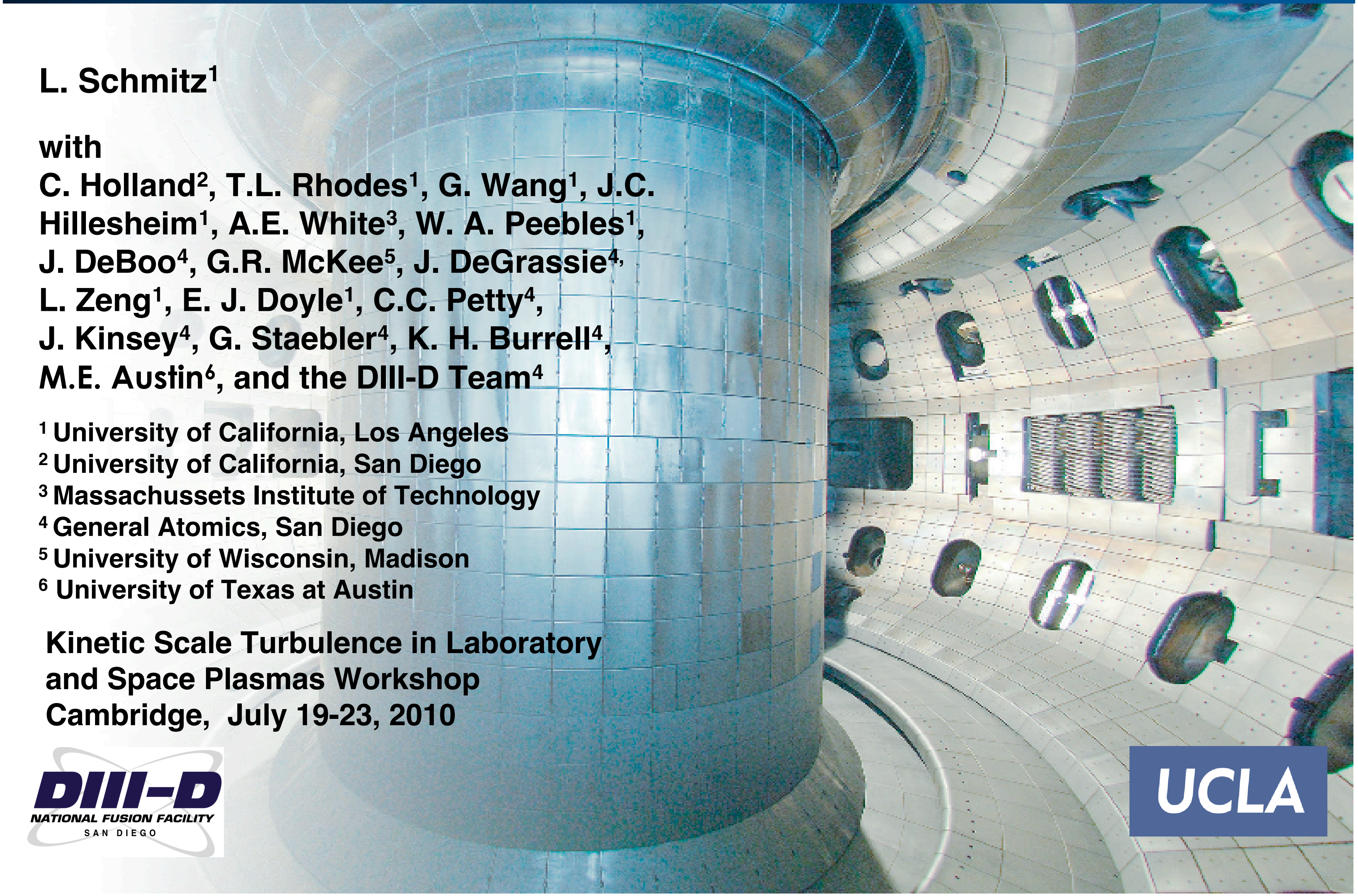
Multi-scale turbulence, electron transport, and Zonal Flows in DIII-D



L. Schmitz[1]

with
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Kinetic Scale Turbulence in Laboratory
and Space Plasmas Workshop
Cambridge, July 19-23, 2010

Why is intermediate/small-scale turbulence important?

- Understanding electron thermal transport in H-mode plasmas is critical for next-step burning plasma experiments such as ITER (α-particle heating).

- Electron transport is driven by multi-scale phenomena. Local measurements of intermediate/smaller-scale density fluctuations ($k\rho_e \lesssim 0.2$) have become available (Doppler Backscattering, DBS).

- Gyrokinetic code results (GENE, GYRO) predict that intermediate/small-scale turbulence may be important (or possibly dominant) in H-Mode.

- Local multi-scale turbulence measurements provide critical tests and validation of Gyrokinetic predictive codes.

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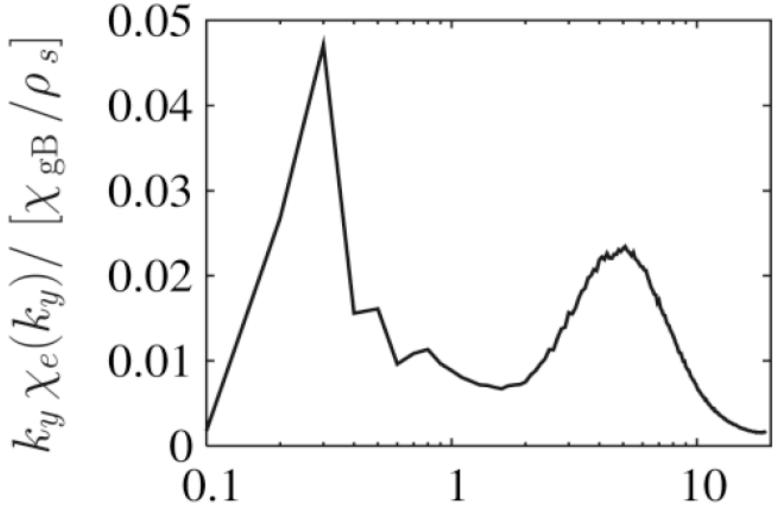
Outline

- Introduction
- Core turbulence behavior across the L-H transition
- Multi-scale turbulence in high temperature, low collisionality H-mode plasmas:
  - radial profiles
  - wavenumber spectra, linear stability
  - GYRO simulations
- ECH-Heated QH-modes: T_e/T_i ~1
- Zonal Flows and intermediate-scale turbulence

Intermediate/high-k turbulence may drive 50% or more of the electron heat flux once ITG modes are subdominant

Cyclone ITG/TEM/ETG simulation: 50% of electron heat flux driven for $k_\theta r_s \geq 0.5$.

$R/L_{T_e} = 6.9$ $R/L_{T_i} = 5.5$
$R/L_n = 0$

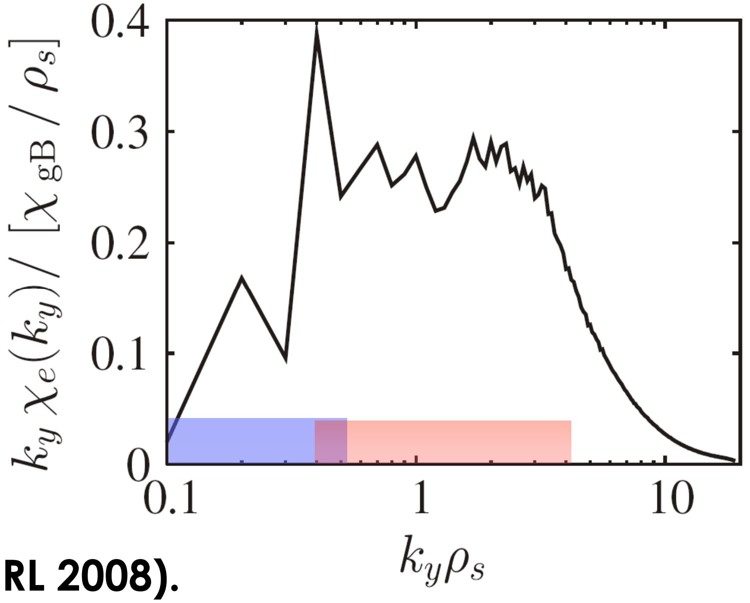


Coupled TEM/ETG simulation (ITG linearly stable): 70% of electron heat flux driven for $k_\theta r_s \geq 0.5$.

$R/L_{T_e} = 6.9$ $R/L_{T_i} = R/L_n = 0$

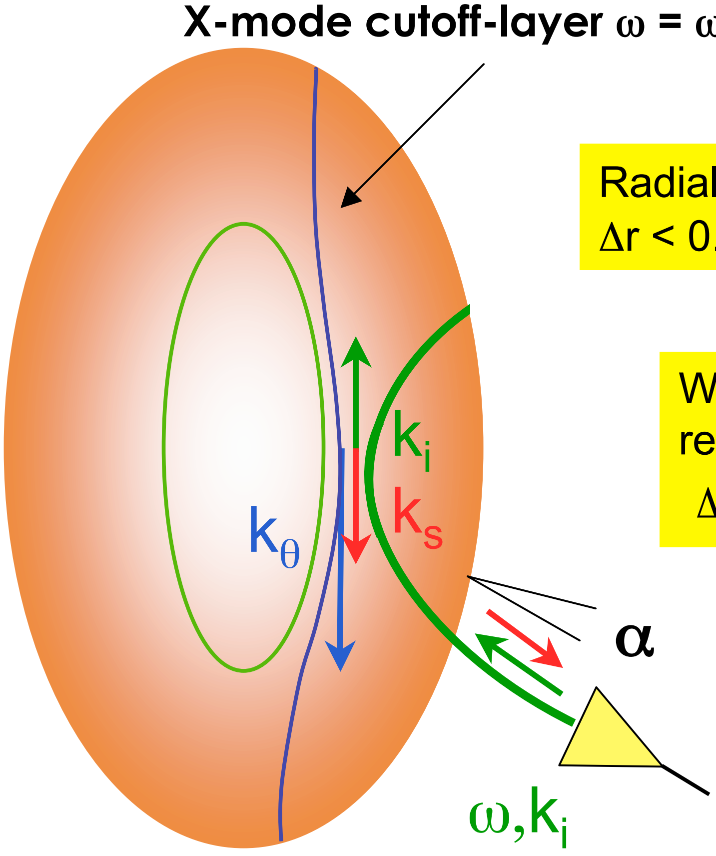
🟦 Accessible By BES and CECE

🟥 Accessible by Doppler Backscattering



(Goerler and Jenko, PRL 2008).

Doppler Backscattering (DBS) measures local density fluctuation level and E×B velocity versus wavenumber



Radial resolution:
$\Delta r < 0.5$ cm

Wavenumber resolution:
$\Delta k_\perp / k_\perp \sim 0.3$

Backscattering off density fluctuations with $k_s = k_i - k_\theta$, $k_\theta = -2k_i$

Several Effects localize backscattering to the cut-off layer.

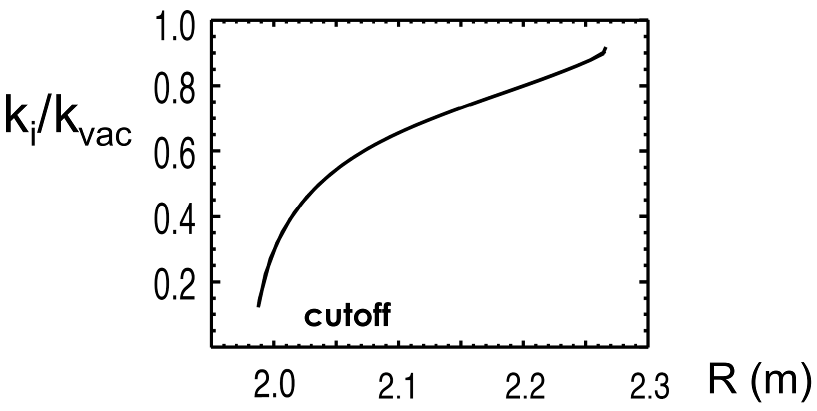
Fluctuation level vs. k_θ from back-scattered amplitude:

$$\tilde{n}(k_\theta) \sim A(k_\theta)$$

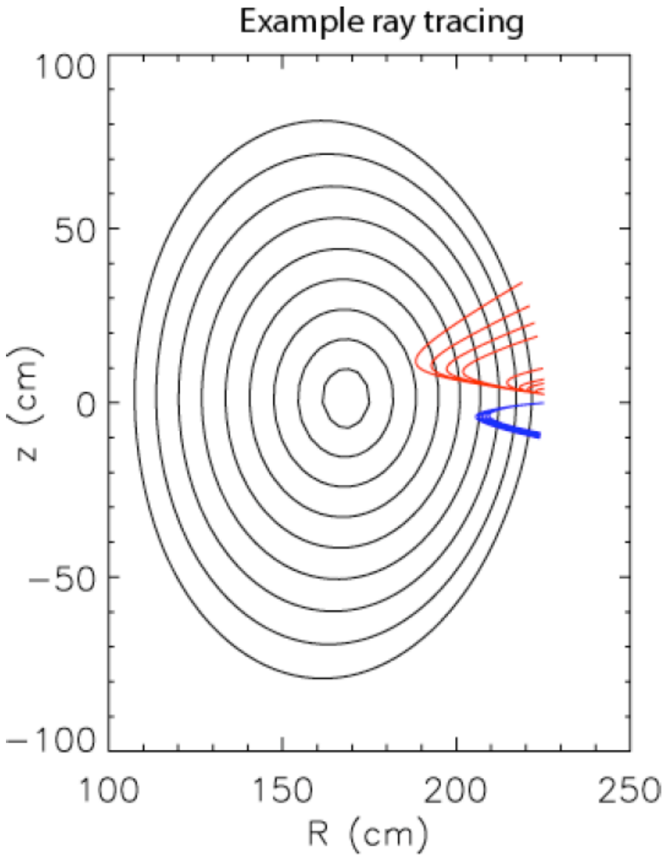
ExB velocity evaluated from Doppler shift $\Delta\omega_D$ of the backscattered signal:

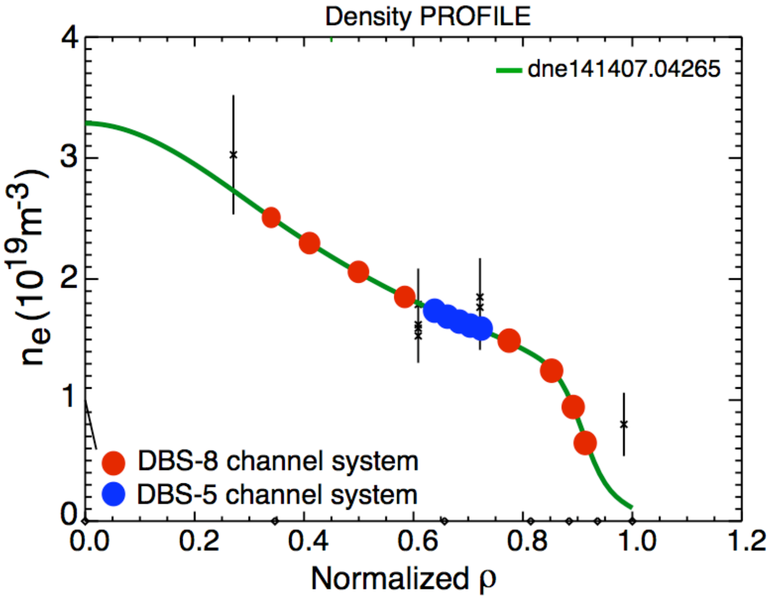
$$v_{E\times B} = v_{meas} - \cancel{v_{ph}} = \Delta\omega_D / 2k_i$$

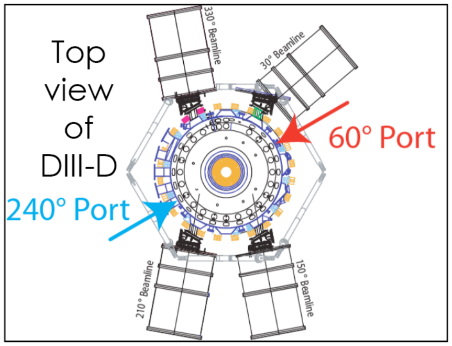
The probed wavenumber is set by the beam tilt angle α. k_θ is obtained from GENRAY ray tracing:



GENRAY ray tracing is used to obtain the DBS probed radius and wavenumber





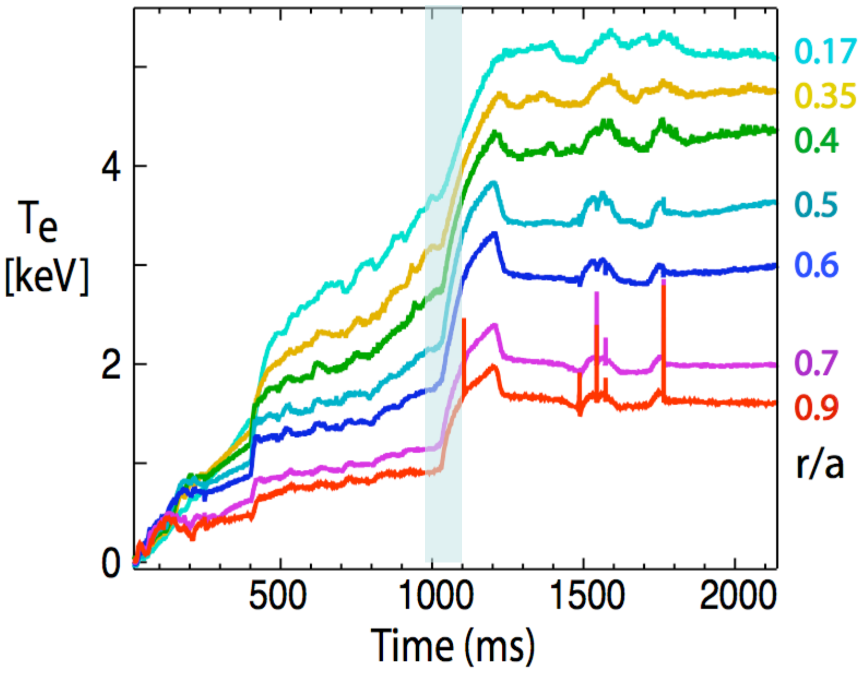


- **Measures (relative) local fluctuation levels ($0.5 \lesssim k_\theta \lesssim 15$ cm^{-1})**
- **Radial resolution Δr < 0.5 cm**
- **Wavenumber resolution:**

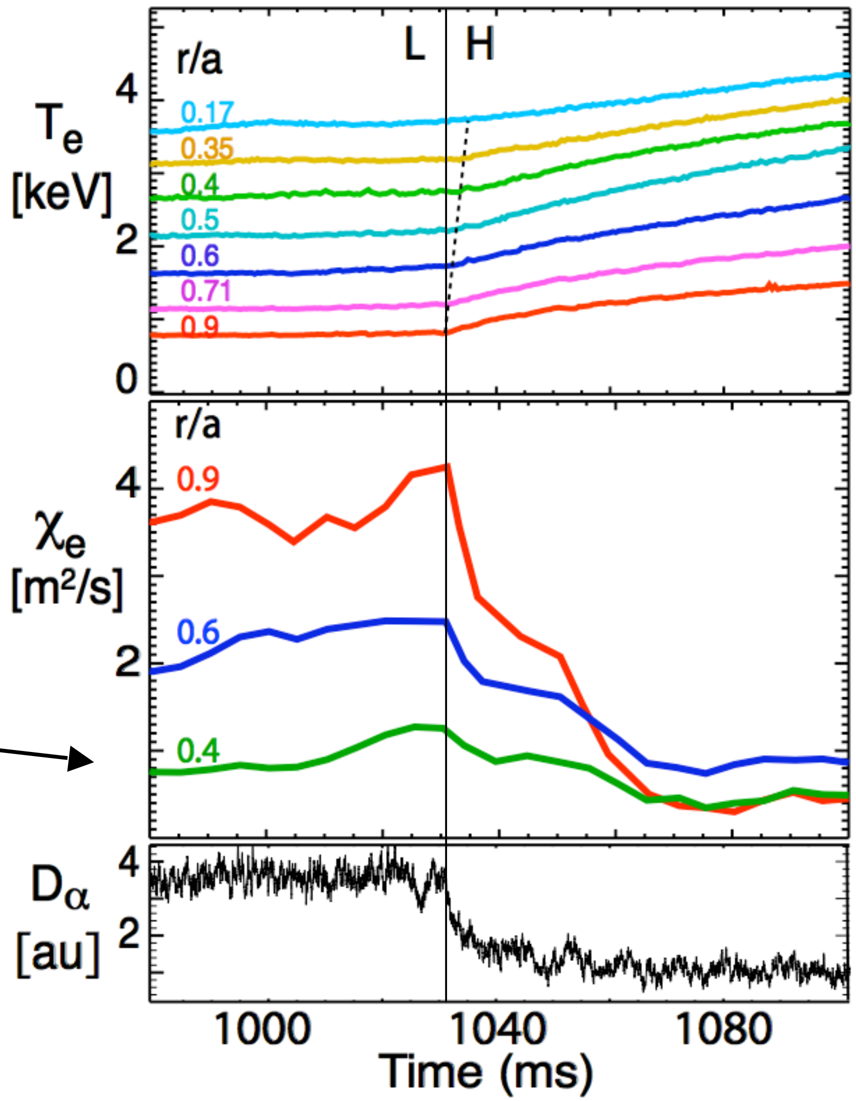
$$\frac{\Delta k_\perp}{k_\perp} = \frac{\sqrt{2}\lambda_0}{2\pi W_0 \sin\theta}\left[1+\left(\frac{2\pi W_0^{\ 2}}{\lambda_0 R_p}\right)^2\right]^{1/2}$$

Δk/k = 0.2…0.5

Core electron thermal diffusivity decreases within ~10 ms of H-mode edge barrier formation

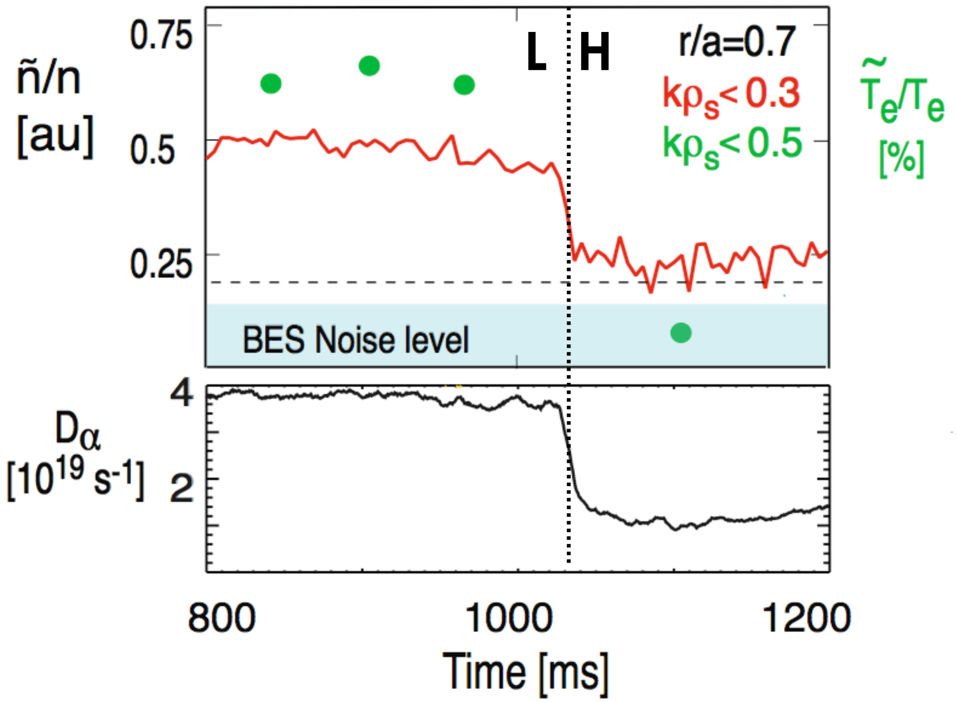


L-H transition



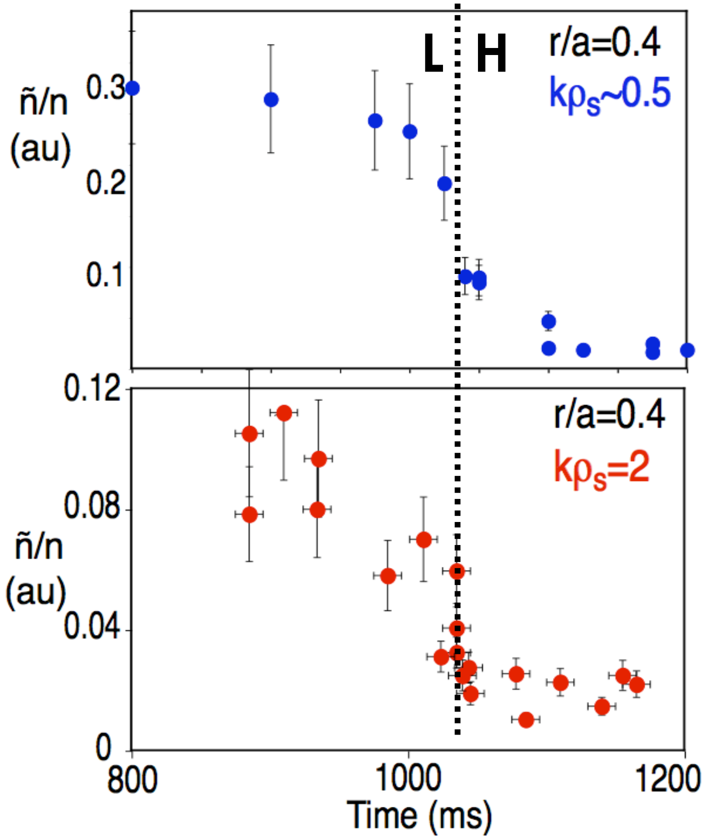
Electron heat diffusivity (from TRANSP) decreases rapidly across minor radius

At the L-H transition, core fluctuations ($0.4 \leq r/a \leq 0.8$) are reduced across a range of wavenumbers



CECE ($\tilde{T}_e/T_e$)*, BES ($\tilde{n}/n$), r/a=0.7

*L. Schmitz, A.E. White et al., Phys. Rev. Lett. 100 (2008).



Doppler Backscattering, r/a=0.4

Moderate reduction before L-H transition due to increasing E×B shear; ñ drops at transition within ~5-10 ms.

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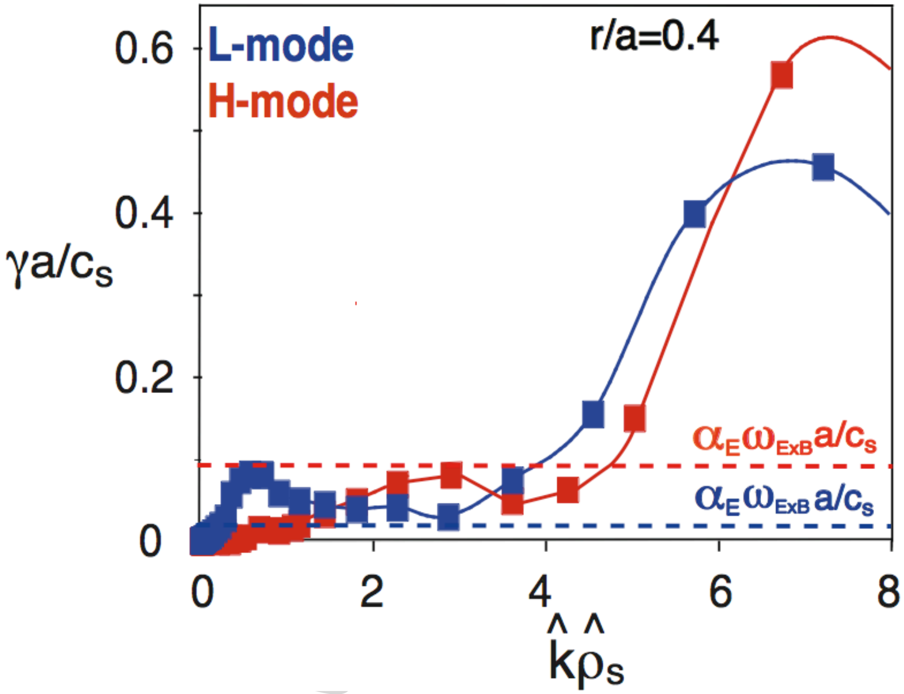
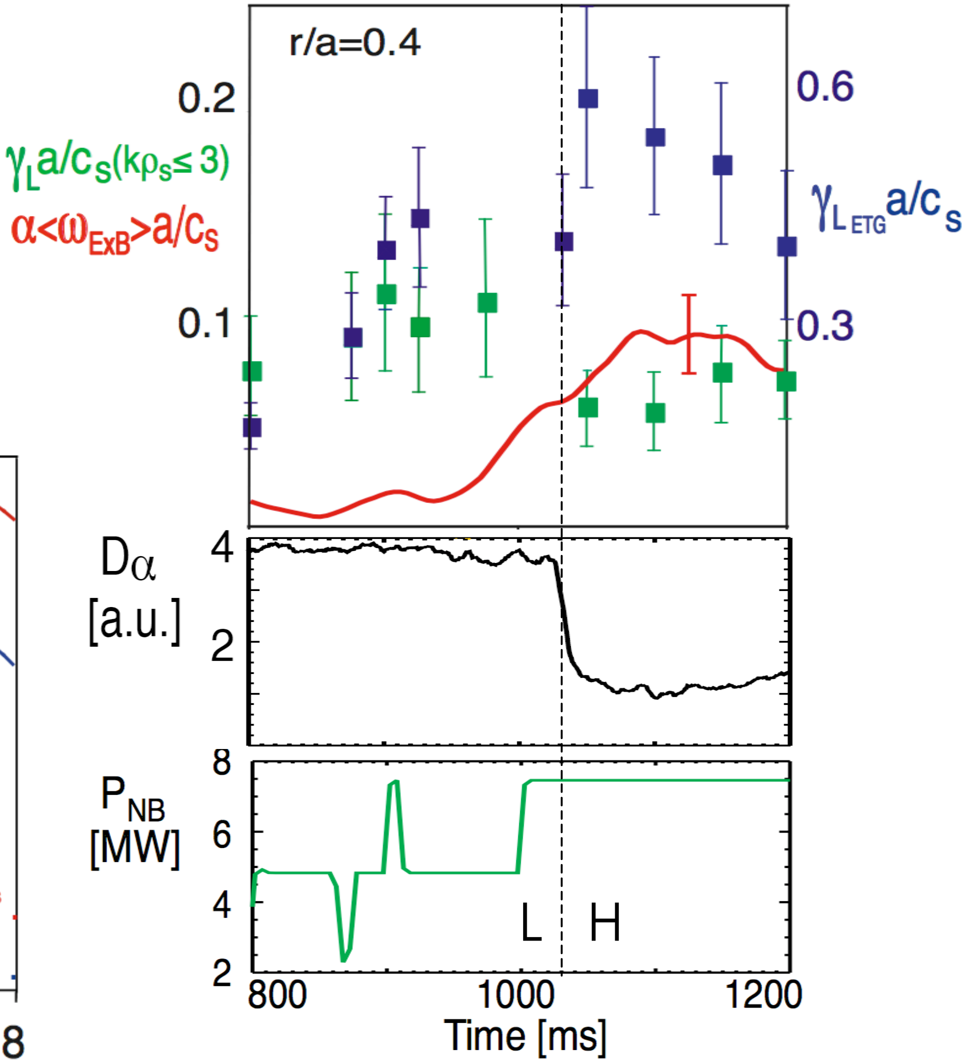
The E×B shearing rate exceeds the linear growth rate in the ITG/TEM range in the core plasma in H-mode

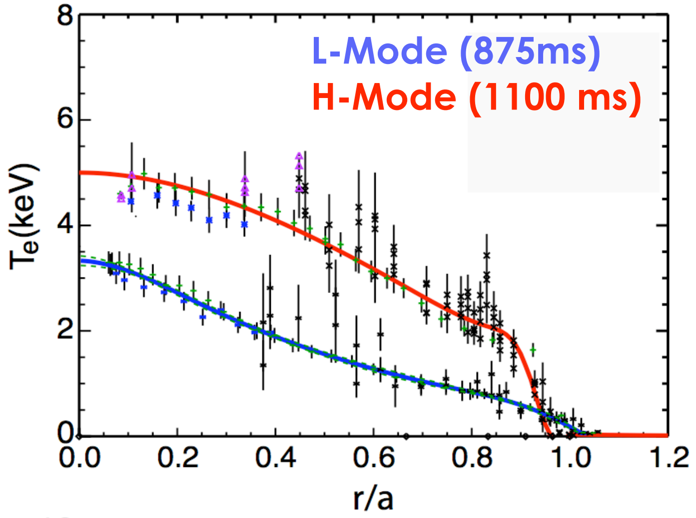
Linear growth rate γ_l is calculated by TGLF. The radial electric field/shear in the core is dominated by toroidal rotation ($E_r \sim v_\phi \times B_\theta$). Fluctuation suppression expected for $k_\perp \rho_s \leq 4$ in H-mode (r/a=0.4).

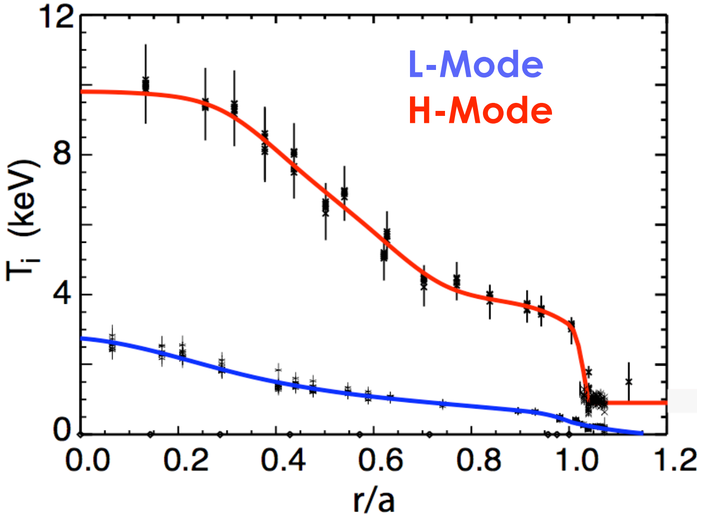
Only ETG expected unstable for r/a ~0.4

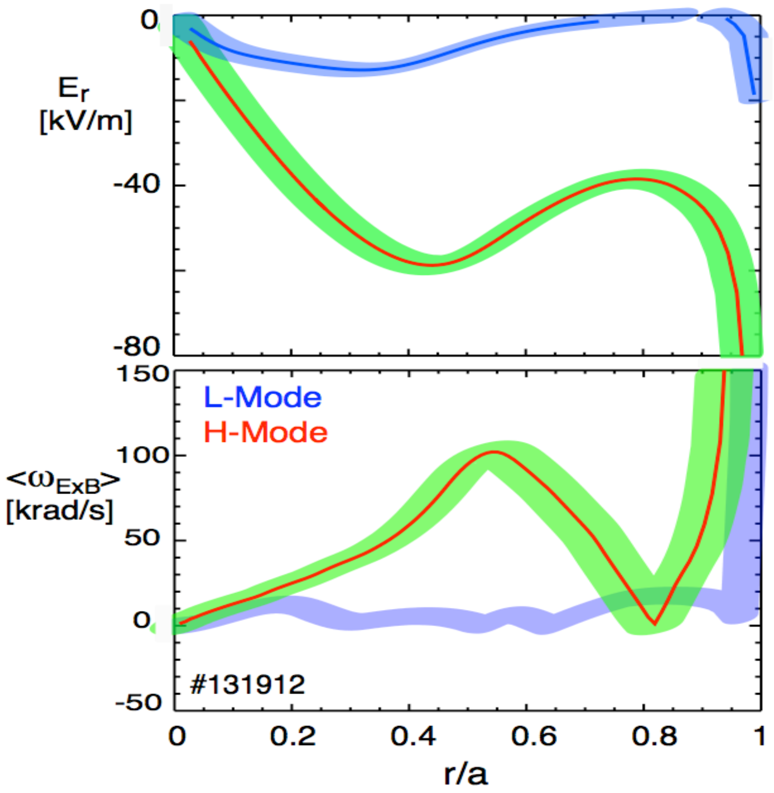




Electron temperature and density profiles and E×B shearing rate in L- and H-Mode, #131912

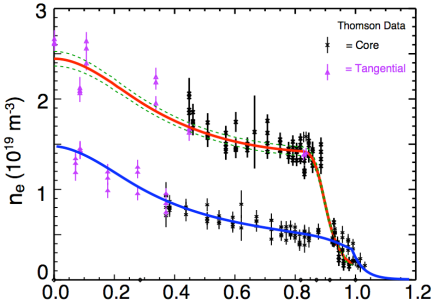






Radial Electric Field

Waltz-Miller Shearing Rate



H-Mode (1100 ms): strong shear in the core plasma (r/a <0.7) in addition to the pedestal region
Low collisionality $\nu_e^*(0.4)$ ~0.04

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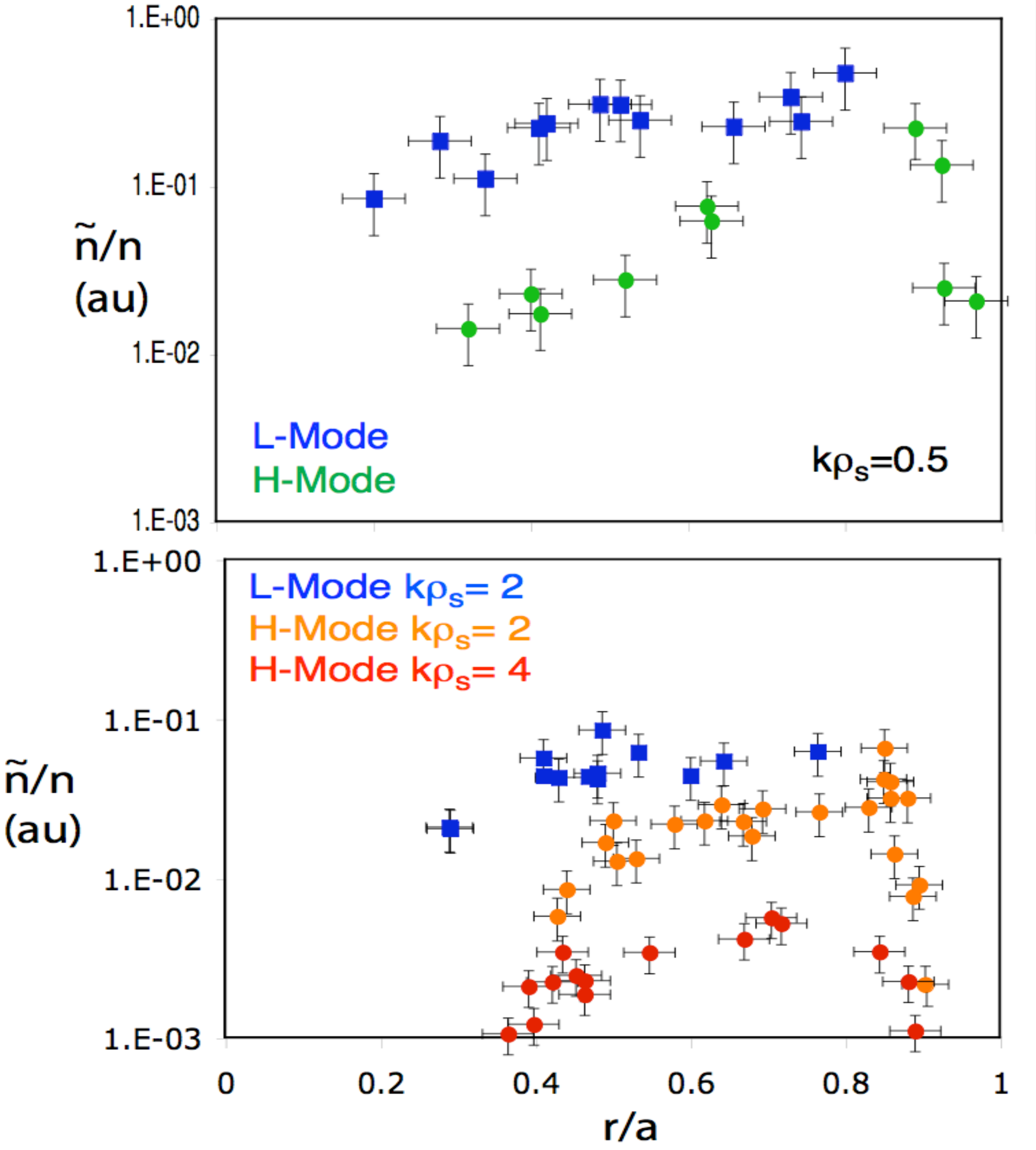
Radial profile of Density Fluctuations in L and H-Mode

Both ITG-scale and Intermediate-scale fluctuations are substantially reduced in H-mode across the core plasma.

ñ/n is reduced by more than an order of magnitude for r/a < 0.45

Very low H-mode intermediate-k turbulence for r/a <0.45



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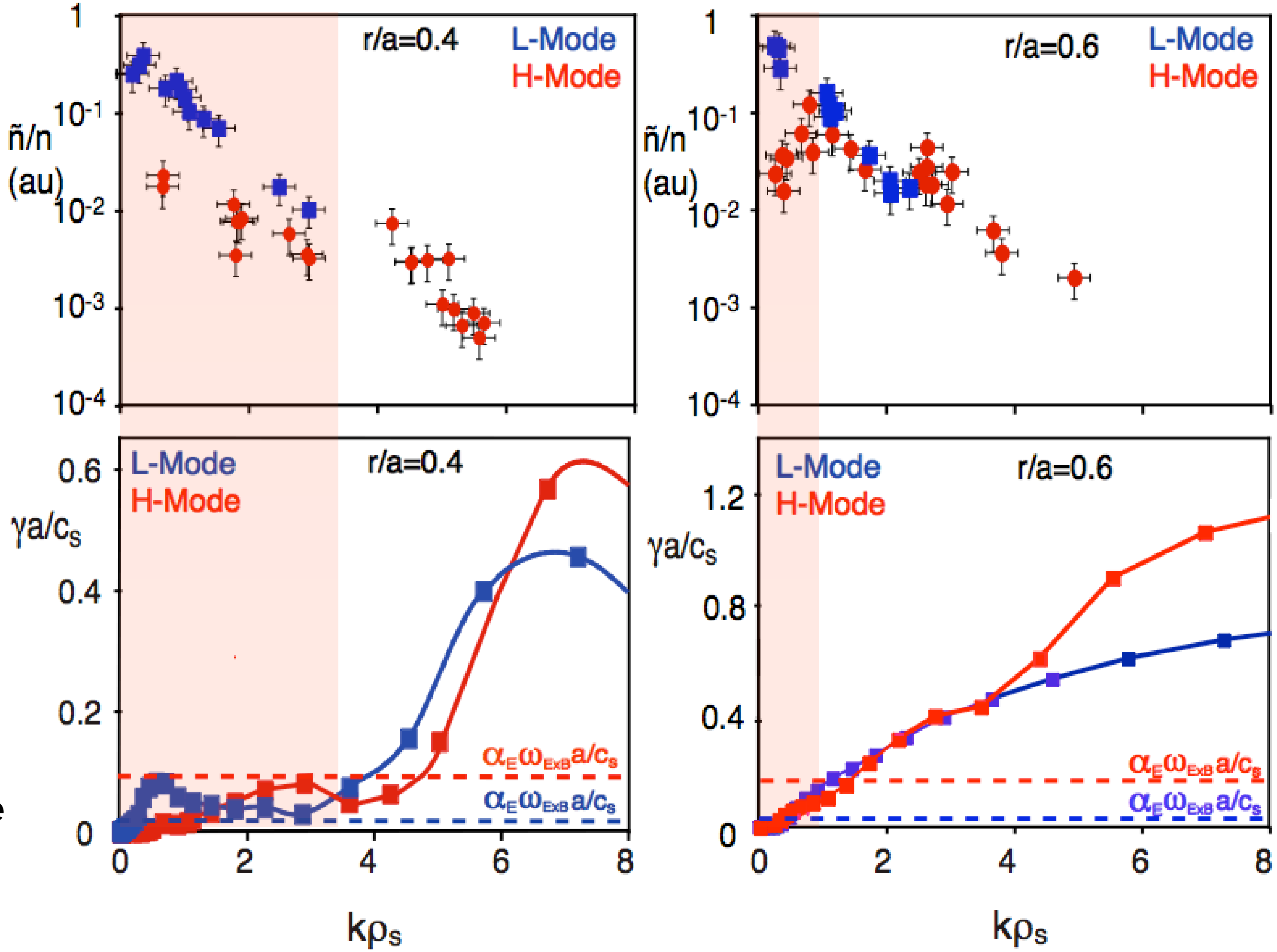
In H-mode, core fluctuations are reduced in the wavenumber range where $\alpha<\omega_{ExB}> > \gamma_I$

Exponential spectra found in L-Mode:

$\tilde{n}/n \sim e^{-\beta(k\rho_s)}$

with β =1.5…1.7



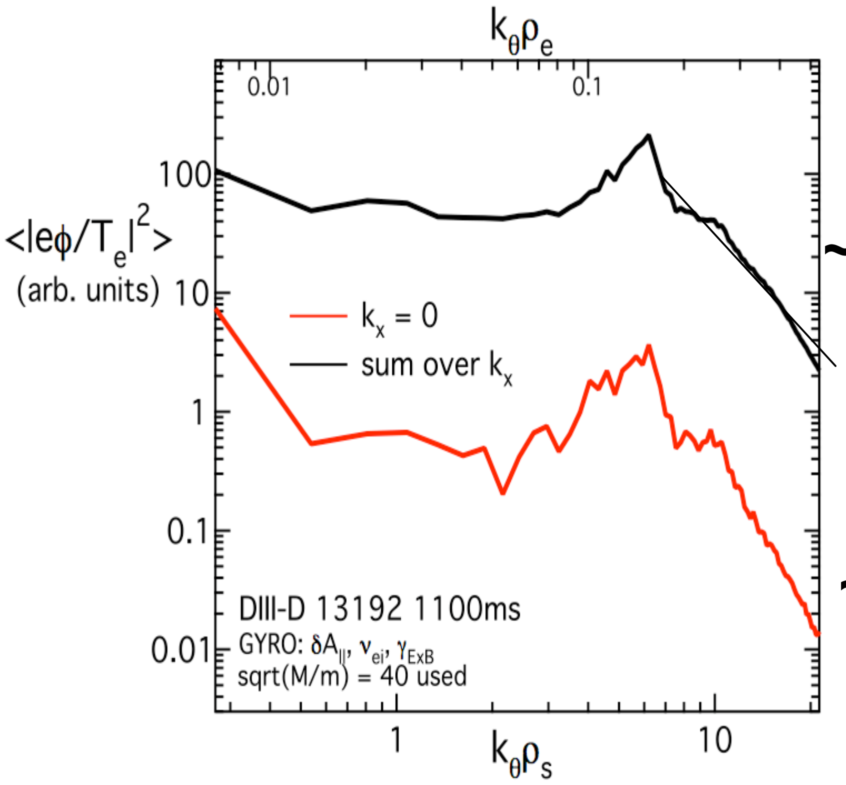
TGLF growth rate of most unstable mode

$\alpha_E \omega_{ExB} a/c_s$ is the normalized shear quench rate

Initial multi-scale GYRO calculations indicate importance of ETG range ($k_\theta \rho_s > 3$) for electron thermal transport

Spectrum of potential fluctuations (outboard midplane)

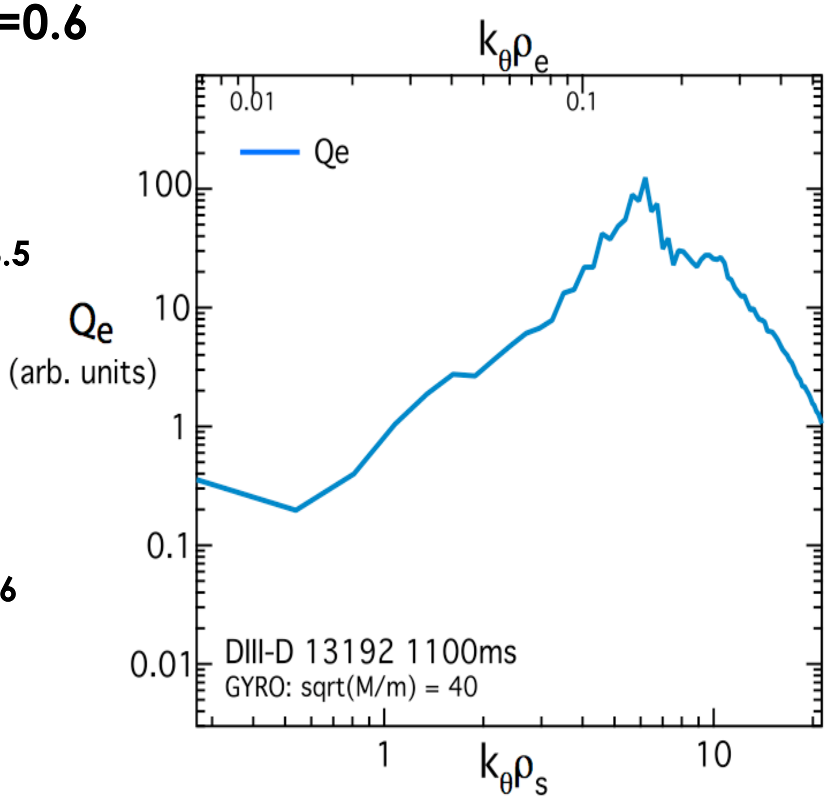
r/a=0.6



$\sim k\rho_s^{-3.5}$

$\sim k\rho_s^{-6}$

Electron transport spectrum

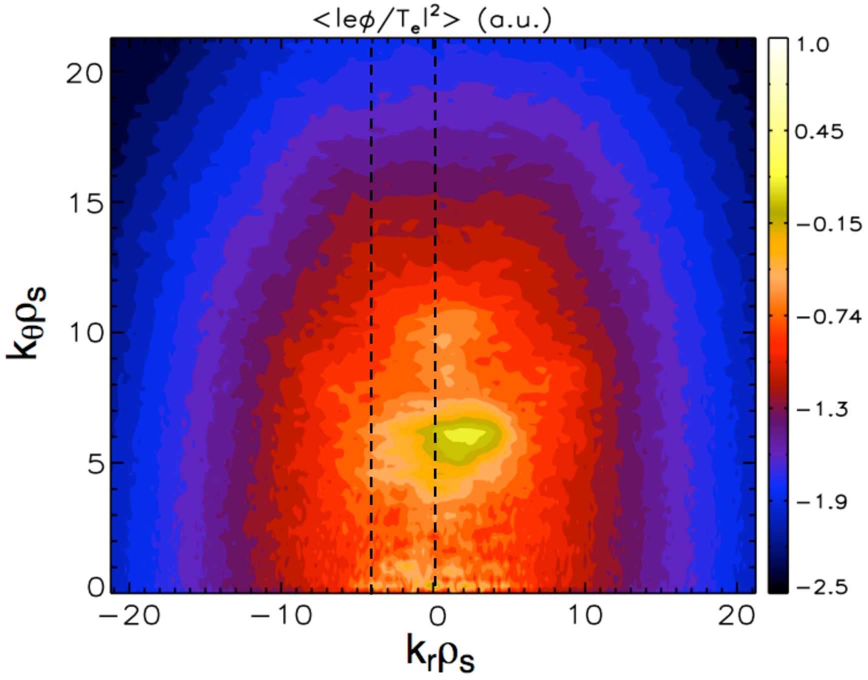


Fixed gradient simulation;
$Q_{e\ GYRO} = 0.28\ Q_{e,\ exp}$

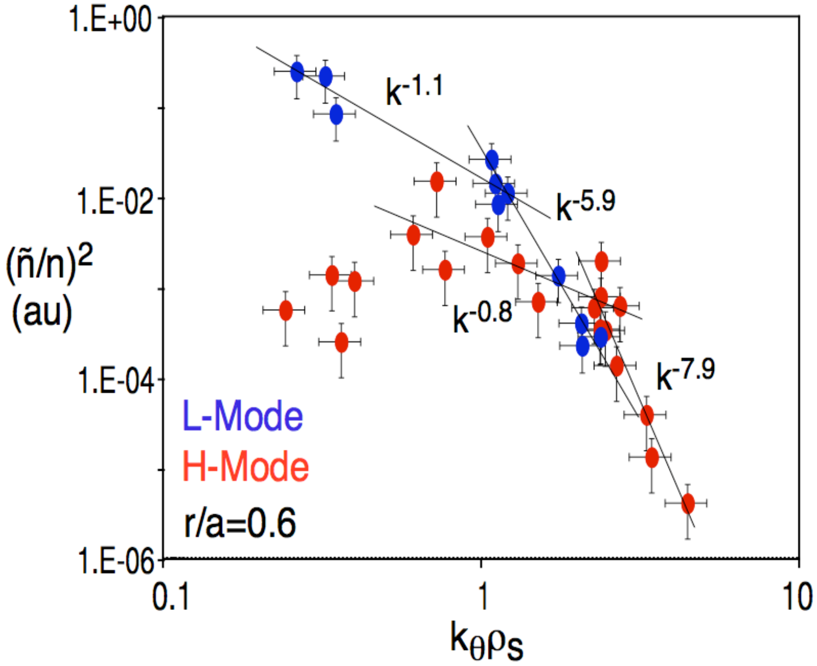
Electron Heat flux almost entirely driven by modes with $k_\theta \rho_s > 2$

2-D wavenumber spectrum (k_r/k_θ asymmetry)

Outboard midplane reconstruction (GYRO)



DBS measurement



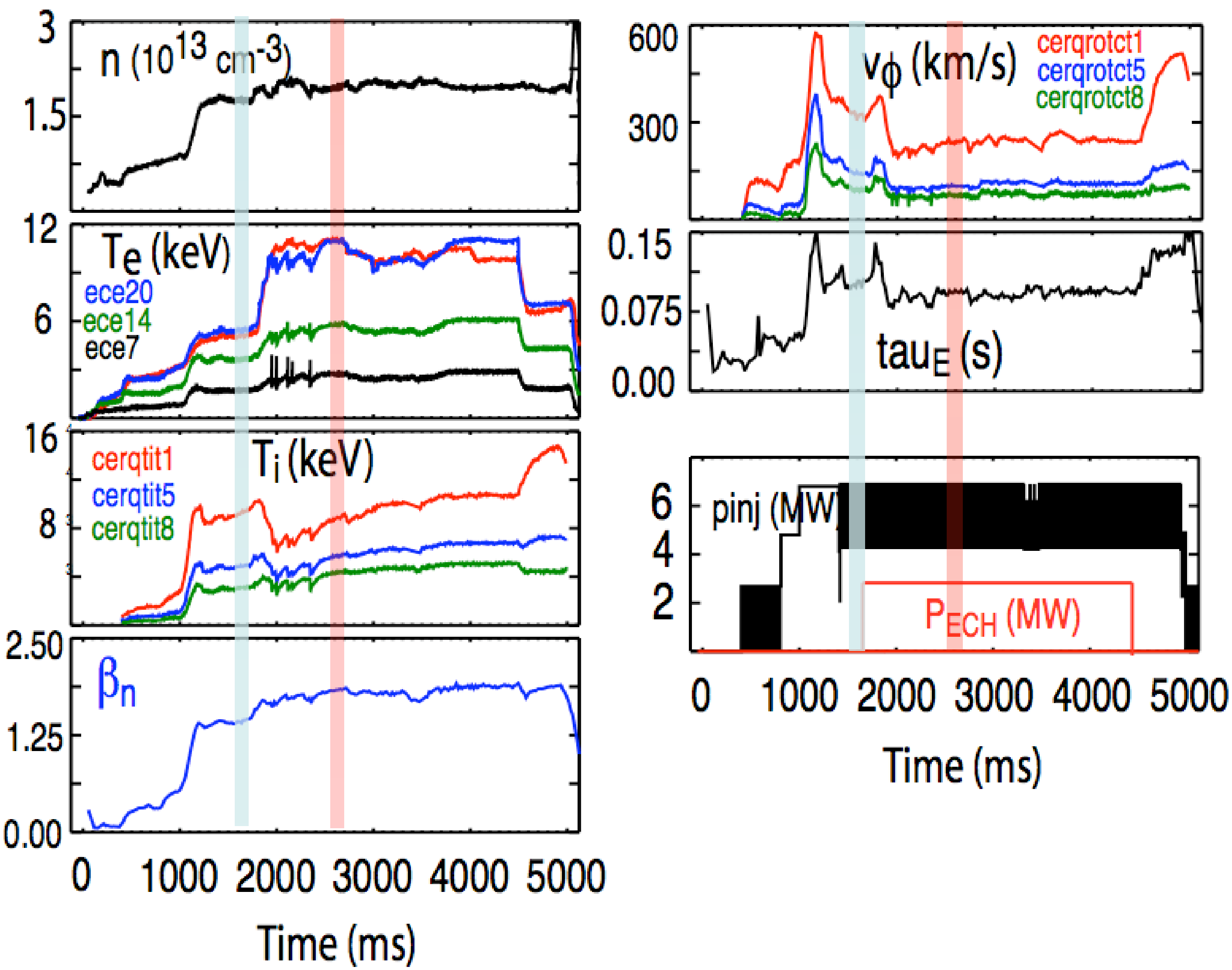
r/a=0.6

Measured DBS spectral index is increased compared to index averaged over $\langle k_r \rangle$

Achieved $T_e/T_i > 1$ and $T_e > 10$ keV in ECH-assisted QH-mode plasma

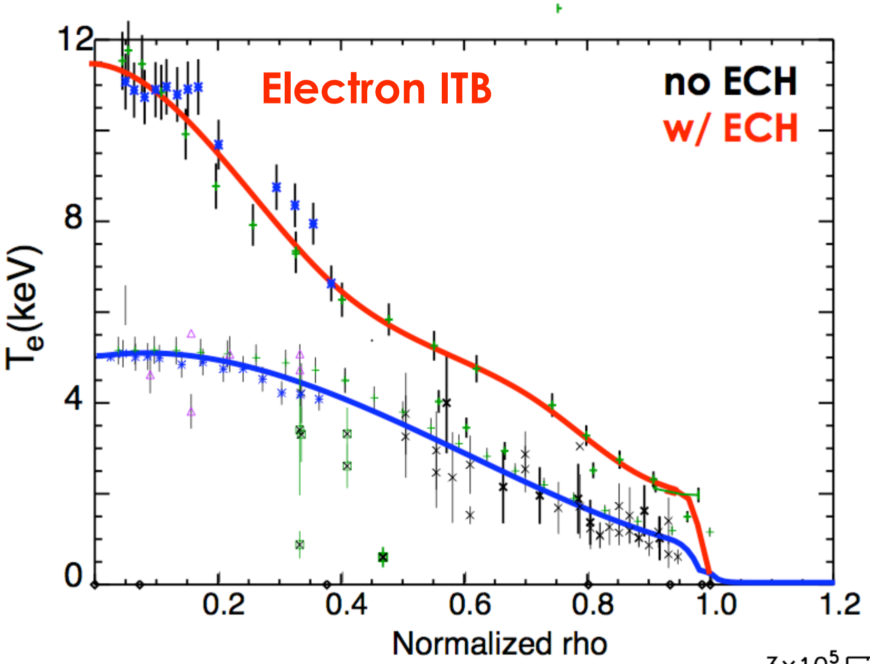
Reduced toroidal rotation and reduced central ion temperature with ECH

Collisionality $\nu^* \sim 0.02\text{-}0.04$ (r/a~0.4; comparable to ITER!)

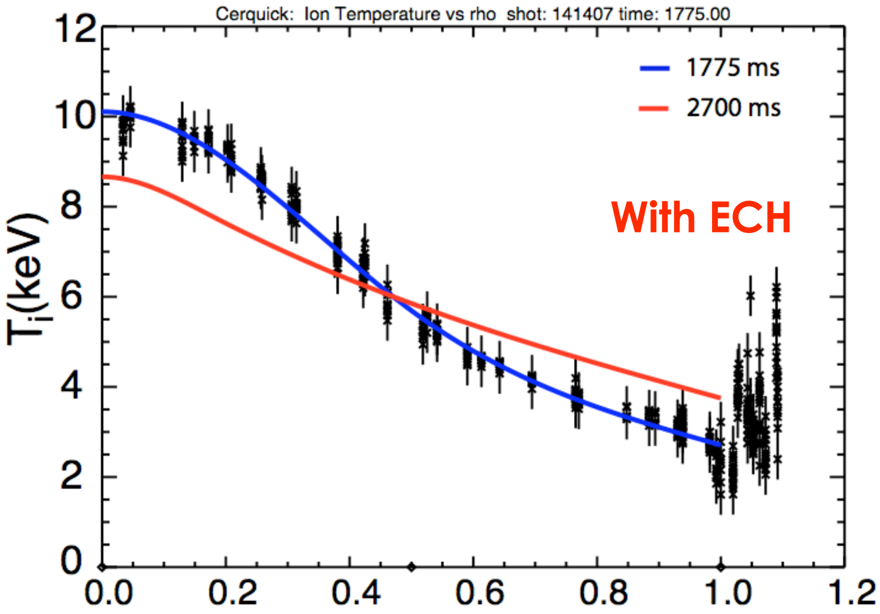


Transport Dependence on T_e/T_i: Radial Profiles with/without ECH (#141407, 2.8 MW ECH)

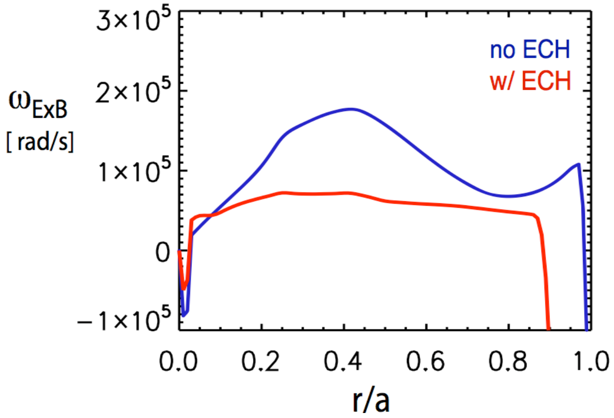
Electron Temperature



Ion Temperature

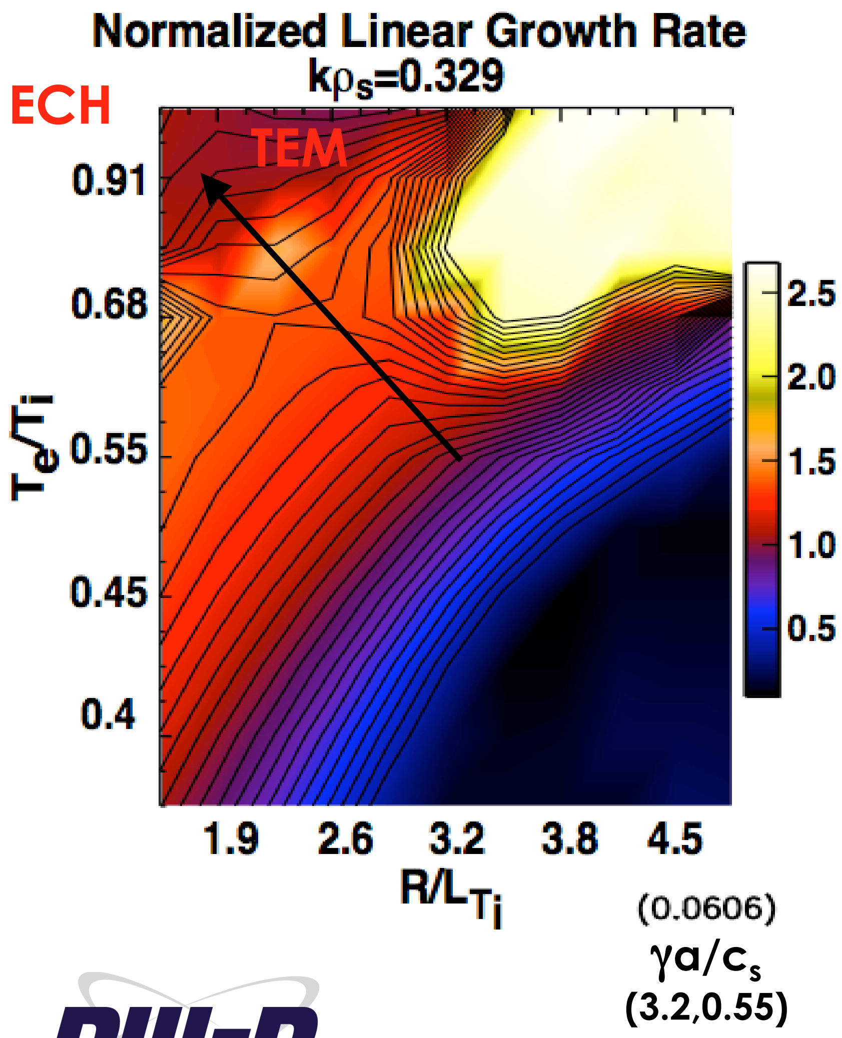


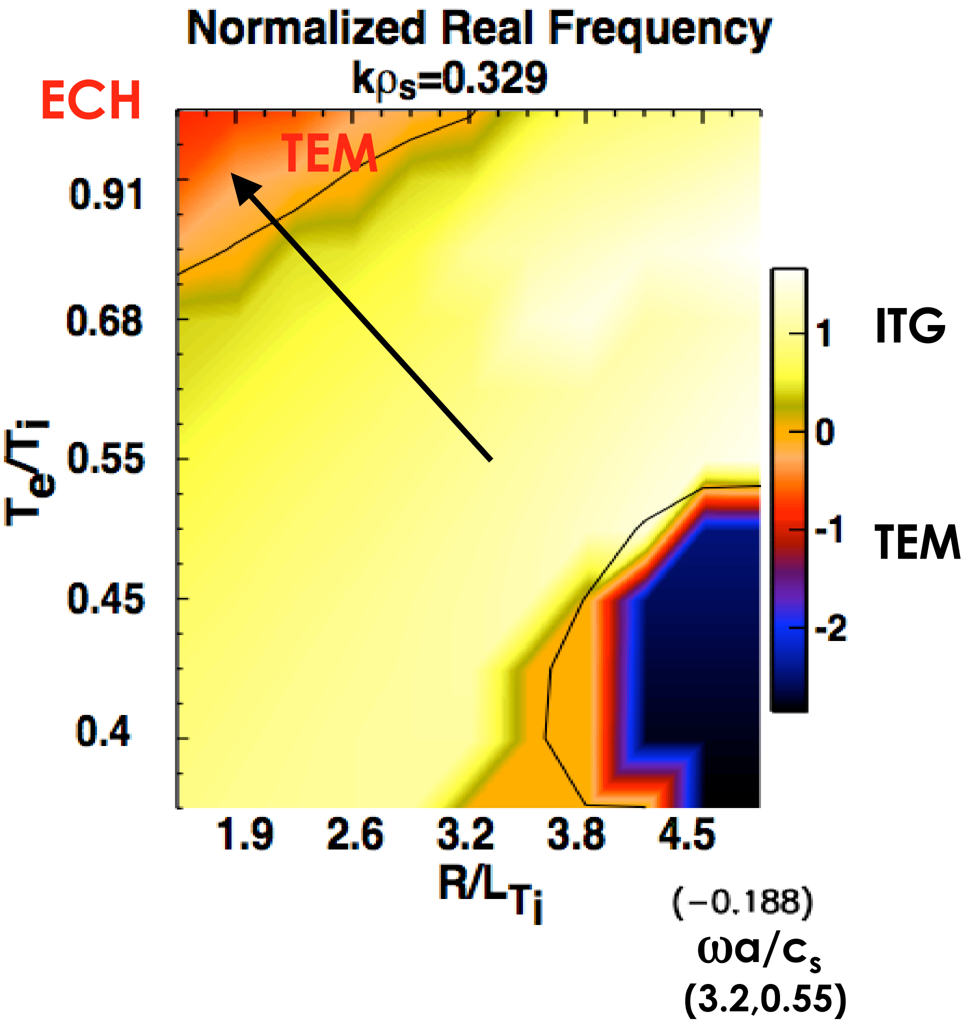
r/a	0.3	0.5	0.7
T_e/T_i	0.62	0.65	0.66
T_e/T_i	1.21	1.07	0.8



- Large variation in T_e/T_i provides good basis for investigating electron transport
- Ion thermal transport increases with T_e/T_i

Increasing T_e/T_i (ECH) leads to increased ion heat transport (flat T_i profile) and ITG/TEM transition





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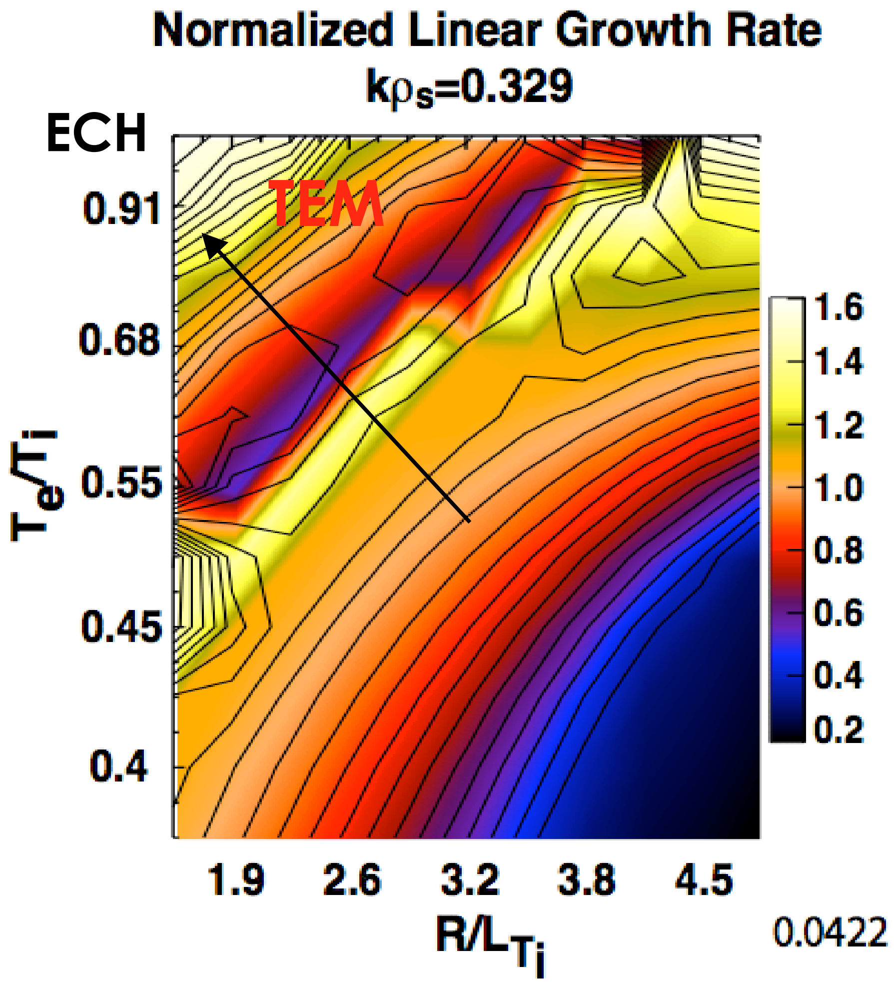
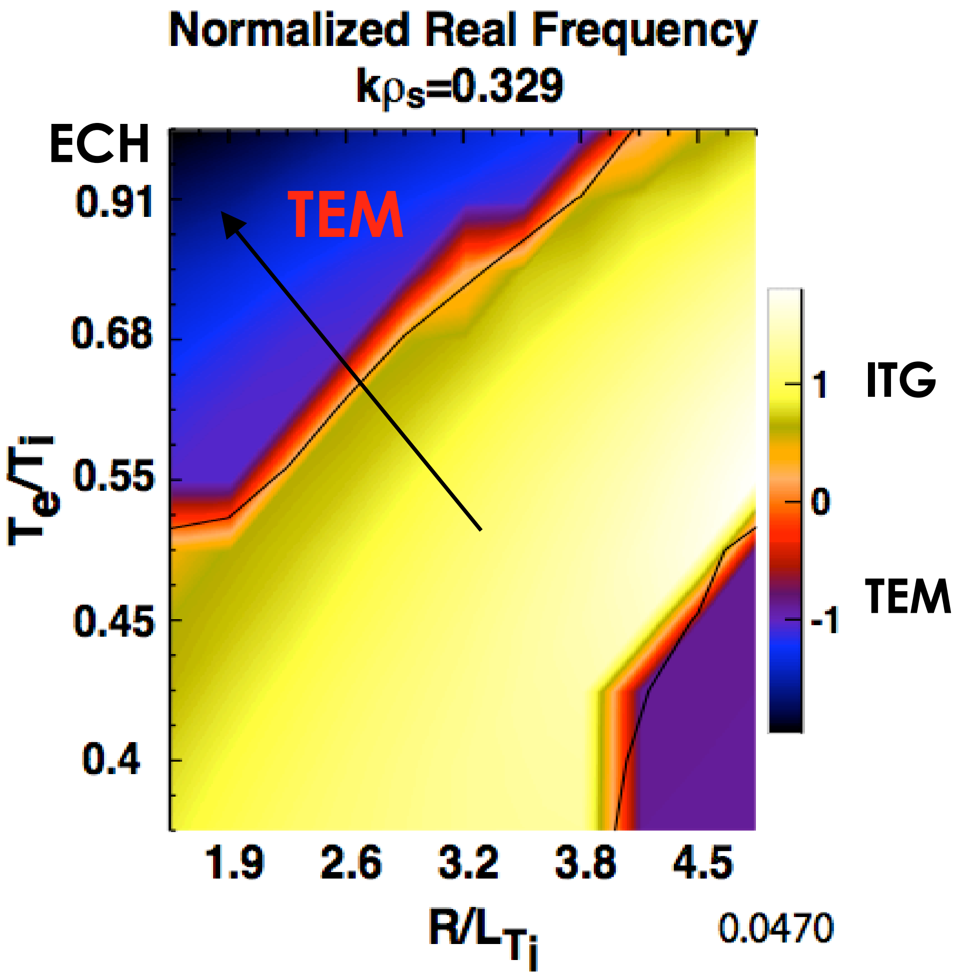
ITG-TEM transition in core plasma with ECH (r/a = 0.4) (using correct L_{Te} during ECH phase)

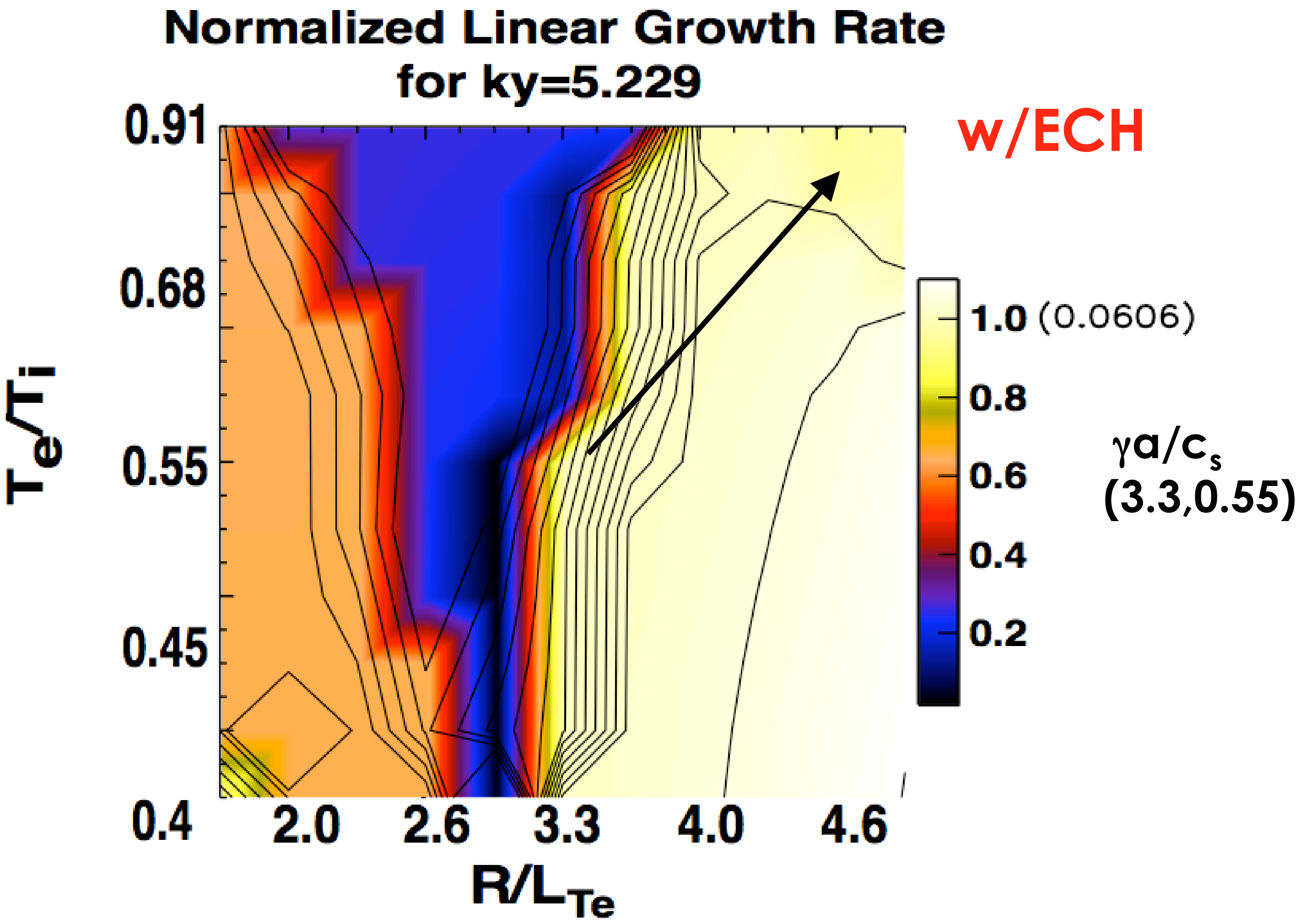

Normalized Linear Growth Rate
$k\rho_s$=0.329

$\gamma a/c_s$
(3.2,0.55)

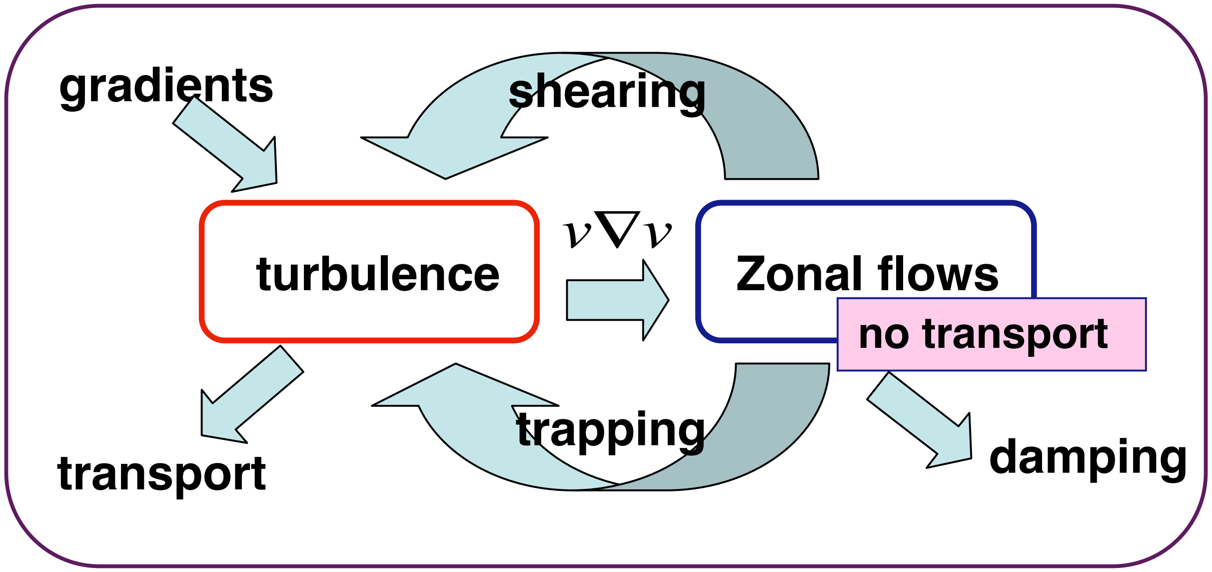

Normalized Real Frequency
$k\rho_s$=0.329

$\omega a/c_s$
(3.2,0.55)

Electron Temperature gradient stays above ETG critical gradient



Evidence of intermediate-scale turbulence regulation by Zonal Flows in an electron ITB



- Zonal Flows thought to regulate ITG-scale turbulence saturation; the influence on intermediate-scale turbulence is less well understood.
- We present evidence of a ZF-induced shear layer and intermediate-scale fluctuation suppression at/near the q=1 rational surface.
- Fluctuation suppression sustains an L-Mode electron transport barrier at the q=2 surface in the data shown.

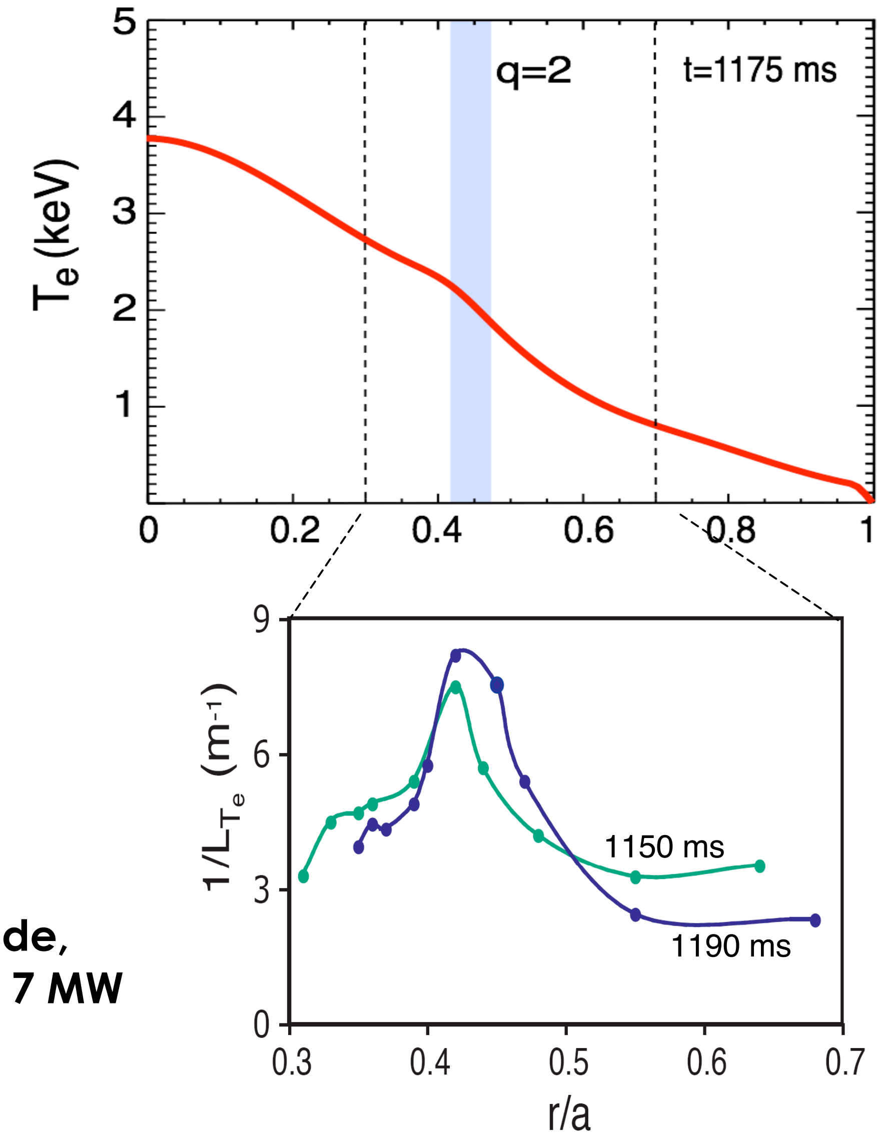
L-Mode electron transport barrier at the q = 2 rational surface

Previous evidence in DIII-D of ion ITBs and transient electron ITBs formed near q_{min} as the q=2 surface enters the plasma.*

We investigate the interaction of ZF's with turbulence in a sustained electron ITB (L-mode).

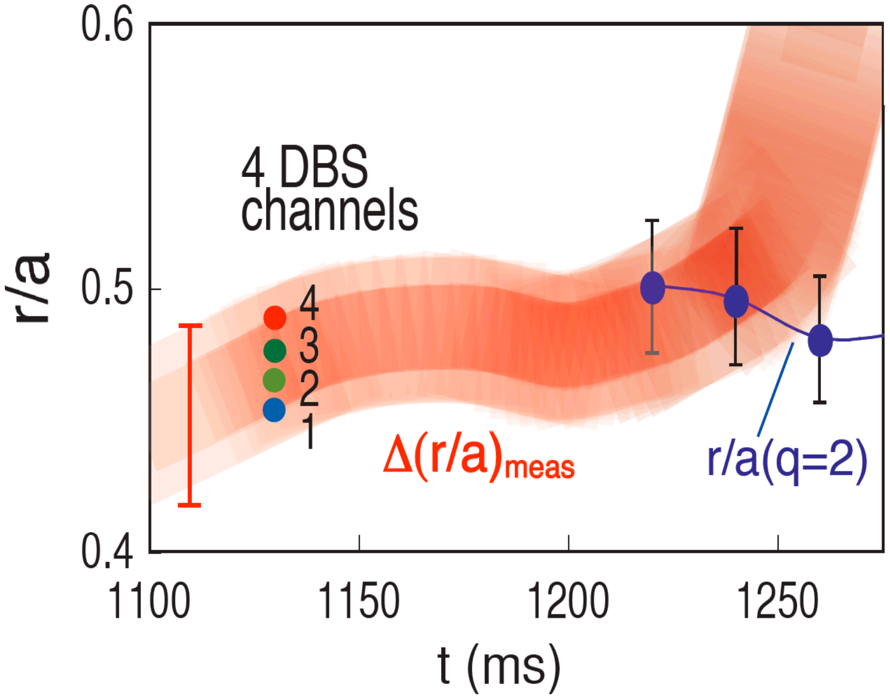
*M. Austin et al., Phys. Plasmas 13, 082502 (2006).

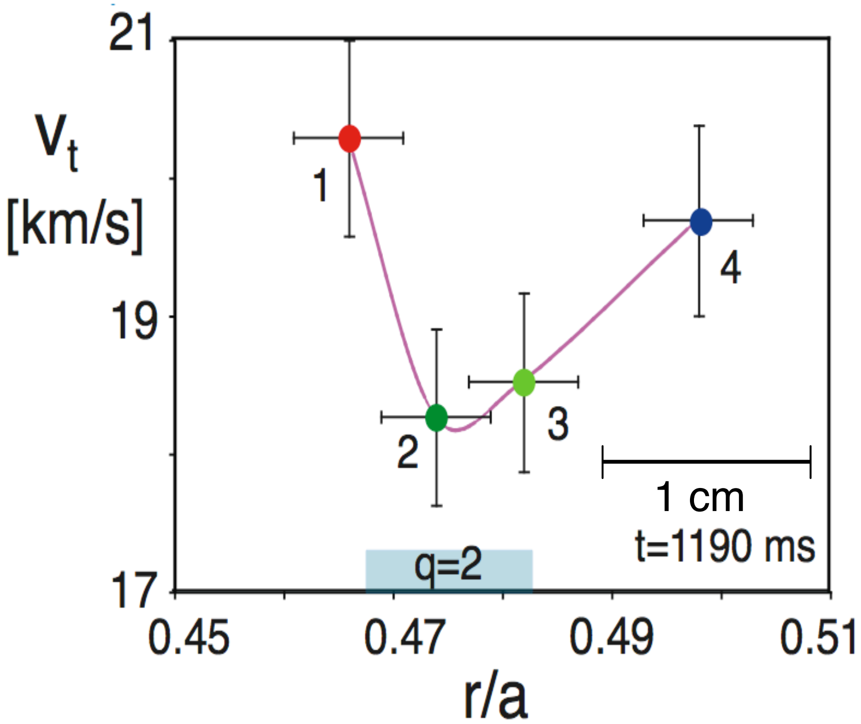
L-Mode, P_{NB} = 7 MW



Localized shear layer (Zonal Flow structure) detected near q=2 surface by Doppler Backscattering

Turbulence velocity $v_{ExB} + \cancel{v_{ph}}$





Phase velocity is neglected ($v_{ph} < 0.05\ v_{ExB}$ from TGLF, $V_t \sim v_{ExB}$)

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Localized Zonal Flows are observed near the q=2 surface

ZMF (zero-mean frequency) and low frequency **Zonal Flows** are observed near the q = 2 surface (r/a ~ 0.5)

A 3/2 tearing mode grows at 1190 ms and is transiently observed at the same radius. An island forms at 1230 m (observed on ECE data), collapsing the shear layer.

L-mode plasma,
co-injected 7 MW

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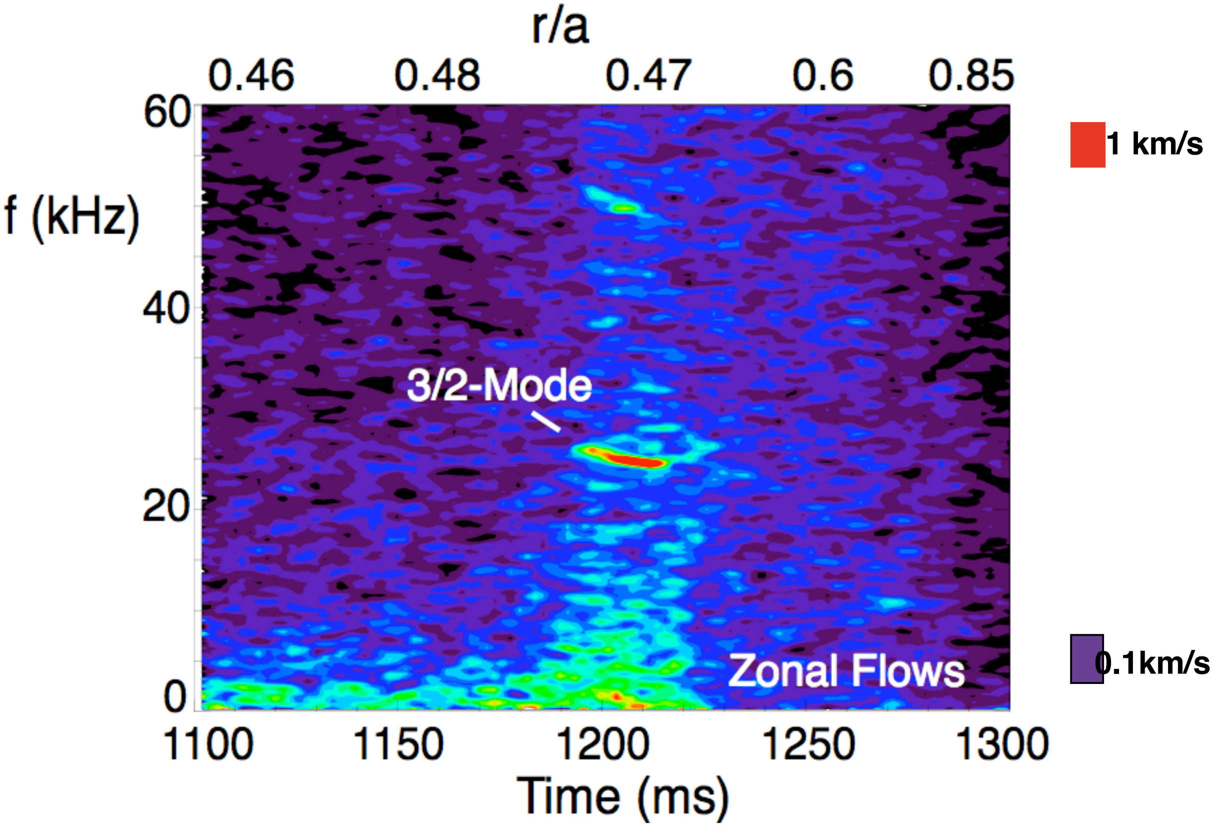
Flow velocity spectrum from Doppler Backscattering

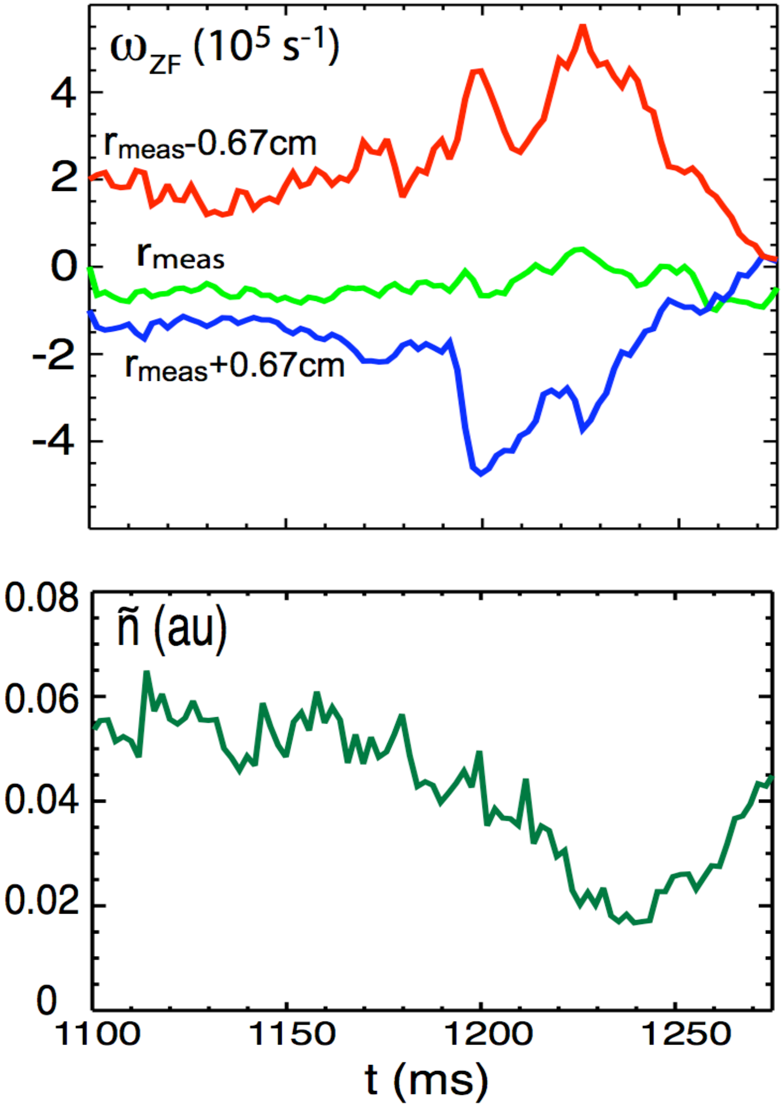


Intermediate-scale fluctuations are reduced in local ZF shear layer near the q=2 surface

E×B shear is calculated from adjacent DBS channels:

$\omega_{E\times B} \sim (v_{r2}-v_{r1})/\Delta r_{12}$

E×B shear reverses across q=2 surface (measured by DBS)



Local ExB shearing rate

$\omega_{ZF+}\ \omega_{eq}$

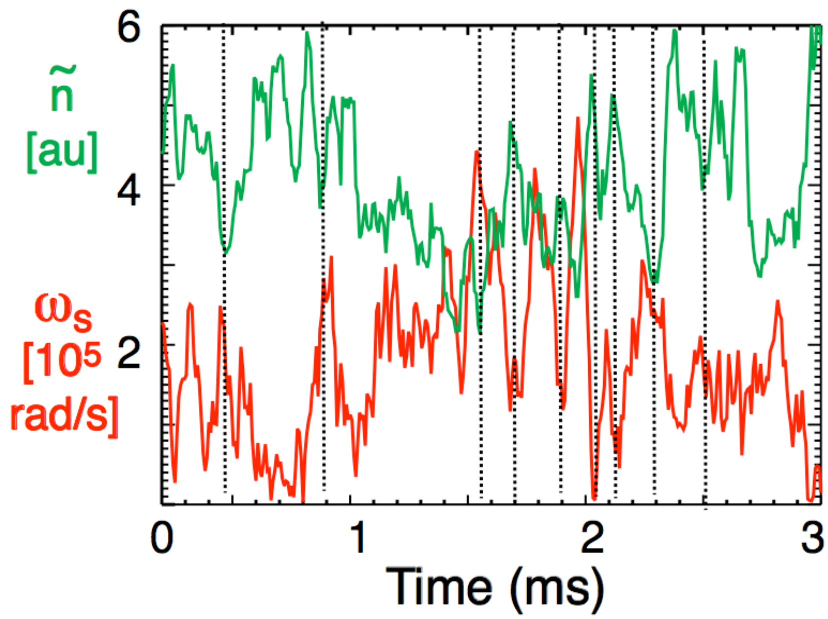
Barrier collapses

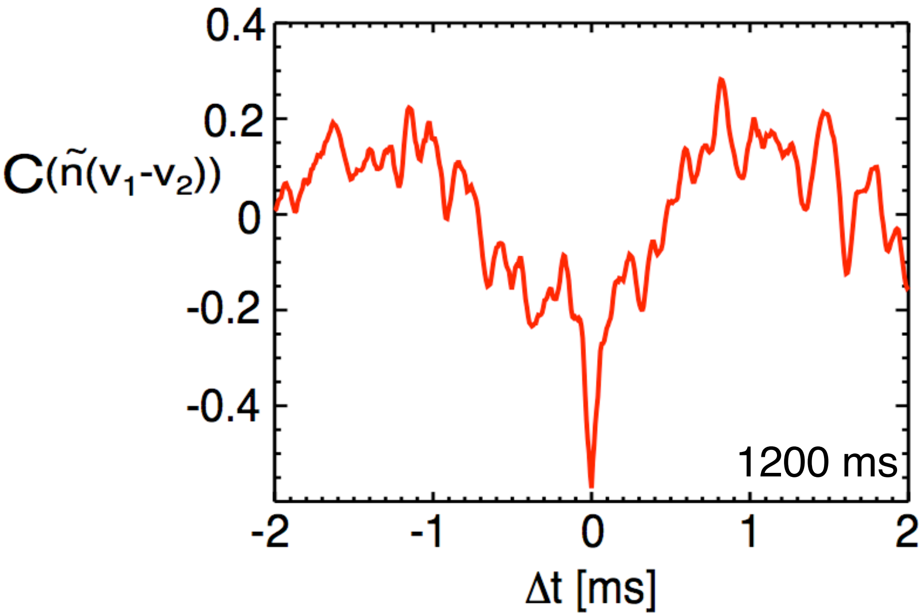
Density Fluctuation Amplitude

$k_\theta \sim 6\ cm^{-1}$

$k_\theta \rho_s \sim 3$

ExB flow shear is anti-correlated with intermediate-scale density fluctuation amplitude





First experimental evidence of Zonal Flow interaction with Intermediate scale turbulence

Anti-correlation is consistent with theoretical expectations.

- **r/a~0.48**
- **Probed**
  $k_\perp$~6 cm^{-1}
  $k_\perp \rho_s$~3

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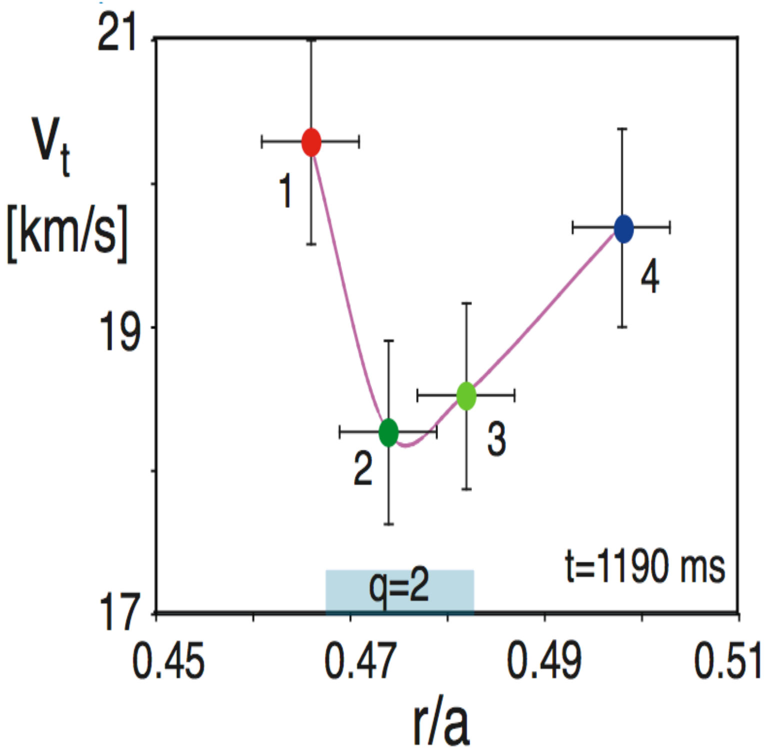
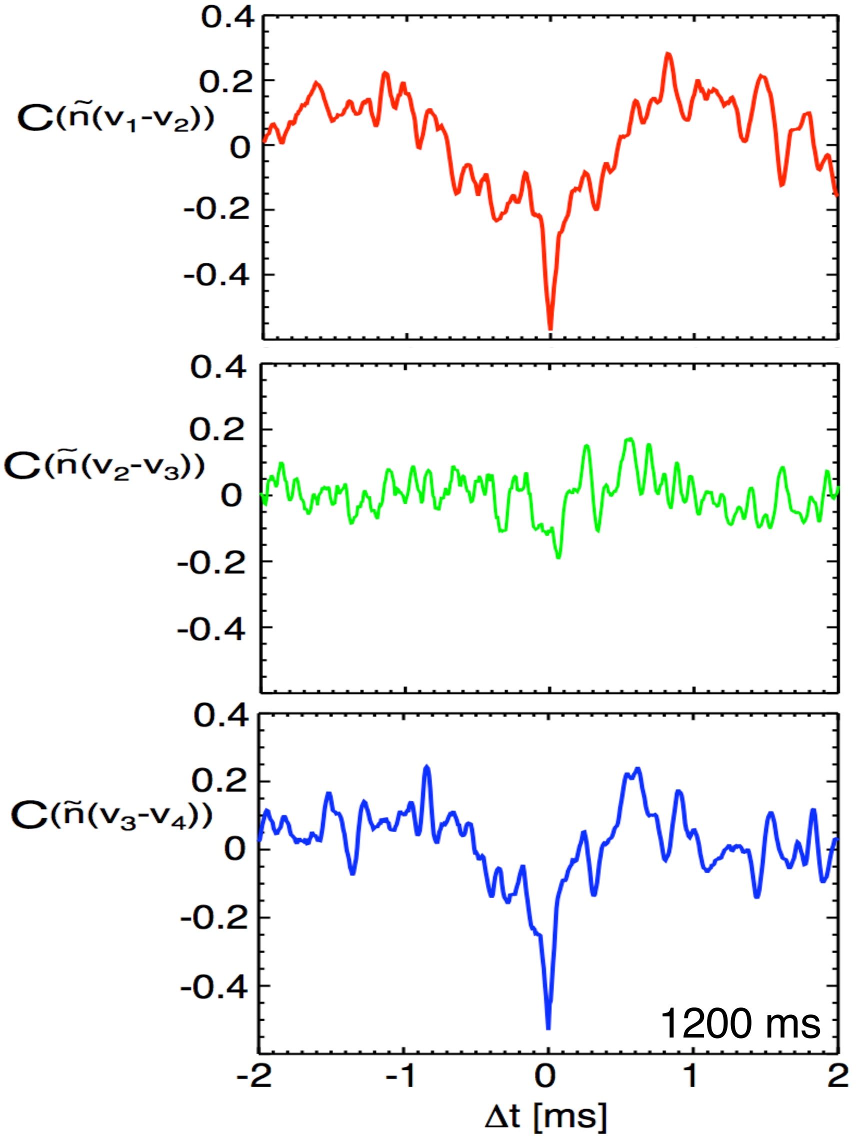
Anti-correlation is most pronounced in regions of high shear



Turbulence velocity (DBS)



Summary

- Core electron transport and ITG/intermediate scale core turbulence are substantially reduced across the L-H transition in low-collisionality H-mode plasmas.
- Wavenumber spectra (measured by Doppler Backscattering) and TGLF/GYRO simulations indicate that core turbulence reduction is consistent with E×B shear.
- Initial GYRO multi-scale modeling results indicate dominance of high-k turbulence in the core. Fixed-flux runs are in preparation to allow quantitative comparisons to experimentally measured density fluctuation wavenumber spectra.
- T_e/T_i ~ 1 achieved with ECH; reduced ExB shear: interesting regime for studying electron transport.
- DBS data indicate intermediate-scale turbulence regulation by Zonal Flows in an electron ITB near the q=2 rational surface (L-Mode).