Turbulence Behavior and Transport Response Approaching Burning Plasma Relevant Parameters

by

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with

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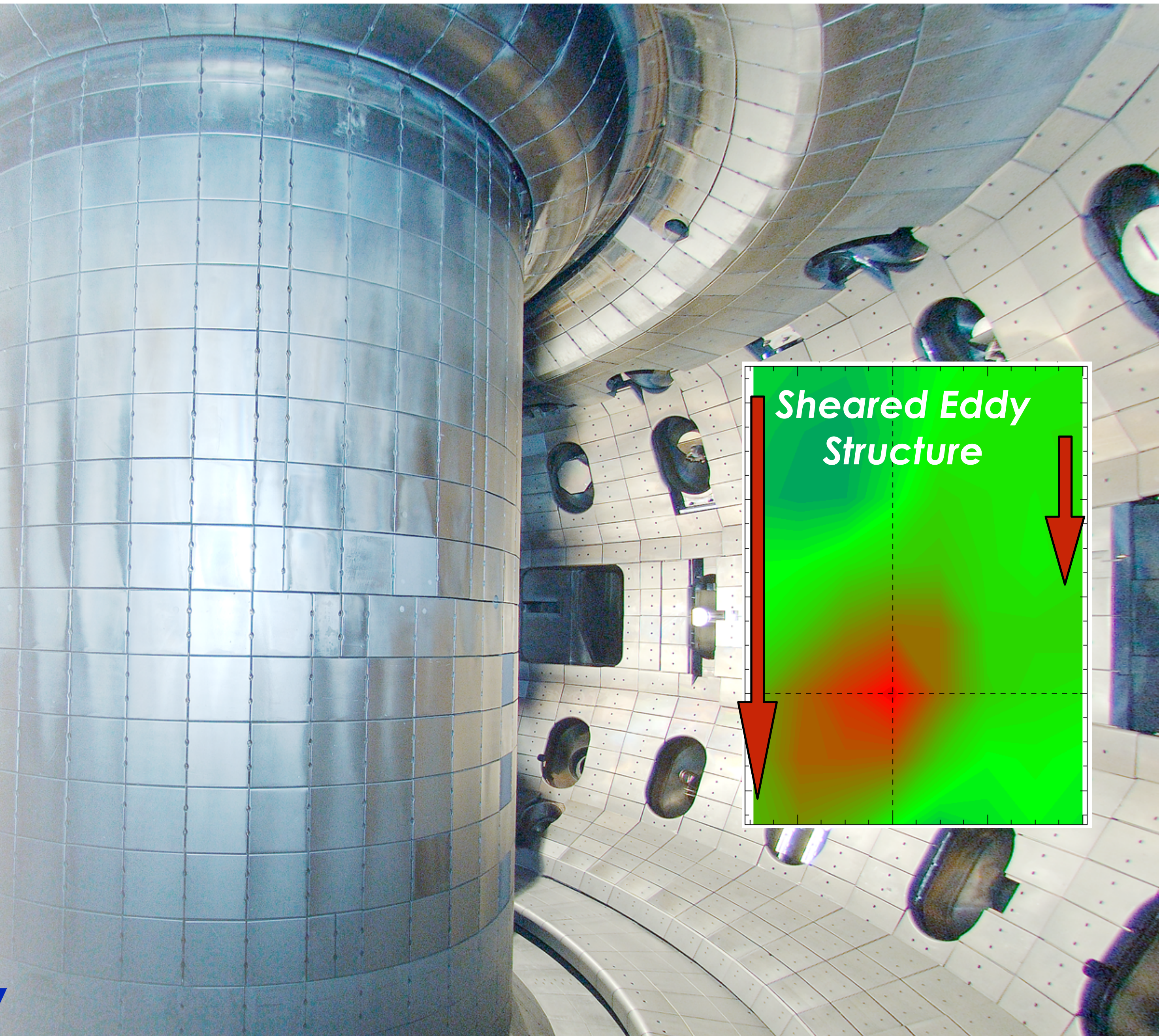

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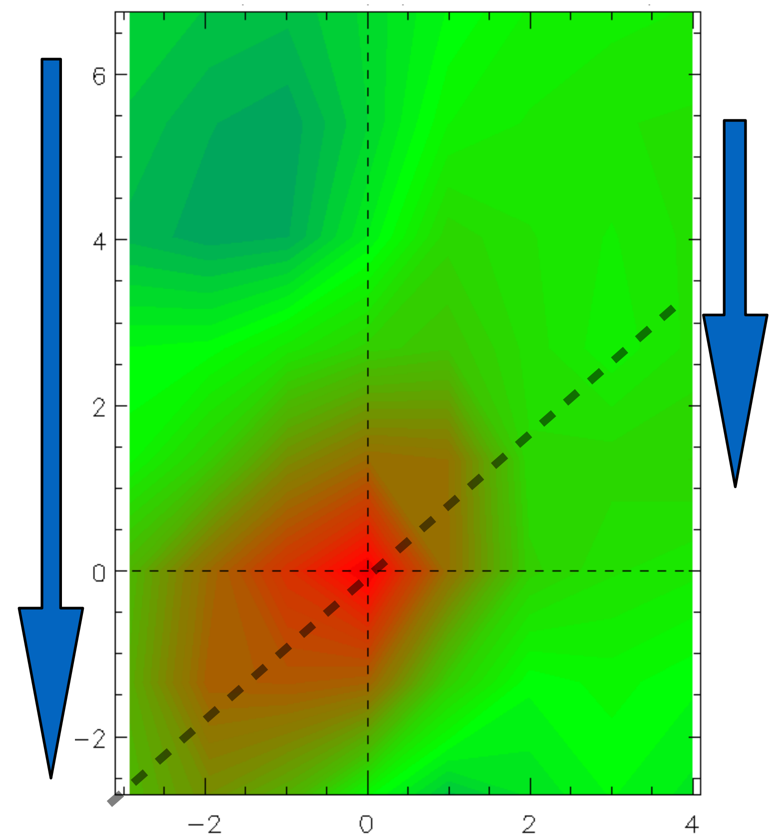
Burning Plasma Parameters Strongly Impact Turbulence, Resulting Transport and the Energy Confinement Time, τ_E

- **Burning plasmas will be dominated by α-driven electron heating and have low injected torque**
  1. Low average toroidal rotation and ***ExB*** shear
  2. Equilibrated temperatures: $T_e \approx T_i$
- ***ExB* shear impacts low *<u>and</u>* high-k turbulence**
- **Turbulence and transport increase as $T_e/T_i \Rightarrow 1$**
- **Experimentally characterize turbulence; test & validate transport models in high performance burning-plasma regimes**
  – How instabilities (ITG, TEM, ETG) affected
  – Impact on thermal, particle, momentum transport

Shear Tilts Turbulent Eddies



Build Confidence in Predicting Confinement in ITER and future Burning Plasmas

1. **Effects of Toroidal Rotation**

2. **Effects of Equilibrated Temperatures**

3. **Conclusions**

1. Effects of Toroidal Rotation

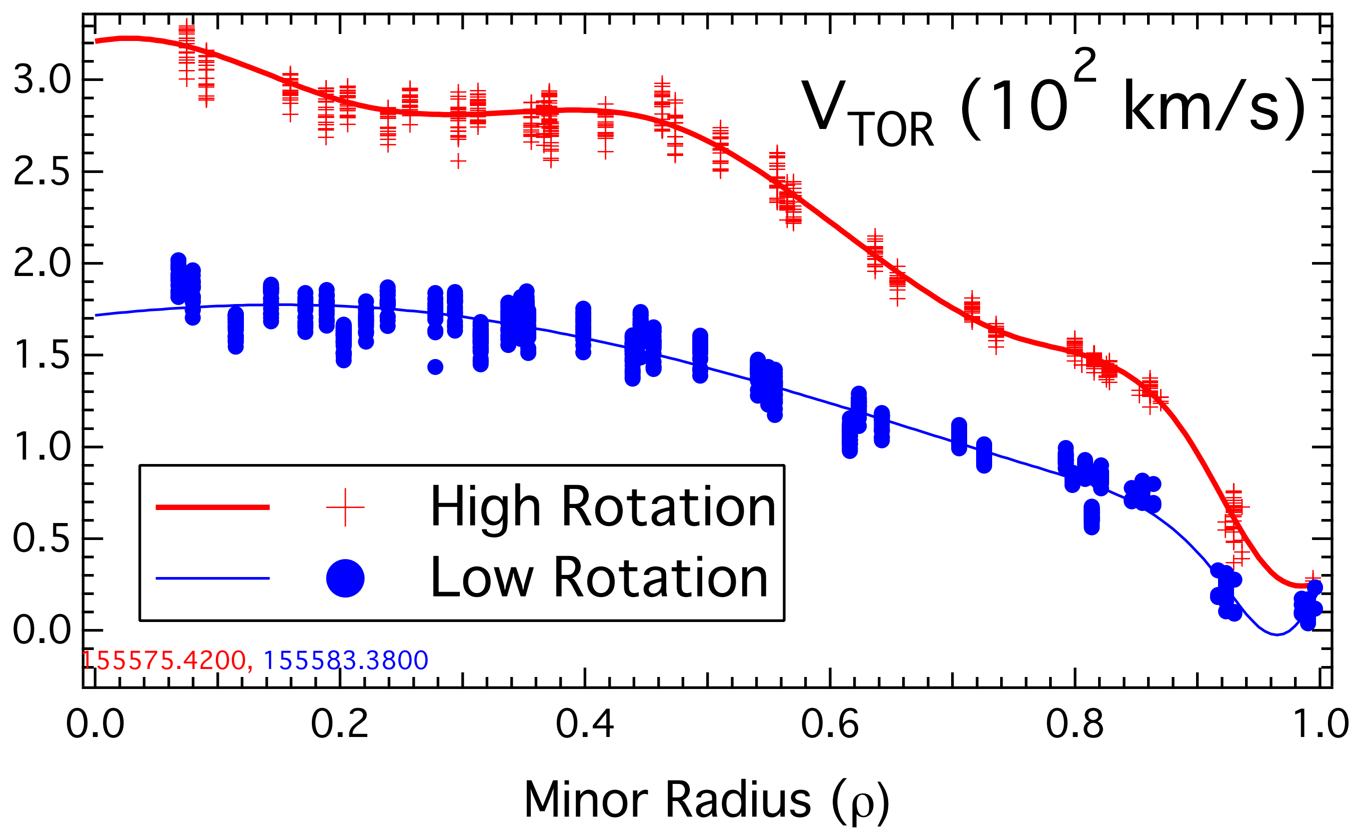
2. Effects of Equilibrated Temperatures

3. Conclusions

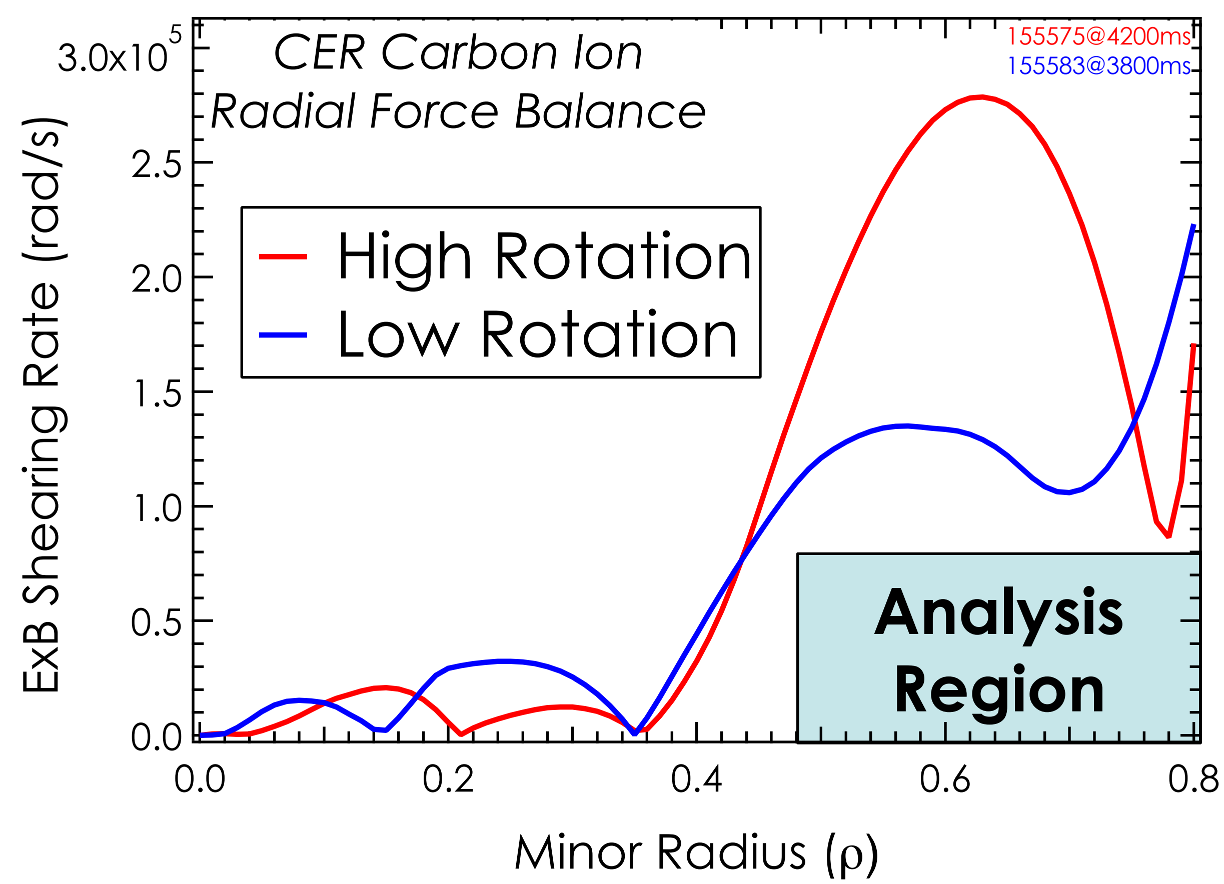
Confinement Increases with Core Toroidal Rotation in High-β_N Advanced-Inductive H-Mode Plasmas

- **Long-pulse, high-pressure plasmas: $\beta_N \approx 2.7$, 2-3 sec steady phase**
  - Density, temperature, rotation held constant via feedback control
- **Highest *ExB* shear *difference* near mid-radii (0.5 < ρ < 0.7)**

Toroidal Rotation (Mach #,max~0.4)



***ExB* Shearing Rate Profiles**



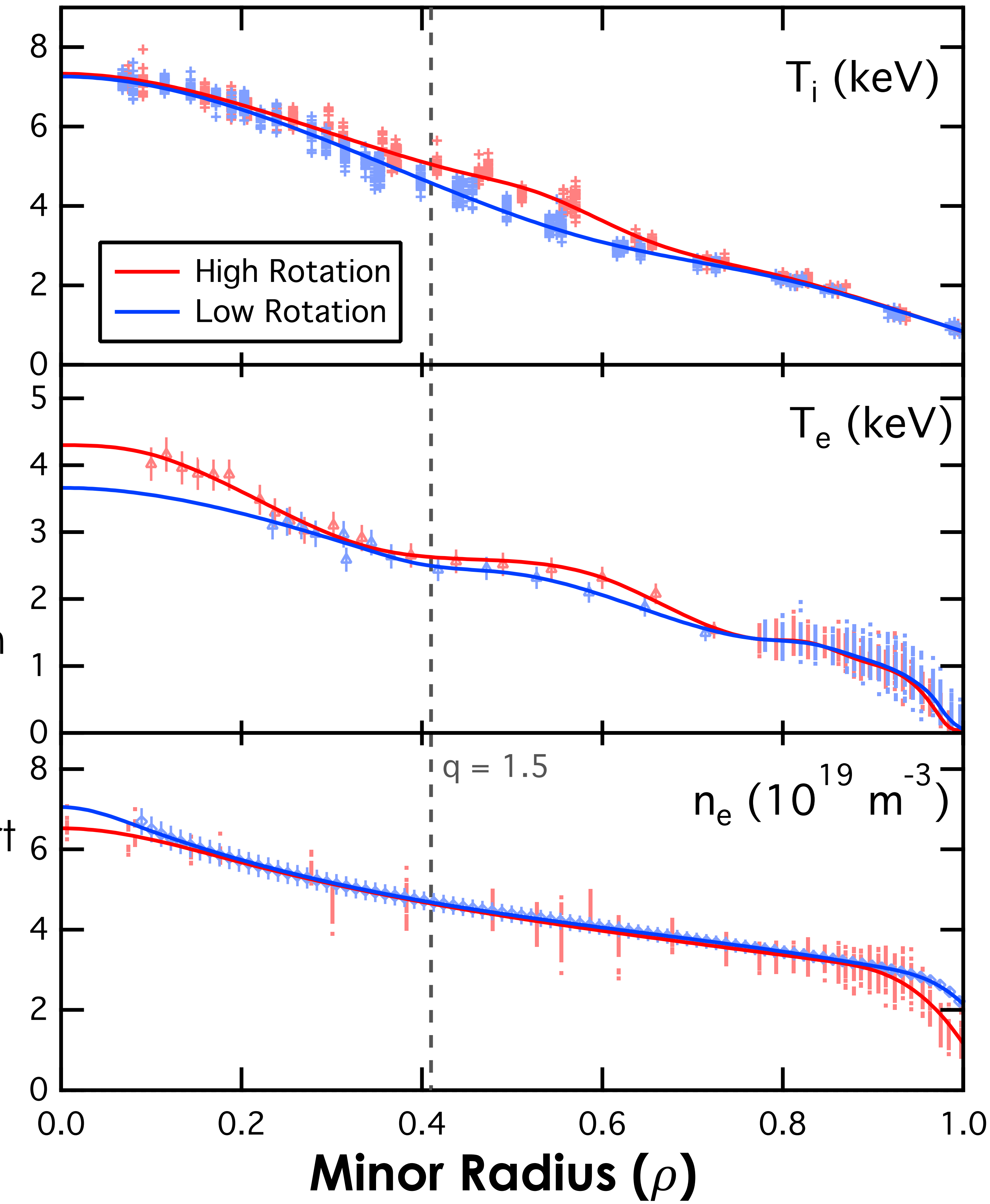
Rotation	τ_E(ms)
Low	105
High	148

Fluctuation Diagnostics:

Beam Emission Spectroscopy: low-k (2D)
Doppler Back-Scattering: intermediate-k
Phase Contrast Imaging: low to high-k

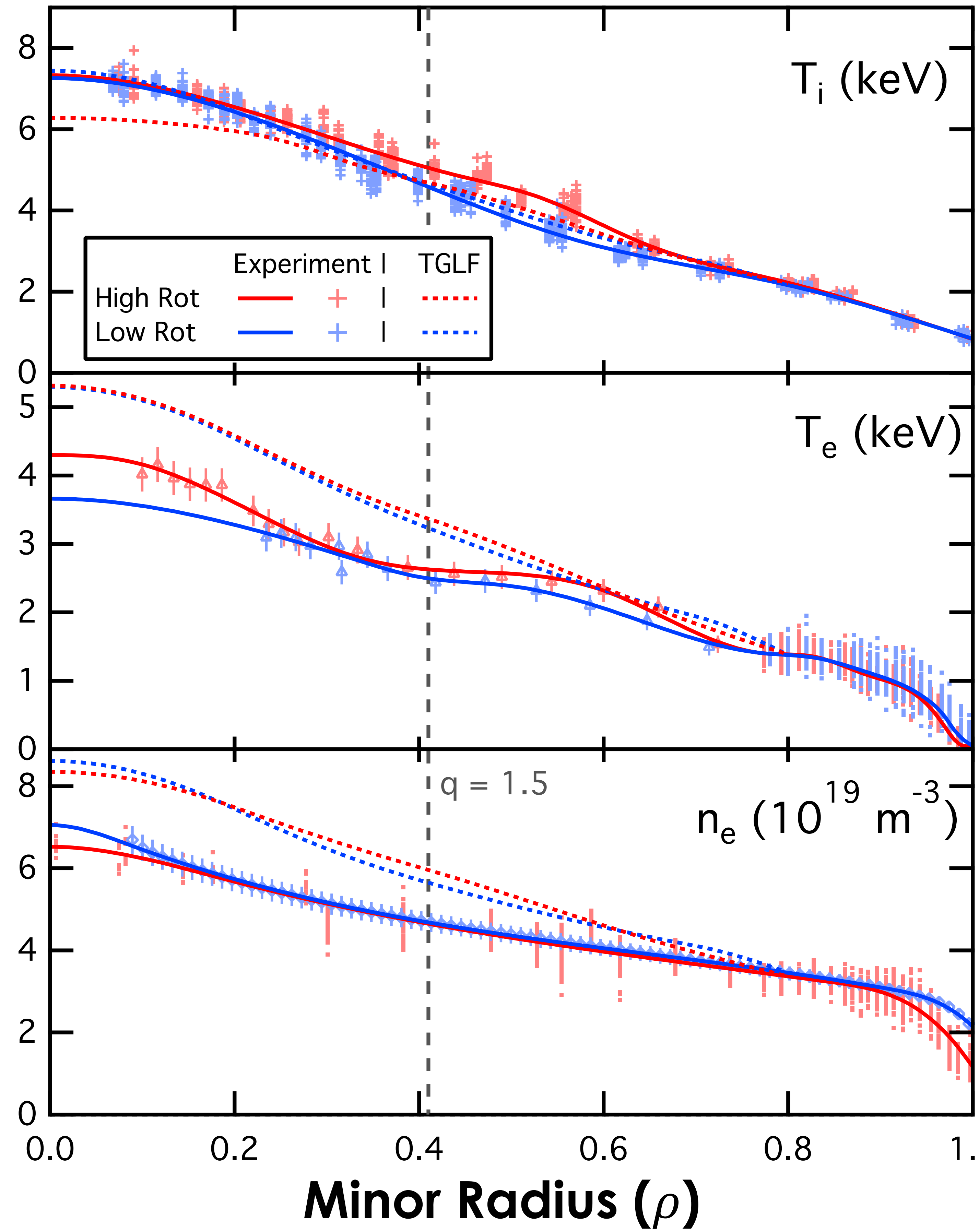
Temperature and Density Profiles Well-Matched as Toroidal Rotation is Varied

- **Feedback control utilized to obtain similar profiles**
  - Core T_i well-matched; modest reduction in mid-radii
  - Increased power required at low rotation
- **T_e profile exhibits effects of 3/2 mode**
  - Sustains q_{min}>1, prevents sawteeth in Advanced-Inductive plasmas
- **Density profiles well matched**
  - Modest changes in particle transport



TGLF Profiles Compare Reasonably Well With Some Notable Deviations

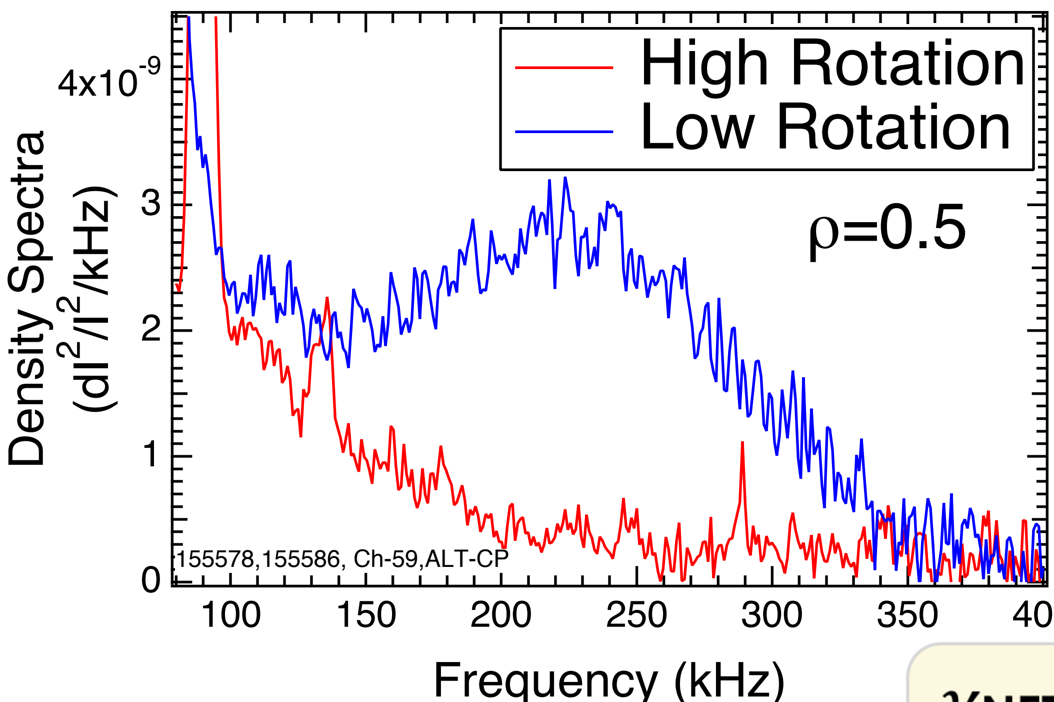
- **TGLF calculates profiles:**
  - Heat and particle sources
  - Gradients drive experimentally measured fluxes
  - Boundary Conditions (ρ=0.8)
- **T_i well-matched in core**
  - Underestimated at high rotation
- **T_e overestimated**
  - Doesn't include 3/2-mode
- **Density profile overestimated**
  - Coupling of temperature and density profiles
  - Large electron-ion thermal exchange at $T_i \gg T_e$



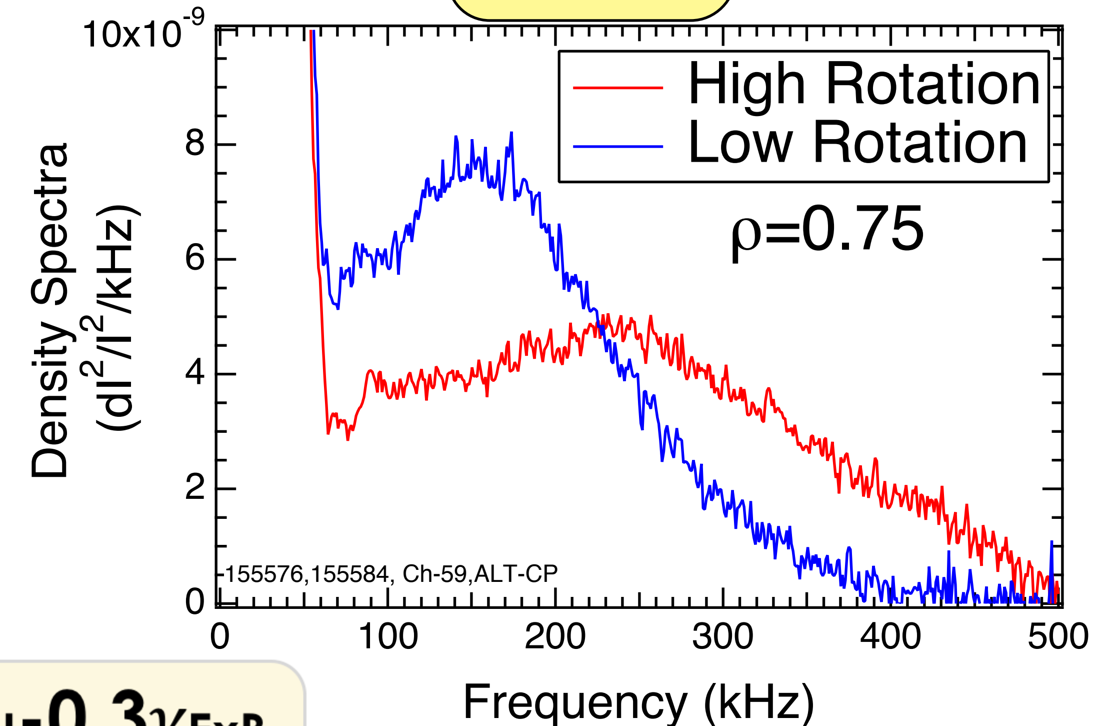
Low-k Turbulence Amplitude Reduced in Core at High Toroidal Rotation yet Remains Similar Radially Outwards

ρ=0.5

BES

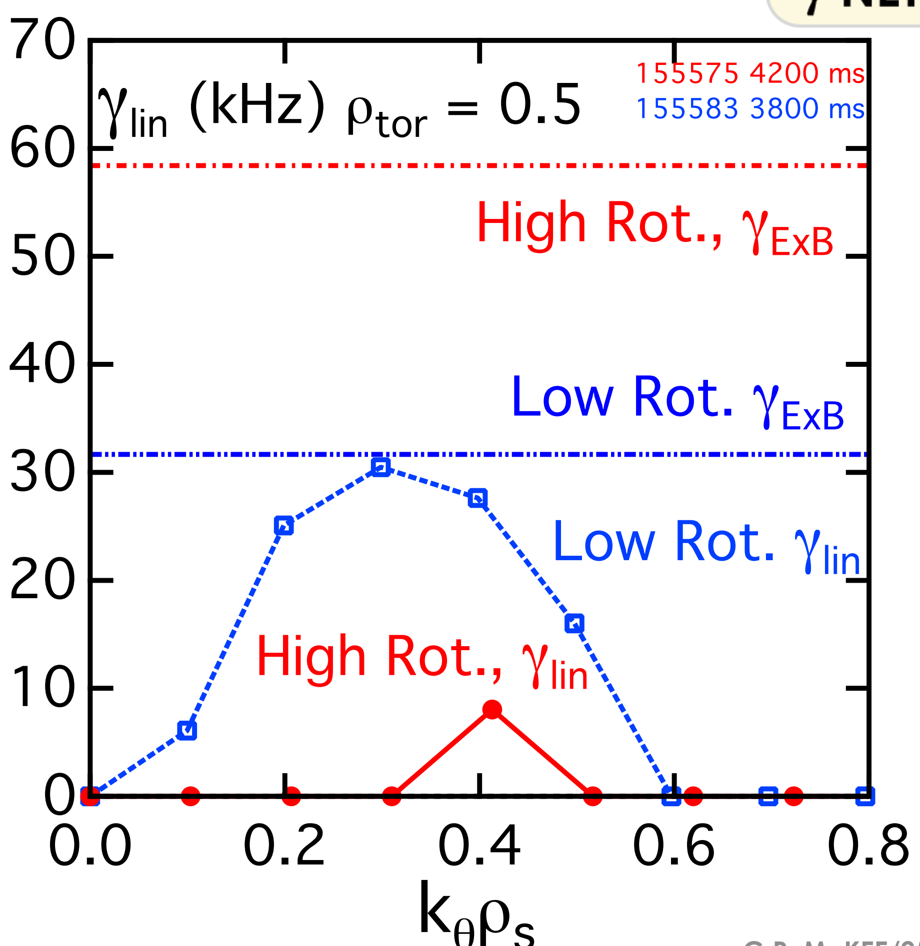


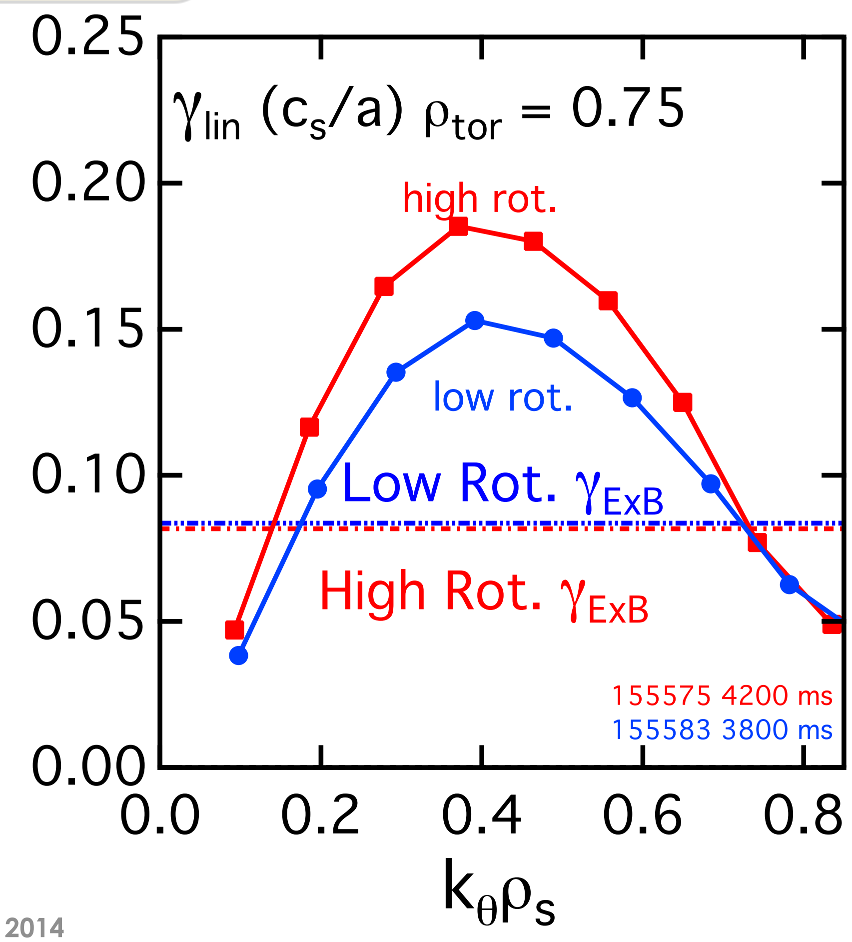
ρ=0.75



$\gamma_{NET} \approx \gamma_{LIN} - 0.3\gamma_{ExB}$

GYRO

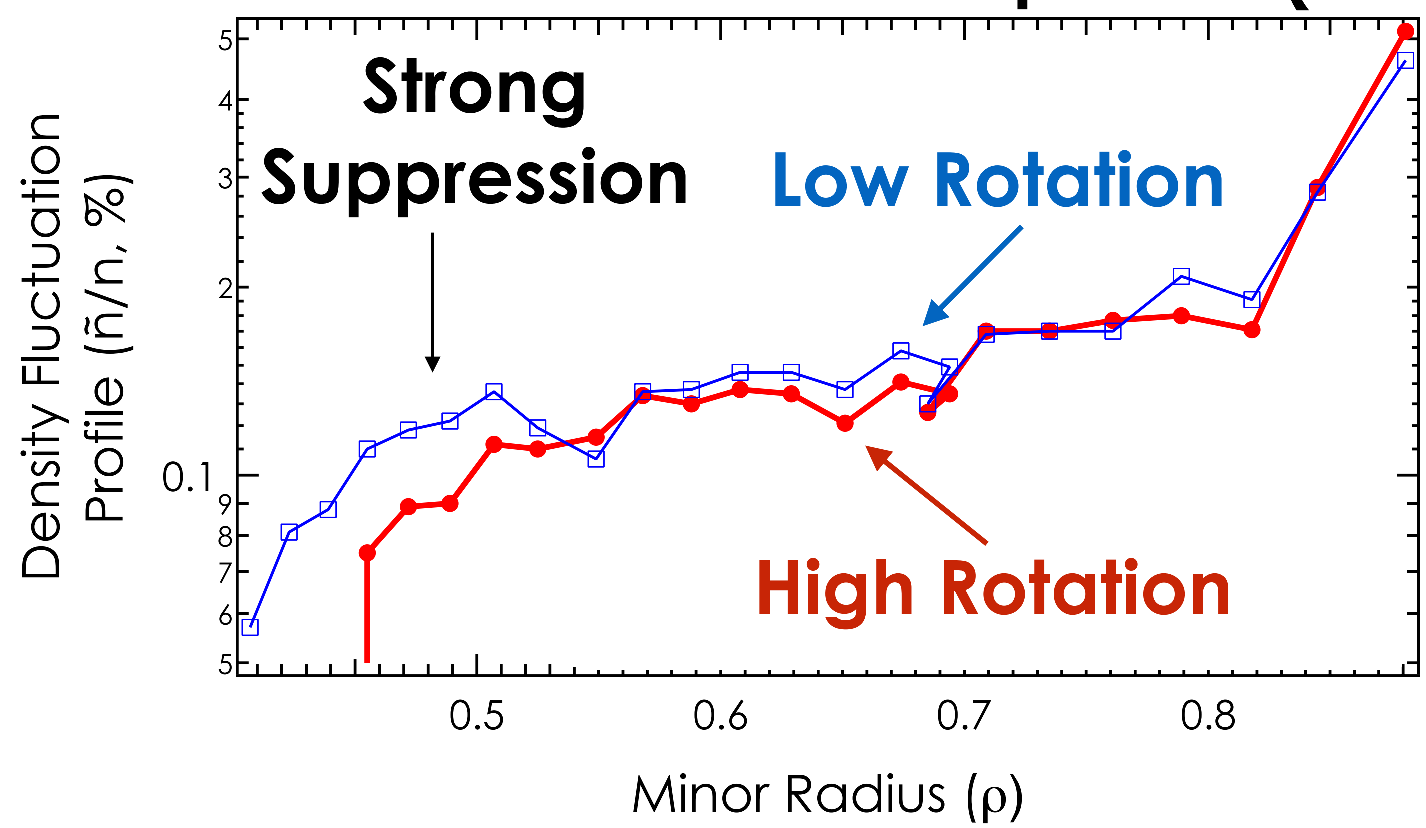




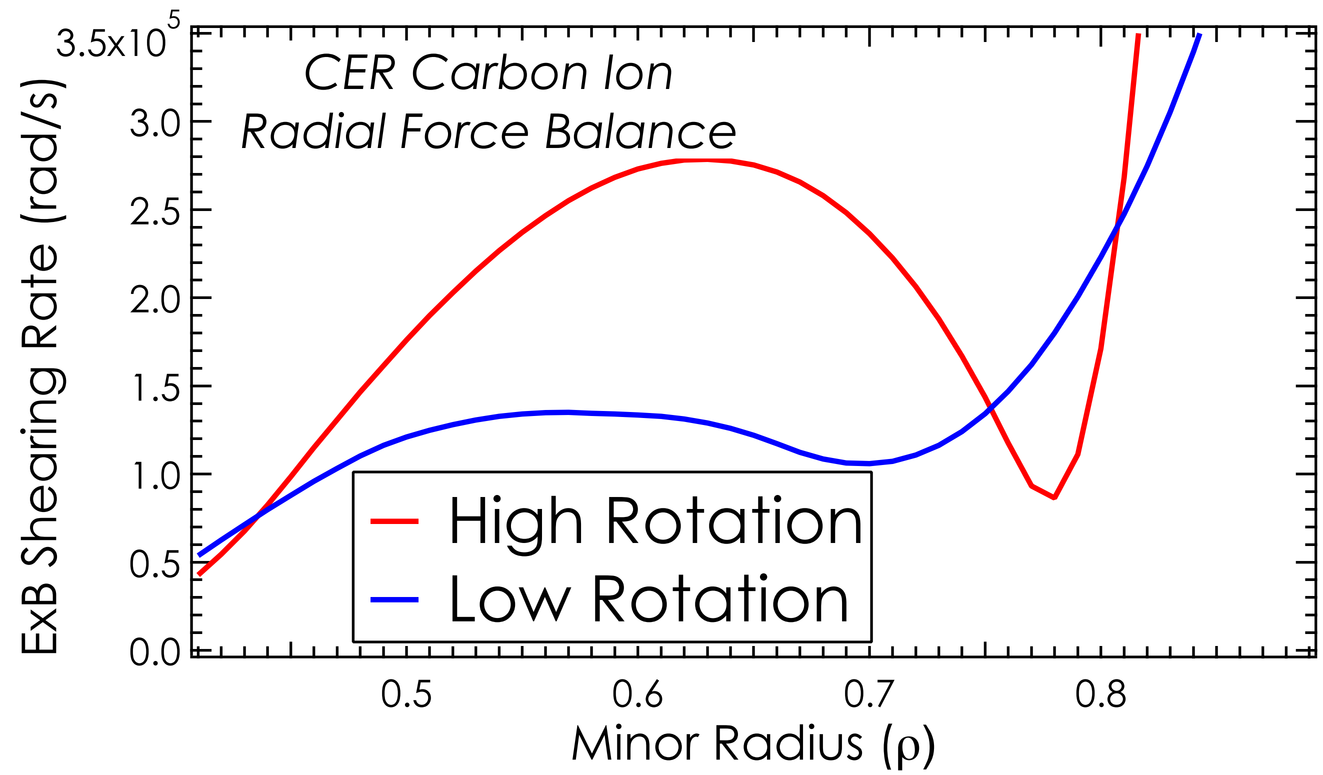
Low-k Turbulence Exhibits Similar Amplitude at Radially Outboard Locations Despite Differing ExB Shearing Rates

- **Low-k turbulence amplitude similar outside ρ=0.5**
  - ***ExB*** shearing rates differ
- **Turbulence amplitude *<u>similar</u>* despite difference in shearing rates in 0.55 < ρ < 0.75**

Low-k Fluctuation Amplitude (BES)

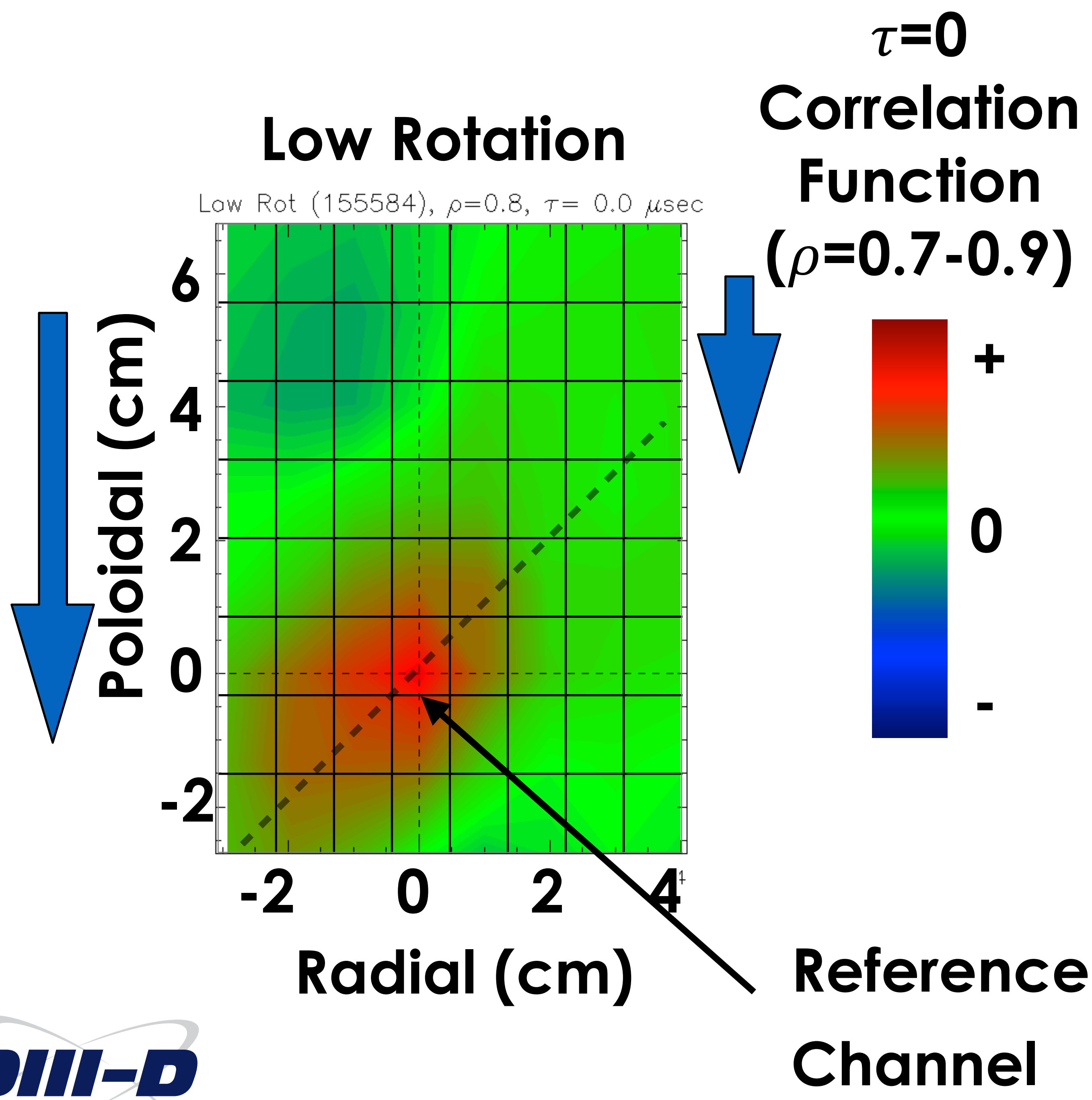


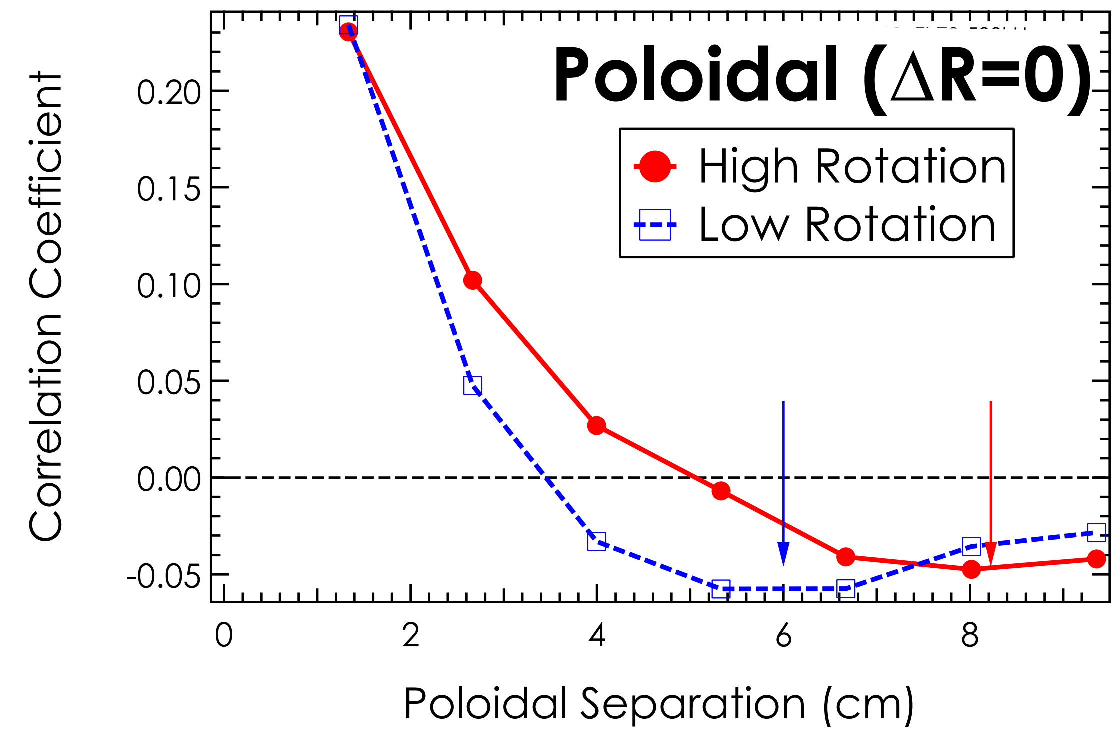
***ExB* Shearing Rate Profiles**



Turbulence Adjusts to Increasing ExB Shearing Rates by Faster Decorrelation and Reduced k_θ

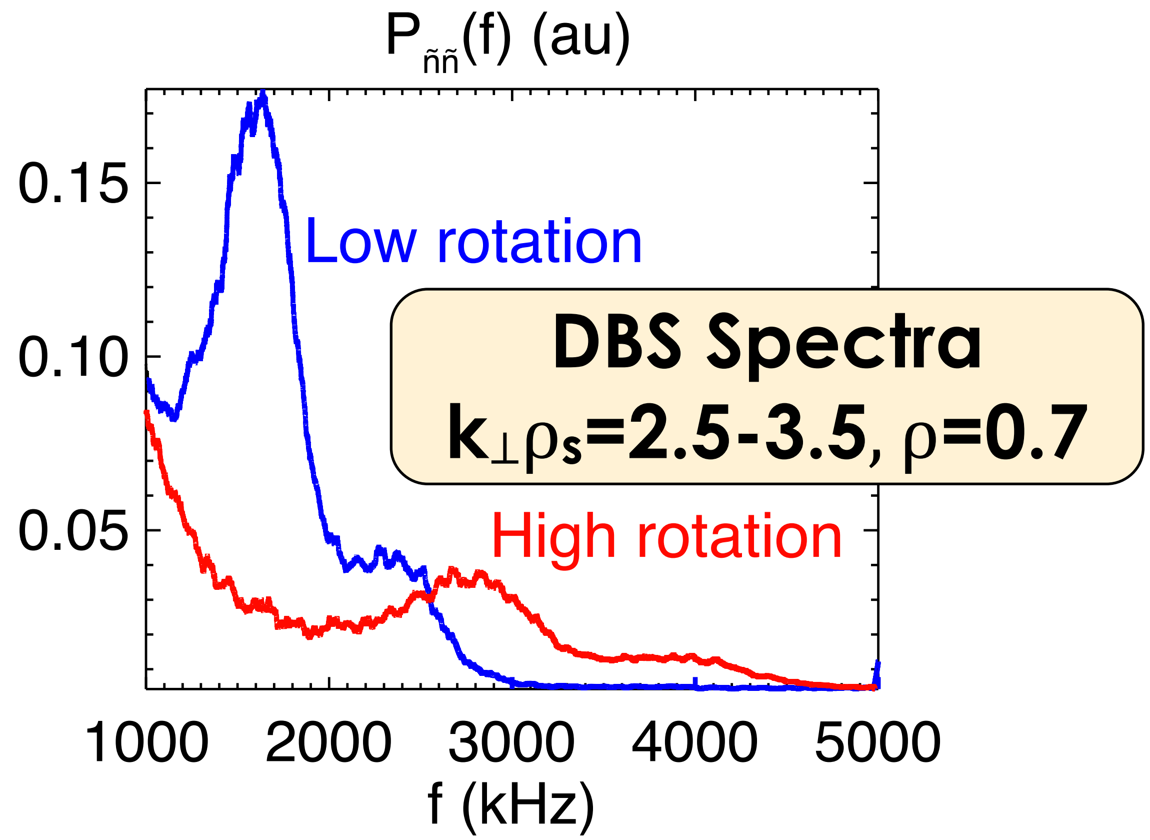
- **Tilted eddy structure observed in both high and low rotation plasmas**
  - ***ExB*** shearing rates similar locally, though toroidal rotation differs
  - Finite k_r: contrasts with L-mode turbulence, which exhibits little/no tilting

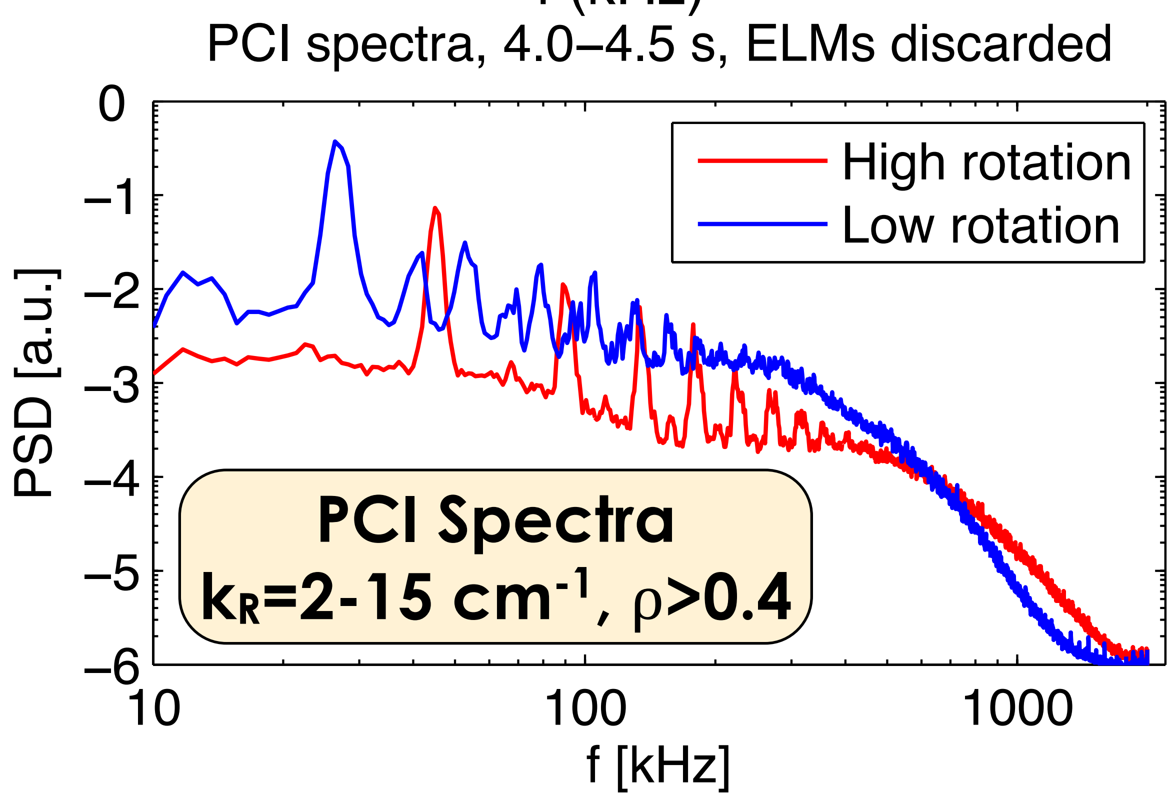




Ω	τ_C (μs)	τ_{ExB} (μs)	$k_{\theta,pk}$ (cm^{-1})
High	2.5	3.5	0.4
Low	5	7	0.5

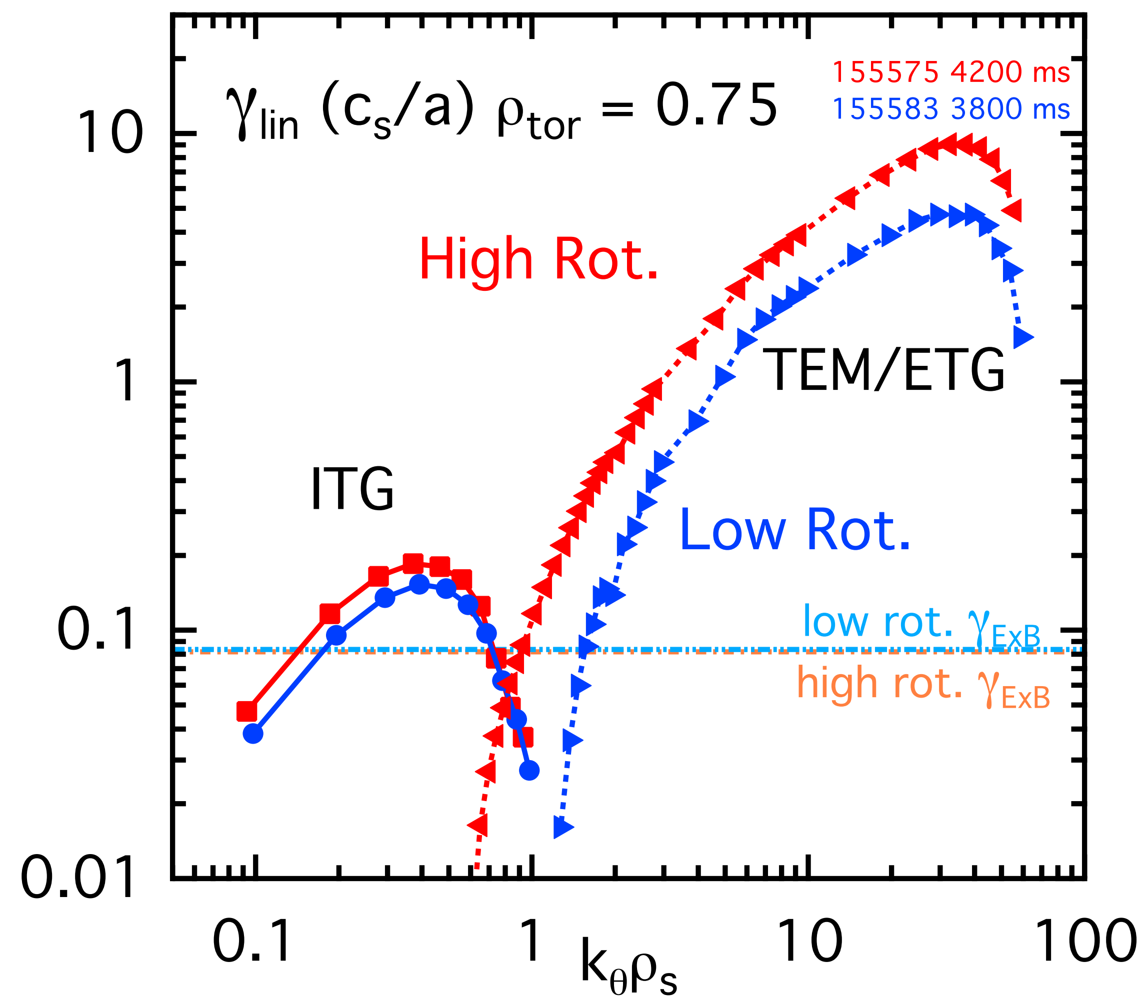
Intermediate & Higher-Wavenumber Fluctuations Suppressed at Higher Toroidal Rotation: Challenges Expectations





$$P(\tilde{n})_{\text{Low Rot}} = 3 * P(\tilde{n})_{\text{High Rot}}$$

GYRO γ_{LIN} Calculations

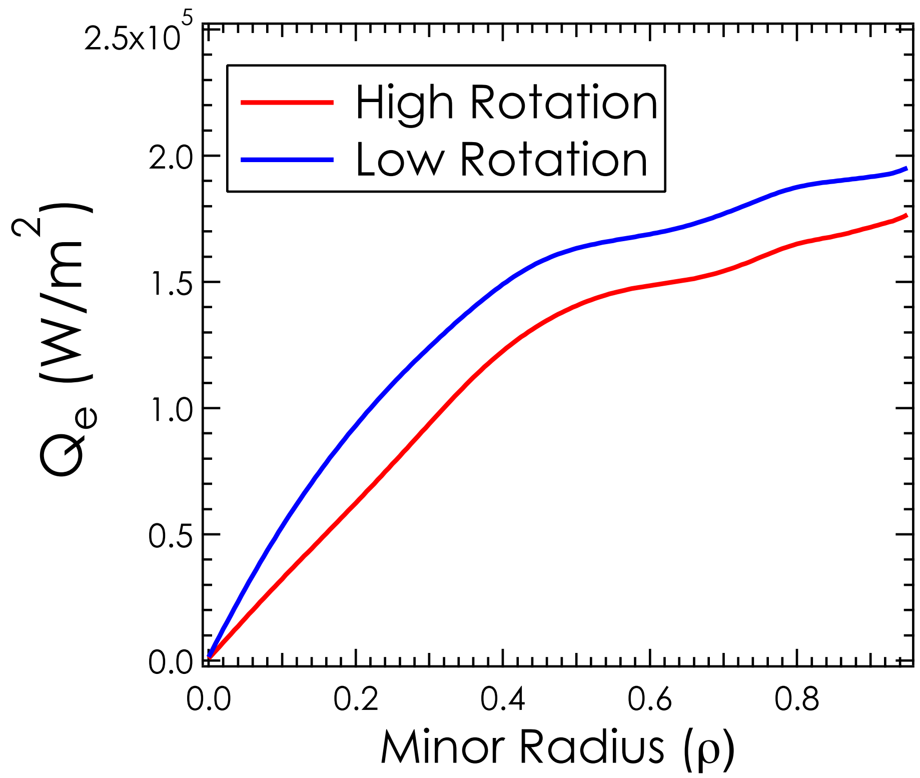


- **DBS & PCI show significantly lower high-k turbulence with increasing toroidal rotation**
  - GYRO calculates higher linear growth rates
  - Exceed ExB shear rates

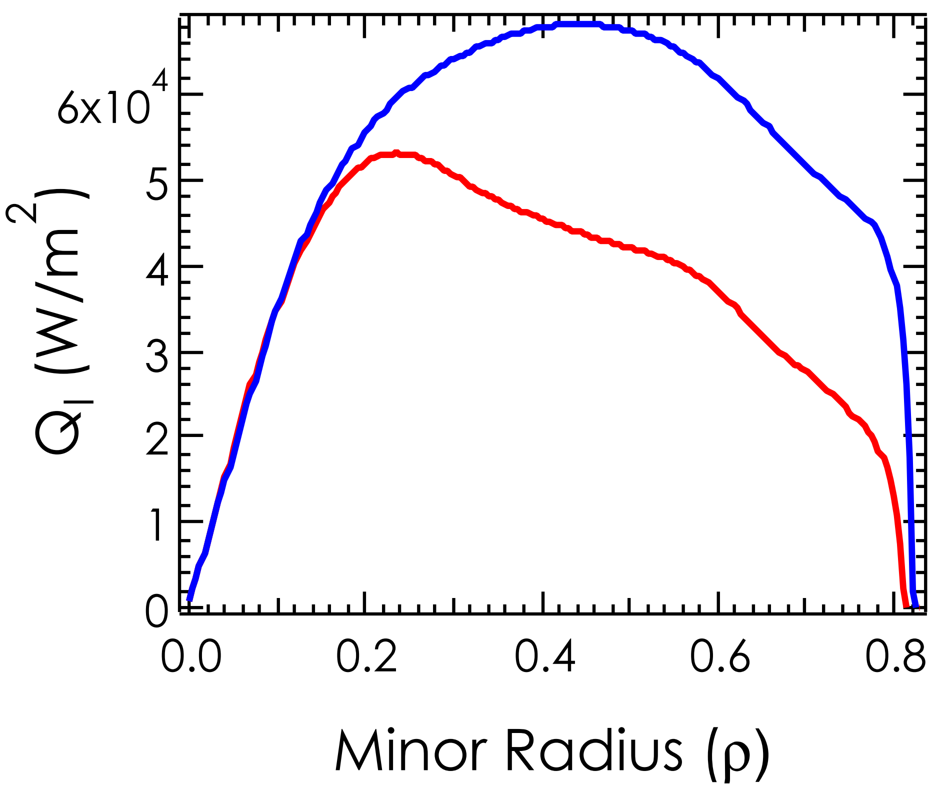
Increased Thermal and Particle Transport at Low Rotation

- **Consistent with turbulence changes at low rotation**
  - Low-k turbulence increase near ρ=0.5
    - *Low-k decorrelation changes at larger radii with little amplitude change*
  - High-k turbulence increases

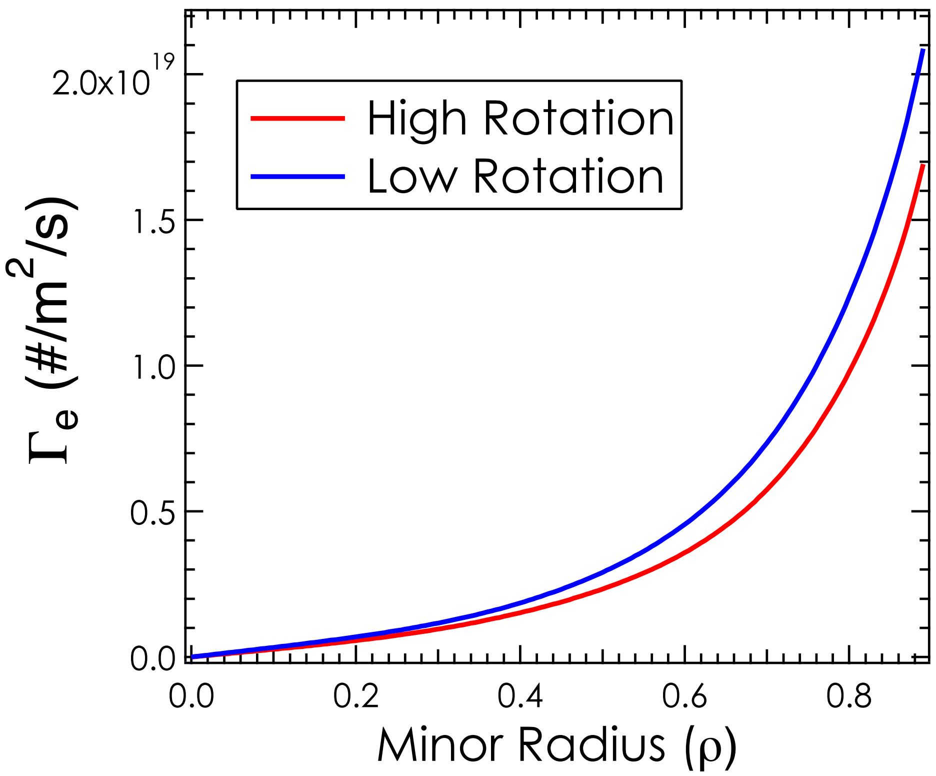
Electron Thermal Flux



Ion Thermal Flux



Electron Particle Flux



1. Effects of Toroidal Rotation

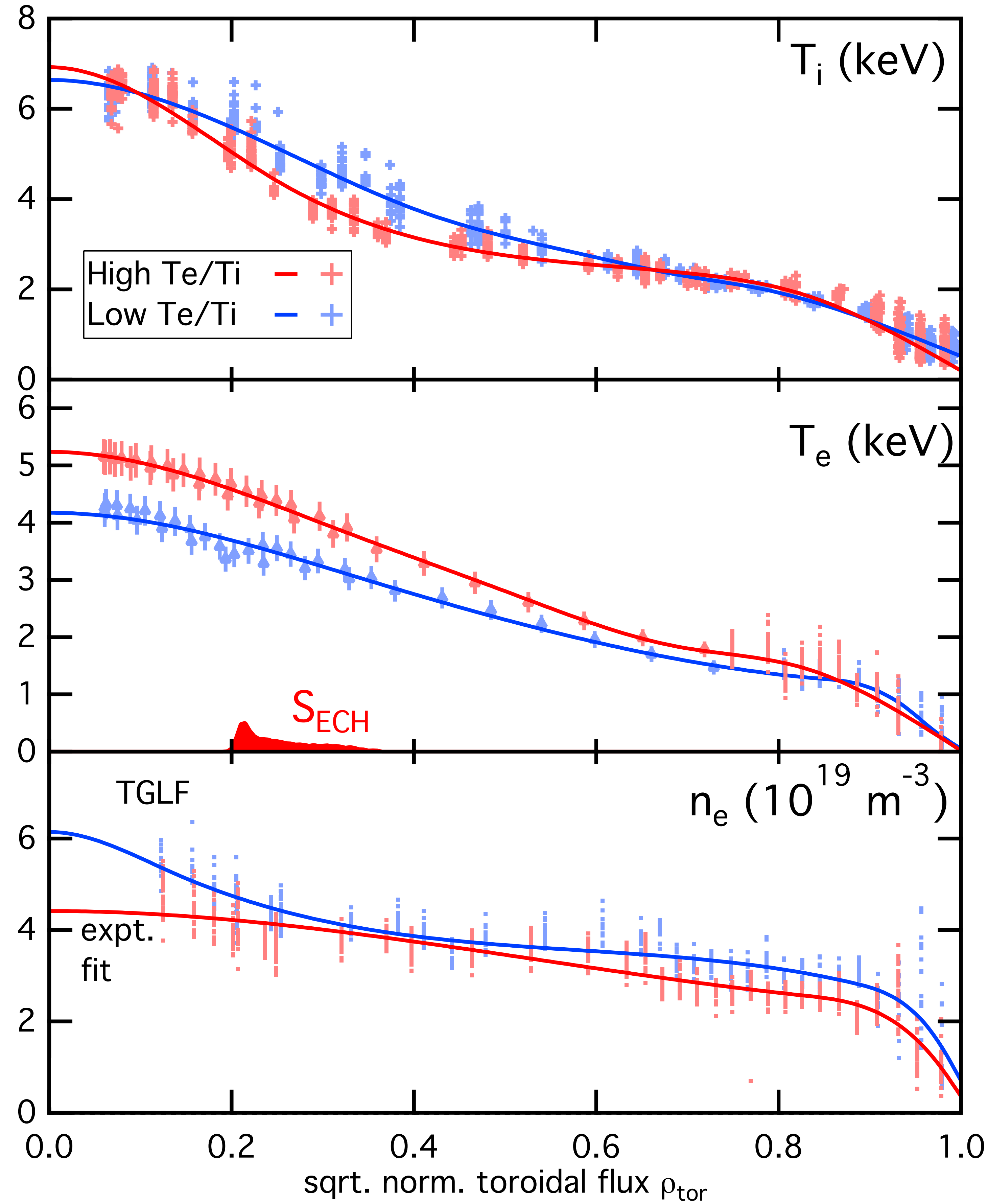
2. **Effects as $T_e \Rightarrow T_i$**

3. Conclusions

T_e Self-Similarly Increased with ECH + Fast Wave to Maintain Nearly Constant Gradient Scale Length

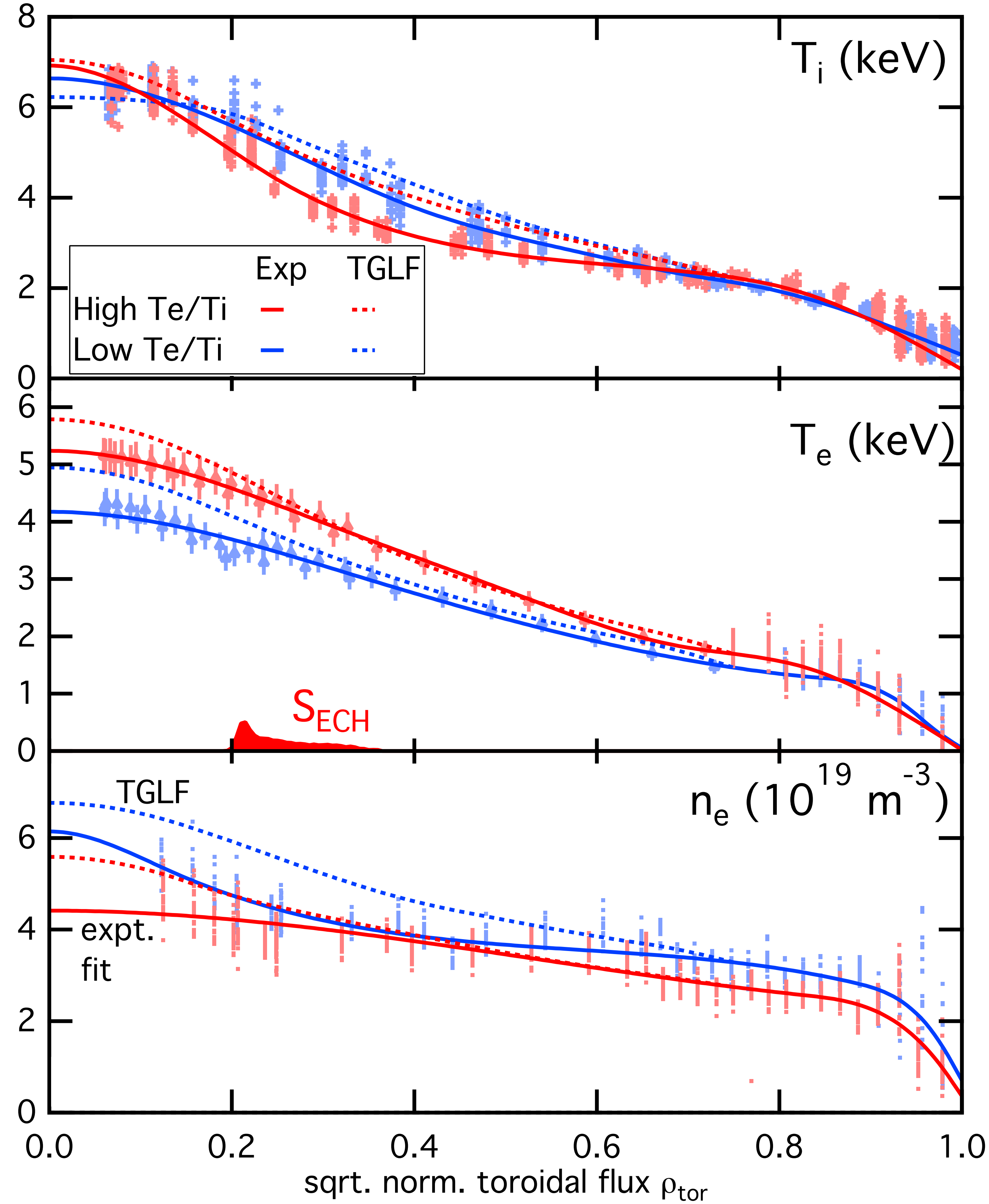
- **Advanced Inductive Plasmas:**
  - β_N~2.5, ITER Shape, q_{95}=5.8
- **Core T_i well matched**
  - Mid-radii T_i exhibits reduction at higher T_e/T_i
- **~25% increase in T_e**
  - Fixed gradient scale lengths
- **Density reduced with T_e/T_i**
  - Density "pump-out"
  - Gas-puffing partially compensates
  - Reduced toroidal rotation with out compensation via NBI

T_e/T_i	τ_E (ms)
Low	115
High	75



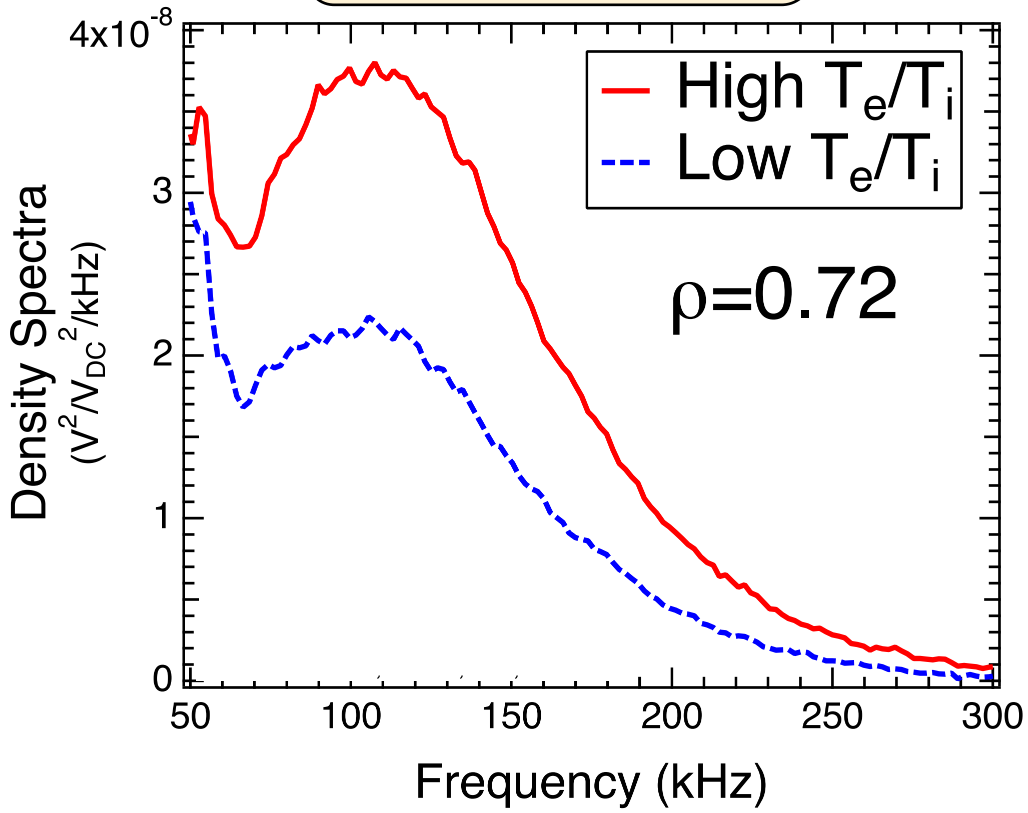
TGLF Calculated Profiles Reproduce Trends with Changing T_e/T_i

- T_i well matched in core, slightly overestimates in mid-radii at higher T_e/T_i
- Accurately reproduces increased T_e profile with core-localized ECH source
- Captures reduction in density at increased T_e/T_i
- All trends in same direction as experiment



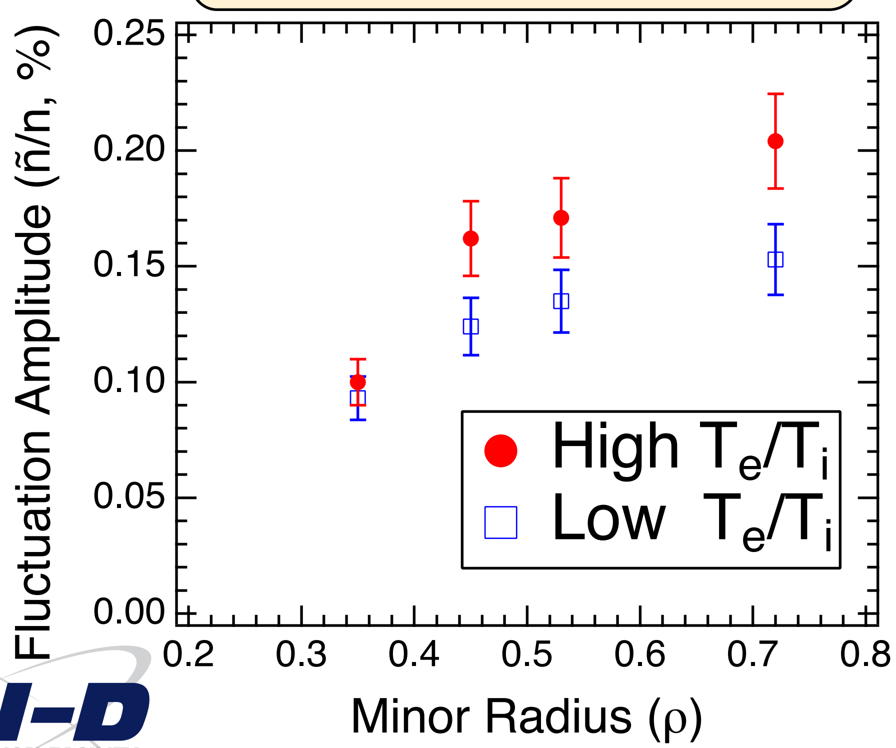
Low-k Density Turbulence and Ion Thermal Diffusivity Increase Across Profile as $T_e/T_i \Rightarrow 1$

BES Spectra

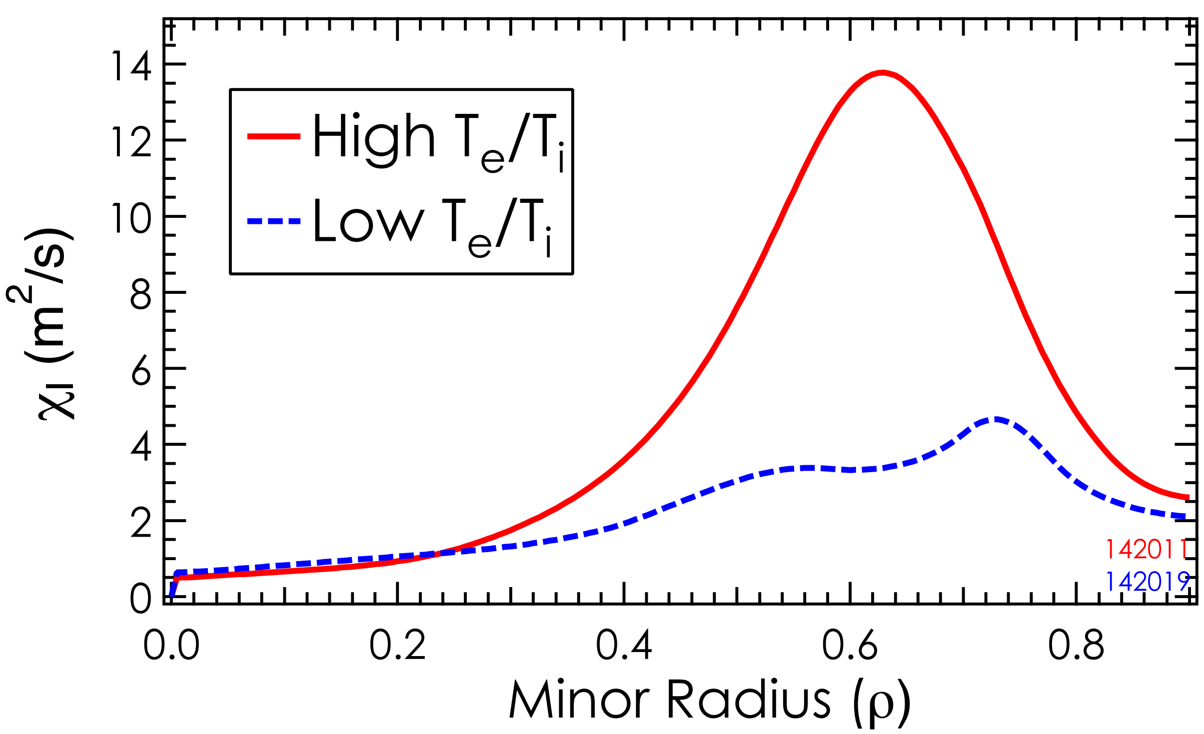


- **Spectrally uniform increase in fluctuation amplitude**
  - Intermediate-k exhibits increase in amplitude with bursty features
- **Ion, electron, momentum and particle diffusivity increase across profile**
  - Explains 35% reduction in τ_E

Fluctuation Profile

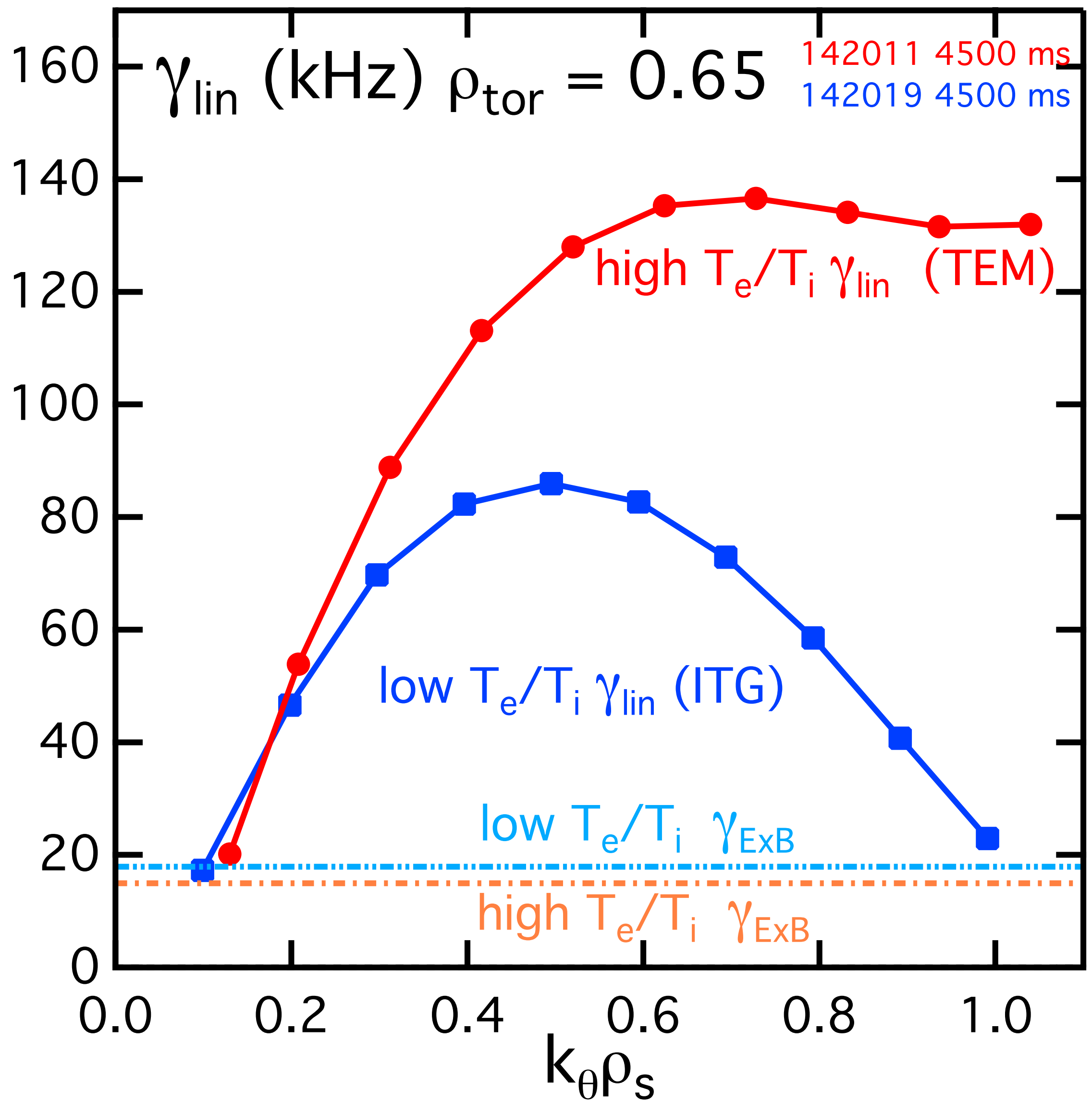


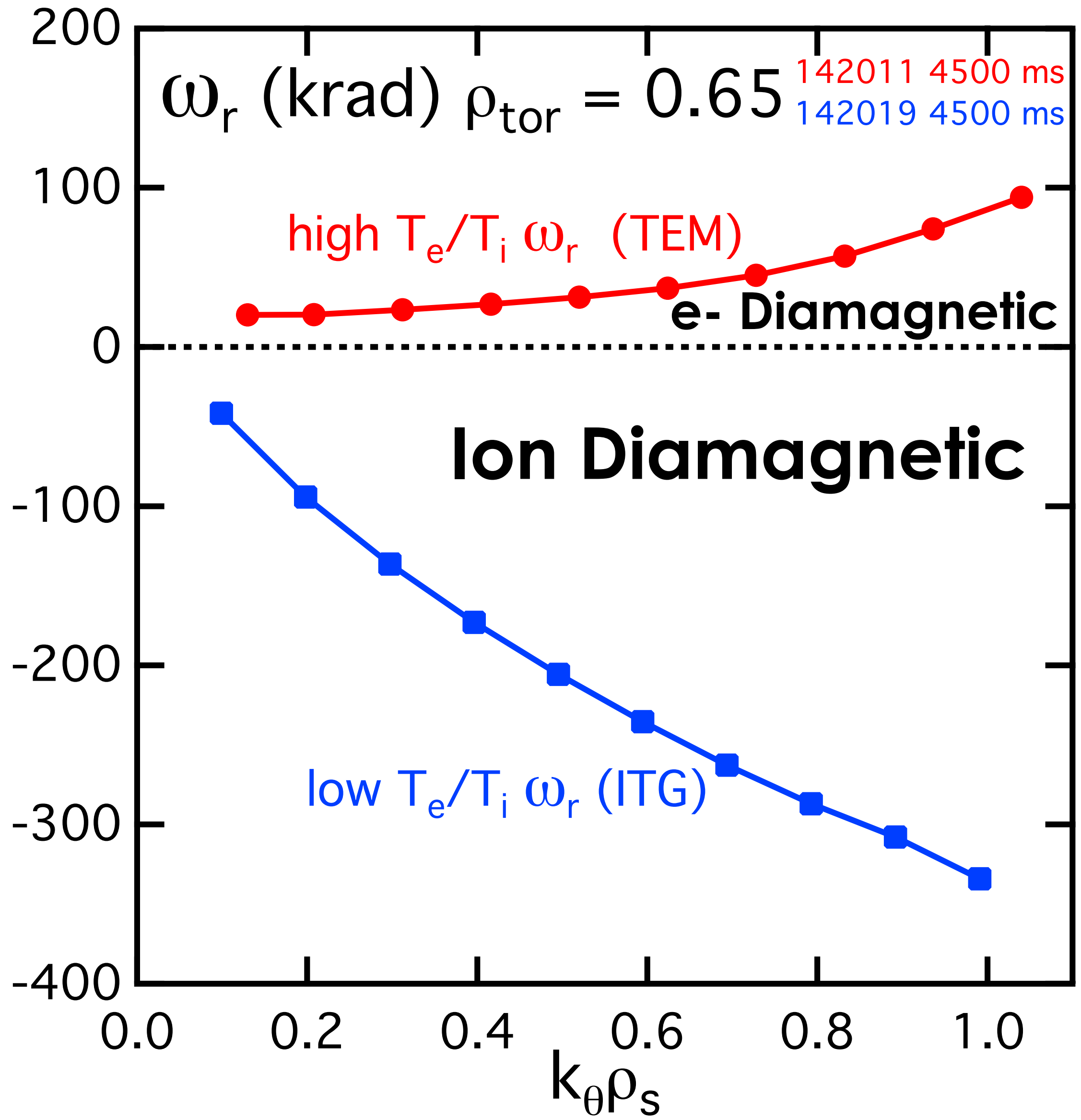
Ion Thermal Diffusivity



GYRO Indicates T_e/T_i Increases Trapped Electron Mode Growth Rates More Than Ion Temperature Gradient Mode

- **Can explain increased particle transport at higher T_e/T_i**
  - Frequency changes to electron diamagnetic direction at higher T_e/T_i
  - Growth rates increase more strongly at intermediate $k_\theta \rho_s$

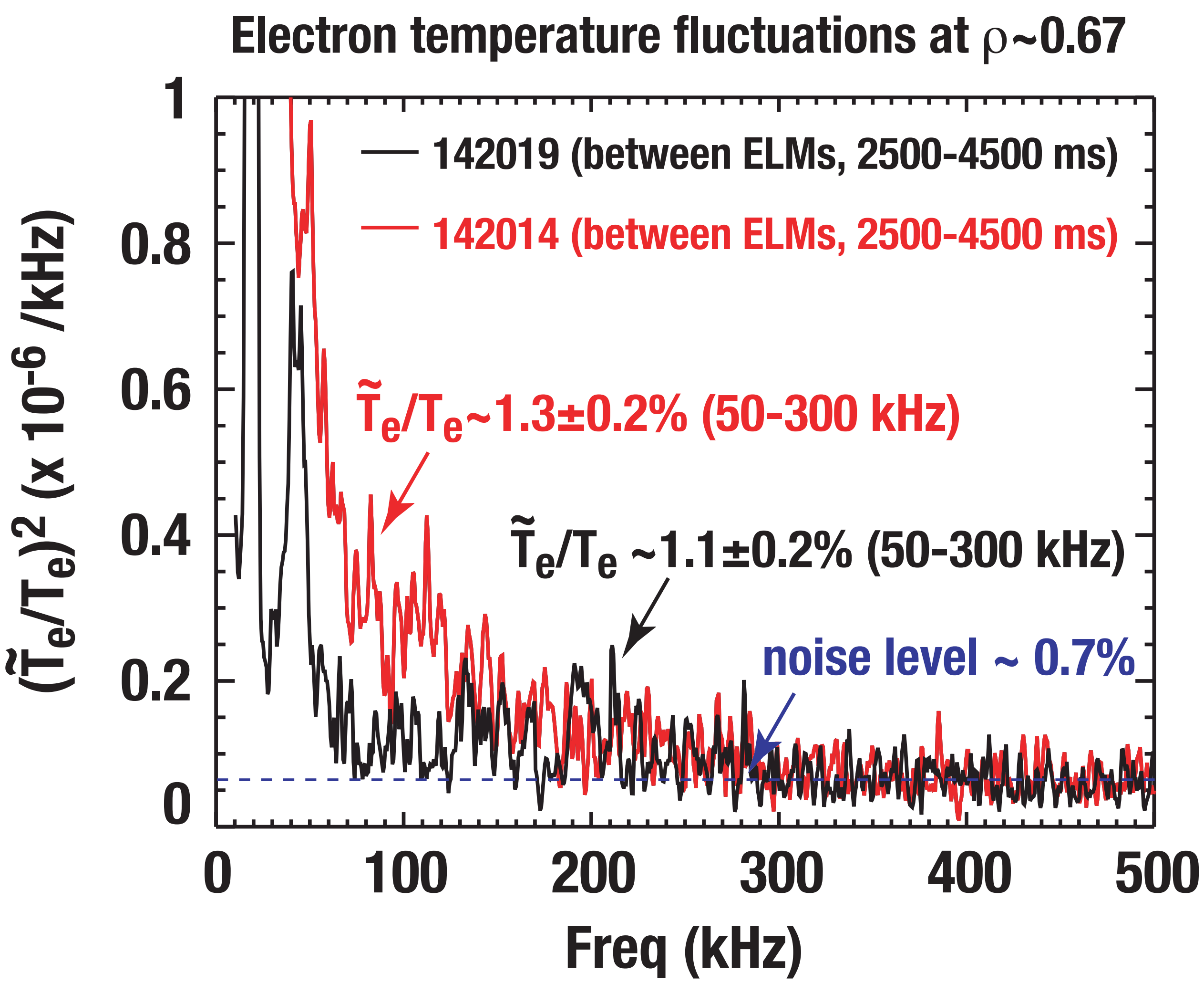




D. Ernst, this session

Low-k Electron Temperature Fluctuations Increase with T_e/T_i

- **CECE (Correlated Electron Cyclotron Emission) measured localized T_e fluctuations**
  - Spatially localized, low-k
- **Consistent with increase in low-k density fluctuations**
  - GYRO: increased linear growth rates for low-k electron mode
  - May reflect increase in Trapped Electron Mode (TEM) turbulence
- **Consistent with increased electron thermal and particle transport with T_e/T_i**

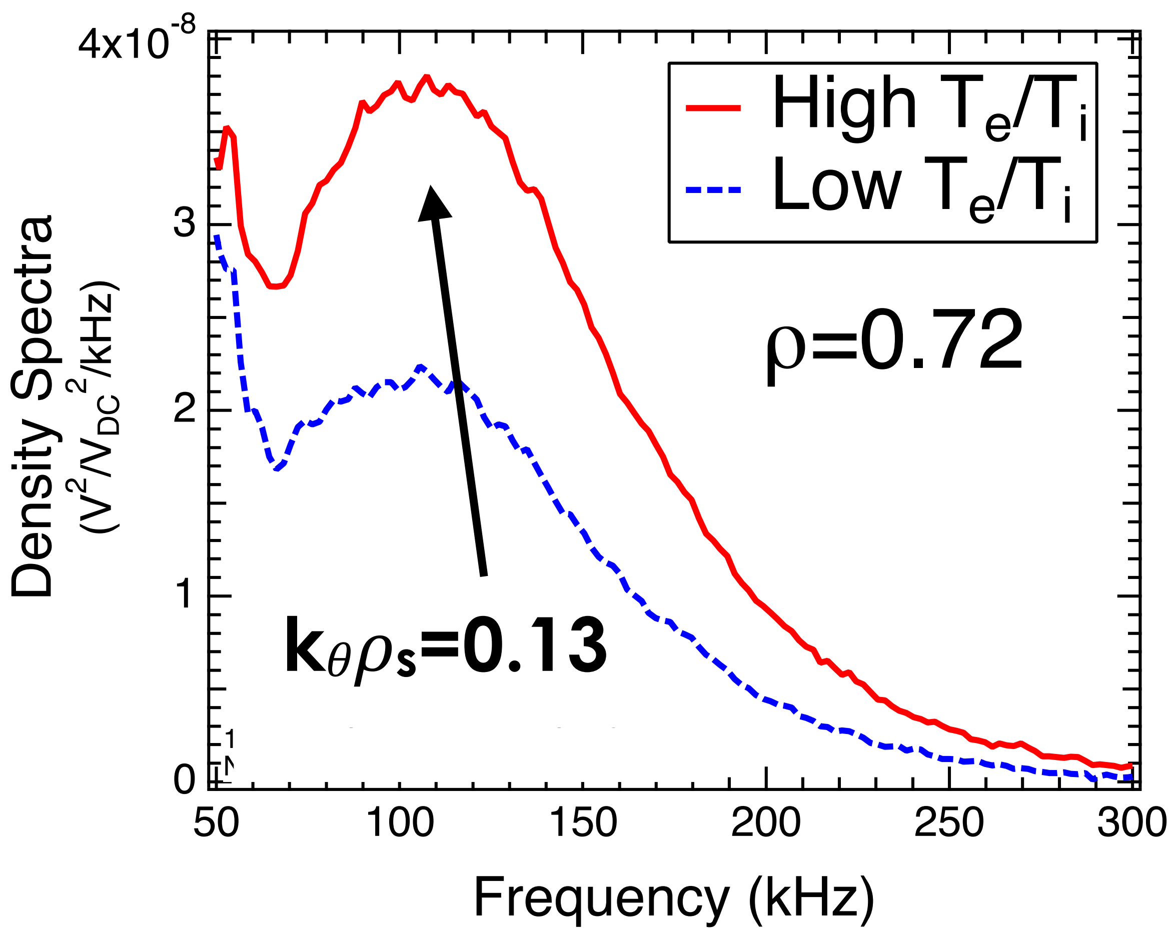


G. Wang, UCLA

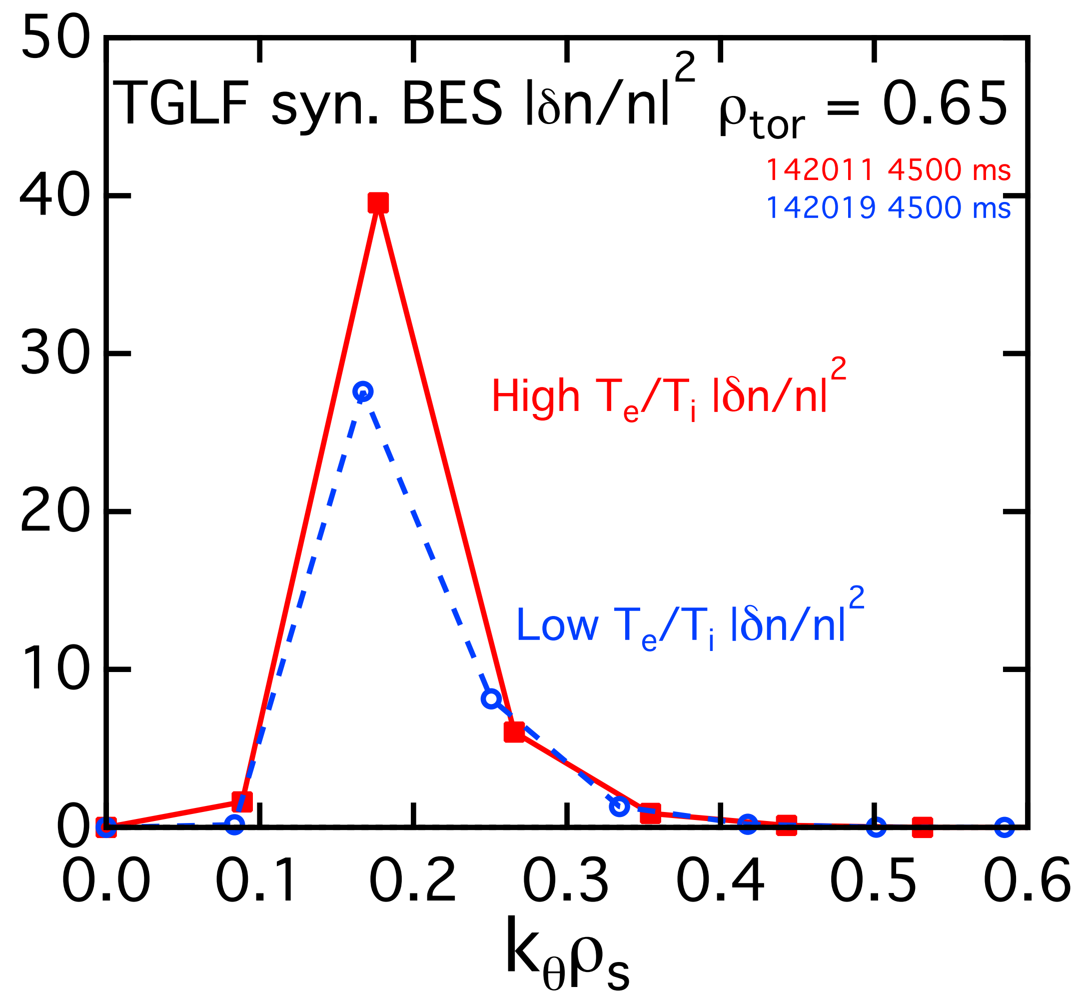
Calculated Quasilinear Density Fluctuation Spectra Compare Well with Measured Turbulence Spectra

- **TGLF spectra reflect turbulence that drives heat fluxes**
  - Consistent with local density and temperature gradients and ***ExB*** shear
  - Peak of spectra very similar

BES Spectra



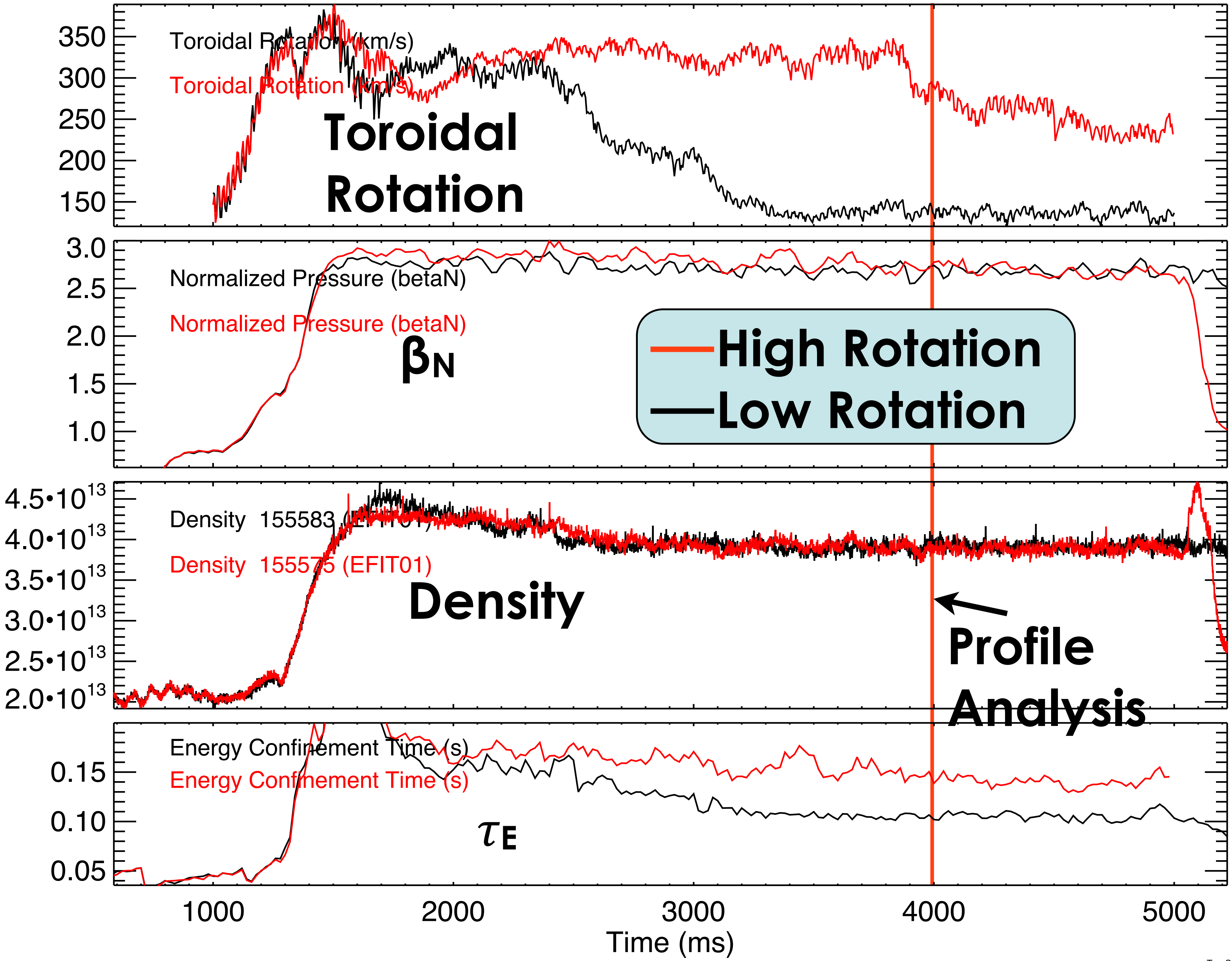
TGLF Quasilinear Spectra

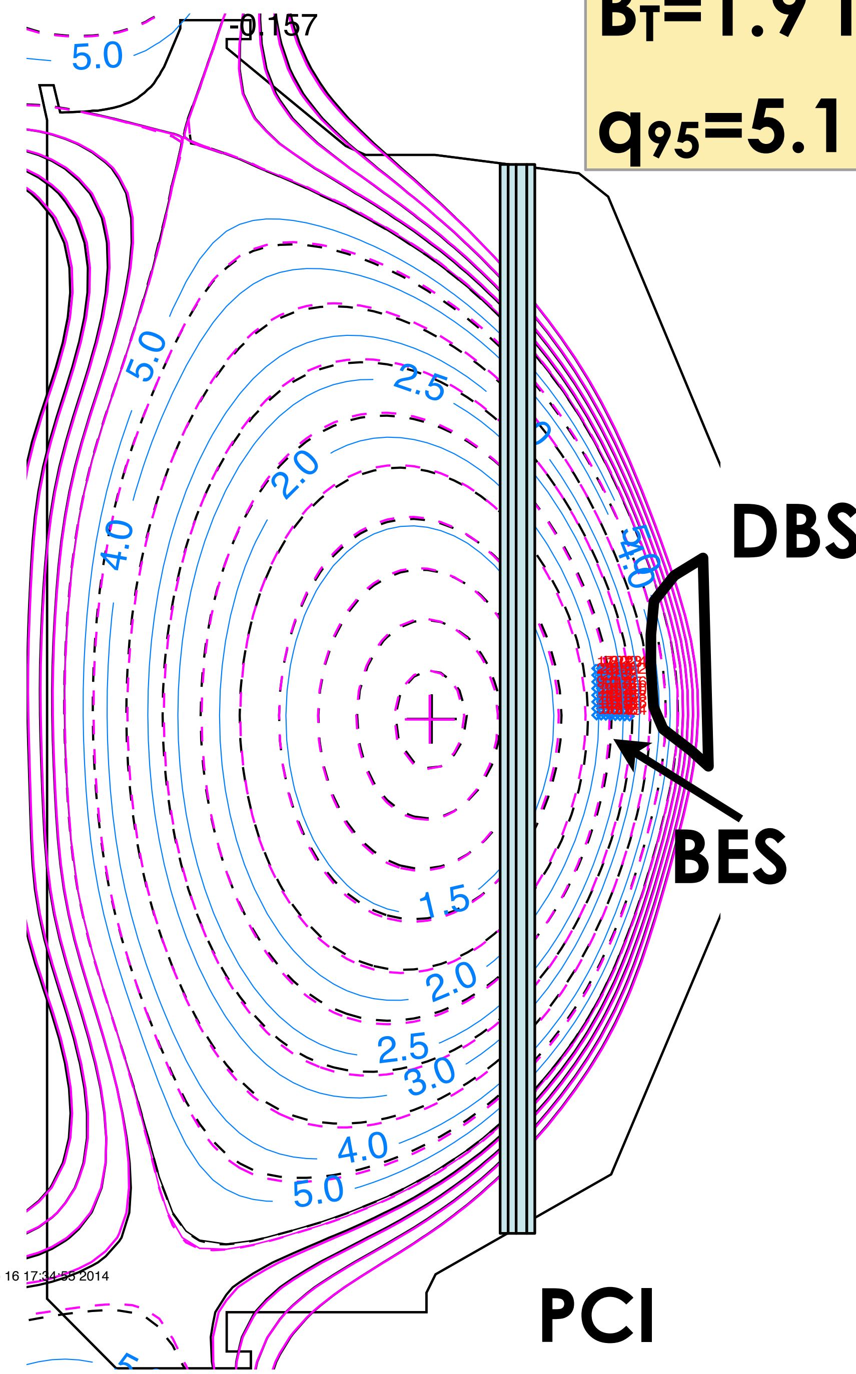


Turbulence and Transport are Altered in Fundamental Ways Approaching Burning Plasma Parameters

- **Toroidal rotation and ExB shear alters high and low-k ñ:**
  - Low-k turbulence: Decorrelation rates change to match ***ExB*** shearing rates, eddy structure shifted, while amplitude is _not_ significantly affected over outer-core (ρ=0.6-0.8); large suppression at ρ=0.5
  - High-k turbulence: _decreases_ amplitude at higher rotation
- **Increasing $T_e/T_i \Rightarrow 1$ increases low-k density and temperature fluctuations**
  - Consistent with GYRO growth rates, TGLF quasilinear fluctuation spectra
  - Transport increases in channels
- **TGLF and GYRO capture profile and turbulence trends**
- **Future nonlinear simulations will quantitatively compare with fluctuation spectra and seek to identify modest discrepancies**

Confinement Increases with Core Toroidal Rotation in High-β_N Advanced-Inductive H-Mode Plasmas





I_P=1.2 MA

B_T=1.9 T

q_{95}=5.1

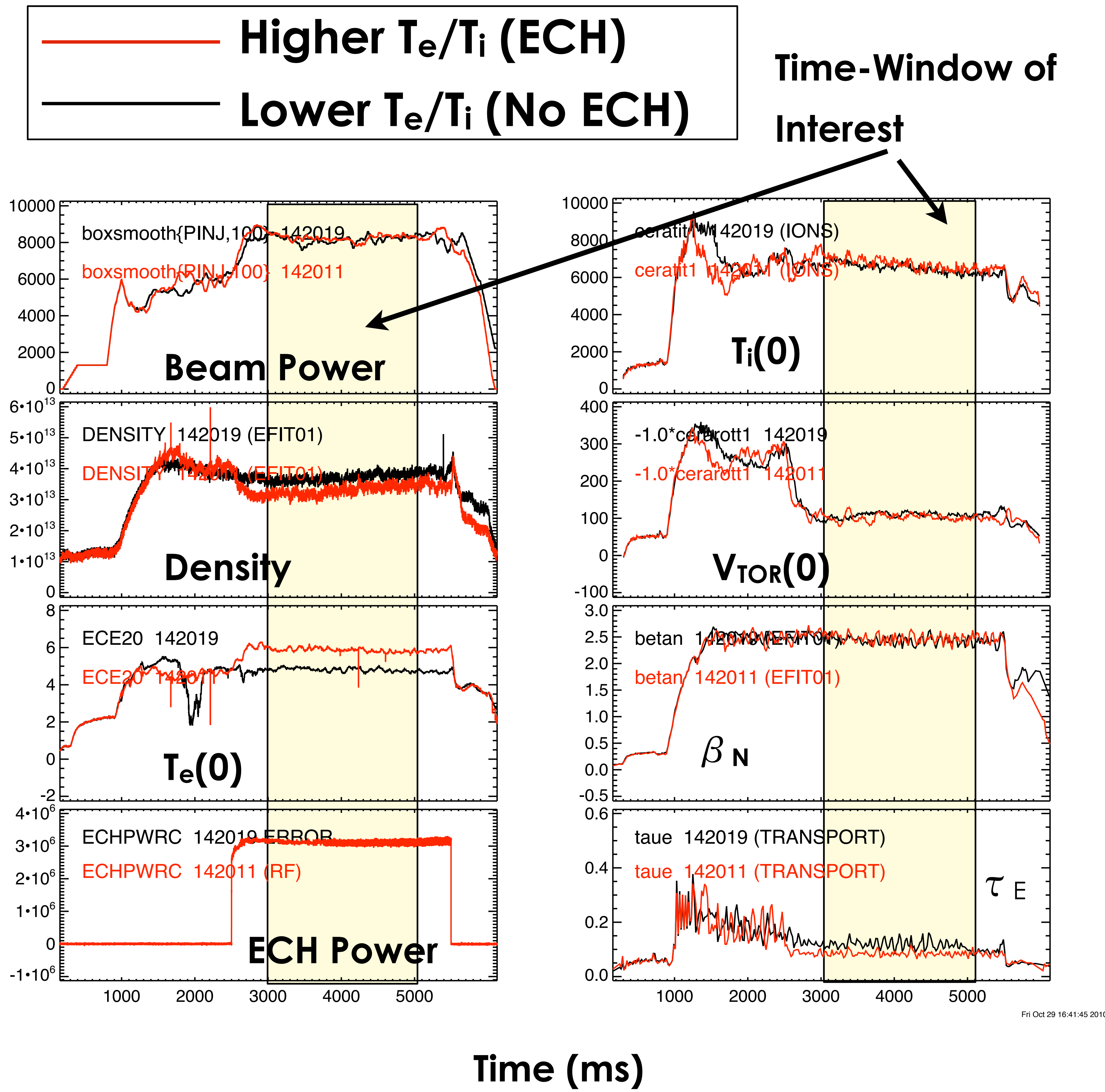
Rotation	τ
Low	105
High	148

Beam Emission Spectroscopy: low-k (2D)
Doppler Back-Scattering: intermediate-k
Phase Contrast Imaging: low to high-k

Confinement Reduced with Increased T_e/T_i

- **ECH/RF increases T_e/T_i**
  - 3.3 MW ECH/0.8 MW RF
  - 25% increase in T_e
- **Advanced-Ind. Plasmas**
  - I_p = 1.06 MA
  - B_T = 1.9 T
  - q_{95}=5.9
  - ITER Shape (ISS)
  - Steady for 2.5 s

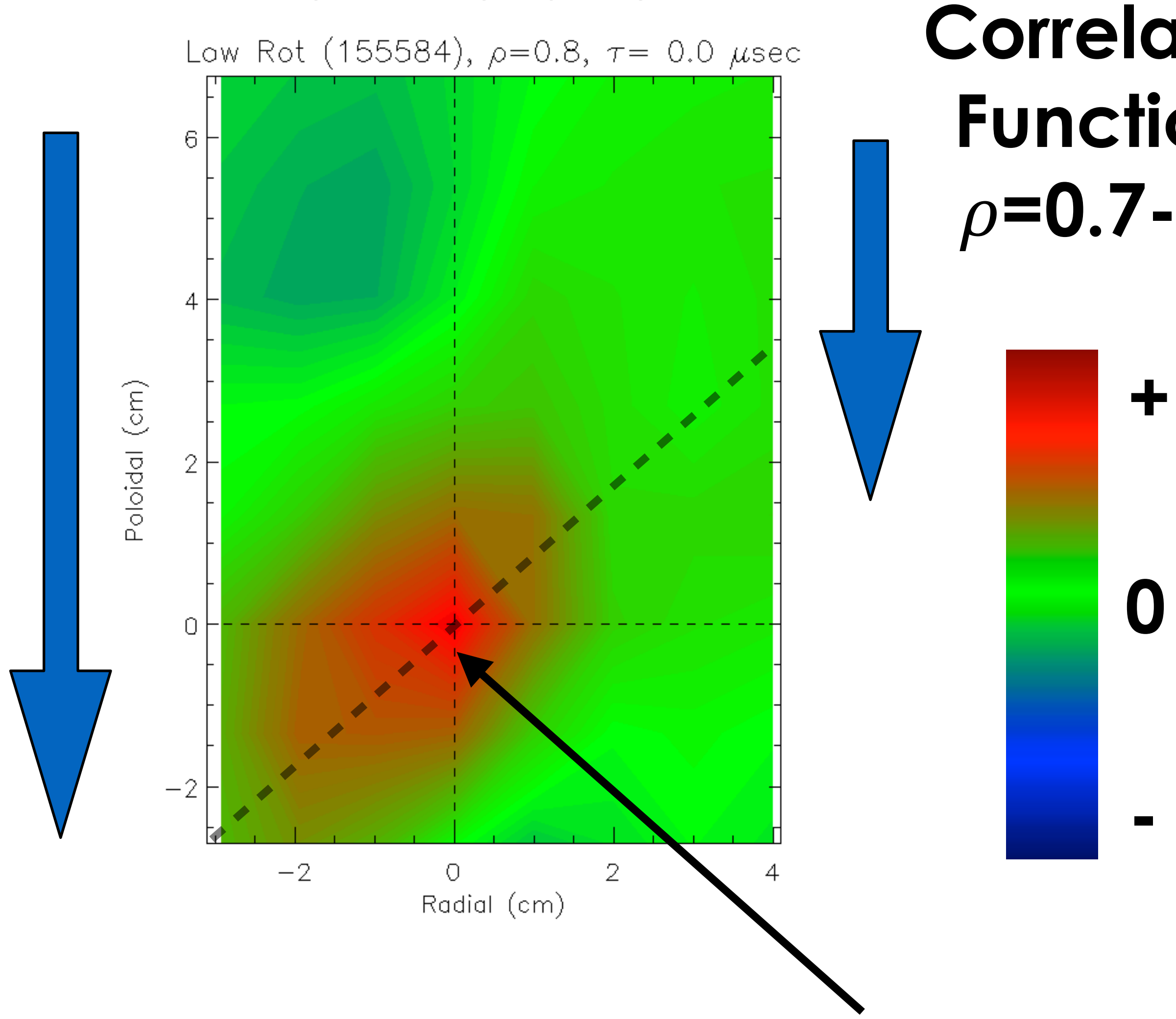
T	τ
Low	115
High	75



Spatial Correlation Structure Demonstrates Velocity Shear Effects on Turbulent Eddy Structure

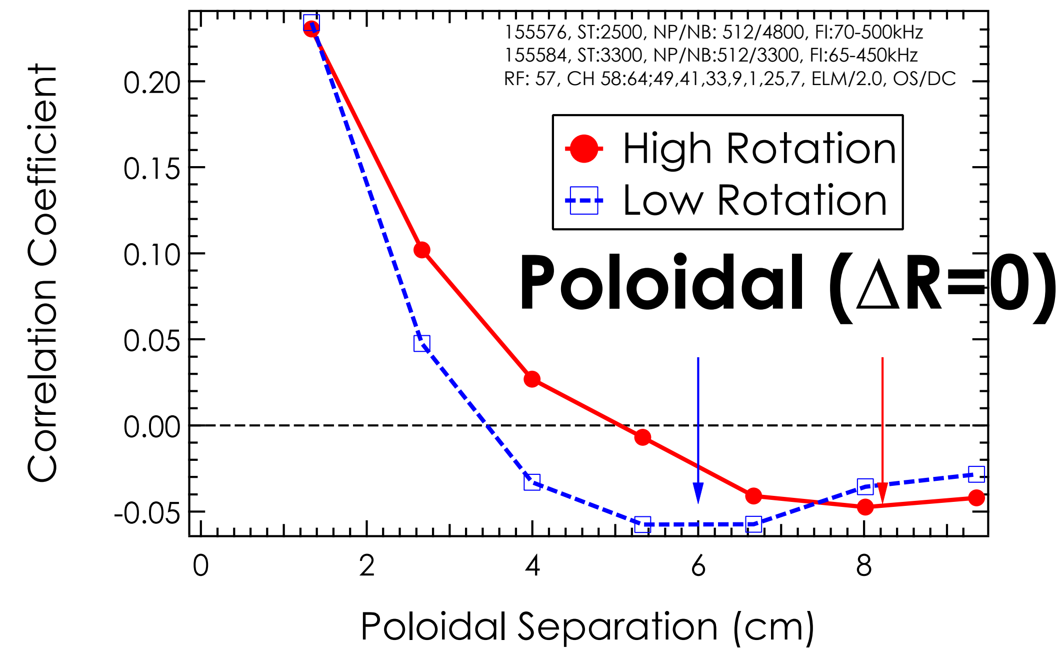
- **Poloidal correlation function in low rotation plasma exhibits shorter wavelength**
  - Consistent with frequency/wavenumber spectra
  - Amplitude is similar: *structure varies with rotation*

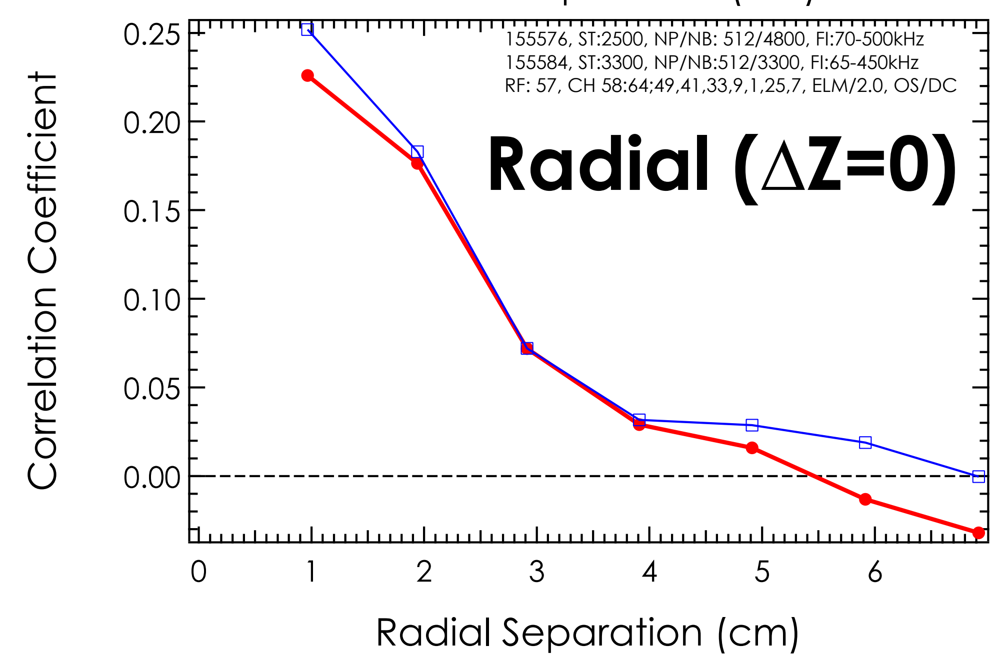
Low Rotation



τ=0
Correlation Functions
ρ=0.7-0.9

Reference Channel





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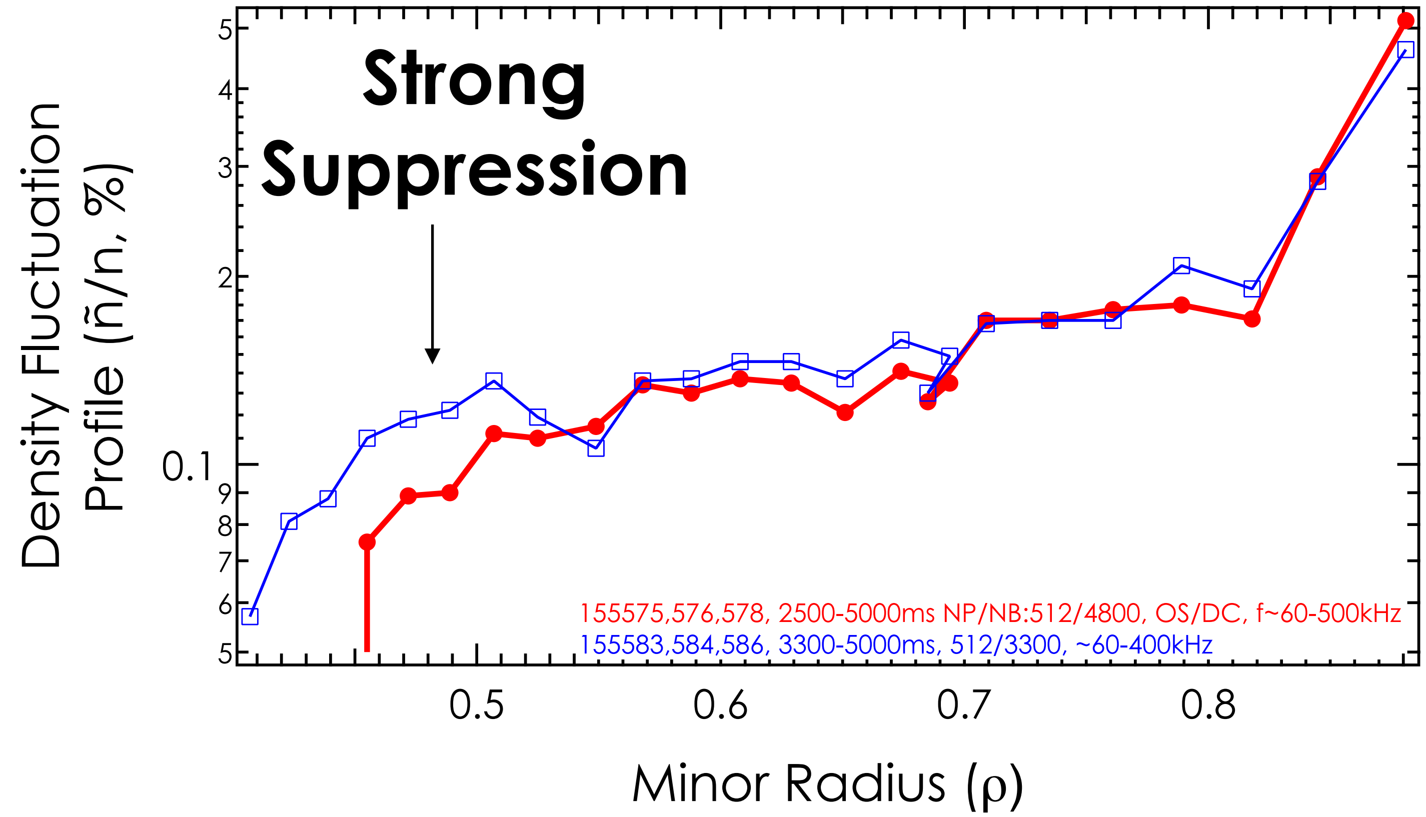
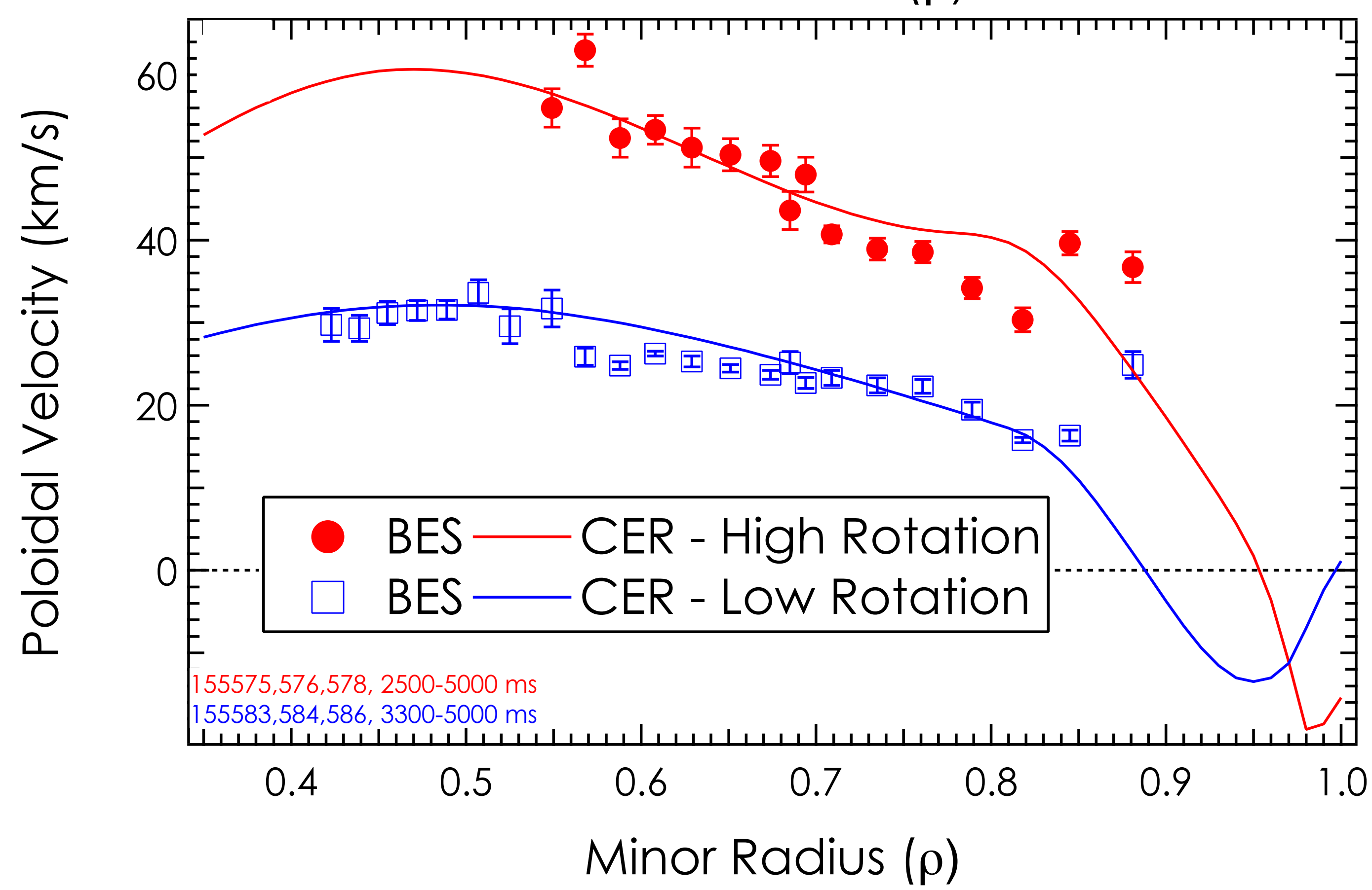
Low-k Turbulence Suppression Localized to Mid-Core Zone

- **Low-k turbulence amplitude similar outside ρ=0.5**
  - ***ExB*** shearing rates differ
- ***ExB*** **and turbulence velocities agree very well**
  - BES: Time-lag cross-correlation
  - CER: Er via Force Balance
  - Deviation at outer radii may reflect strong diamagnetic flows

Low-k Fluctuation Amplitude (BES)



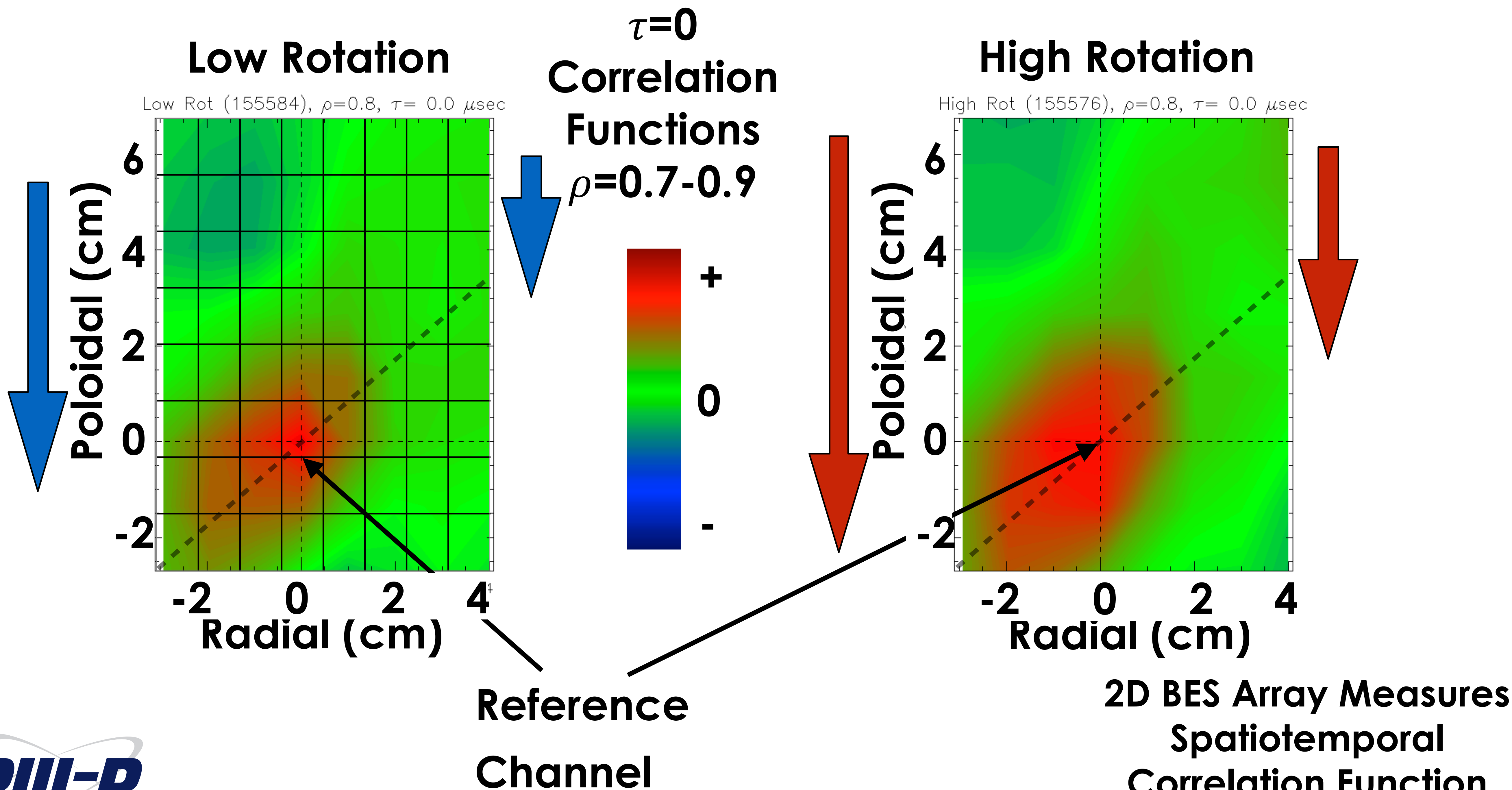


Establishing the Connection between Local Turbulence Behavior, Transport and τ_E in Burning Plasma Conditions

- **Systematically evaluated dependence of turbulence, transport, growth rates, profiles, τ_E approaching burning plasma parameters:**
  - Lower injected torque: lower toroidal rotation, averaged *ExB* shear
  - Increasing T_e/T_i towards unity
- **Fluctuations consistent with and explain transport modification:**
  - Increased *ExB* shearing at higher toroidal rotation => reduced turbulence, transport, higher τ_E
    - *Consistent with low-k linear growth rates*
    - *Reduced high-k fluctuations, yet higher calculated growth rates*
  - Increase fluctuation amplitude as $T_e \Rightarrow T_i$
    - *Particle, momentum and thermal transport increased*
- **Testing TGLF and GYRO in BP-relevant high-performance scenarios**
  - TGLF modeling reasonably reproduces observed profiles
    - *Identified notable discrepancies (density profiles, mid-radii temperatures)*
  - Developing the scientific basis for predicting transport in burning plasma conditions

Turbulent Eddy Structure Tilted by Velocity Shear

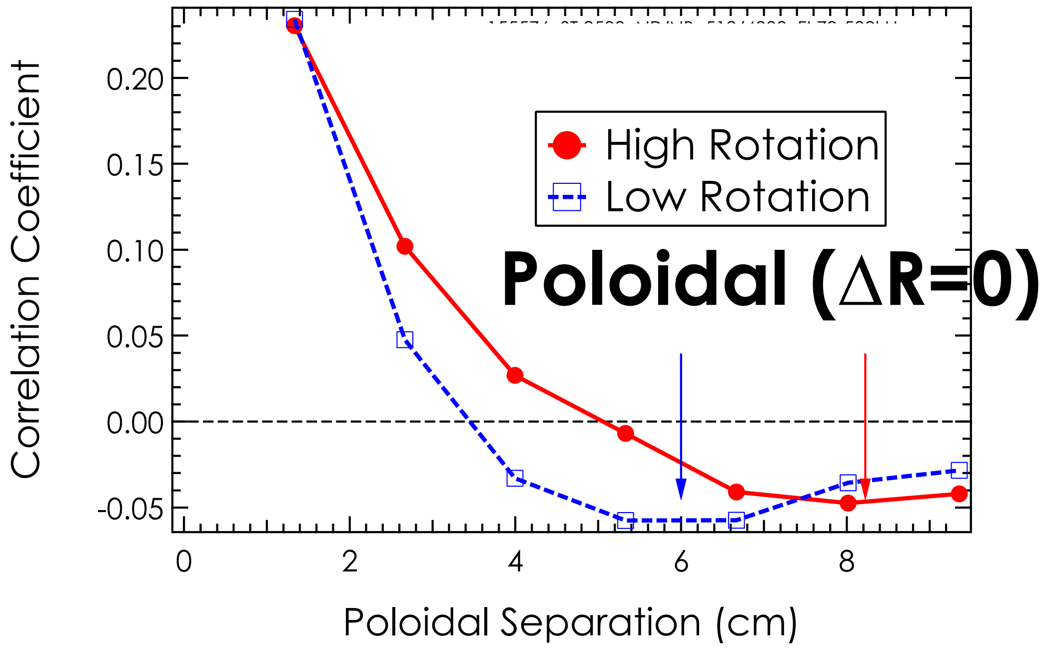
- **Tilted eddy structure observed in both high and low rotation plasmas**
  - ***ExB*** shearing rates similar locally, though toroidal rotation differs
- **Contrasts with L-mode turbulence, which exhibits little tilting**

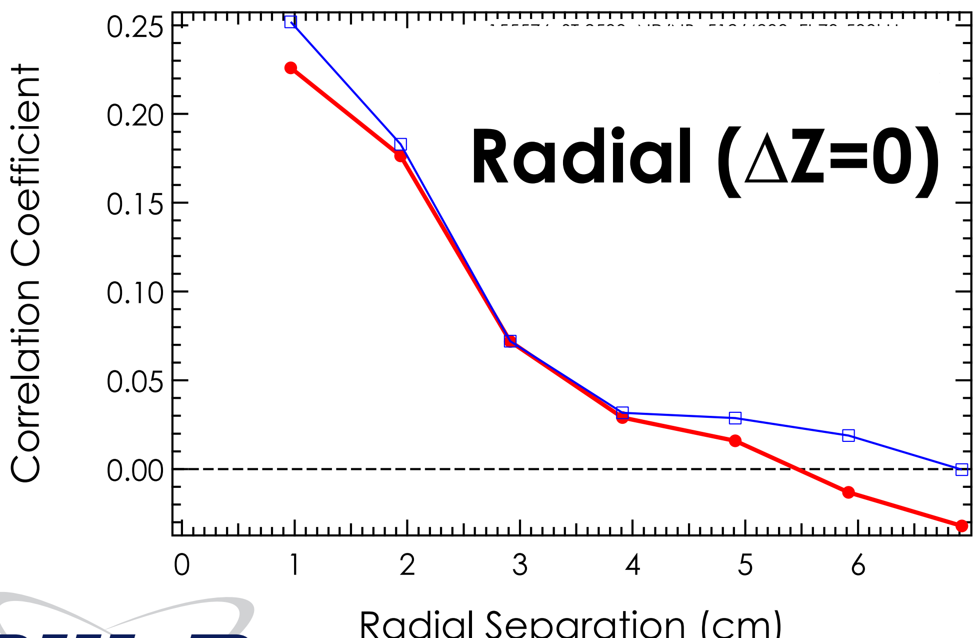


2D BES Array Measures Spatiotemporal Correlation Function

Turbulence Adjusts to Increasing ExB Shearing Rates by Faster Decorrelation and Reduced k_θ

- **Turbulence reorganizes to new shearing rates, but *isn't suppressed***
  - Consistent with frequency/wavenumber spectra changes
  - Similar ñ/n amplitude with rotation over $0.6<\rho<0.8$ region
  - Little change in radial correlation length





Comparison of Turbulence Decorrelation time, *ExB* time poloidal wavenumber (ρ=0.6)

Ω	τ_C (μs)	τ_{ExB} (μs)	$k_{\theta,pk}$ (cm^{-1})
High	2.5	3.5	0.4
Low	5	7	0.5

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