Comparison of experimental measurements to ITG turbulence predictions

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Abstract

The understanding and control of heat and particle transport in fusion plasmas is a problem of longstanding interest. This transport is often larger than predictions based upon collisionallity treatments and the primary suspect is turbulence or instability induced transport. A large amount of progress has been made in this area by many researchers and theorists, however the underlying instabilities have yet to be conclusively identified. We report here further work in this area that is ongoing at the DIII-D tokamak. Experimental measurements of the radial correlation length, fluctuation level, propagation direction, and spectra of density fluctuations have been made on the DIII-D tokamak and are compared to analytical and numerical predictions. Numerical diagnostics that simulate real diagnostic systems are being employed to make close comparisons between simulations and experiment. Results of these comparisons will be presented and discussed. Such comparisons are important as they serve to benchmark theory and codes as well as to help identify the type(s) of turbulence involved.

Outline

Part I - Compare to analytic models of radial correlation length.

Part II - Compare to gyro-kinetic code calculations.

Part III - Experiment to investigate existence of ITG on DIII-D.

Points in Presentation

- Compare to analytic models of radial correlation length.
  - Measured Δr similar to analytic predictions of **both** ITG and electron drift wave.
- Compare to gyro-kinetic code calculations.
  - **Similarity** found between measured and calculated Δr.
  - Encouraging but comparisons just beginning.
- Experiment to investigate existence of ITG on DIII-D.
  - Measurements of poloidal propagation indicate an **ion diamagnetic feature** as the density is increased.
  - See **C. Rettig, Invited Presentation this afternoon,**
    - Session HI2 - Transport Barriers and ITG Modes.

Part I: Comparison of correlation lengths to analytic predictions

$$\frac{L_s}{L_n}\left(\frac{T_e}{T_i}\right)^{1/2}\rho_s$$

Electron drift wave, slab (EDW)

F.Y. Gang, et al. *Phys. Fluids* B **3**, 68 (1991)

$$\rho_s\left[\frac{1+\eta_i}{\tau}\right]^{1/2}$$

$$\rho_s\left[\frac{qR}{\hat{s}L_n}\frac{1+\eta_i}{\tau}\right]^{1/2}$$

Slab ITG

G.S. Lee and P. Diamond, Phys. Fluids 29 3291 (1986)

H. Biglari, et al., Phys. Fluids B 1, 109 (1988)

$$\rho_s\left[\left(\frac{q}{\hat{s}}\right)^2\frac{R}{2L_n}\frac{1+\eta_i}{\tau}\right]^{1/4}$$

Toroidal ITG

Wendell Horton, et al., Phys. Fluids **24** 1077 (1981)

H. Biglari, et al., Phys. Fluids B 1, 109 (1988)

$$\rho_{s,\theta}\left[1+\eta_i\right]^{1/2}$$

neo-classical ITG

Y.B. Kim, et al. Phys. Fluids B 3, 384 (1991)

Analytic predictions of correlation lengths

$$\left(\rho_i L_{Ti}\right)^{1/2}$$

$$\left(\rho_i L_{Ti} / \hat{s}\right)^{1/2}$$

- **Mesoscale structures**

  Romanelli and Zonca, Fluids B 5, 4081 (1993)

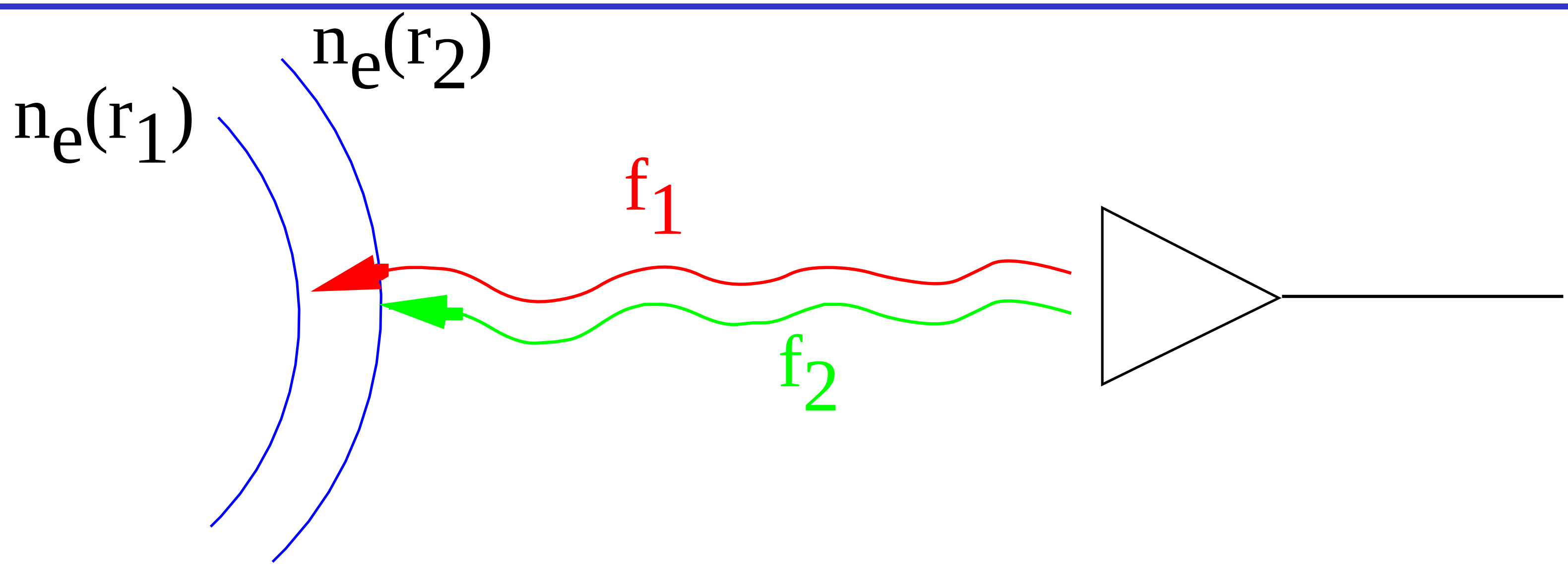
  Connor, et al., PRL **70** 1803 (1993)

  G. Furnish, et al., Phys. Plasmas **6** 1227 (1999)

Definitions of various parameters

- ρ_s = Larmor radius using T_e and ion mass m_i.
- ρ_i = Larmor radius using ion temperature and mass.
- $\rho_{\theta,s}$ = Larmor radius using T_e, m_i and the poloidal magnetic field B_θ
- $\rho_{\theta,\, i}$ = Larmor radius using T_i, m_i and B_θ
- τ = T_e/T_i
- η_i = $d\, ln(\, T_i\,) \,/\, d\, ln(\, n_i\,)$
- n_i = the ion density (the electron density n_e is used for this study
- s_{hat} = $d\, ln(\, q\,) \,/\, d\, ln(\, r\,)$ the magnetic shear parameter
- L_s = $Rq/\, s_{hat}$ the magnetic shear length
- q = the magnetic safety parameter.
- r and R are the minor and major radius respectively.

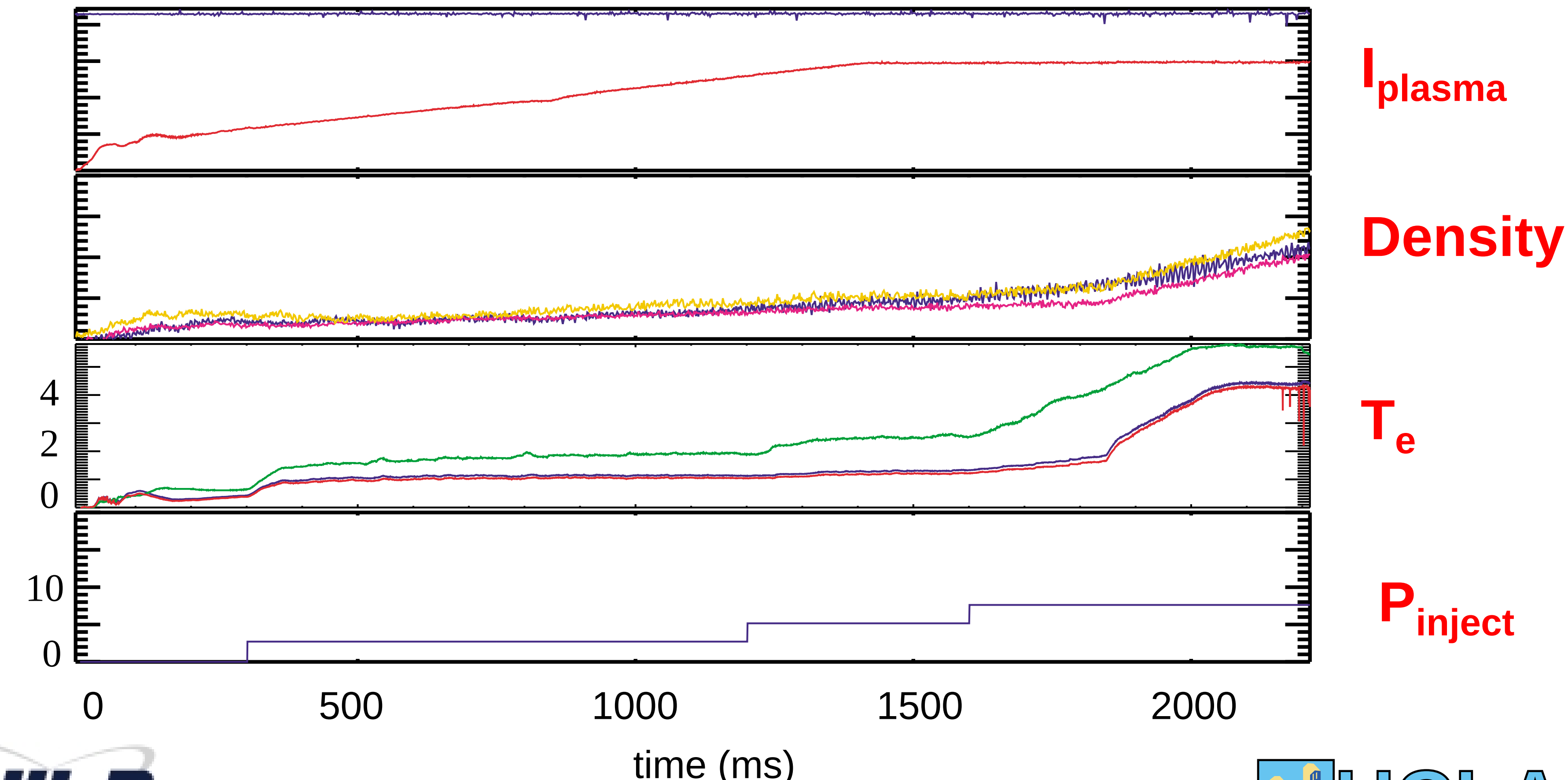
Correlation reflectometry used to obtain Δr



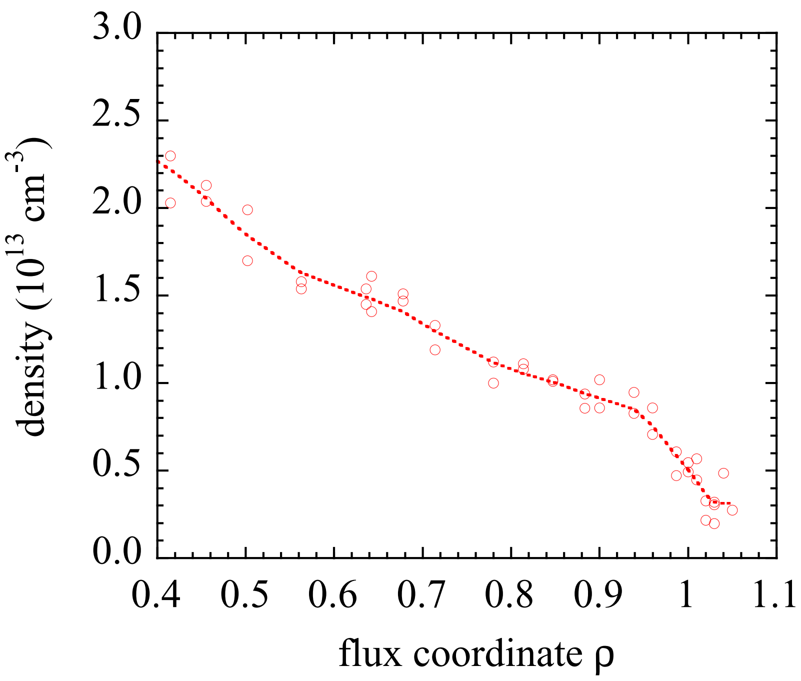
- **Launch two different frequencies** f_1, f_2 into plasma.
- Microwaves reflect from different locations.
- Reflectometer responds to fluctuations at different radial positions.
- Correlate resulting two signals:
  - $S_1 = A_1 \cos(\Phi_1(t))$
  - $S_2 = A_2 \cos(\Phi_2(t))$

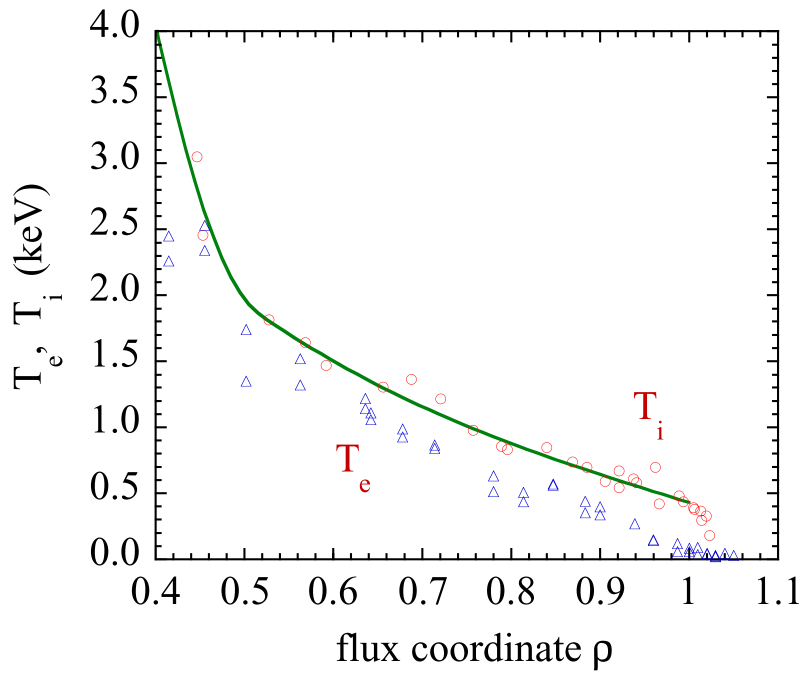
Data obtained from L-mode plasma

- Experimental data obtained in non-sawtoothing, 7.5 MW beam heated **L-mode plasma**

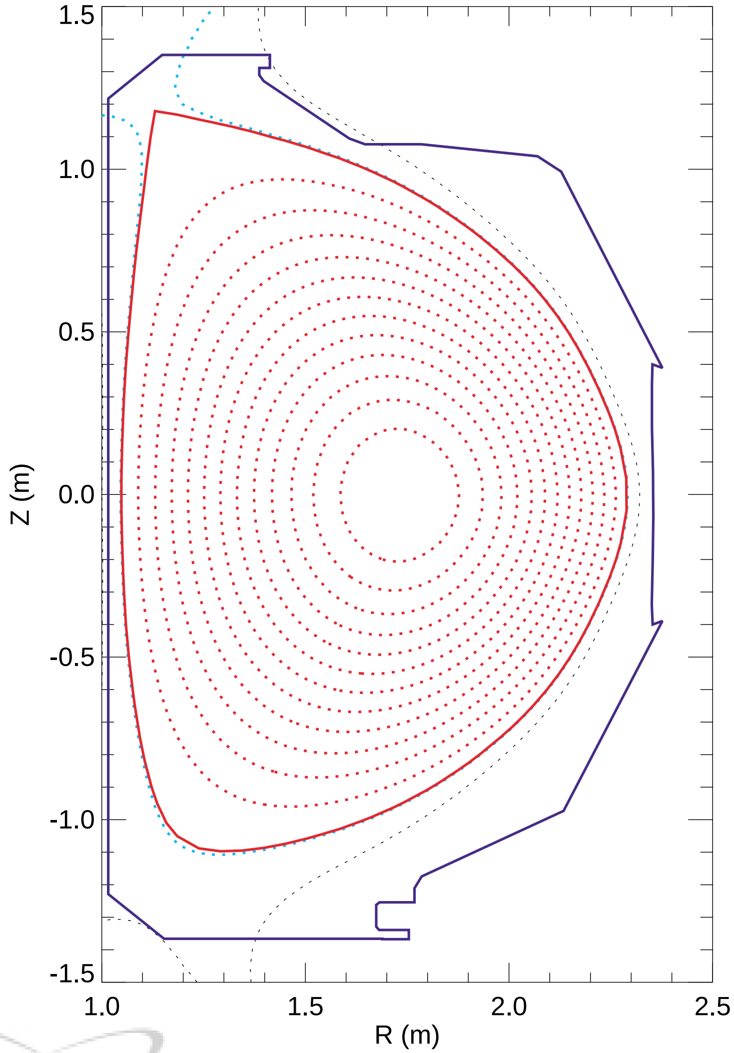


L-mode discharge parameters: $n_e(\rho)$ and $T_{e,i}(\rho)$





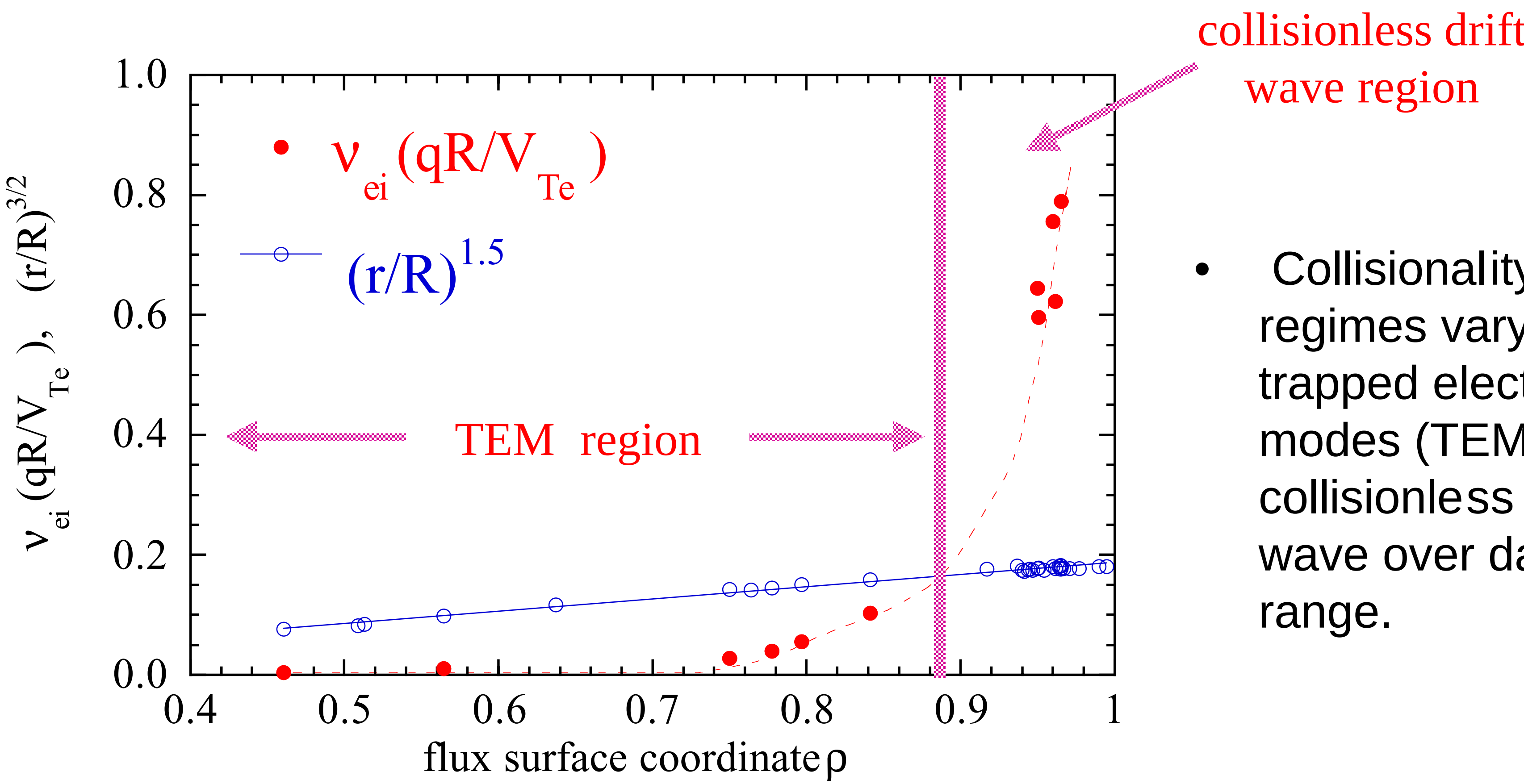
L-mode discharge parameters: plasma shape



Wed Nov 10 09:55:00 1999

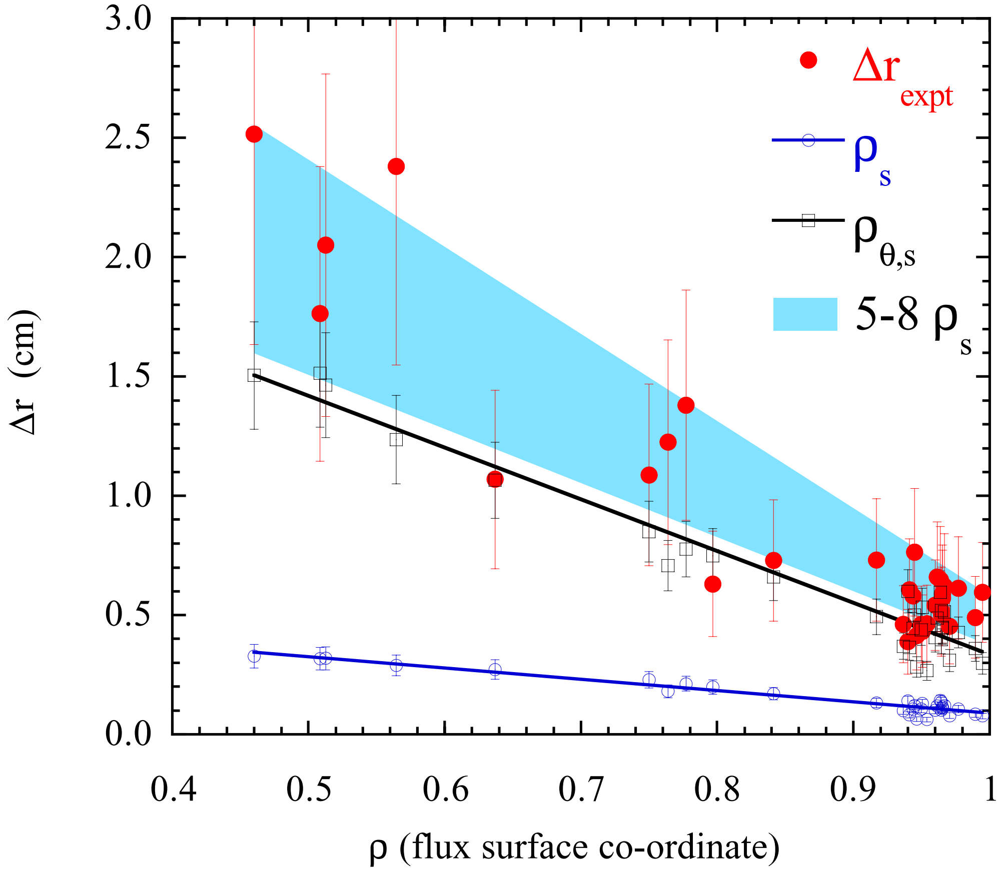
shot number =	92952	
efit time =	1778.0000	
configuration = SNT		
mw, mh =	65	65
Ip [A]=	1.47056e+06	
r(z)out [cm]=	166.908	4.08328
ssep [cm]=	0.510698	
bcentr =	-2.12281	
betapd =	0.718757	
betat, betap =	1.33527	0.606963
Vol, Area =	21.2327	2.12832
NB power inj. [W]=	0.00000	
qmerci =	1.07556	
q1,q95 =	14.6999	4.98326
qqmagx =	1.12707	
r(z)magx [cm]=	173.540	-0.236279
r(z)seps1 [cm]=	113.812	-118.919
r(z)seps2 [cm]=	113.081	117.880
taudia(mhd) =	1997.01	1686.40
terror =	0	
chisq =	17.7646	
wplasm =	786846.	
wplasmd =	931772.	
utri, ltri =	0.866554	0.607761
r(z)vsout [cm]=	118.857	135.150
r(z)vsin [cm]=	101.600	119.186
zuperts [cm]=	78.1256	
ssibry(mag) =	0.0194948	-0.336168
in(out)er gap =	3.19179	6.37550
up(low)er gap =	10.8787	24.2740
a, li =	62.1164	1.14936
vloop =	0.317283	
elongm =	1.39132	
kappa =	1.83470	

Collisionality regime: collisionless electron drift wave in edge and trapped electron mode deeper into core



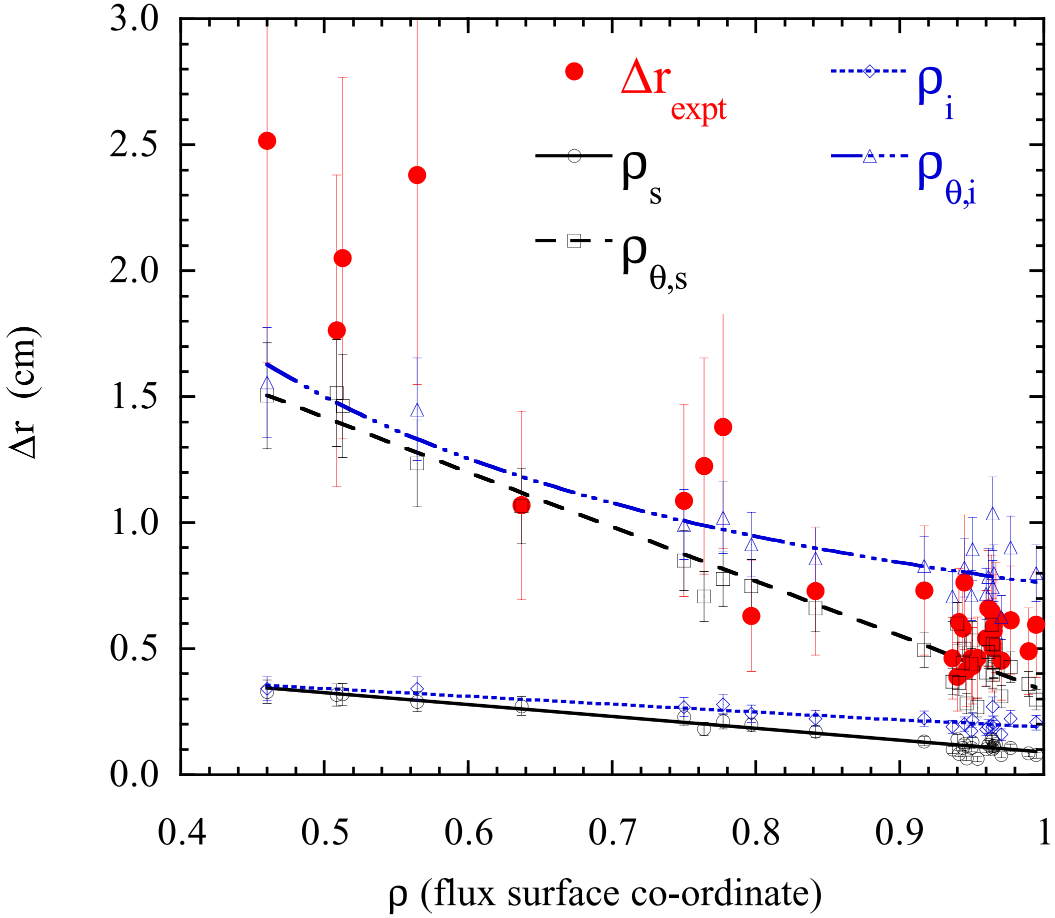
- Collisionality regimes vary from trapped electron modes (TEM) to collisionless drift wave over data range.

Radial correlation length greater than ρ_s, approximately same as either $\rho_{\theta,s}$ or 5-8 ρ_s



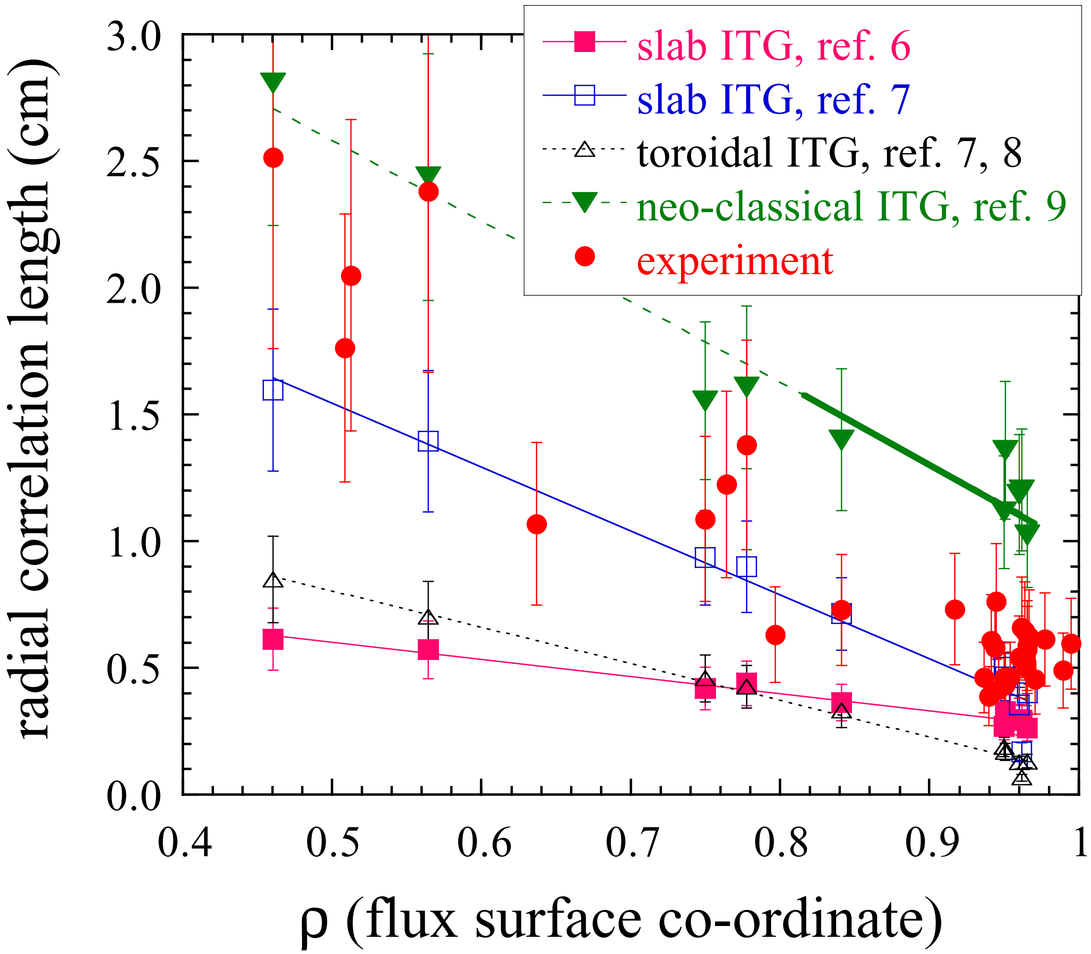
- Generally $\Delta r > \rho_s$
- $\Delta r \sim$ 5-8 ρ_s is general prediction of many theories.
- Δr increases towards core being
  - 0.5-1 cm at edge
  - as much as 3-4 cm in deep core ($\rho \sim 0.2$)

Radial correlation length approximately same as either $\rho_{\theta,s}$ or $\rho_{\theta,i}$



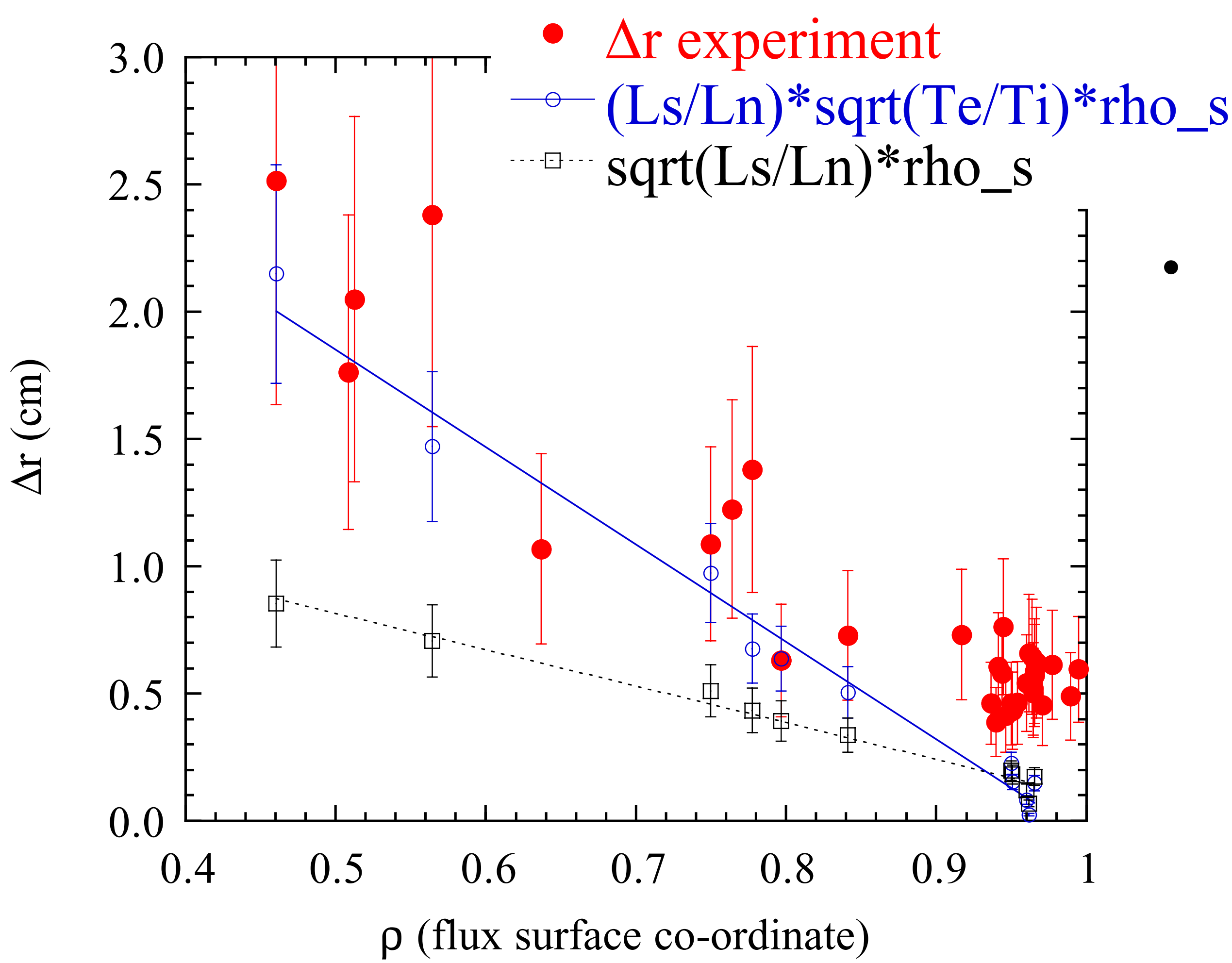
- Within error bars Δr not differentiated from $\rho_{\theta,s}$ or $\rho_{\theta,i}$

Radial correlation length comparable with predictions of slab ITG driven turbulence



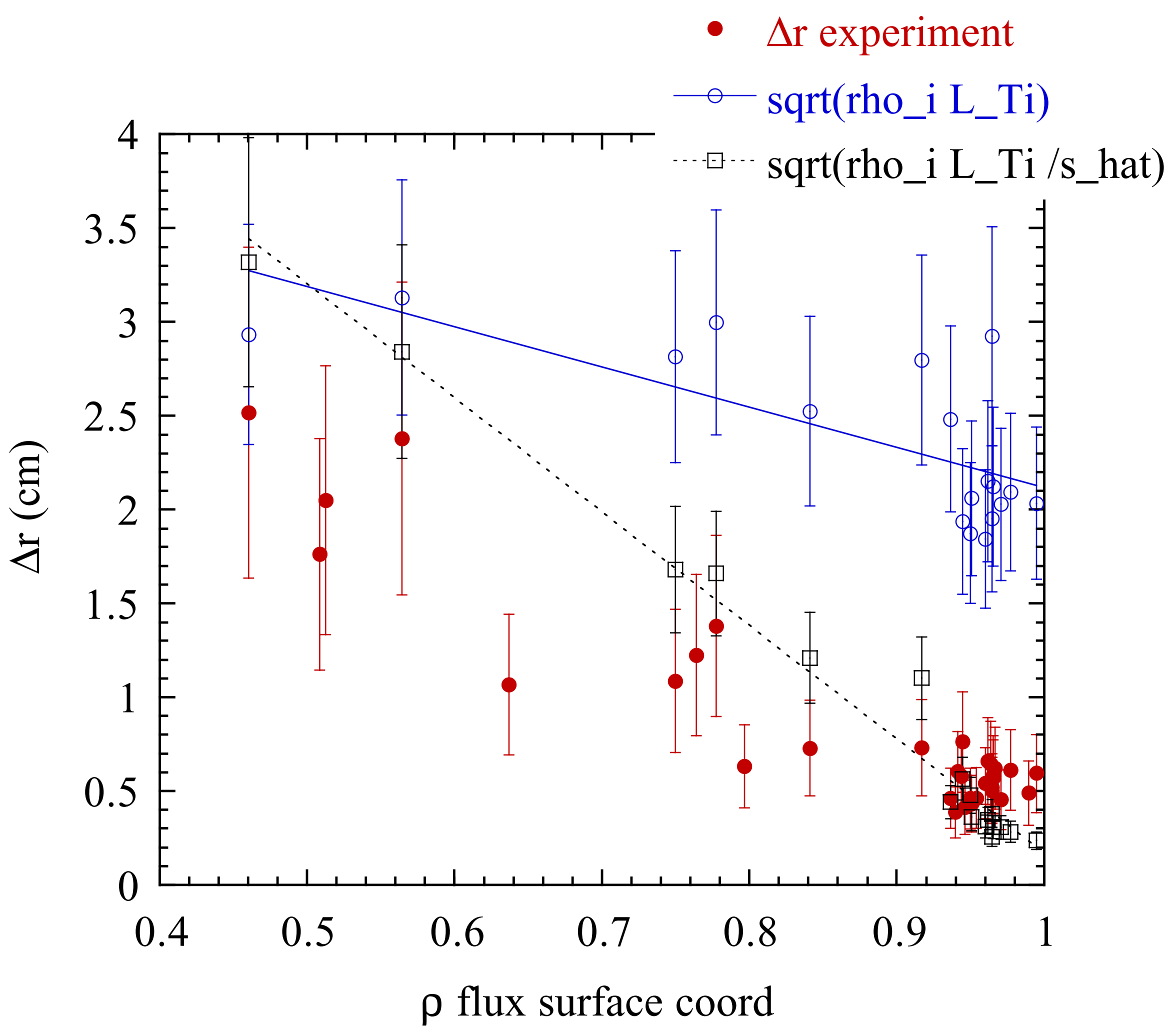
- Experimental values larger than slab ITG model of Lee, et al. and toroidal ITG model of Biglari, et al.
- Data comparable to slab ITG of Horton et al. and Biglari, et al.
- neo-classical ITG of Kim, et al.is likely valid only near edge and is consistent with experiment there.

Radial correlation length comparable with predictions for electron drift wave



- Data also consistent with generic electron drift wave type correlation length $(L_s/L_n)(T_e/T_i)^{1/2}\rho_s$ for radii < 0.9

Radial correlation length is comparable to one formulation of mesoscale Δr



- Data is comparable with $(\rho_i L_{Ti}/s)^{1/2}$ mesoscale.
- At edge this mesoscale prediction is of order .3 cm. This is due to large shear parameter s_hat and small ρ_i.
- Data not consistent with $(\rho_i L_{Ti})^{1/2}$ mesocale.

Need dedicated experiments and closer connection to theory and simulation

- Experimental error bars preclude definitive conclusion.
- Experiments are planned to differentiate between predictions:
  - Test for ρ_s or $\rho_{\theta, s}$ scaling via q scan at constant T_e, T_i, …
  - Slab ITG and electron drift wave $\Delta r_{ITG} / \Delta r_{DW} \approx (L_n / L_s)^{1/2} (T_i / T_e)(1+\eta_i)^{1/2}$

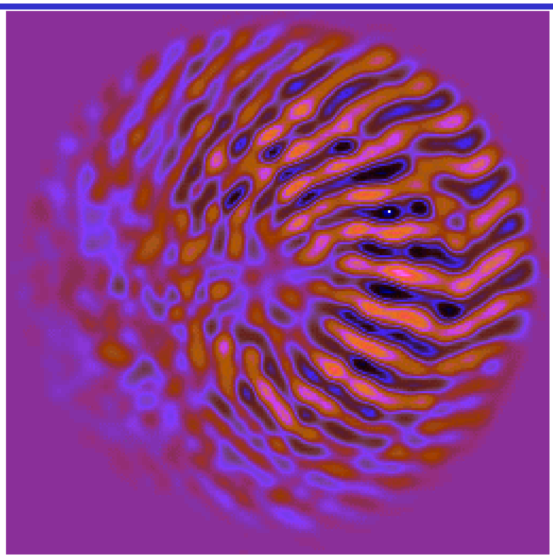
    $\Rightarrow$ vary T_i / T_e, with other variables constant
- Possibility that near equality of different predictions is real physics result - plasma supports various types of turbulence/modes simultaneously.
- Also possible to compare data to numerical modeling.
  - Able to model specific discharges and conditions.
  - Compare multiple measurements to codes.
  - A beginning of this comparison is shown next.

Part II: Compare turbulence measurements to numerical modeling

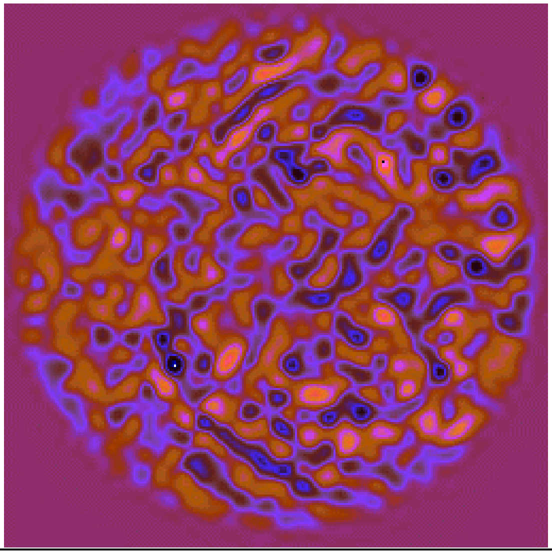
- **Global gyrokinetic particle code UCAN** [R. D. Sydora, V. K. Decyk, and J. M. Dawson, Plasma Phys. Control. Fusion **38** (1996) A281-294]
  - Whole plasma cross section
  - Full radial profiles
  - Toroidal geometry (Cartesian coordinates)
  - Circular cross section (shaped version available)
  - Adiabatic electrons
  - Massively parallel implementation using MPI and PLIB parallel particle manager developed by Viktor Decyk

Example of tokamak turbulence simulation

- Contour plot of potential fluctuations
- Early linear stage shows long radial structures.
- Later, non-linear stage shows much shorter radial structures.
- Simulations performed by J.-N. Leboeuf, UCLA



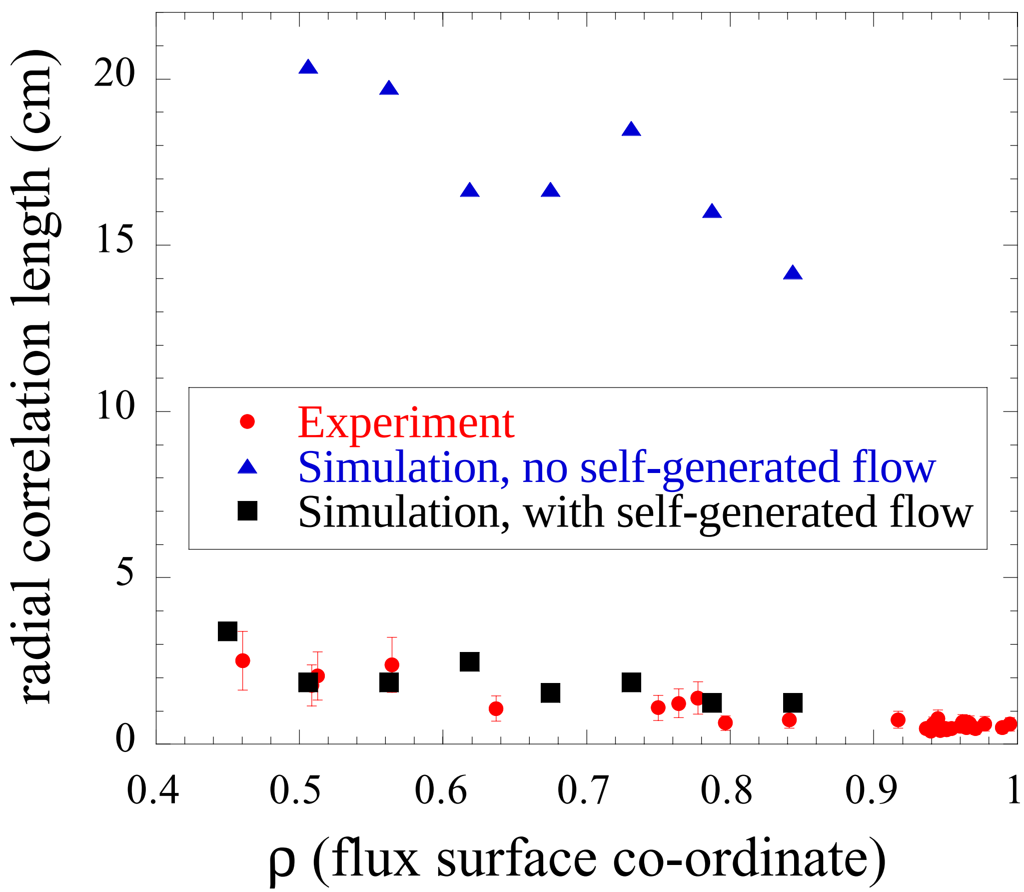
Linear Phase



Nonlinear Steady State

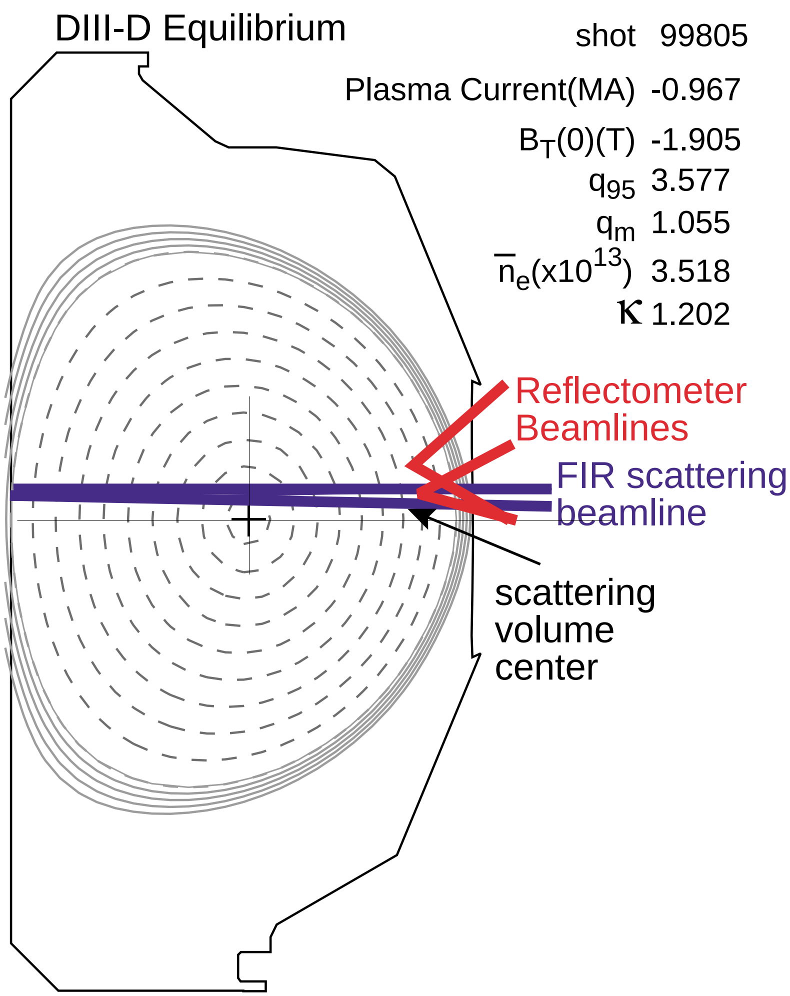
Numerical model: Δr with zonal flows comparable to experiment values

Simulations performed by J-N. Leboeuf



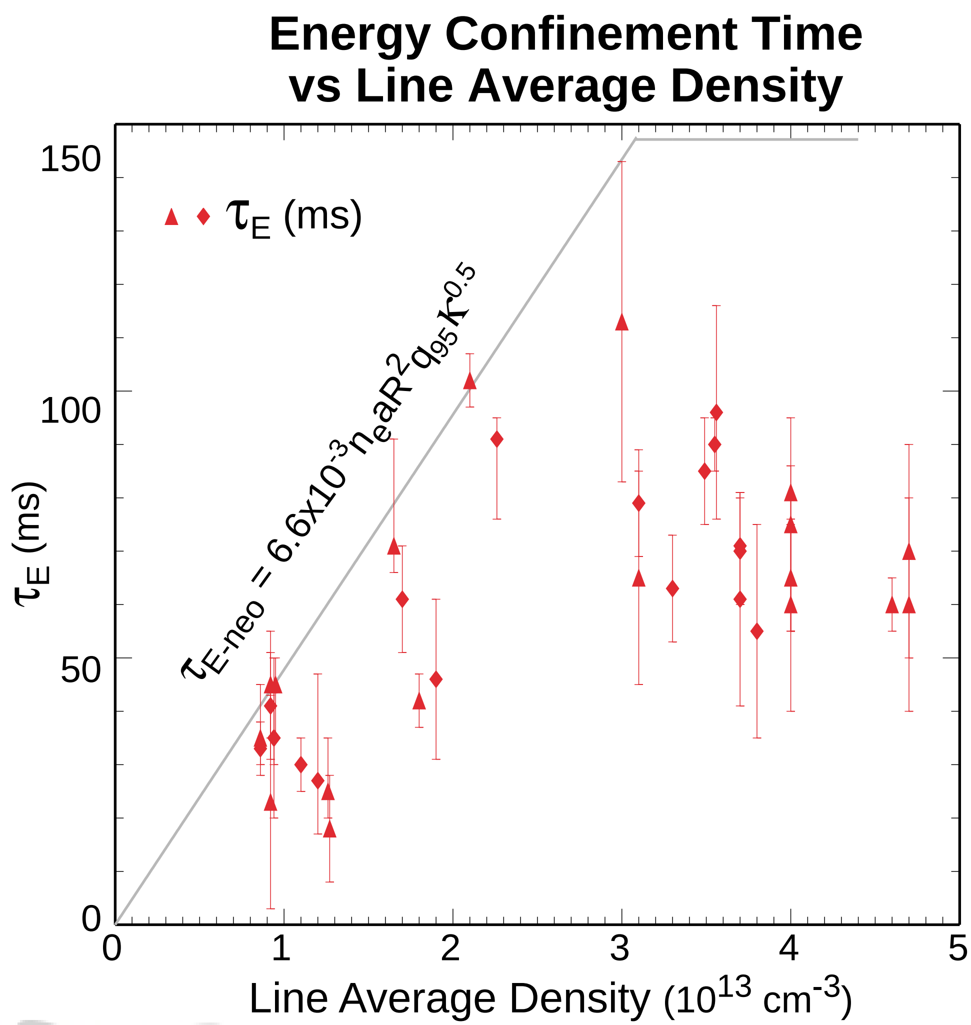
- With zonal flows the numerically determined lengths drop to near the measured Δr.
- Although agreement is intriguing this is a very early stage of the comparison and more work remains.
- For example, the plasmas simulated are circular while the real plasmas were shaped
- A fully shaped code is currently being utilized and broader, more complete comparisons are in progress.

Part III: Experiment designed to investigate existence of ITG on DIII-D



- Circular, ohmic discharges.
- Density scanned from 0.8 to $4x10^{13}cm^{-3}$.

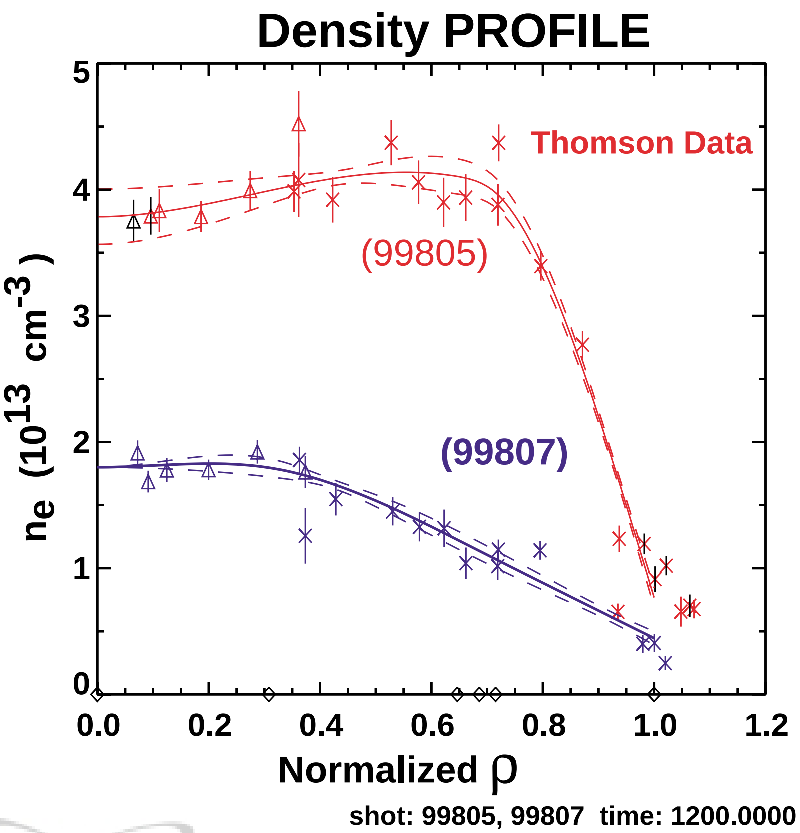
Energy confinement initially increases with density then saturates.

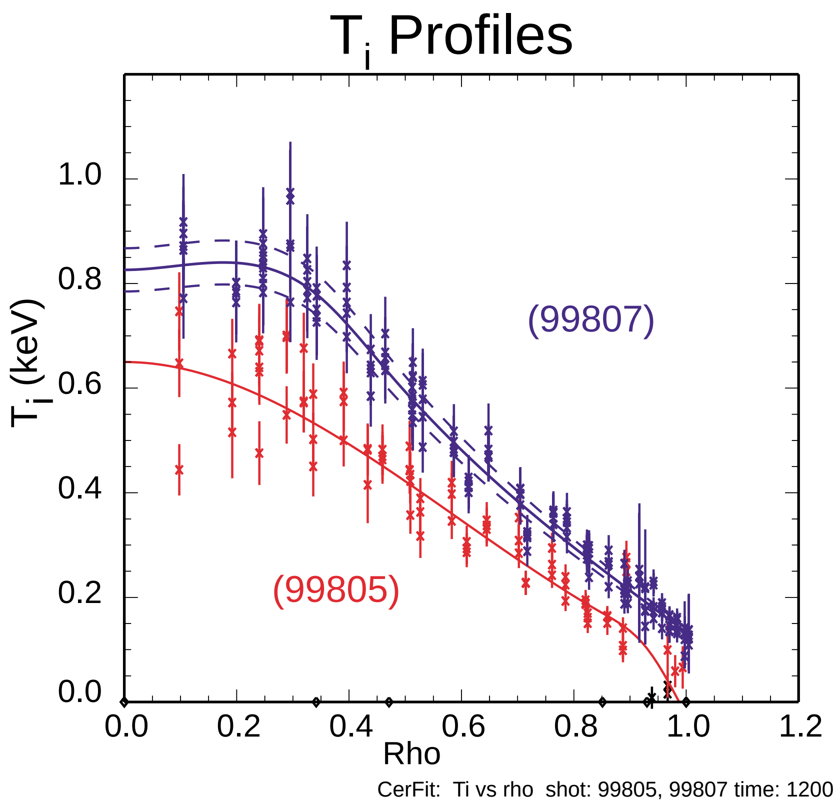


- Saturation of τ_E conjectured due to onset of ITG modes (ref. TEXT tokamak, D. Brower, et al.).
- Experiments designed to further test this hypothesis.

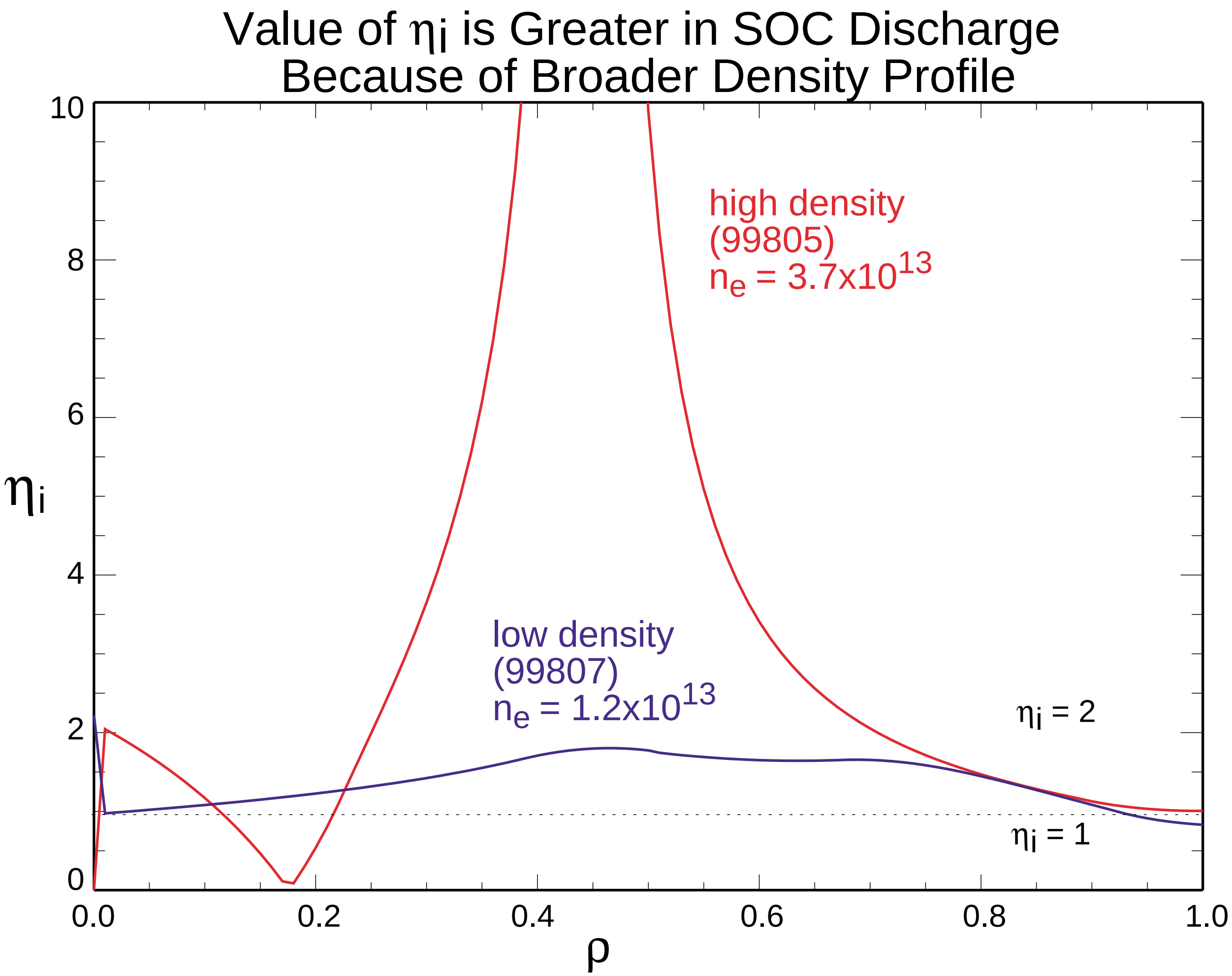
Two discharges selected for simulation with gyro-kinetic code UCAN

- Low density (linear ohmic confinement) and high density (saturated ohmic confinement) used.





High density η_i clearly above stability while low density is near marginal ITG stabilty

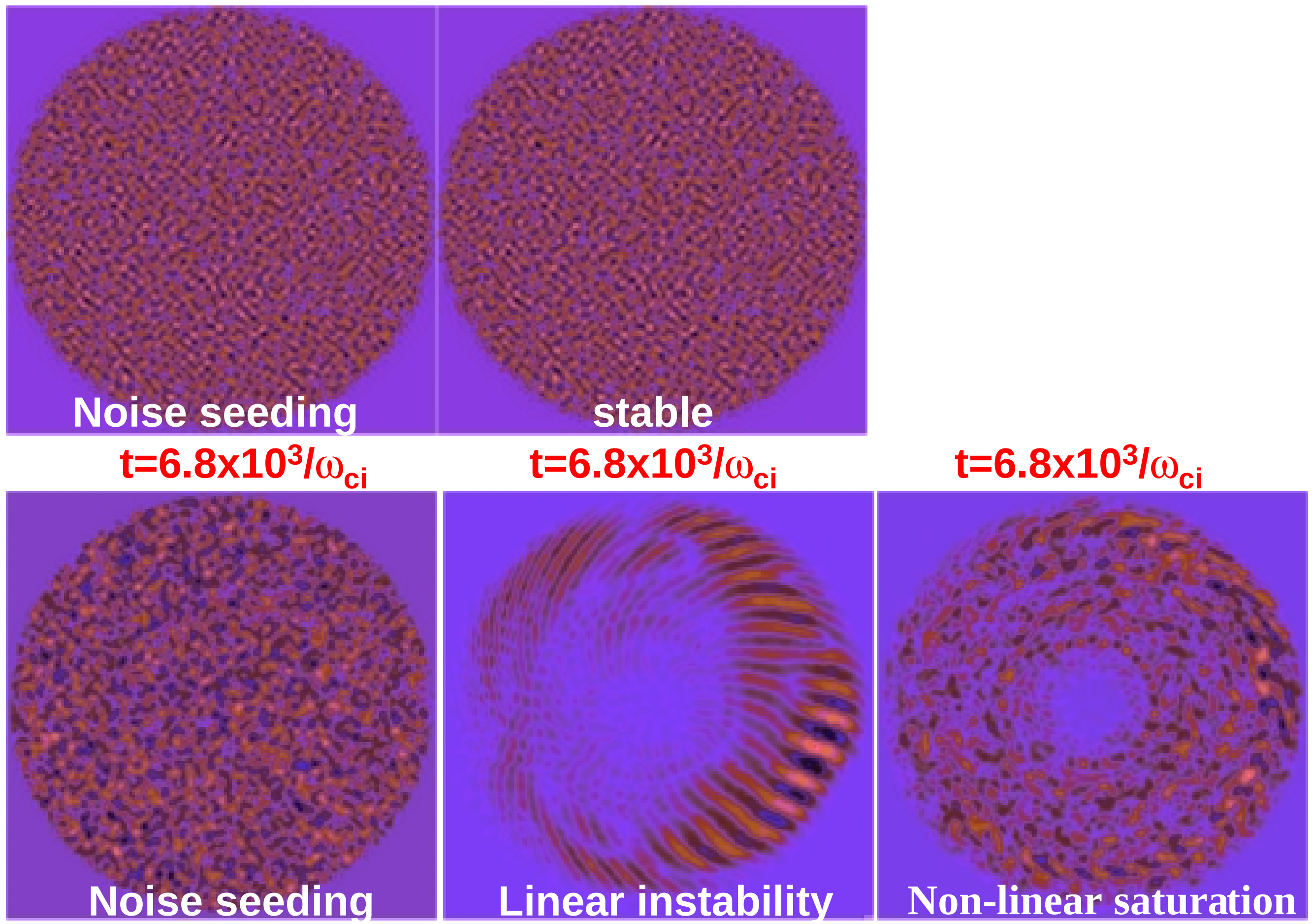


UCAN Simulation: High density discharge unstable while low density is stable to ITG

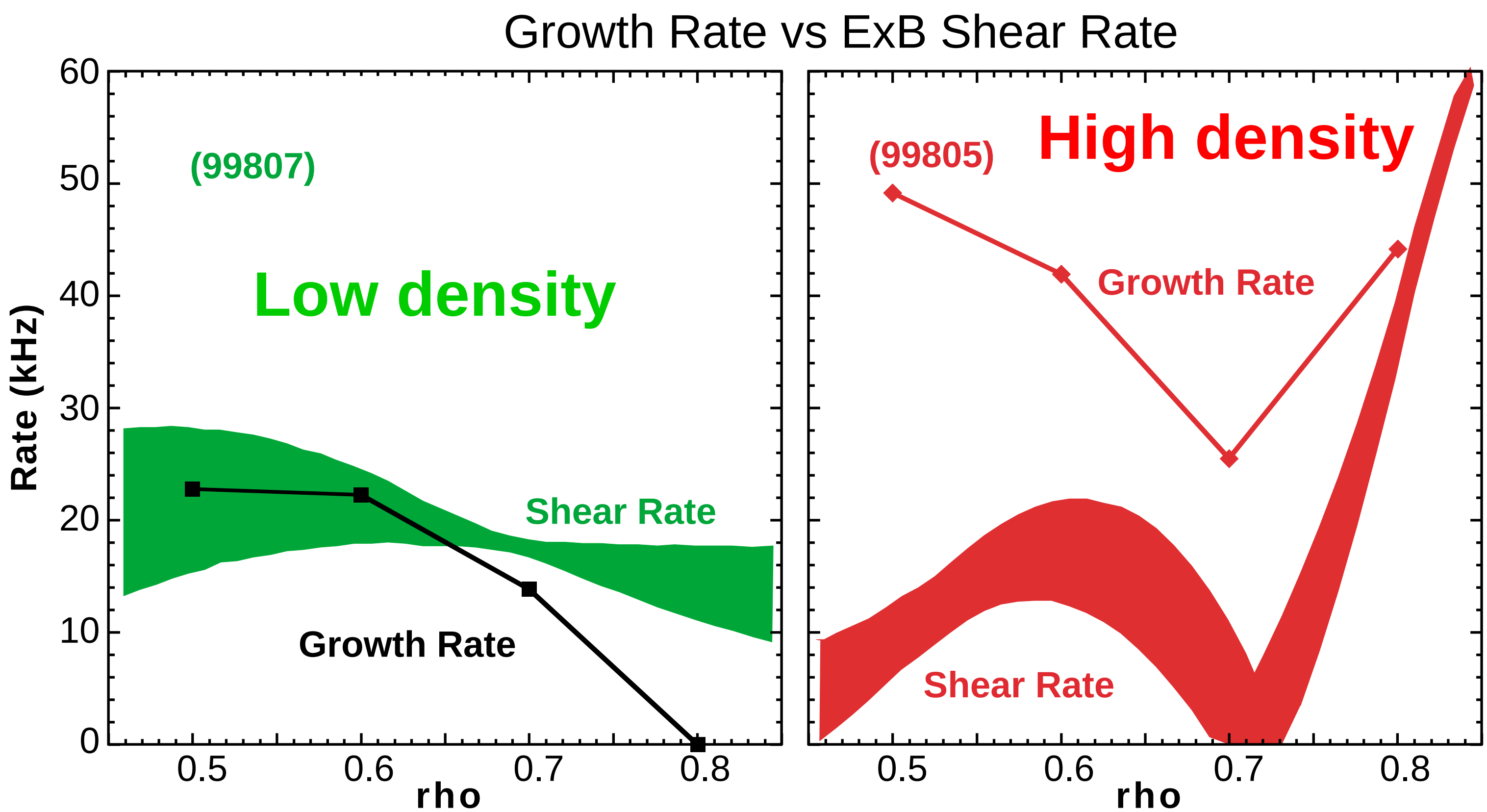
Plasma potential fluctuations from simulation shown below

Low density discharge

High density discharge

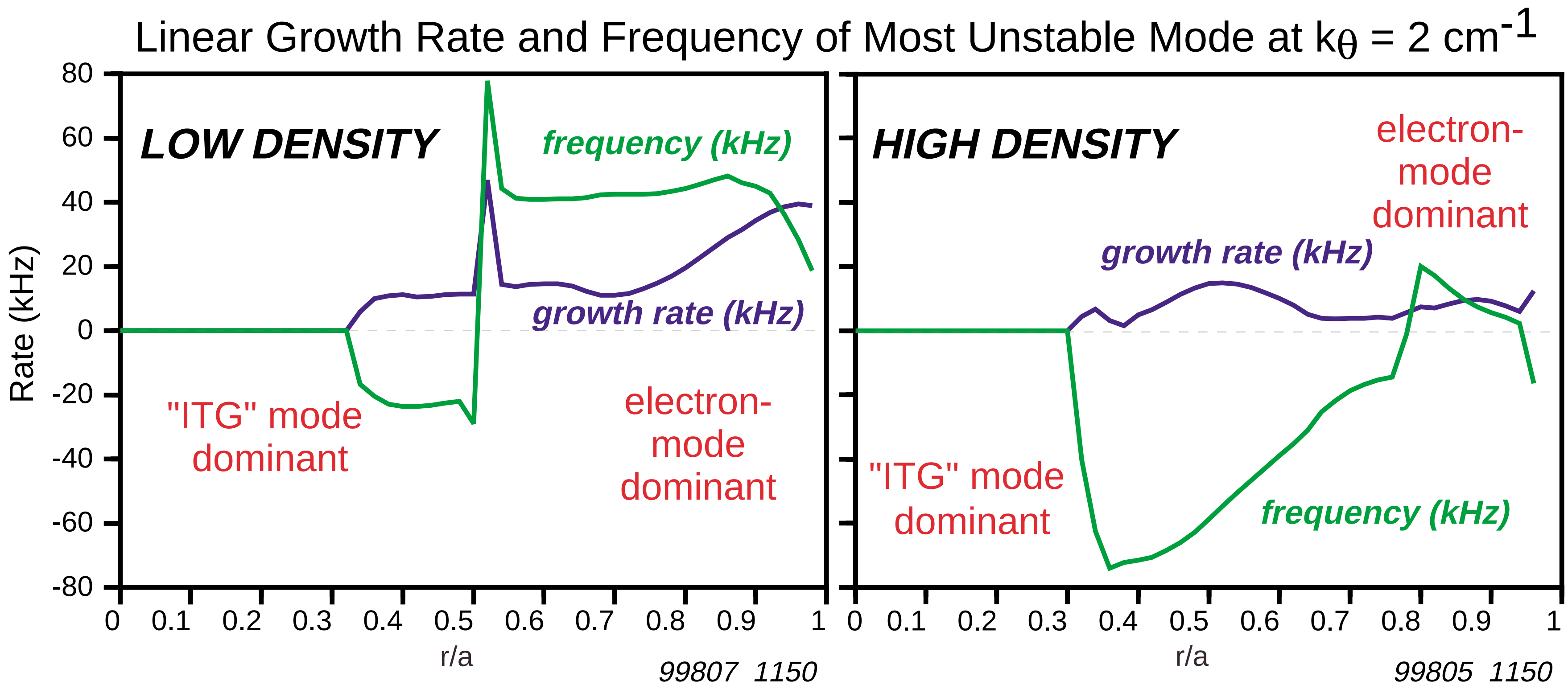


Linear growth rates at or below shearing rate for low density and above for high density



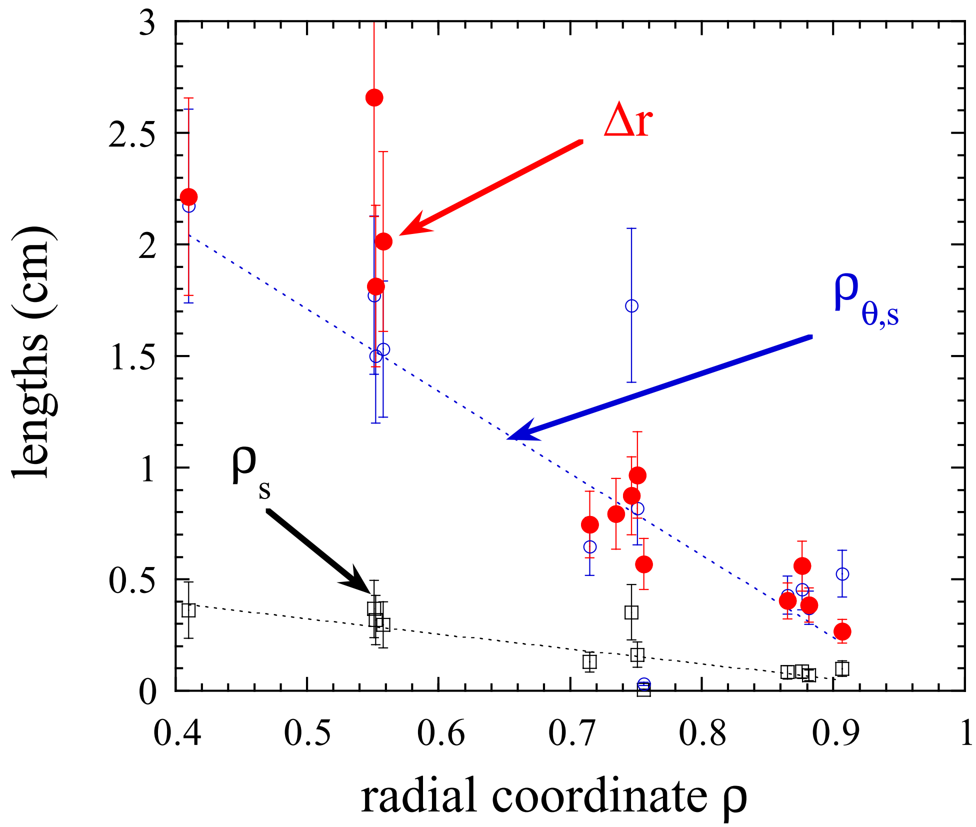
- **May explain lack of ITG instability in low density UCAN simulation.**

At high n_e ITG mode appears to be unstable over large region of plasma



- At high n_e a higher frequency ion mode appears over a large region of plasma.

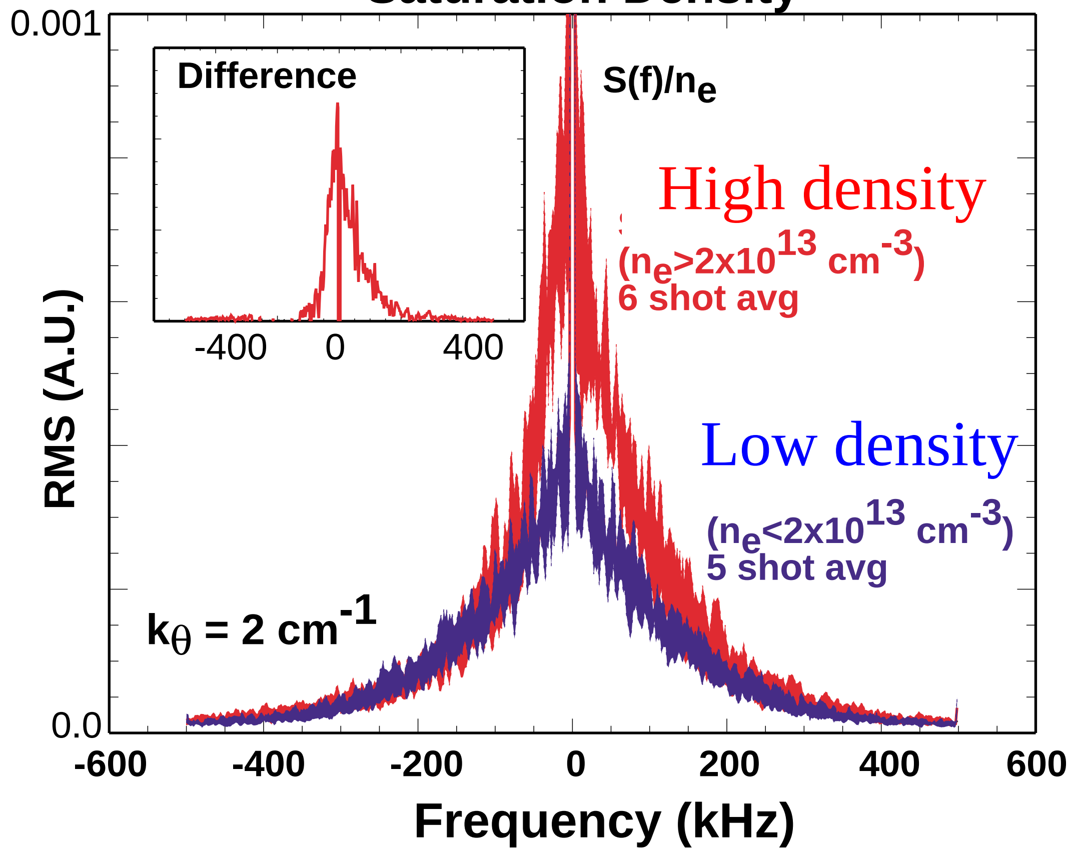
Radial correlation length ~5-8 ρ_s in general agreement with ITG and elect. drift wave predictions



- Many densities shown.
- Δr ~ 5-8 ρ_s is general prediction of many theories.
- Magnitude and radial behaviour generally consistent with both ITG and electron drift waves (see Part I of poster).

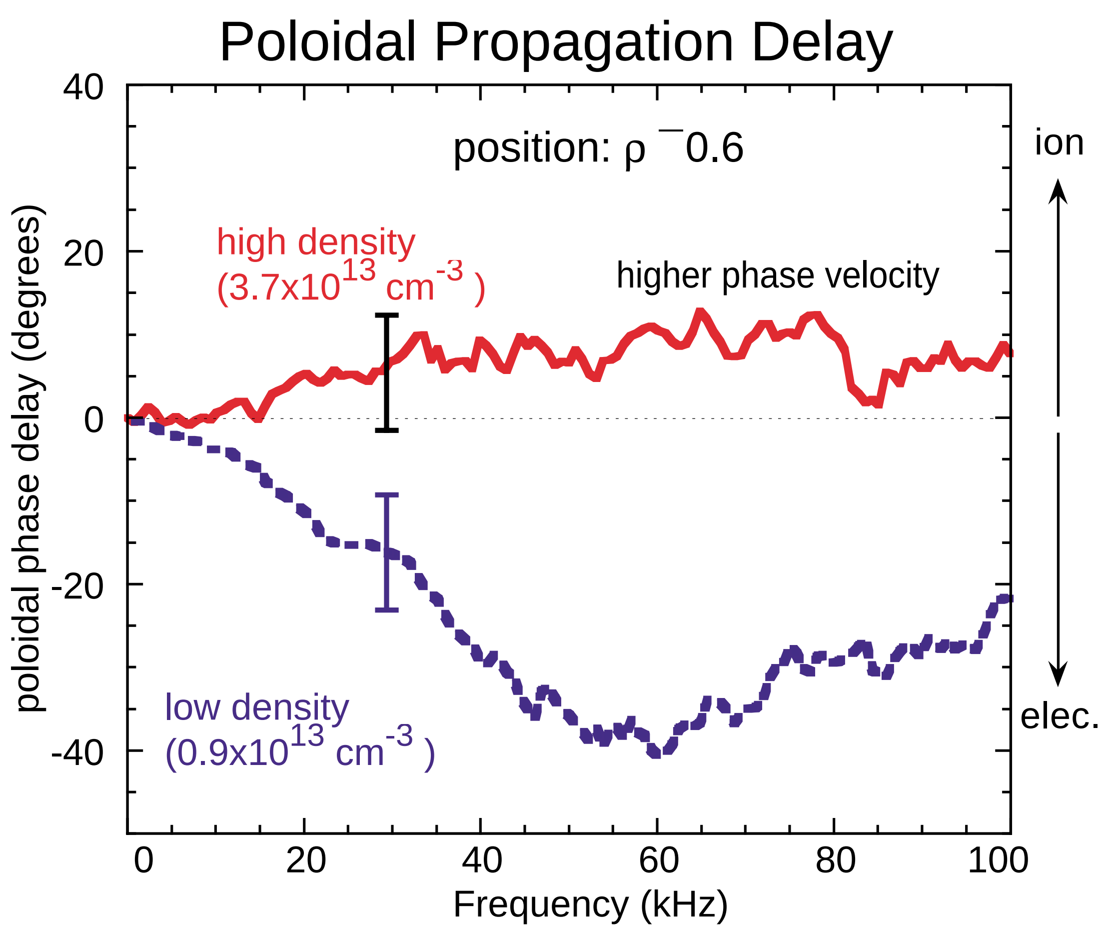
FIR scattering shows increase of low frequency fluctuations at high density

Average of Multiple Discharges: Spectra are Well Separated by Saturation Density



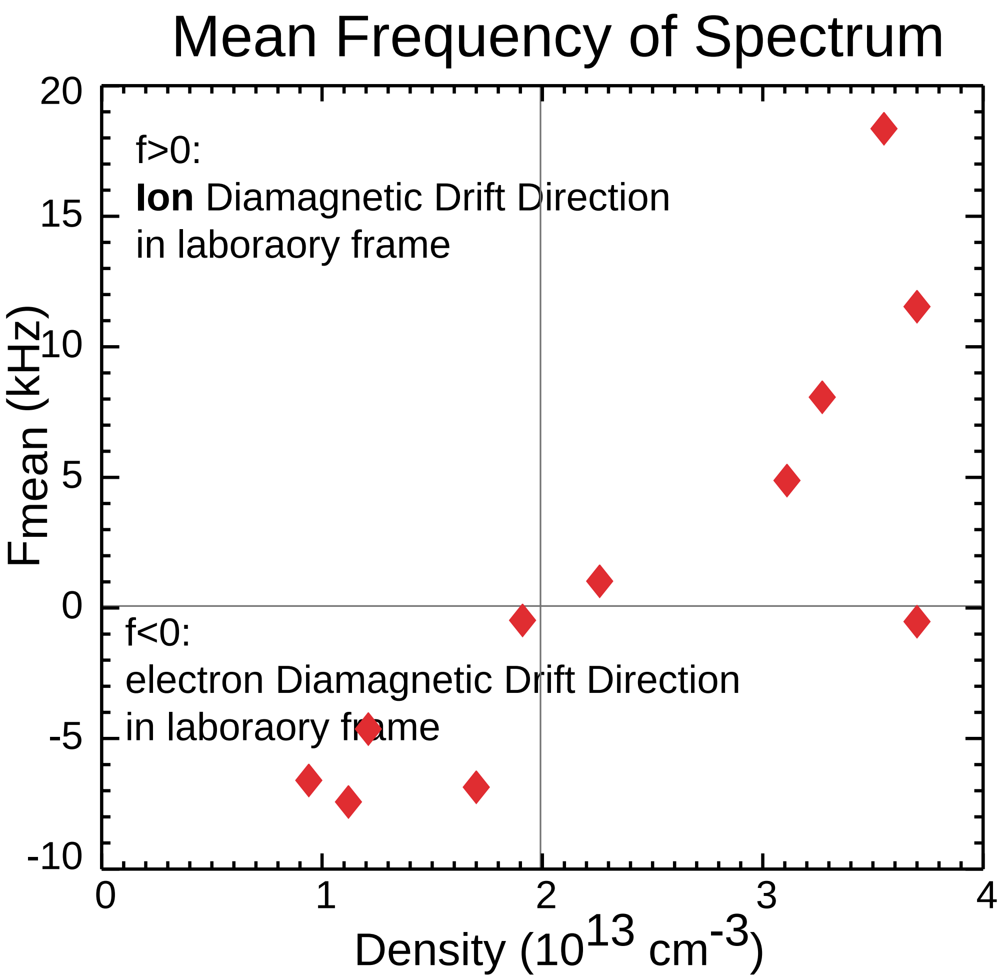
- Power spectra of density fluctuations at $k_\theta = 2\ cm^{-1}$ shown.
- Data averaged over multiple discharges.
- Observed frequency range similar to linear instability predictions.

Data consistent with broadband feature propagating in ion diamag direction at high n_e.



- Poloidal dispersion obtained from two poloidally separated reflectometer channels.
- At low n_e observe clear propagation in electron diamag. drift direction.
- As n_e is increased propagation direction reverses, but phase velocity is high, consistent with appearance of fluctuations propagating in ion diamag. drift direction.

FIR scattering finds similar change in mean frequency direction as density increased



- Direction switches from electron to ion diamagnetic drift direction as n_e increased.

Summary

- Measured Δr similar to analytic predictions of **both** ITG and electron drift wave.
- **Similarity** found between measured Δr and that calculated by gyro-kinetic code UCAN.
  - Encouraging, however comparisons just beginning.
- From ITG experiments on DIII-D measurements of poloidal propagation indicate an **ion diamagnetic feature** and increased fluctuation level as the density is increased.
  - See **C. Rettig, Invited Presentation this afternoon,**
    - Session HI2 - Transport Barriers and ITG Modes.