Core Turbulence Structures and ρ^* Scaling in H-mode Plasmas on DIII-D

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American Physical Society - Division of Plasma Physics
Denver, Colorado
October 24-28, 2005

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INTRODUCTION AND OVERVIEW

- **Core turbulence in H-mode discharges are investigated via the significantly upgraded Beam Emission Spectroscopy (BES) at DIII-D**
- **Turbulence characteristics are examined during ρ^* scan of Hybrid Scenario (H-mode) discharges, a stationary plasma at high beta with good confinement**
  - ρ^* *scan performed to examine non-dimensional scaling of turbulence characteristics*
  - *Broadband fluctuation levels measured and compared ($\tilde{n}/n < 1\%$)*
  - *Radial and poloidal correlation lengths*
  - *Decorrelation times*
  - *Flow shear of turbulence (v_{ExB} vs. $v_{\theta,BES}$)*
- **Tilted turbulent eddy structure observed in H-mode, and *not* in L-mode**
  - *Finite time-lag observed in radial cross-correlations*
  - *2D spatiotemporal correlation functions examined*
  - *Visualization of core L-mode and H-mode turbulence*

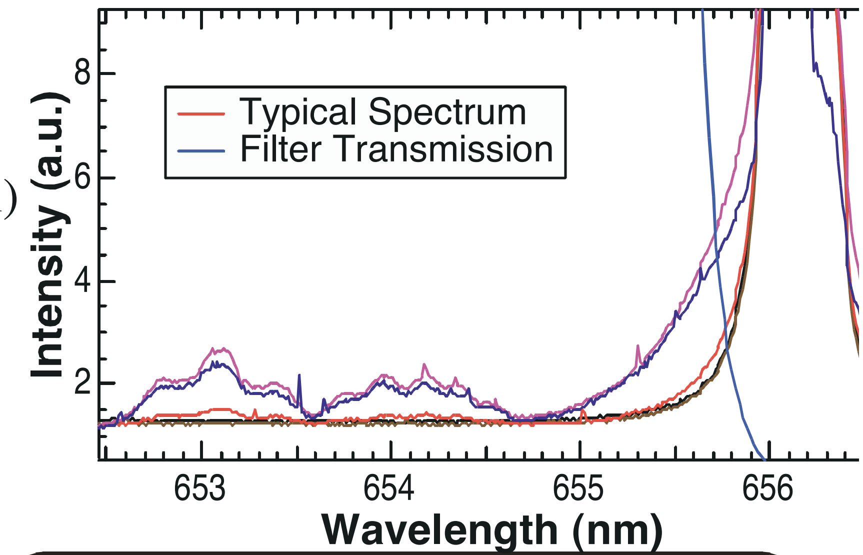
ABSTRACT

The characteristics of long-wavelength density fluctuations $k_\perp \rho_I$ are examined in the core region (0.5 < r/a < 0.9) of H-mode discharges and compared to turbulence in L-mode discharges. Measurements are obtained with the upgraded 16-channel (4-radial x 4-poloidal), high-sensitivity beam emission spectroscopy system at DIII-D. The ρ^* scaling of turbulence structures in hybrid scenario H-mode plasmas demonstrates that the radial correlation lengths scale closely with the local ion gyroradius, as predicted theoretically and observed in L-mode plasmas. Eddy spatial structures, in contrast, differ dramatically between L and H-mode plasmas, with H-mode turbulence exhibiting a highly tilted structure in the radial-poloidal plane, as measured via 2D spatiotemporal correlations. Whether this difference results from flow-shear, radial propagation, or inherent turbulence dynamics will be investigated via comparison to measured flow shear.

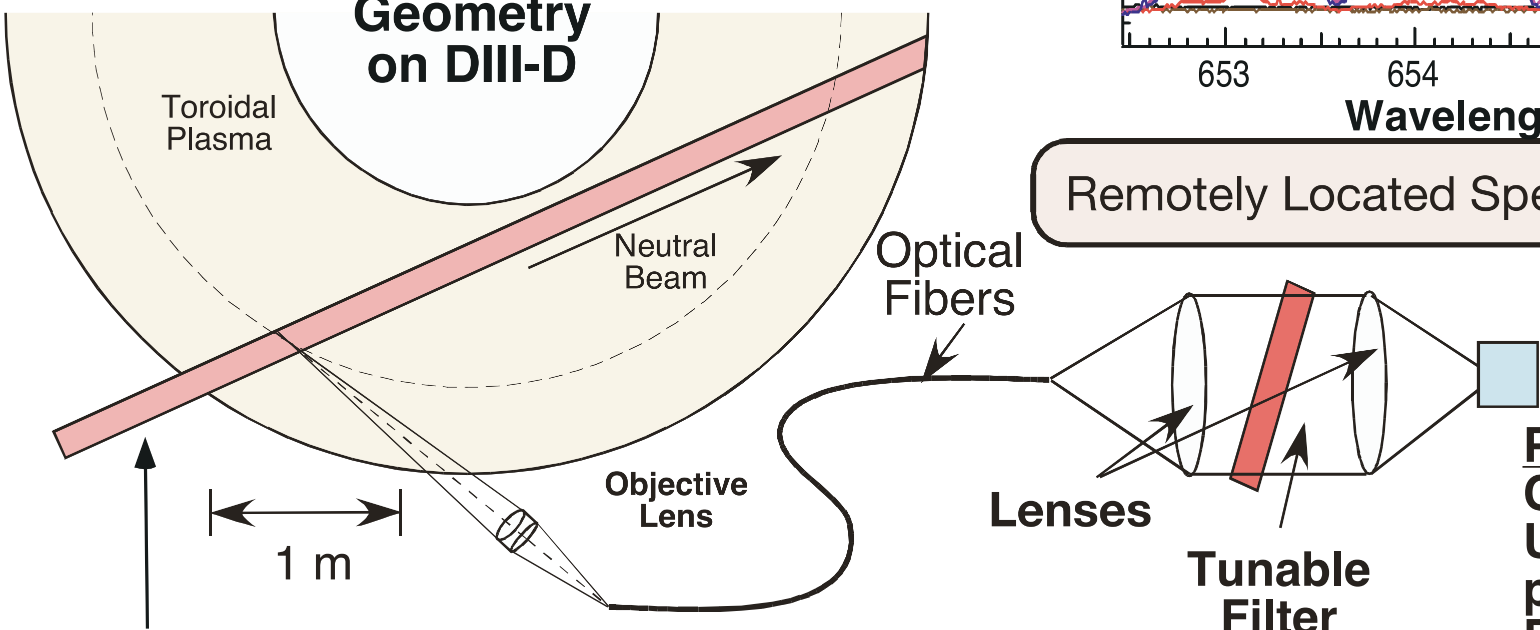
Beam Emission Spectroscopy Measurement of Long-Wavelength ($k_\perp \rho_I < 1$) Density Fluctuations

Collisionally-excited, Doppler-shifted neutral beam fluorescence

$$D^o + e,i \rightarrow \left(D^o\right)^* \rightarrow D^o + \gamma(n = 3 \rightarrow 2, \lambda_o = 656.1\ \text{nm})$$



BES Viewing Geometry on DIII-D



75 KeV D^{O} Neutral Beam (150 L (R))

$k_\perp < 3\ \text{cm}^{-1}$

Photodiodes
Cryo-cooled, Ultra-low-noise pre-amplifiers, DAQ: 1 MHz, 14-

$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$ (via Atomic Physics)

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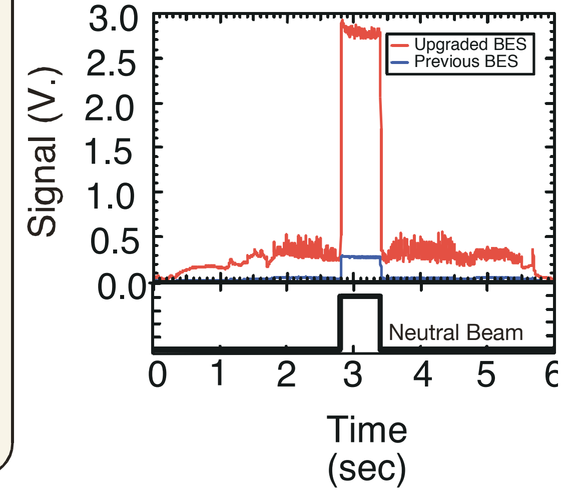
BES System Significantly Upgraded to Enhance Sensitivity for Core Turbulence and Nonlinear Studies

Upgrades:

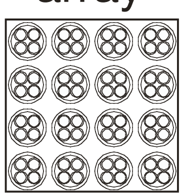
- **Increased Optical Fiber Light Collection Area**
- **Advanced Filters to Exploit Thermal CX emission**
- **Improved High-Efficiency, High Throughput Optics**
- **Larger Area Photodiode**
- **Higher Resolution, Deep Memory Digitizers**



Result:

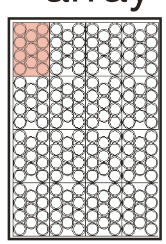
5-10x Increase in Signal → 10-30x Increase in Signal-to-Noise Power

4x4 Previous array



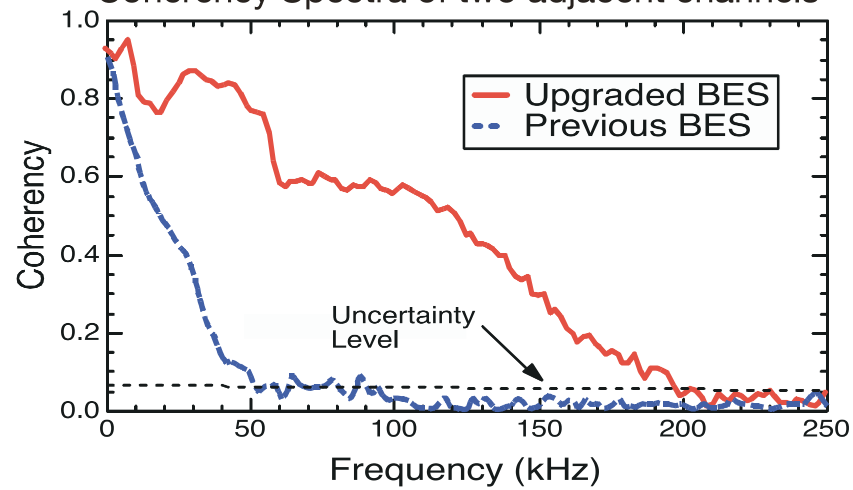
Areal Coverage: 19%

4x4 Upgraded array



Areal coverage: 79%

Coherency Spectra of two adjacent channels



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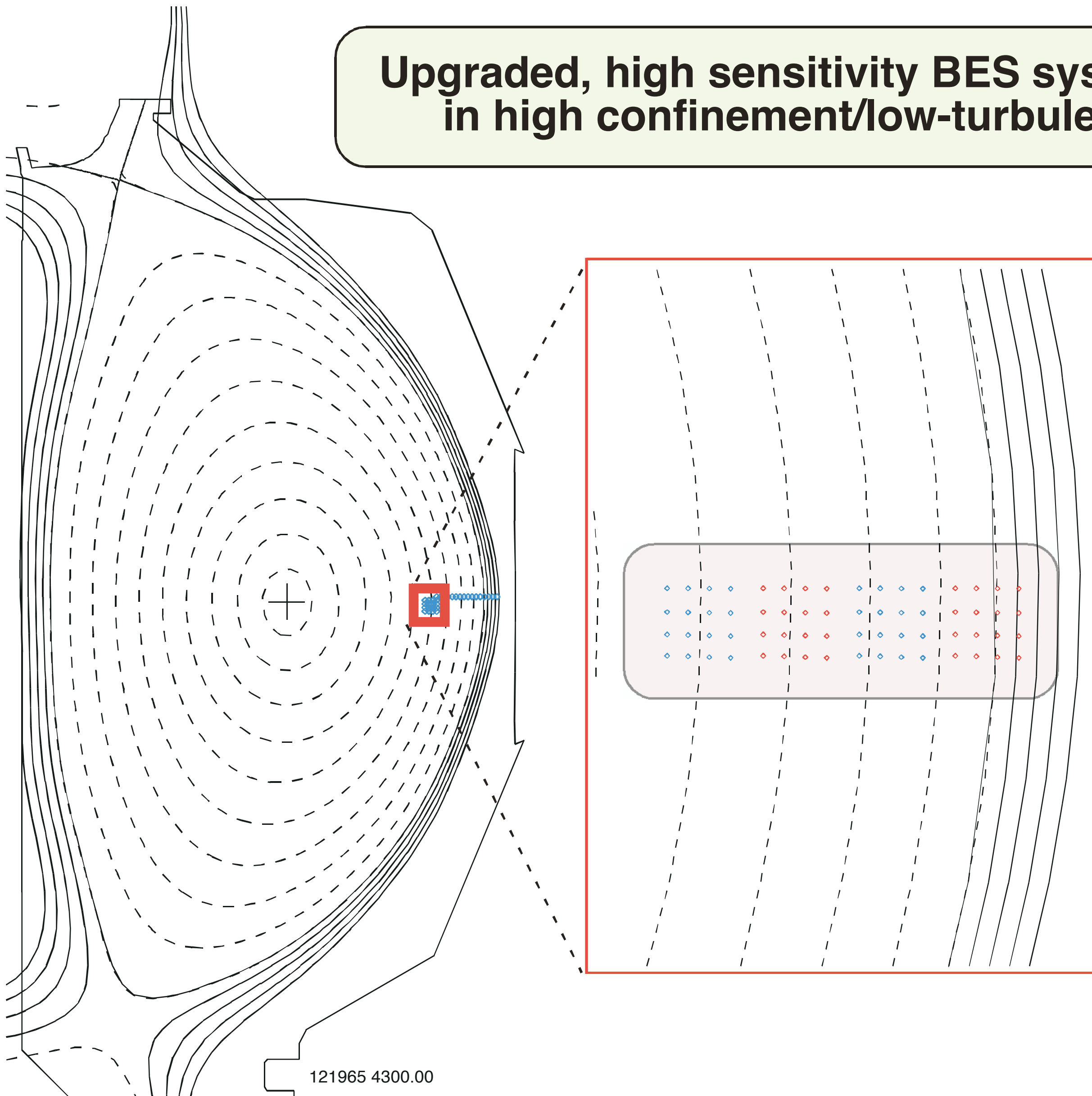
Turbulence Characteristics Measured via Radial Scans of BES

Upgraded, high sensitivity BES system measures turbulence in high confinement/low-turbulence plasma conditions



- 4x4 Channel Grid (Radial/Poloidal) 3.5 x 4.5 cm
- Located on outboard midplane
- Radially Scanned shot-to-shot

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HYBRID SCENARIO DISCHARGES ACHIEVE HIGH PERFORMANCE WITH STATIONARY CONDITIONS

- **"Hybrid" scenario discharges seek to achieve high beta and good energy confinement at moderate q: overall performance between conventional ELM'ing and Advanced Tokamak:**
  - *Stationary performance on τ_r time-scale (55 τ_E, 9 τ_r)*
  - *Pressure near n=1 no-wall beta limit*
  - *Good energy confinement (20-50% above conventional scaling)*
  - *ExB shear mitigates transport according to GLF23*
  - *Small 3/2 NTM inhibits sawteeth, help sustain performance*
  - *Wide operational range: $2.8 < q_{95} < 4.7$; $0.35 < n_G < 0.7$*
  - *Projects to Q_{fus} = 10 - 40 operation in ITER*
  - *Hybrid Scenario discharges achieved on DIII-D, JET, JT-60U, ASDEX-U*
- **Nearly stationary plasma conditions for many τ_E (several seconds)**
  - *Permits long-time ensemble - averaging of fluctuation data to improved signal-to-noise*
- **ρ* scan performed to examine turbulence and transport scaling**
  - *1.6 * change in ρ_I*
  - *Other relevant dimensionless parameters held nearly constant*

ρ* Scan of Hybrid Discharges Performed to Examine Turbulence and Transport Scaling

$\rho^* = \rho_I / a$

Fixed Dimensionless <u>Parameters:</u>

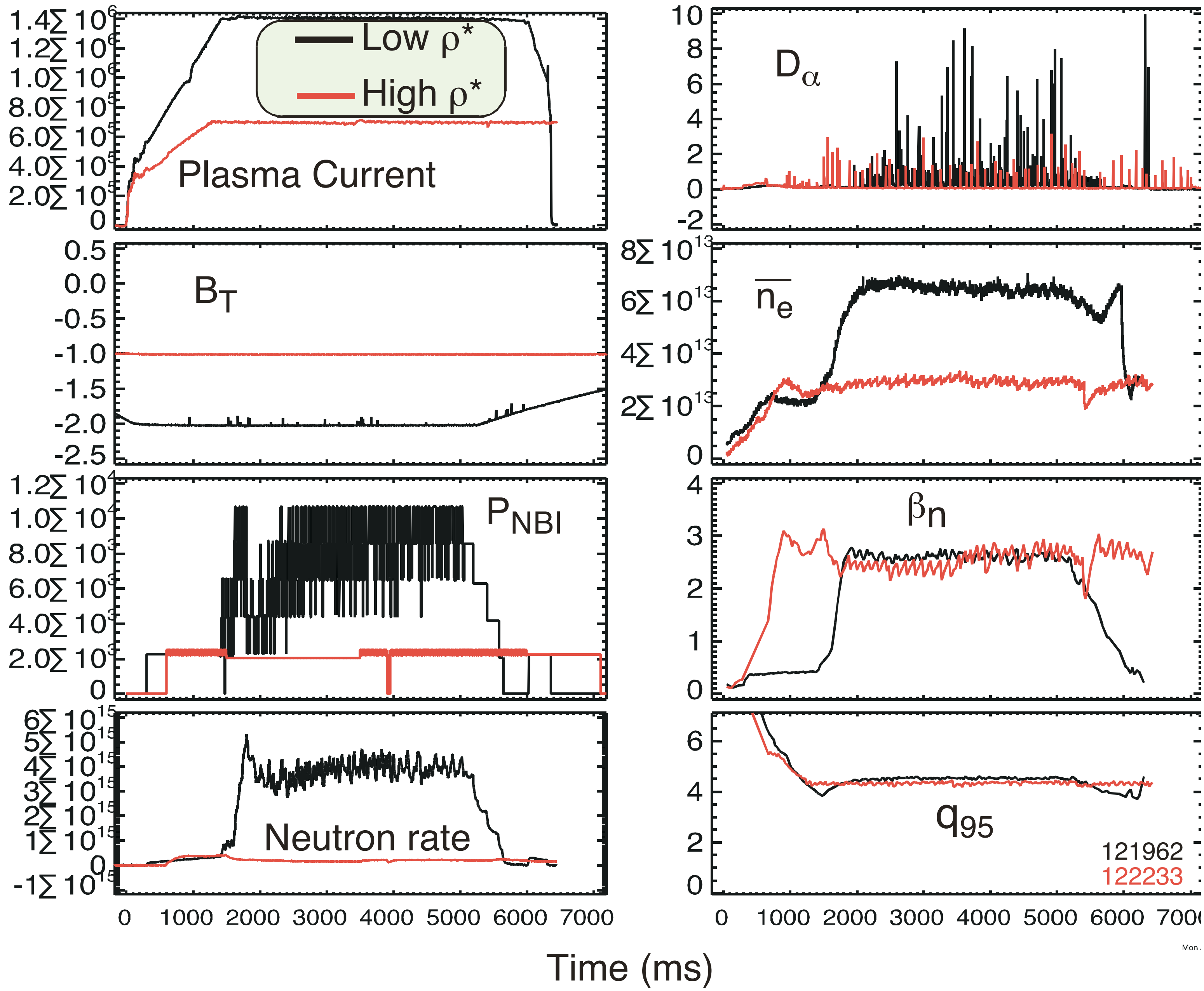
$\beta = nT/(B^2/2\mu_o)$

$\nu^* = \nu_{ii} / \omega_b$

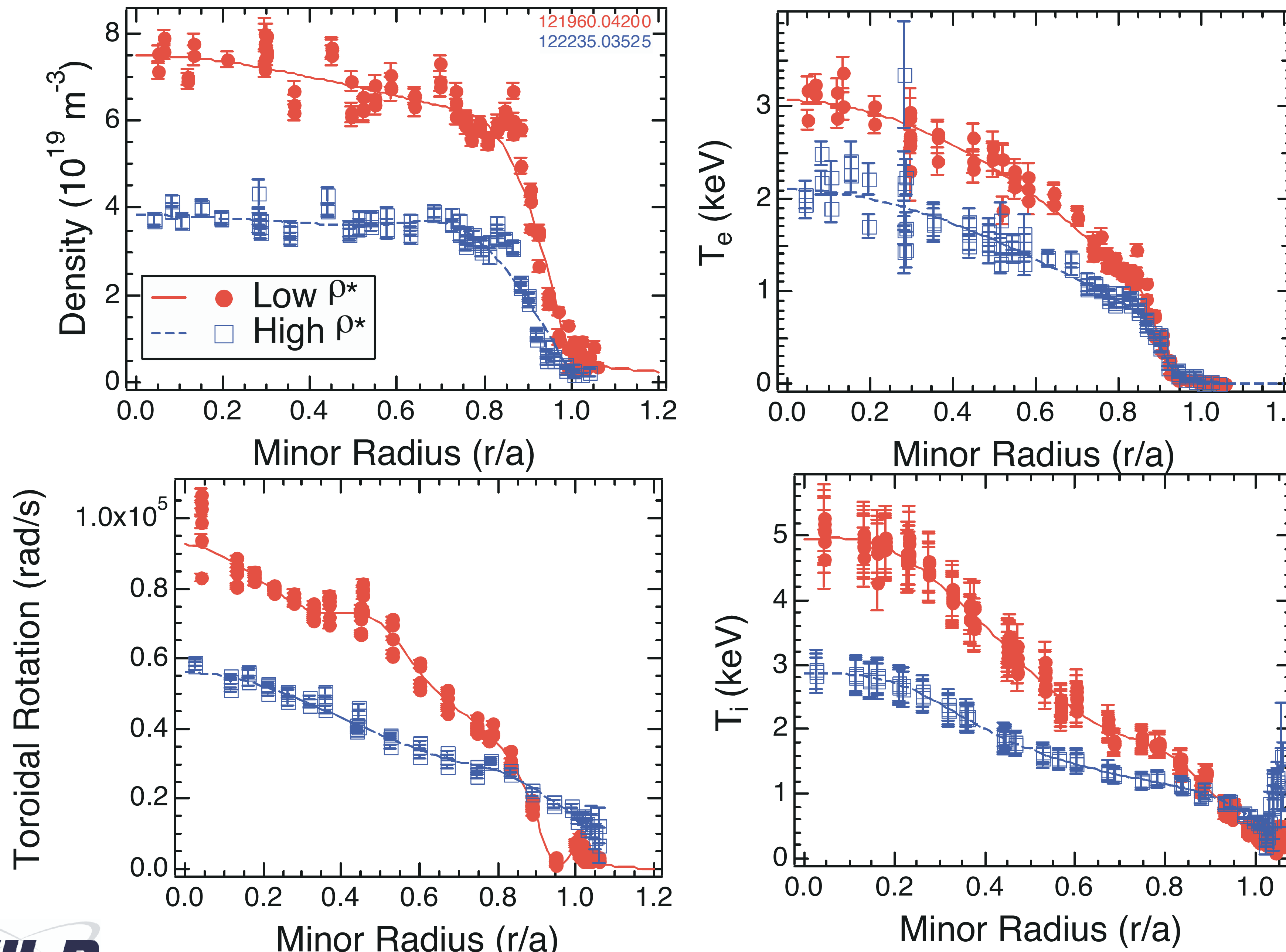
T_e / T_i

$M = V_{rot}/V_{th,i}$

q_{95}



Profiles For ρ* Scan of Hybrid Discharges



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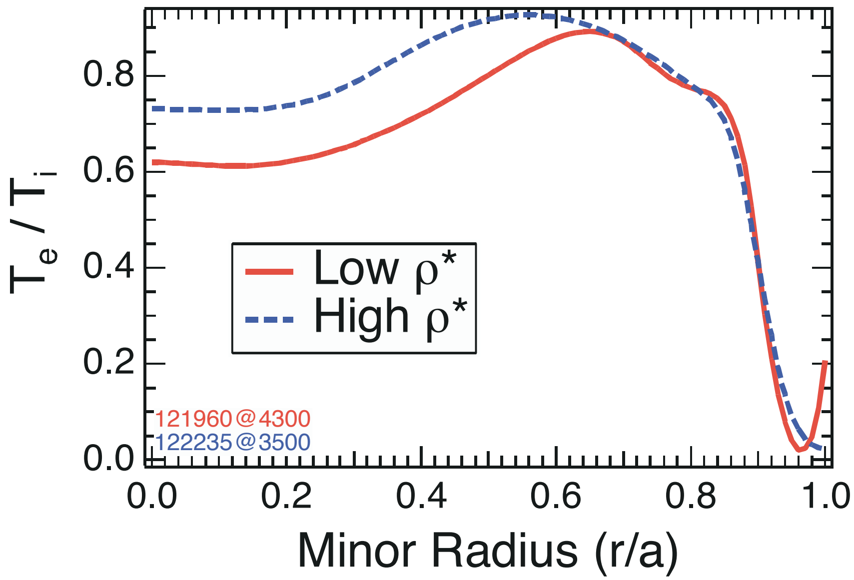
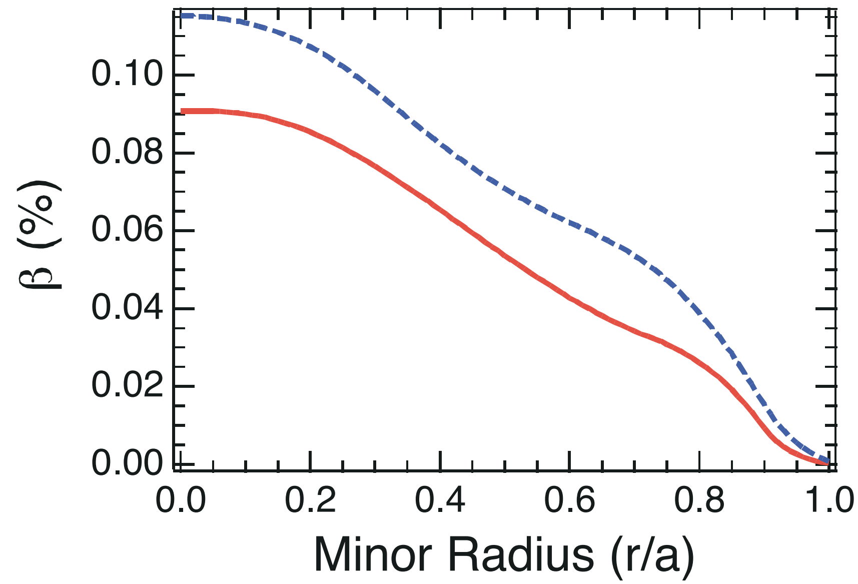
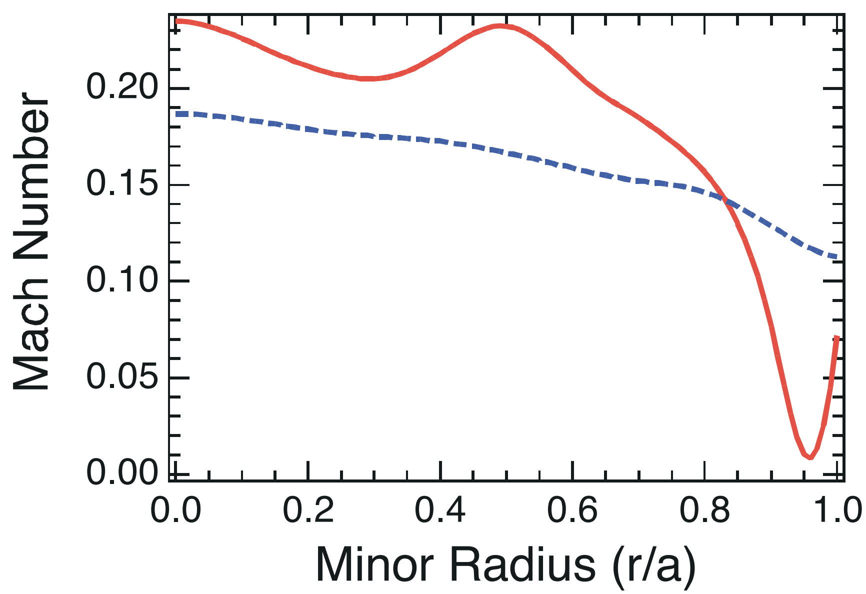
Profiles of Dimensionless Quantities Reasonably Well Matched







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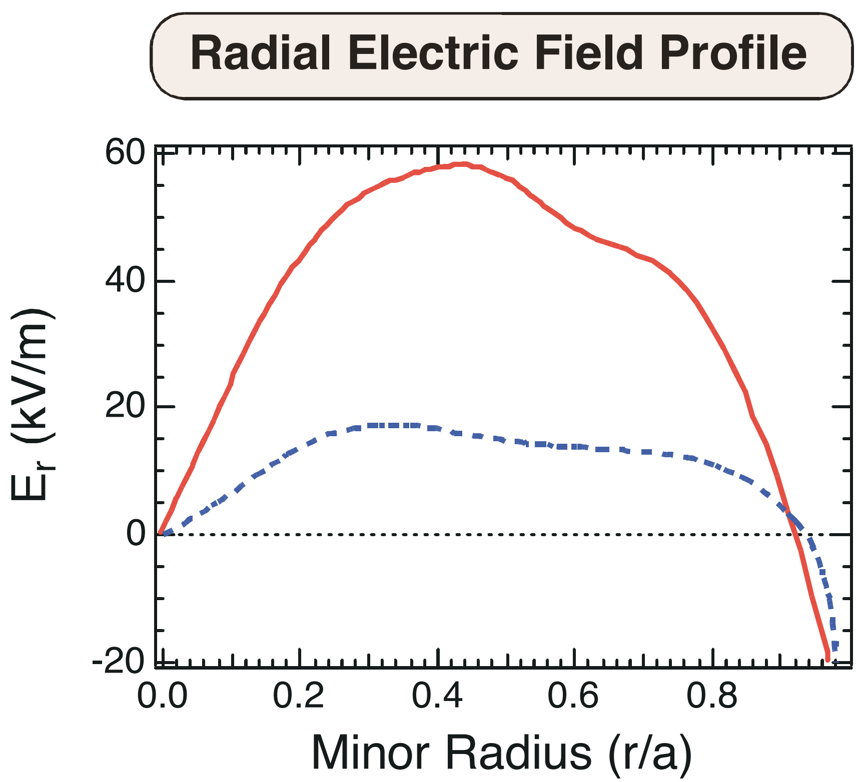
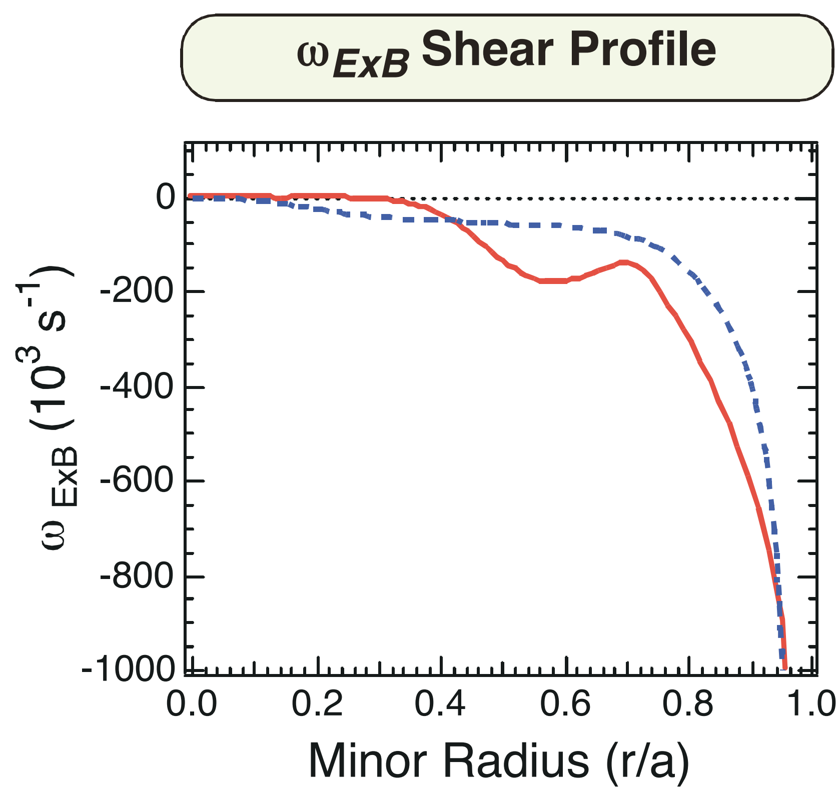
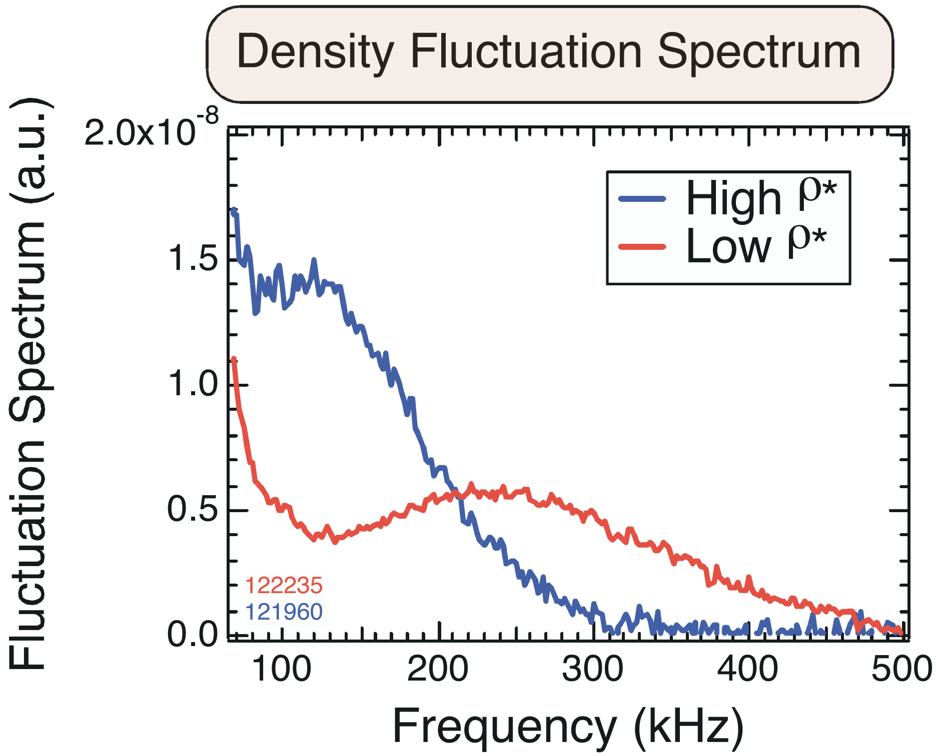
ExB Shear Stabilization Sustains Low Transport

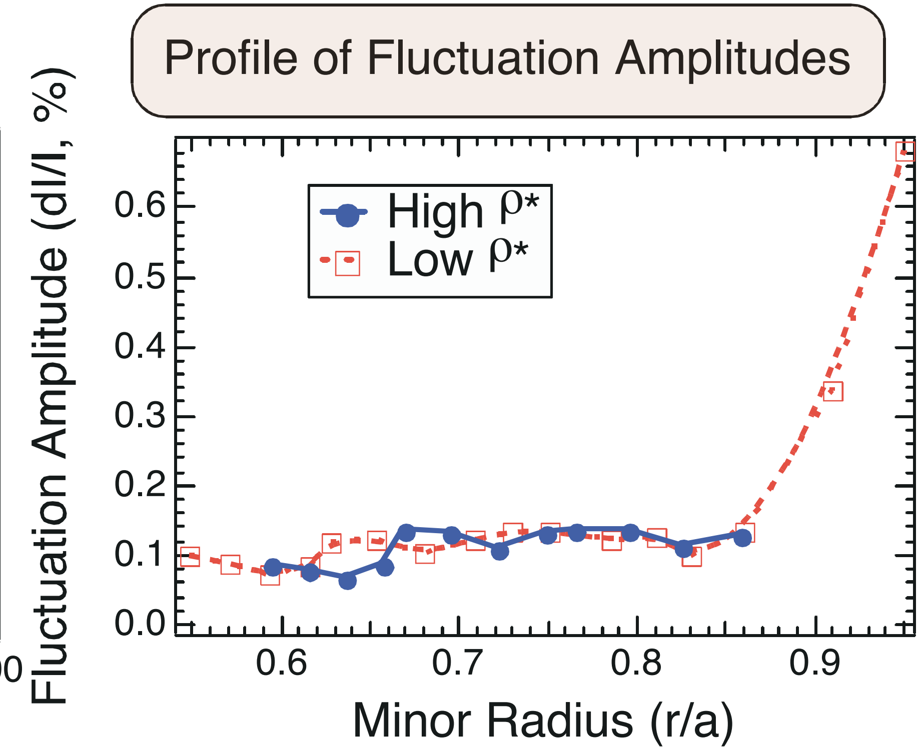
- GLF23 simulations demonstrate role of shear stabilization of turbulence to maintaining high confinement





Normalized Density Fluctuation Levels < 1%; Exhibits Little Dependence on ρ^*





- **Fluctuation amplitudes much lower than L-mode (~one order of magnitude)**
  - Typical amplitude $\tilde{n}/n < 1\%$
  - Spectra Doppler shifted (greater shift at low-ρ^* due to higher power and torque to match the Mach number)
- **Low turbulence amplitude qualitatively consistent with high confinement:**

  $H_{89P} = 2.1$, $H_{98y2} = 1.3$
- ***Not* consistent with gyroBohm predictions ($\tilde{n}/n \sim \rho^*$): why is this?**

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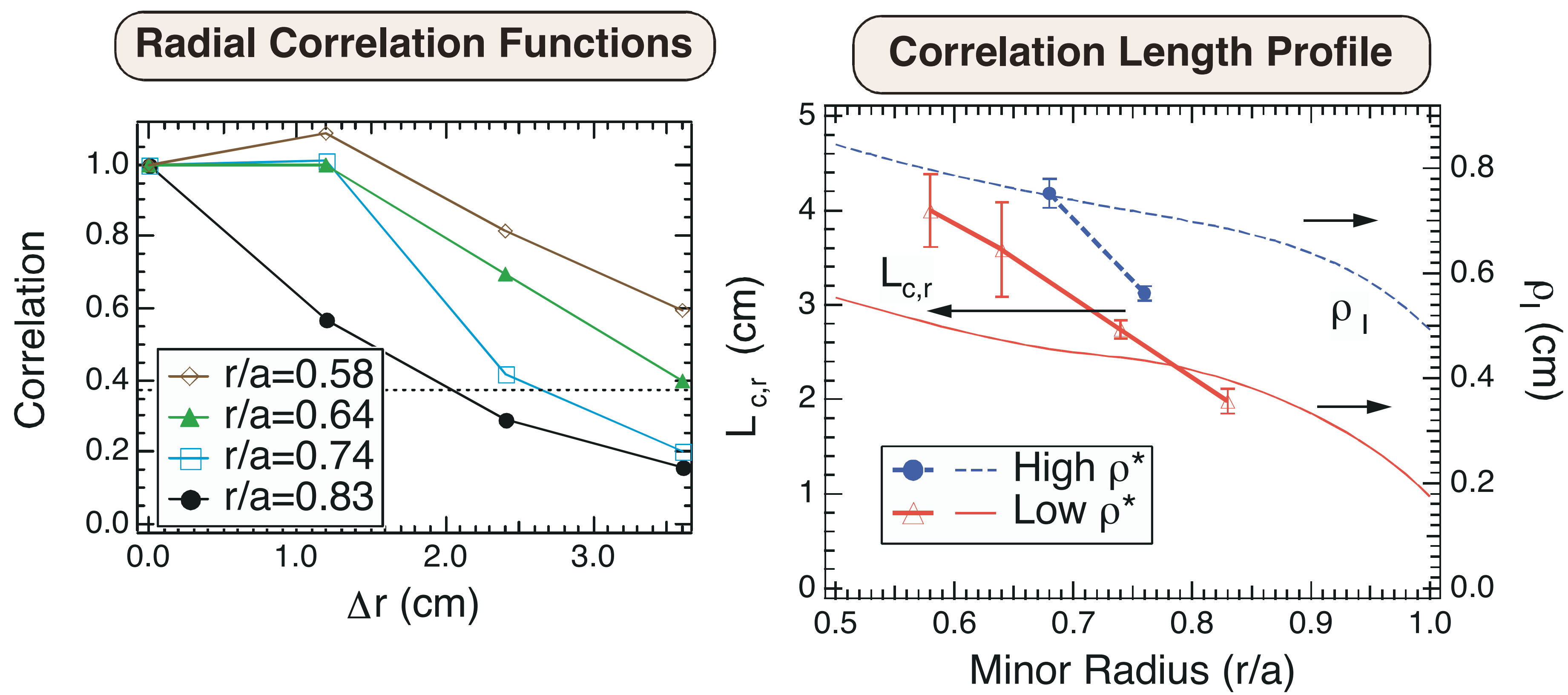
Radial Correlation Lengths of Turbulence Scale with ρ_I

- **Correlation functions broaden in core relative to edge, as expected with increasing temperature**
  - 4-point measurement with 4x4 array allows for improved accuracy



- **Correlation length increases with temperature and ρ_I, ρ^*, consistent with previous measurements performed in L-mode**

(Error bars represent statistical variation of 4 measurements)

(McKee et al., IAEA-2000, Nuc. Fus. 2001)

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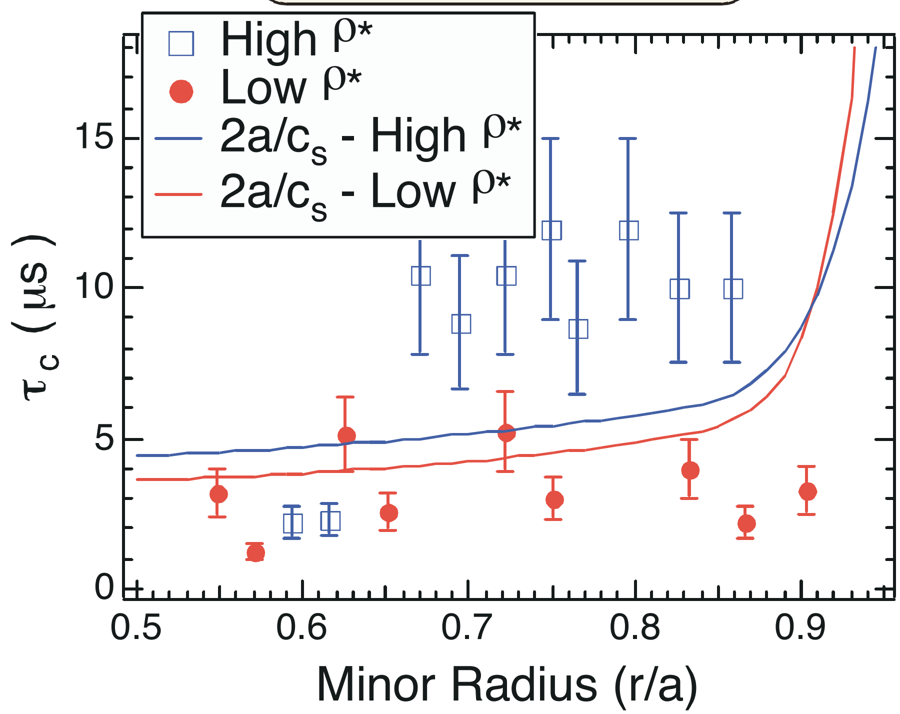
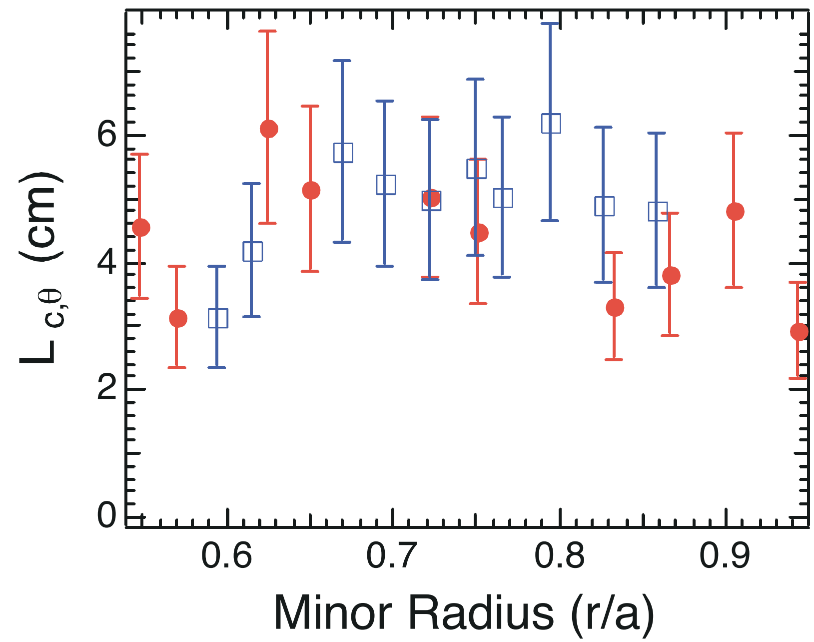
Decorrelation Time and Poloidal Correlation Length of Turbulence

- **Gyrokinetic equations predict $\tau_c \sim a/c_s$ with ρ^* scan**
- **Poloidal correlation lengths exhibit little dependence on ρ^***

Decorrelation Time of Turbulence



Poloidal Correlation Length of Turbulence



- **Low turbulence amplitude and limited spatial extent of measurements leads to significant noise in derived parameters**

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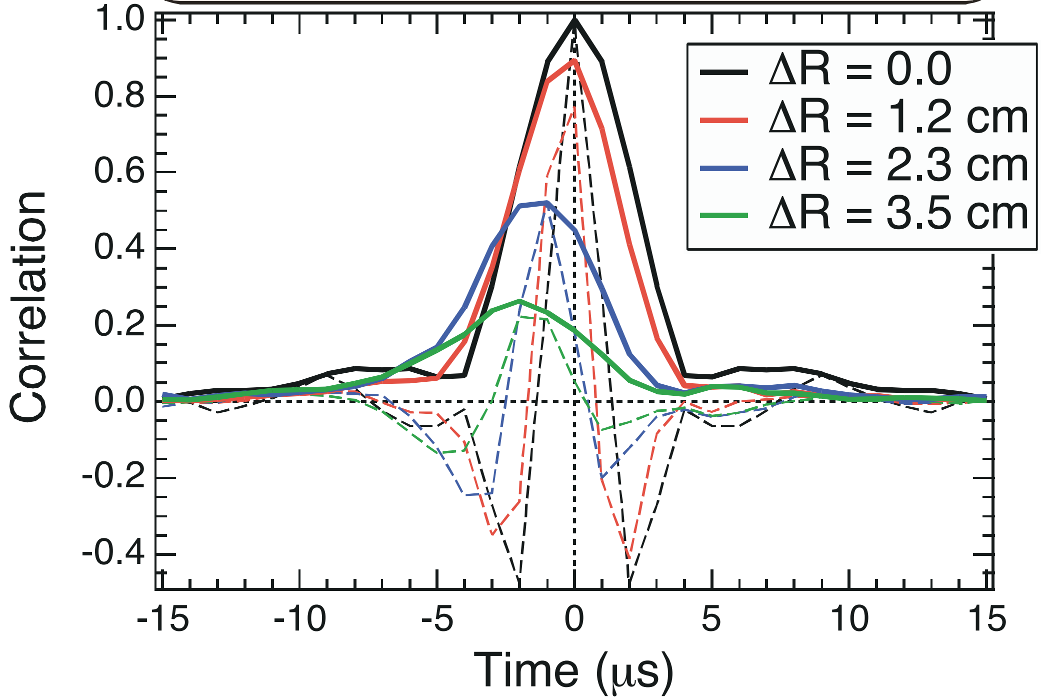
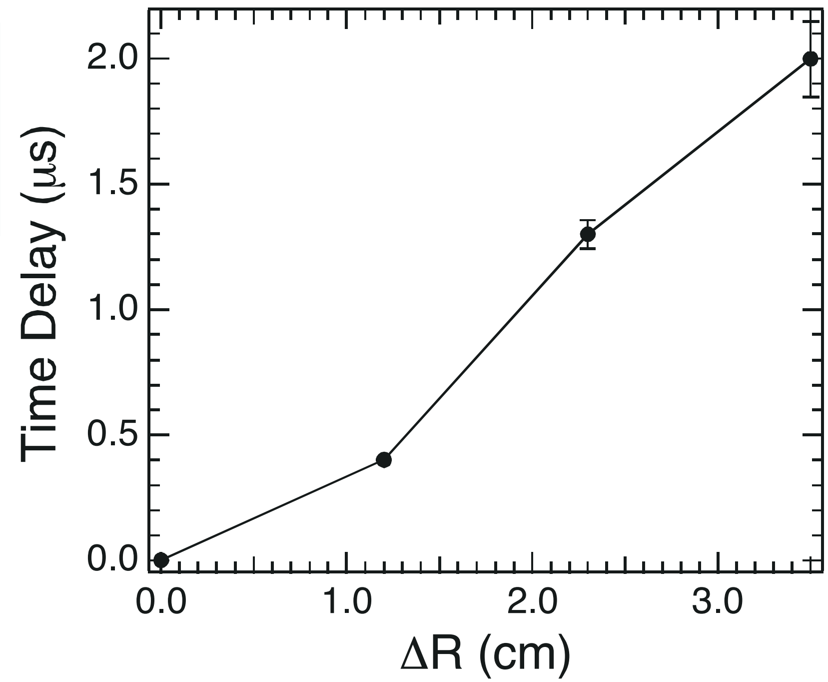
Finite *Radial* Time-Delay Apparent in Hybrid Scenario Plasmas

- **Correlation functions indicate wavenumber spectra has finite k_r, radially *outv***
  - L-mode plasmas typically exhibit $k_r \approx 0$ (except at very edge)

Time-Lag Cross-Correlation Functions for increasing ΔR



Time-Delay at Cross-Correlation peak amplitude



- **Characteristic of Hybrid scenario discharges (and H-modes in general)**
- **Consistent feature across 4 radial arrays and mid-radii, 0.6 < r/a < 0.9**
- **Finite k_r condition ceases near inside of pedestal region, r/a > 0.9**

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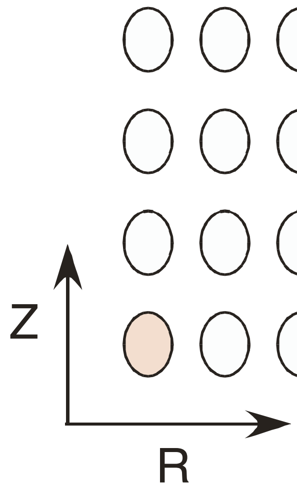
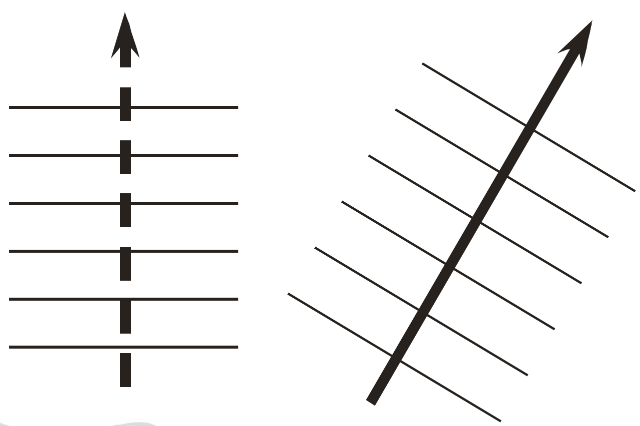
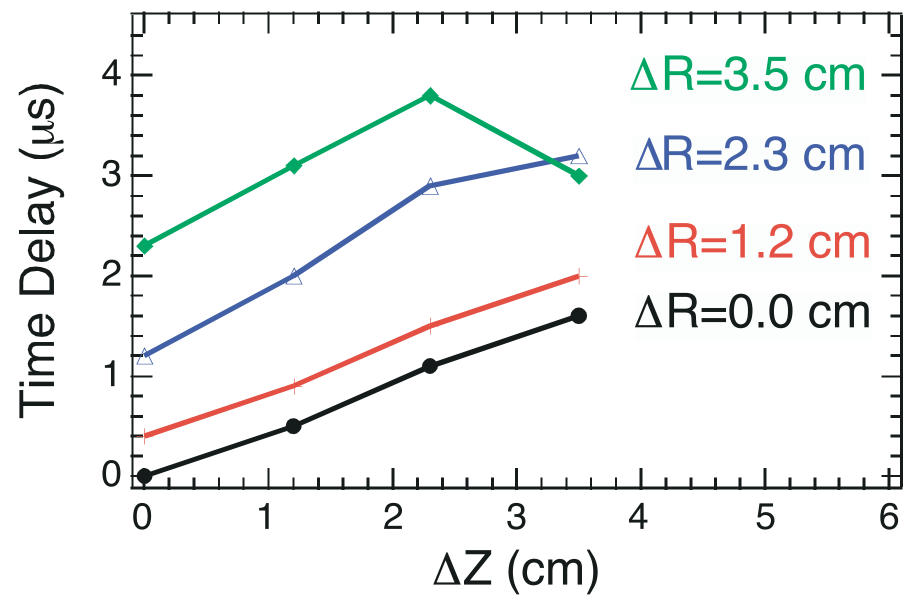
FINITE RADIAL TIME DELAY OBSERVED ACROSS 2D MEASUREMENT ARRAY

$V = \Delta X/\tau_d$ - Simple relation no longer correct; requires geometric correction



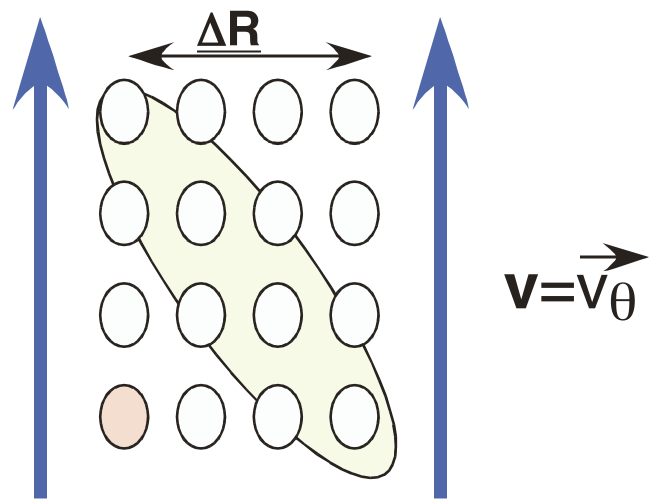


Time-delay of peak Correlation Across 4x4 array (Ref @ corner)

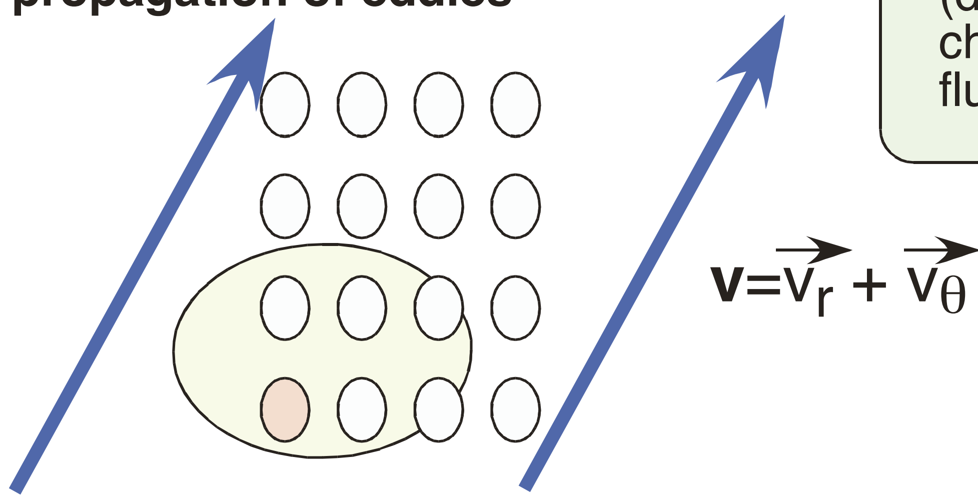


WHAT MIGHT CAUSE FINITE *RADIAL* TIME-LAG?

- **Strongly tilted eddies in the radial-poloidal plane propagating passed fixed detectors**



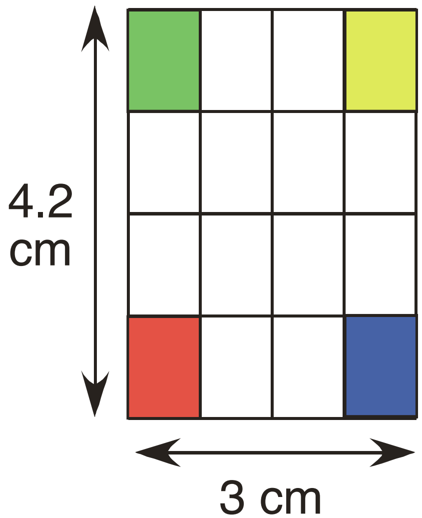
- **Radial propagation of eddies**



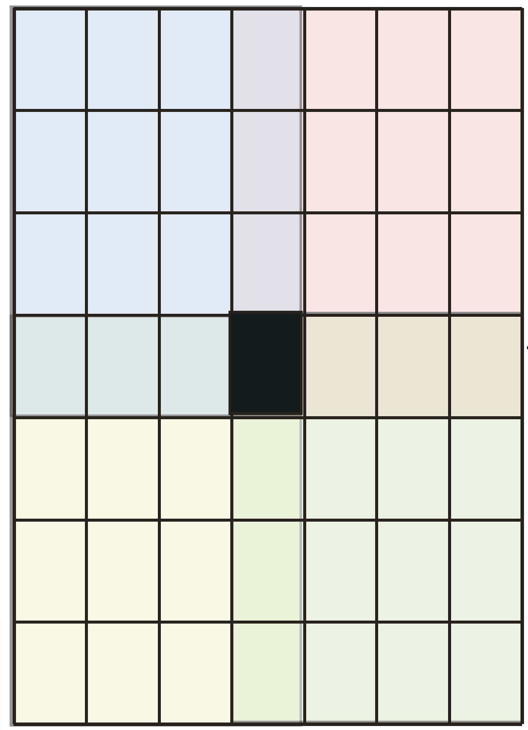
Use 2D Spatiotemporal Cross-correlation to examine propagation dynamics
(direct visualization challenging at low fluctuation amplitudes

"Expanded" 2D Spatiotemporal Correlation Function Obtained from Ensemble-Averaged 2D Data

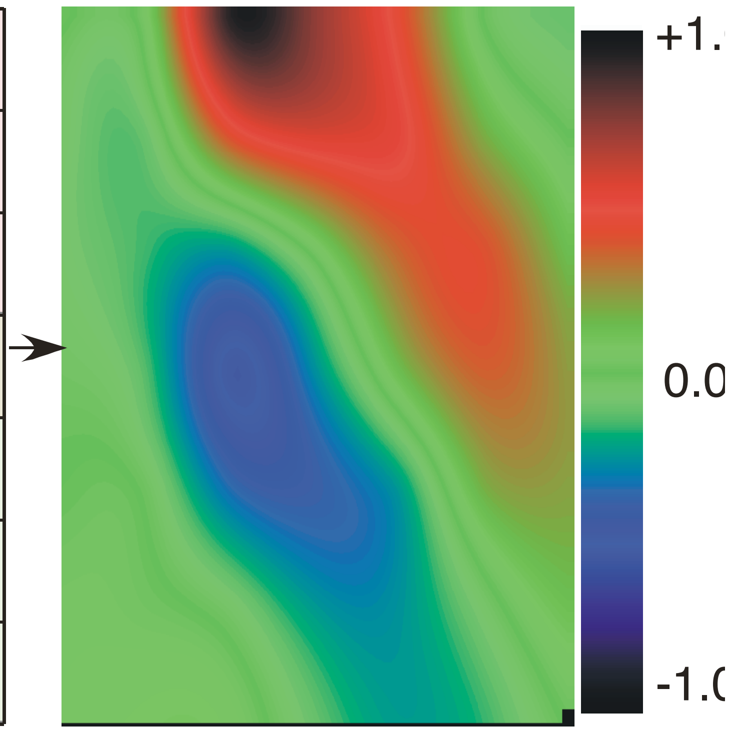
BES Channel Configuration (4x4)



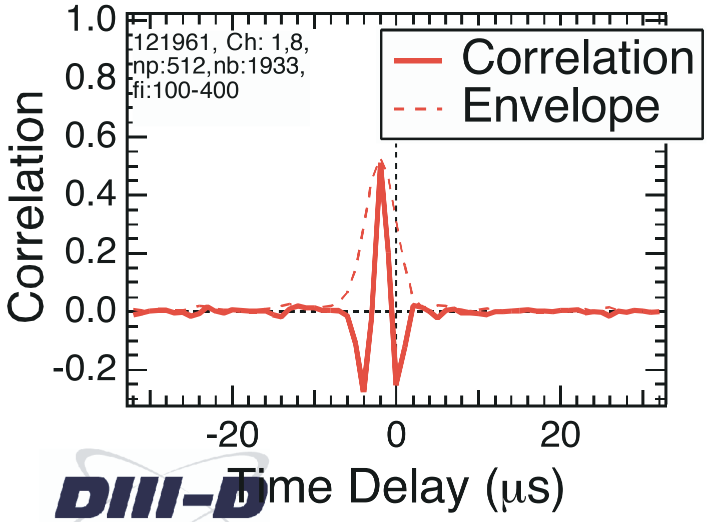
Inferred 7x7 Correlation Matrix (Time-Dependent)



Smoothed Image (2D Spline)



Sample Correlation Function



- Cross correlation evaluated across 2D array fro 4 corner reference channels
- Temporal spline (10*)
- 2D spatial spline (10*)

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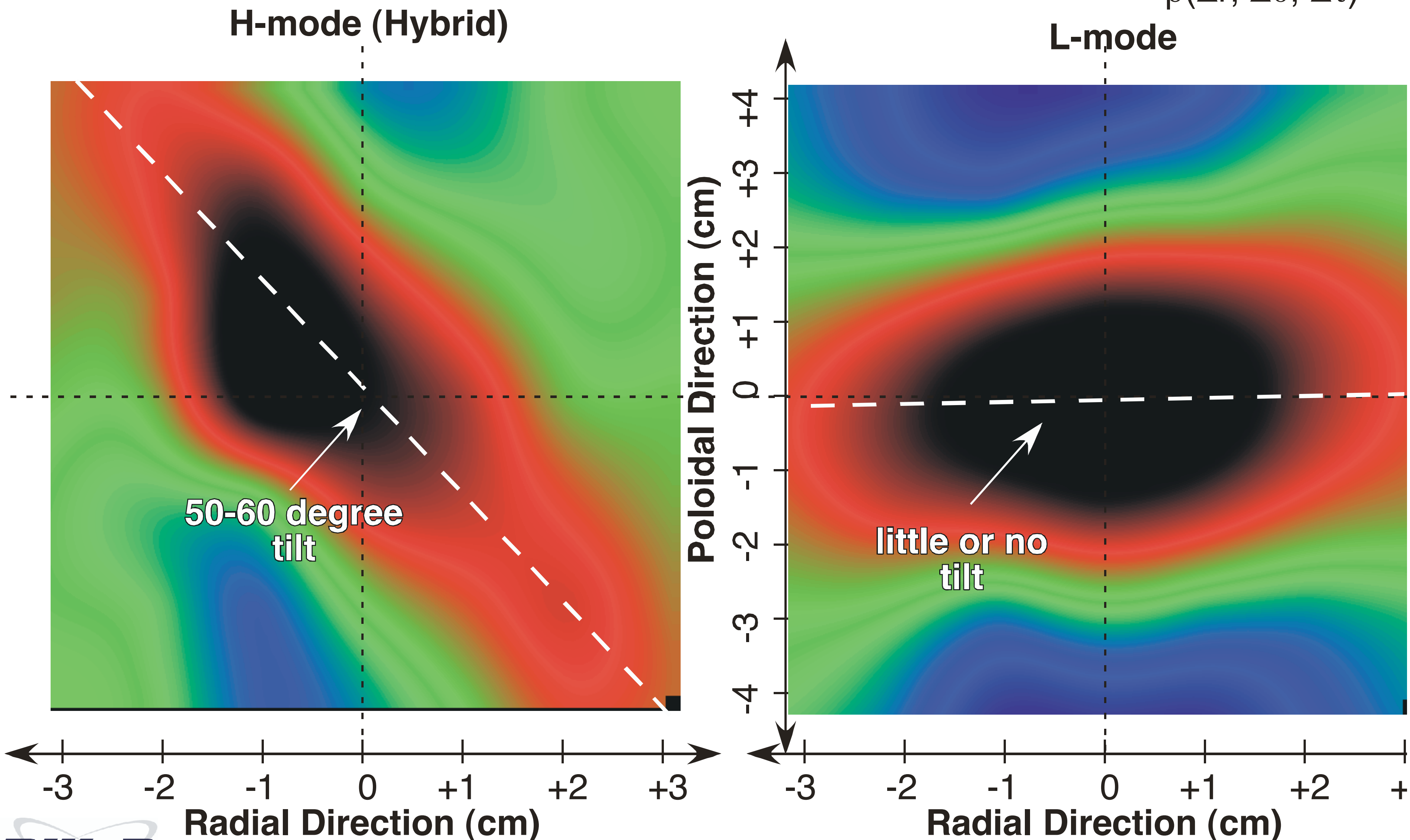
Strongly-Tilted Turbulent Eddy Structure in H-modes That is NOT Apparent in L-Mode Eddy Structures

2D Spatial Correlation Function ($\Delta\tau = 0$) in (Hybrid) H-mode Discharge

see time-resolved correlation function $\rho(\Delta r, \Delta\theta, \Delta\tau)$



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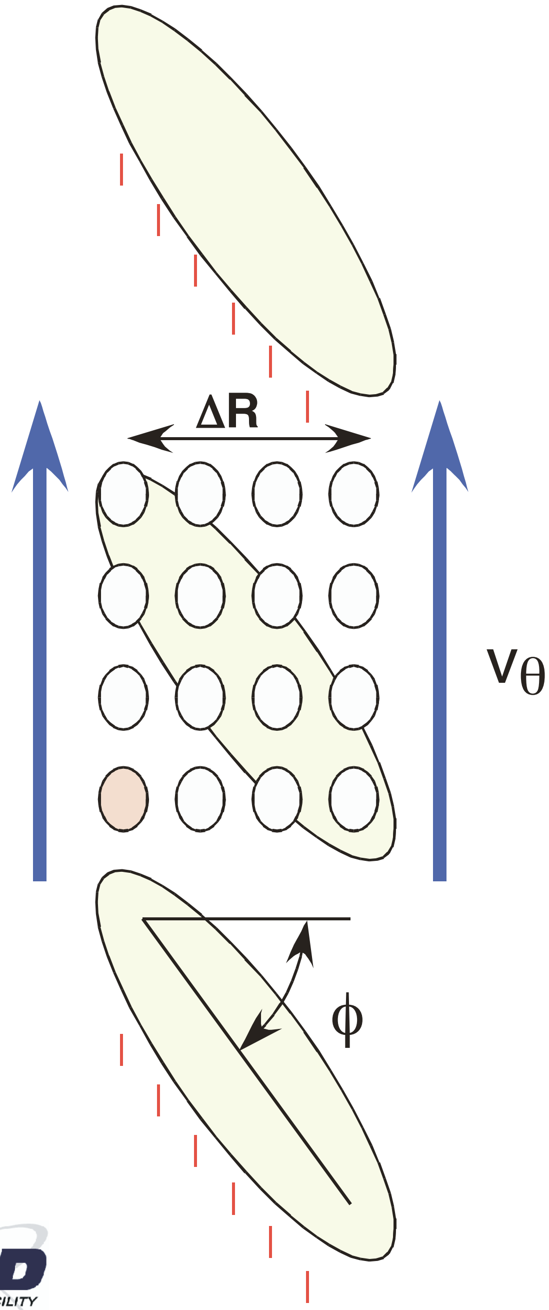
TILTED EDDY EXPLAINS OBSERVED RADIAL TIME-DELAY



- **Consider simple elongated, tilted structu advecting purely poloidally through fixe detection locations**

$$\Delta\tau_R = \frac{\Delta R \tan(\phi)}{v_\theta}$$

$= 3.0 \text{ cm} * \tan(50^\circ)/22 \text{ km/s}$

$= 1.6\ \mu s$ (tilting effect)

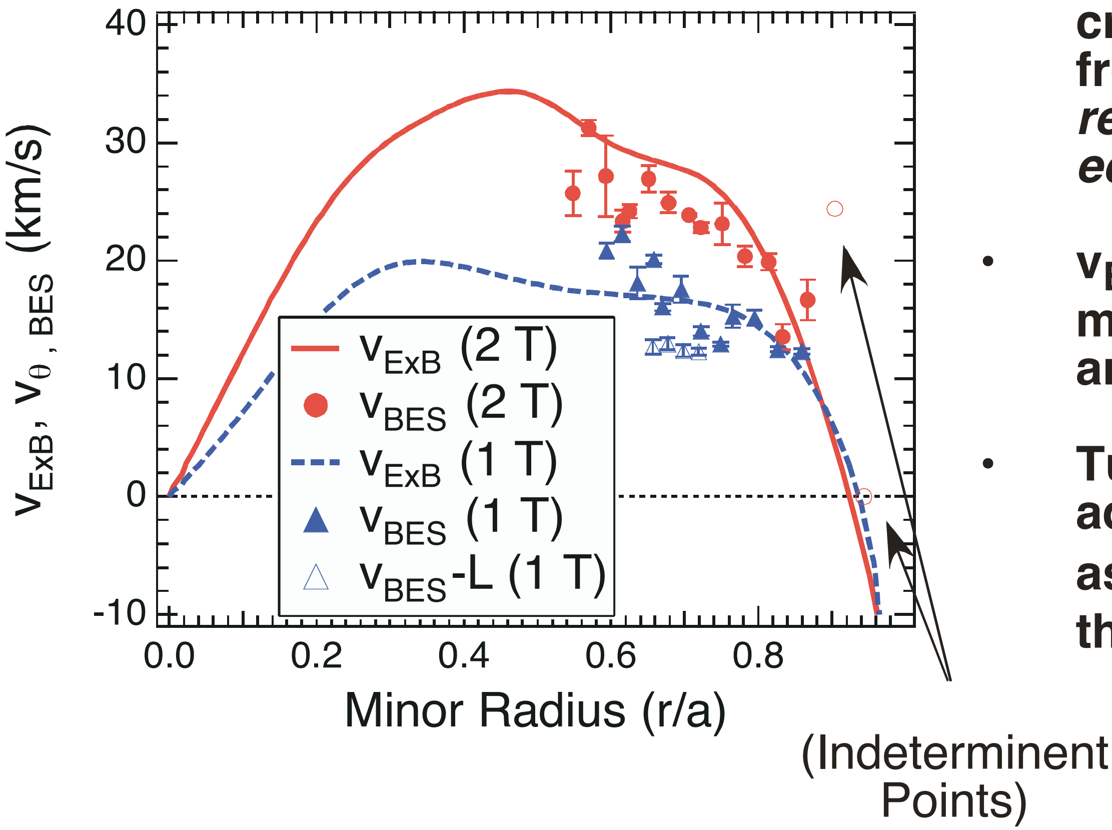
$= 2.0\ \mu s$ (measured)

Quantities from
Shot 121961

- **Measured time-delay and that inferred from poloidal velocity and structure compare well**

Measured Poloidal Turbulence Velocity Compares Well to Measured ExB velocity

Comparison of ExB velocity from CER and measured turbulence velocity from BES



- v_{BES} obtained from time-lag cross correlation measurements from BES: *represents advection of turbulent eddy structures*
- v_{ExB} obtained from CER measurements of ion distribution and radial force balance
- Turbulence expected to advect at near ExB velocity assuming v^*_i is small (as is the case)

- Velocity shear can be obtained from CER measurements or directly from BES measurements

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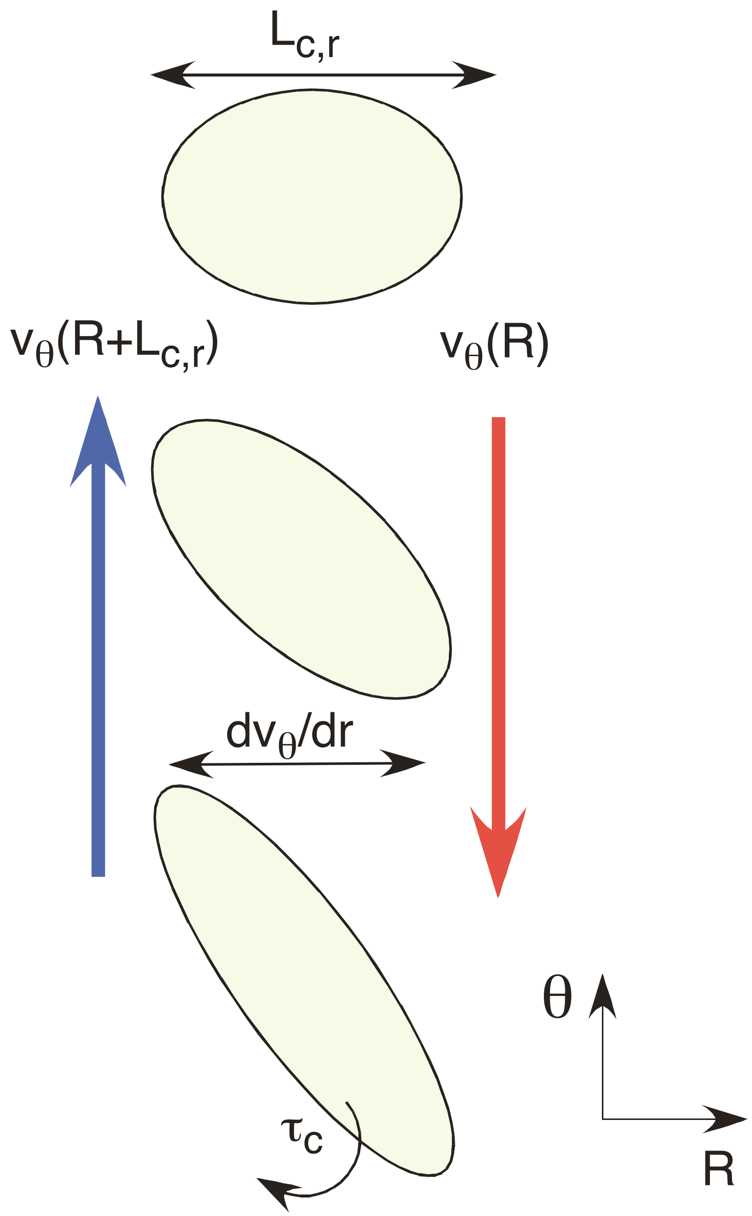
VELOCITY SHEAR APPEARS TOO SMALL TO EXPLAIN EDDY TILT



Simple Eddy Shear Model

$\Delta L_\theta \sim dv_\theta/dr * L_{c,r} * \tau_c$

with

dv_θ/dr	- measured shearing rate
$L_{c,r}$*	- radial correlation length
τ_c	- decorrelation time (eddy lifetime)

$\Delta L_\theta \sim (7 \times 10^4\ s^{-1})(3\ cm)(5\ \mu s) \sim 1.0\ cm$

(or about 20 degree tilt)

Significantly less than observed tilt:

$\Delta L_\theta \sim 4$ cm, (50 degree tilt)

Simple shear appears *too small* to explain eddy tilt:

More fundamental differences in L-mode vs H-mode turbulence likely needed to explain difference

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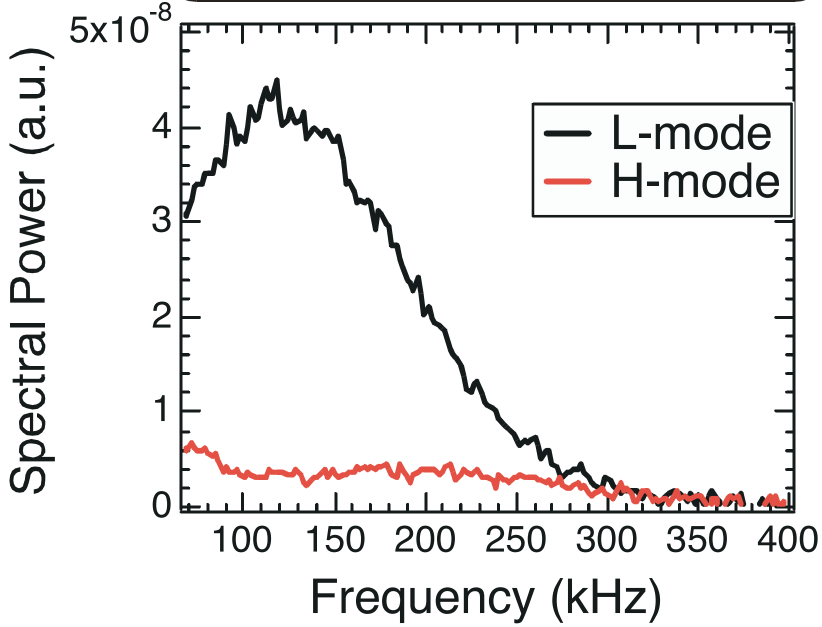
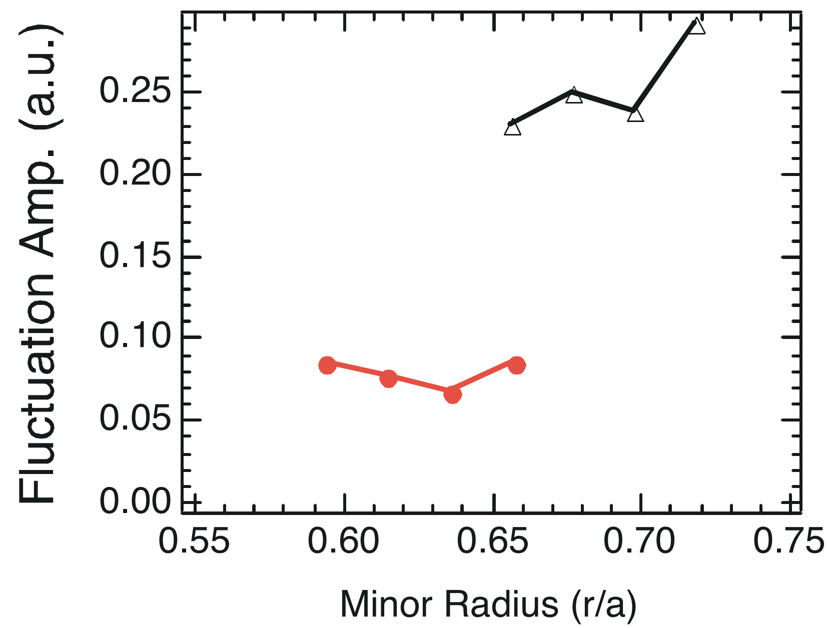
Dramatic Increase In Core Turbulence at H-L Back Transition

- One discharge "accidentally" had an H-L back transition, allowing direct comparison of turbulence characteristics at mid-radius

Fluctuation Spectra, r/a=0.6



Fluctuation Amplitudes

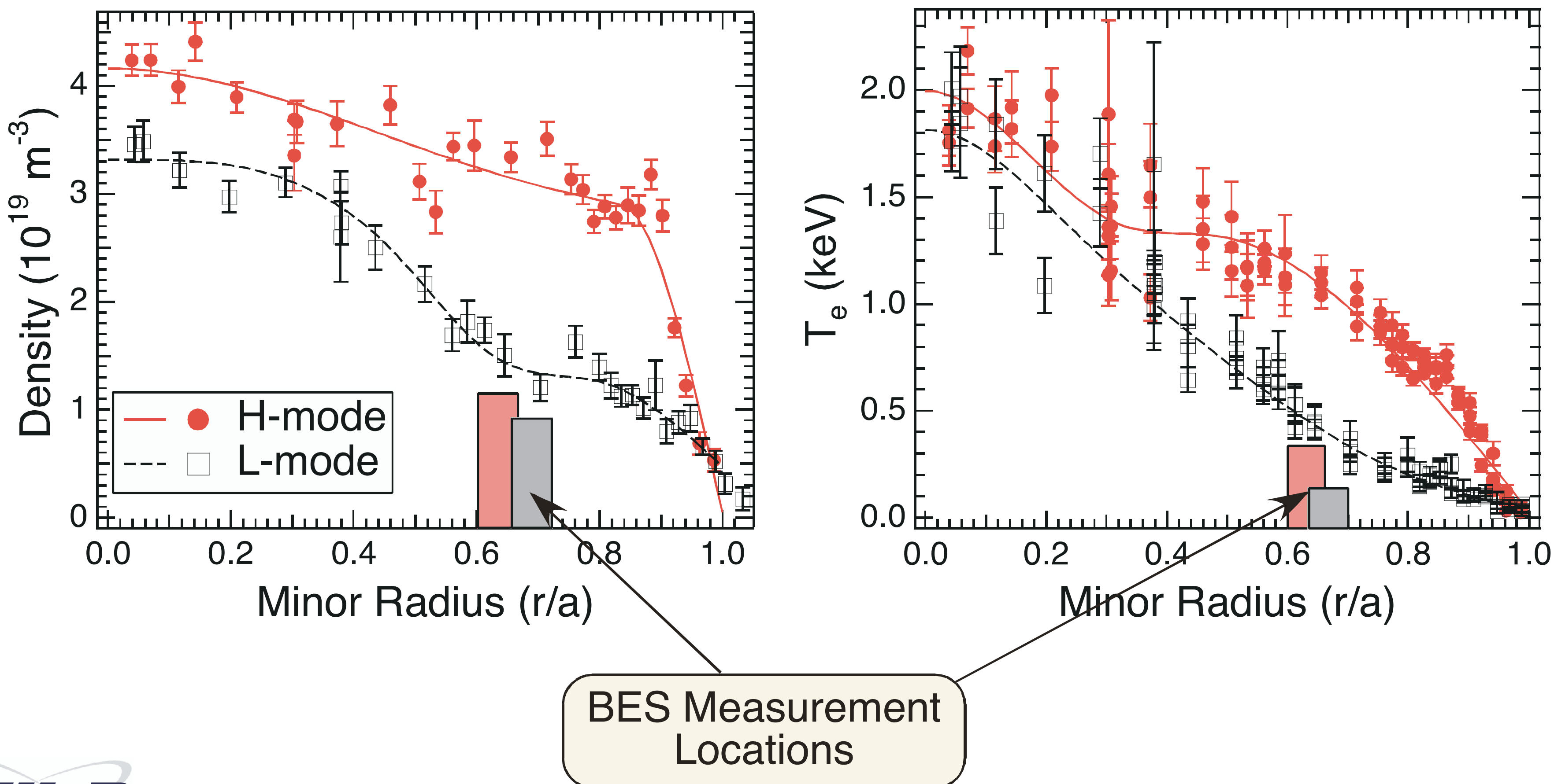


- Indicates that turbulence parameters change dramatically in core, in addition to edge region

- Poloidal Flow Shear in L-mode generally too small to incur tilt based on model shown previously

PROFILES RELAX SIGNIFICANTLY AT H-L BACK-TRANSITION

- **Both magnitude and gradients of density and electron temperature vary:**
  - Higher gradients in L-mode phase
  - Higher magnitude in H-mode phase
- **Can be expected to lead to large changes in turbulence**



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SUMMARY

- **ρ* Scaling of Turbulence Characteristics in H-mode:**
  1) *Radial Correlation Length Scales with local ion gyroradius:* $L_r \sim 5 * \rho_I$
  2) *Amplitude does not exhibit gyro-Bohm scaling:* $\tilde{n}/n \sim constant$
  3) *Decorrelation time scales as* $\tau \sim a/c_s$ *(gyro-Bohm like)*
  4) *Poloidal turbulence velocity (BES) matches measured ExB (CER)*

- **Tilted Turbulent Eddy Structure in H-mode**
  - *Small amplitude fluctuations (* $n/n = 0.1\text{-}0.5\%$ *)*
  - *Eddies sharply tilted in radial-poloidal plane in H-mode plasmas*
    - *L-mode eddies are elliptical, do not exhibit tilt*
    - *Poloidal flow shear appears insufficient to explain tilt*
  - *2D spatiotemporal cross-correlation suggests no radial propagation*
  - *Finite radial wavenumber observed from* $0.5 < r/a < 0.9$ *contrasts with L-mode plasmas (* $k_r = 0$ *)*