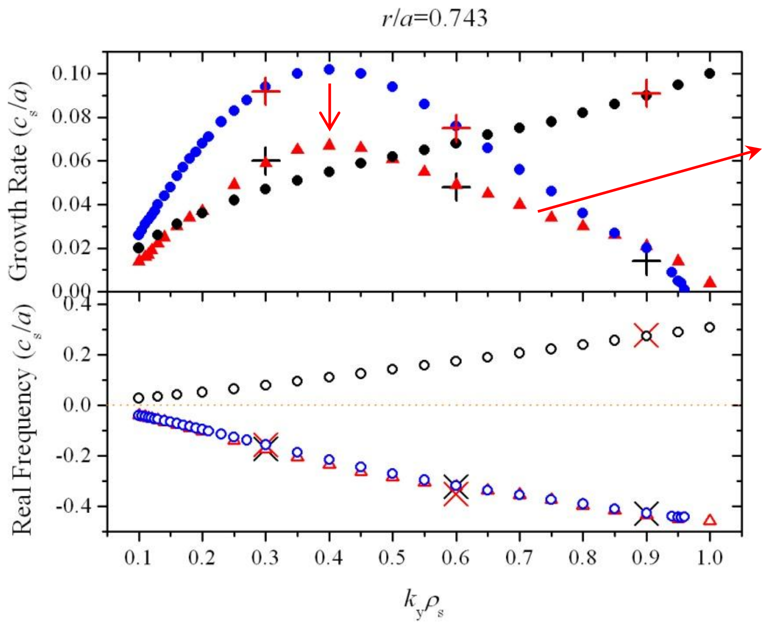
The eigen functions are well shaped in ballooning space w/ full physics term (cf. previous pedestal simulation)

Some parameters in simulation:
ν_{ei}=0.107, γ_E=-0.014 and γ_p=-0.243 in c_s/a
β_e=0.47%

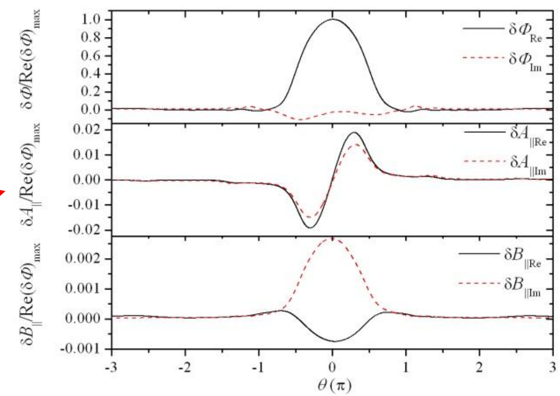
- Feature of ITG
  - ✓ Ion mode
  - ✓ Stabilized by increasing β_e
  - ✓ Even sym in ϕ
  - ✓ Odd sym and in-phase structure in $A_{||}$

ITG: the dominant unstable mode at *r/a*=0.743 Electron mode is stabilized by collision

dot: eigen value w/o collision
triangle: eigen value w/ collsion
cross : initial value w/ and w/o collsion

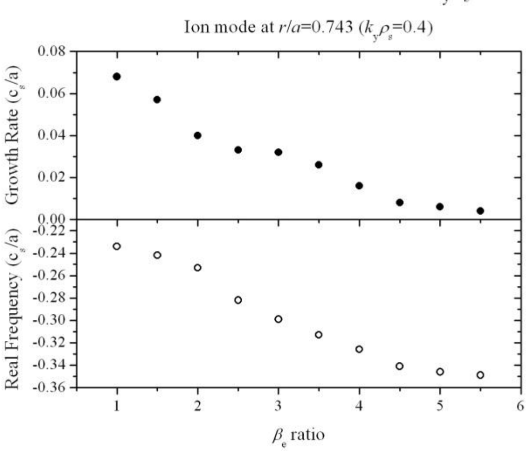


Eigen Functions:

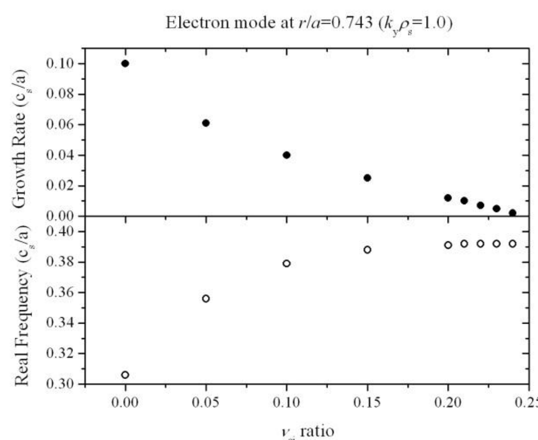


Well shaped ITG structure
ν_{ei}=0.589, γ_E=-0.004 and γ_p=-0.059 in c_s/a
β_e=0.14%

- Generally, collision term has great stabilizing effect on the modes in this $k_y\rho_s$ range
- Electron mode is stabilized by collision term
- Ion mode is the only unstable mode
- This ion mode can be identified as ITG



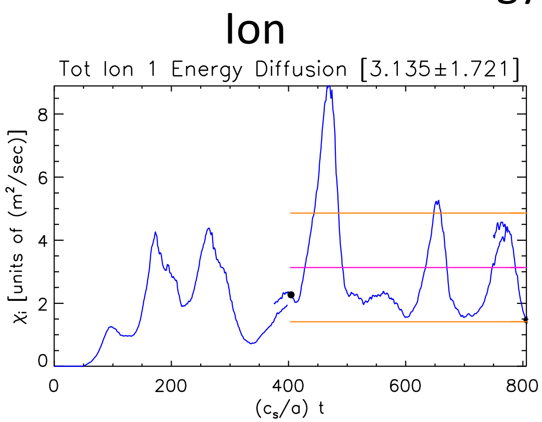
Ion mode can Be stabilized by increasing β_e

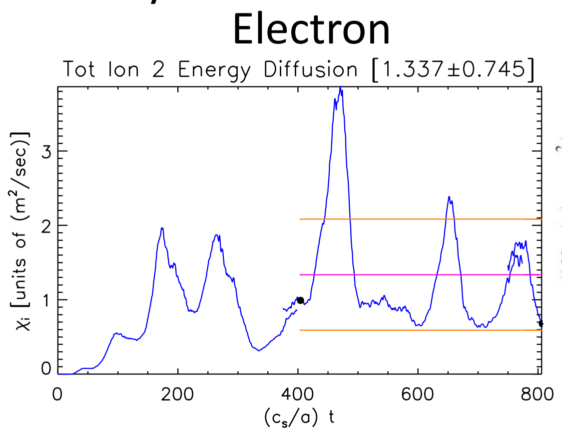


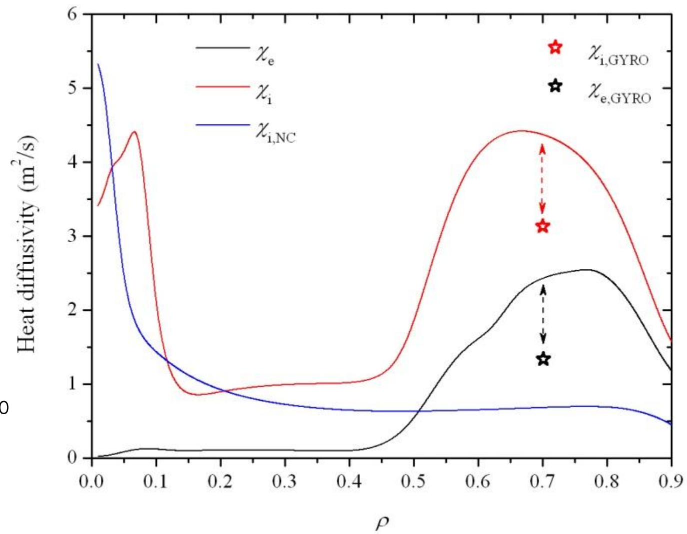
Electron mode is stabilized by collision w/ 25% of its exp value

EAST nonlinear simulation w/ full physics model is underway

Energy diffusivity

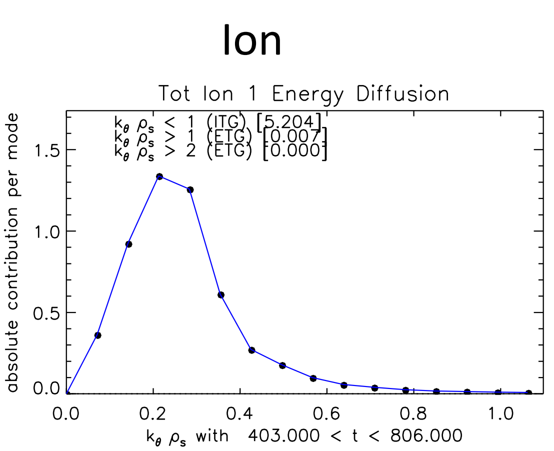


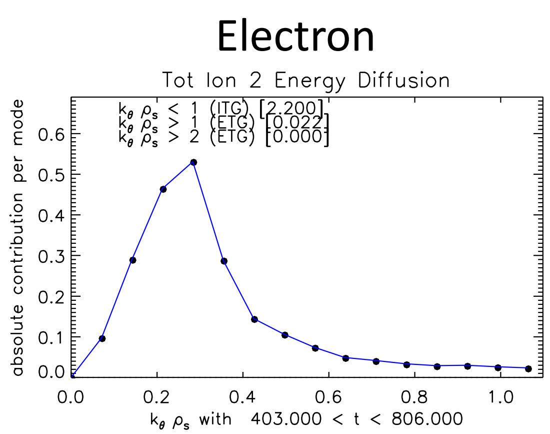




The local nonlinear run w/ full physics model runs more than 800*a/c_s. No sign of saturation yet.

Contribution of each mode to energy diffusion





- The errors between presented energy diffusivity results from incomplete GYRO simulation and TRANSP power balance analysis are among 25-50%
- GYRO predicts lower transport levels than power balance method

Comparison of GYRO parameters in DIII-D pedestal simulations and EAST core simulations

GYRO parameters	DIII-D pedestal peak gradient region	EAST core region
$\hat{s}$	3.985	1.085
ρ_*	0.003	0.004
γ_p	-3.035	-0.059
γ_E	-0.164	-0.004
ν_{ei}	1.23	0.589
n_i/n_e	1	1
T_i/T_e	1.714	0.929
a/L_n	64.1	0.246
a/L_{Ti}	11.8	1.24
a/L_{Te}	59.5	1.529
β_e	0.0087%	0.14%
α_{MHD}	2.558	0.122
ρ_*/L_n	0.19	9.8×10^{-4}

Discussion

- In flux tubes, there are often very unstable electron modes which may be numerical but remain with collisions. Inclusion of collisions is very time consuming (run time and convergence) but remains a top priority in characterizing general pedestal properties. Previously unstable modes (non Alfvenic frequencies) appear to be stabilized by experimental values of collisionality.
- Global simulations using gyro will require clever modification of the pedestal profile to avoid the last closed flux surface, in particular if we wish to compare with flux tubes. We have a profile prepared and analysis will begin soon.
- The comparison between pedestals (EPED to DIII-D's new discharge# 145781) in a reduced physics model finds similarities at the top of the pedestal, and a micro tearing mode in the real discharge in the peak gradient region. We note that the $\eta_{i,e}$ are noticeably different between the two profiles, so direct comparison between the two pedestals in the peak gradient region will not be exact.
- Initial simulations of an EAST discharge find ITG to be weakly unstable, which would likely imply the experimental parameters are in a regime with nonlinear up shift of the critical gradient. Nonlinear full physics simulations are underway.

Summary

In the presented work, we demonstrate that:

- ➢ By using reduced physics model w/ full pedestal current (cf. previous work of DIII-D shot# 131997 in E. Wang, NF, `12), some results can be obtained from DIII-D pedestal data (shot# 145781)
  - ✓ ITG is the dominant mode in pedestal top
  - ✓ Modes are stabilized in radial scan from pedestal top to peak gradient region (PGR)
  - ✓ The unstable modes in PGR are with MT and ITG parity, and they are basically in electron diamagnetic direction
- ➢ By using full physics model:
  - ✓ With collision and other physics term, some modes are detected in PGR
  - ✓ The most unstable mode is in the electron diamagnetic direction, near Alfvenic frequencies
  - ✓ Need to further identify whether they are numerical or physical
- ➢ Global simulation shows mode peaks in damping region
- ➢ For EAST (shot# 38300) core plasma simulation:
  - ✓ Linear simulations show ITG is the only unstable mode in plasma core region with real experimental condition
  - ✓ Nonlinear simulation is underway, while GYRO has the tendency to under predict transport level in comparison with power balance method