Investigation of Edge Turbulence Properties in Negative Triangularity Plasmas on DIII-D using Beam Emission Spectroscopy

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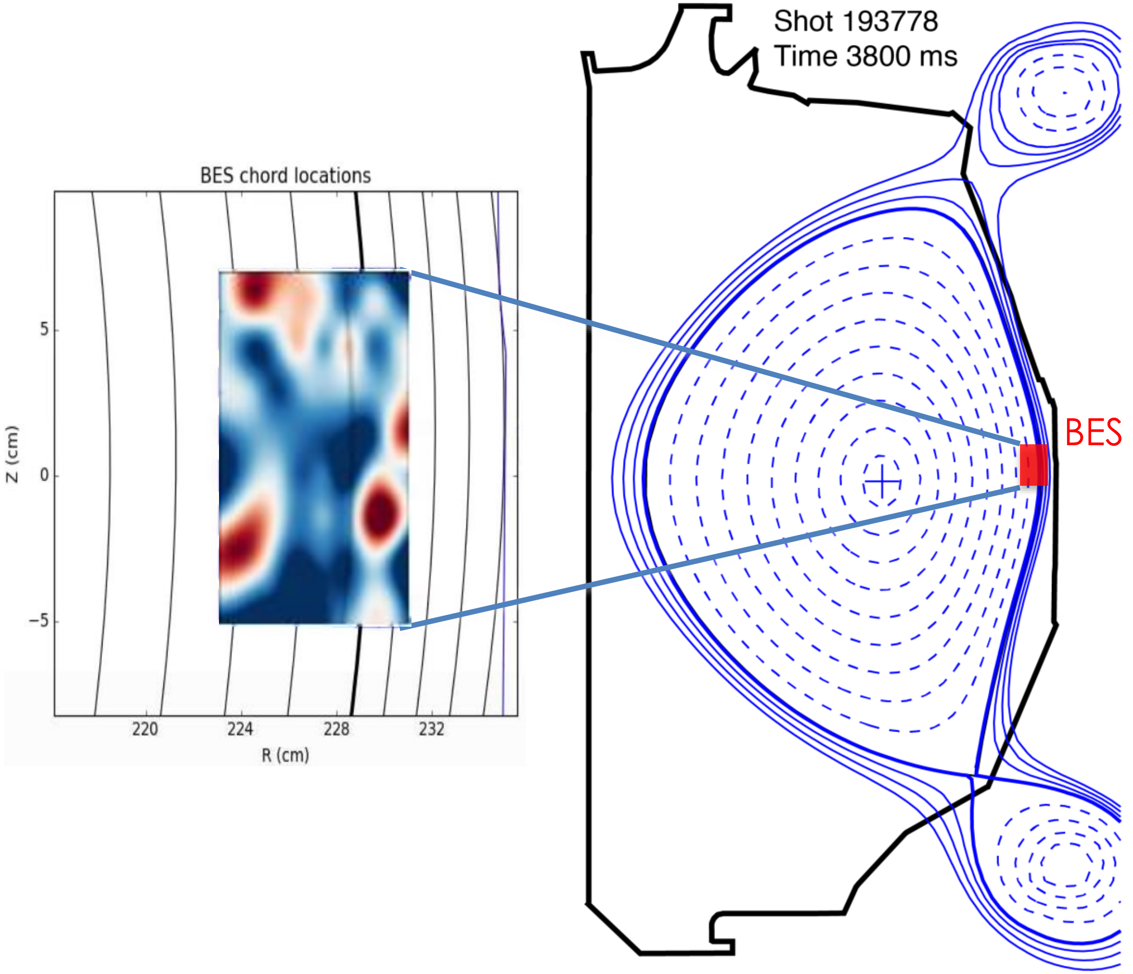

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Introduction and Motivation

What are the unique edge turbulence properties of Negative Triangularity (NT) that impact confinement?

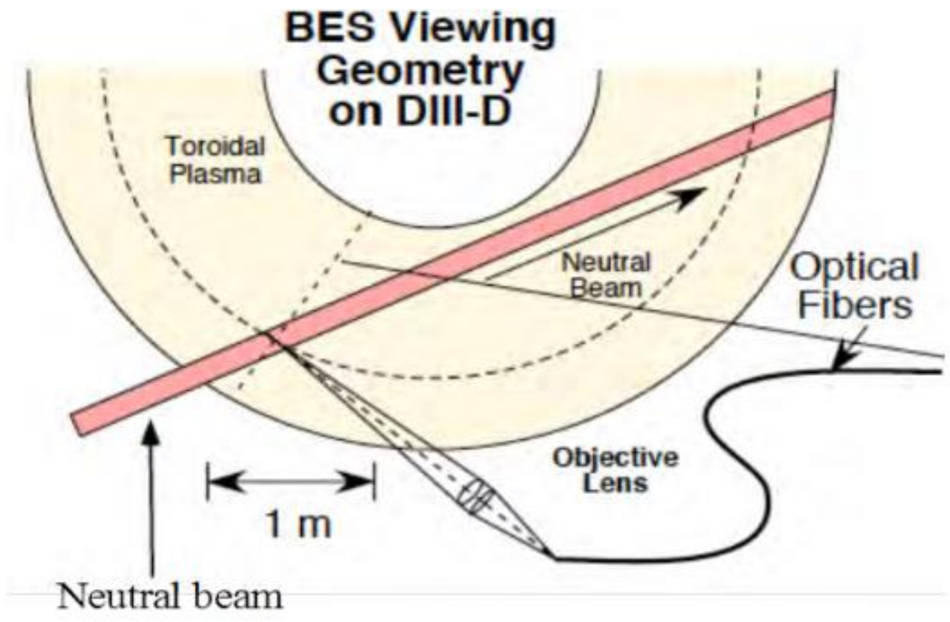
- **Methodology**
- **Strong Negative Triangularity Case**
  - Identify net turbulent properties
  - Turbulence consistent with ∇n-branch TEM
- **H-mode to NT Transition**
  - Effect of triangularity on net properties
  - Turbulent particle flux reduced
  - Suppression of an ion-directed mode

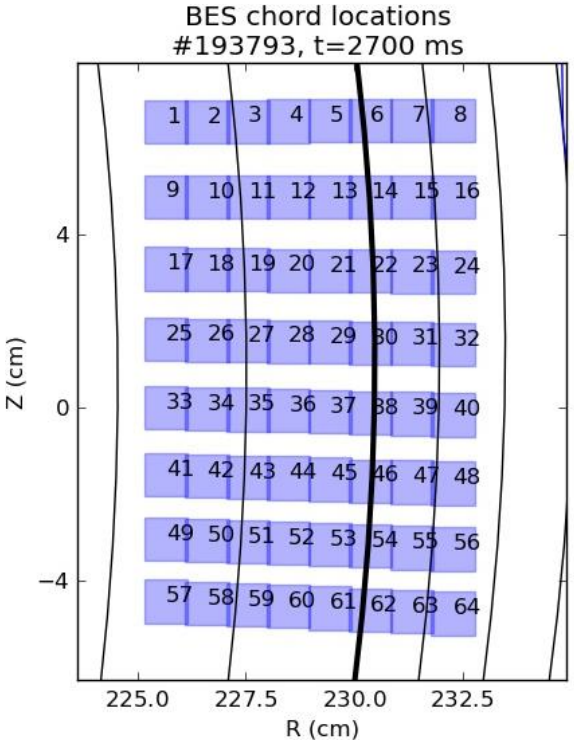
Why does NT not undergo L-H transition?

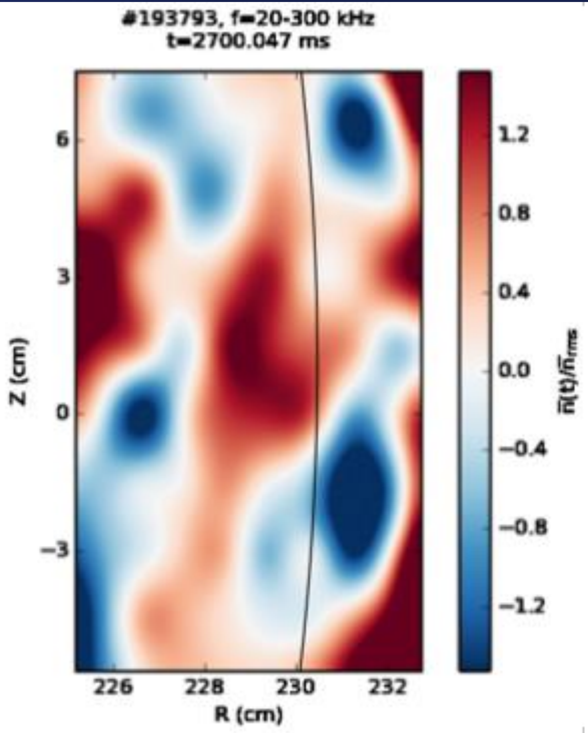
Why is confinement better than L-mode?

Beam Emission Spectroscopy (BES) measures turbulent properties

- Measures electron/ion density fluctuations on turbulent scales using beam induced doppler shift on D-alpha line
- 2D array 64 channels, 1MSps (Fluctuations < 500 kHz)
- Spacing ΔR~1 cm ΔZ~2cm (Fluctuations $k_y\rho_s < 1$)







BES Measures:

- Density Fluctuation Spectra
- Density Fluctuation Amplitude
- Radial and Poloidal Correlation Lengths
- Turbulence Correlation times
- Equilibrium and fluctuation velocities

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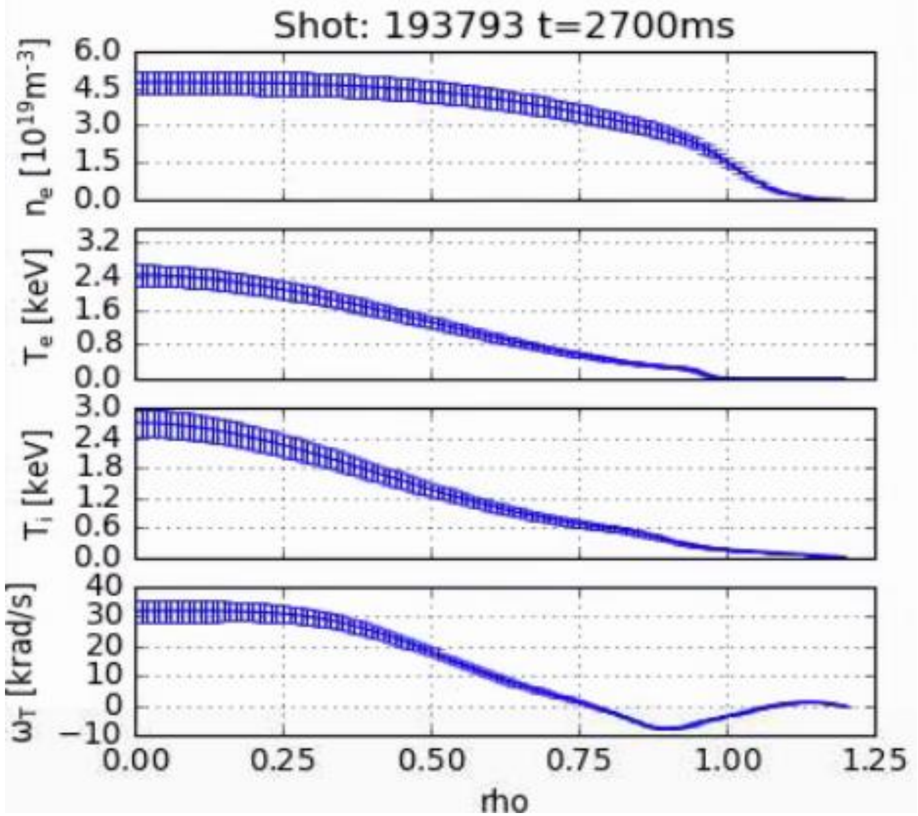
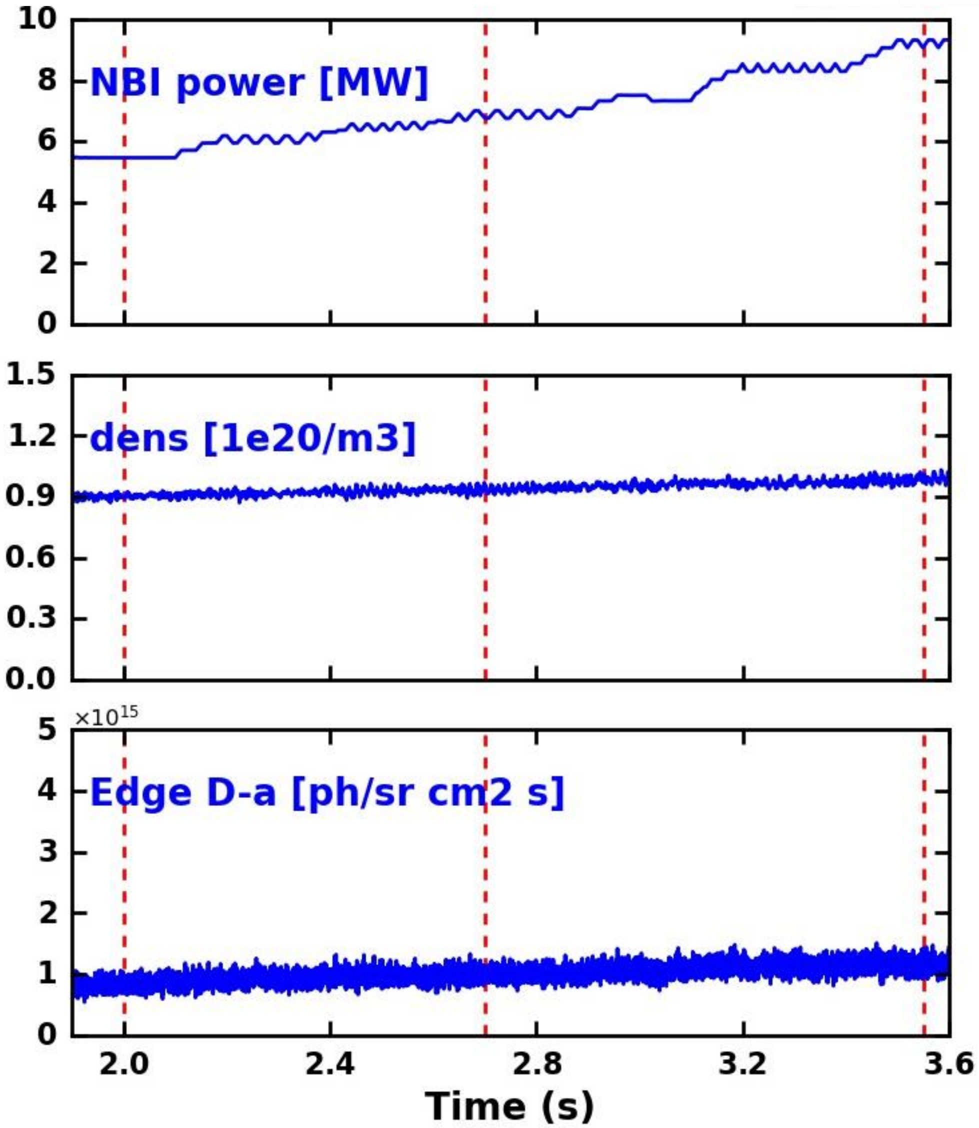
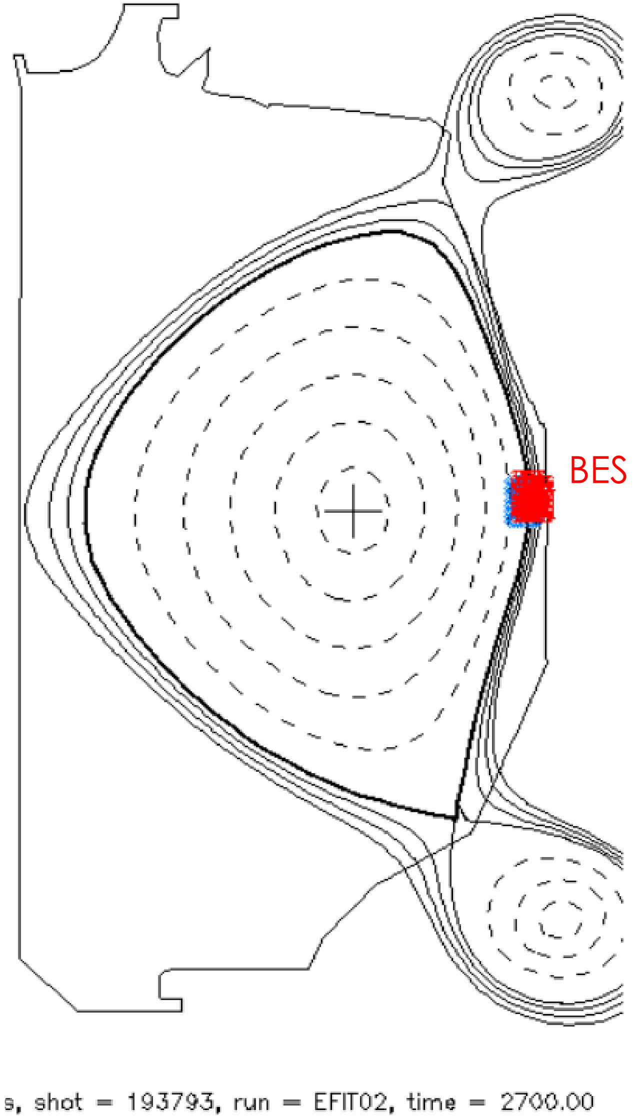
Strong NT case stays ELM free

Shot: 193793 [1875-3650 ms]
δ_{top} = -0.35, δ_{bot} = -0.67,
I_p = 0.6 MA, q_{95} = 3.5, B_T = -2 T



Stays ELM free >3x pos-D LH threshold[1]





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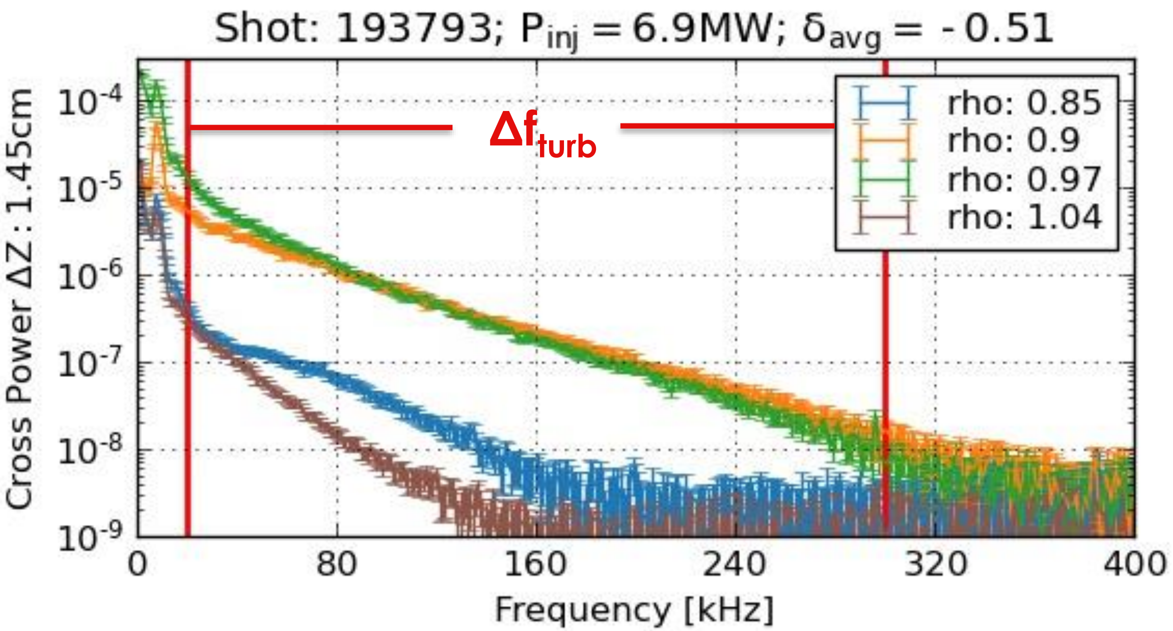
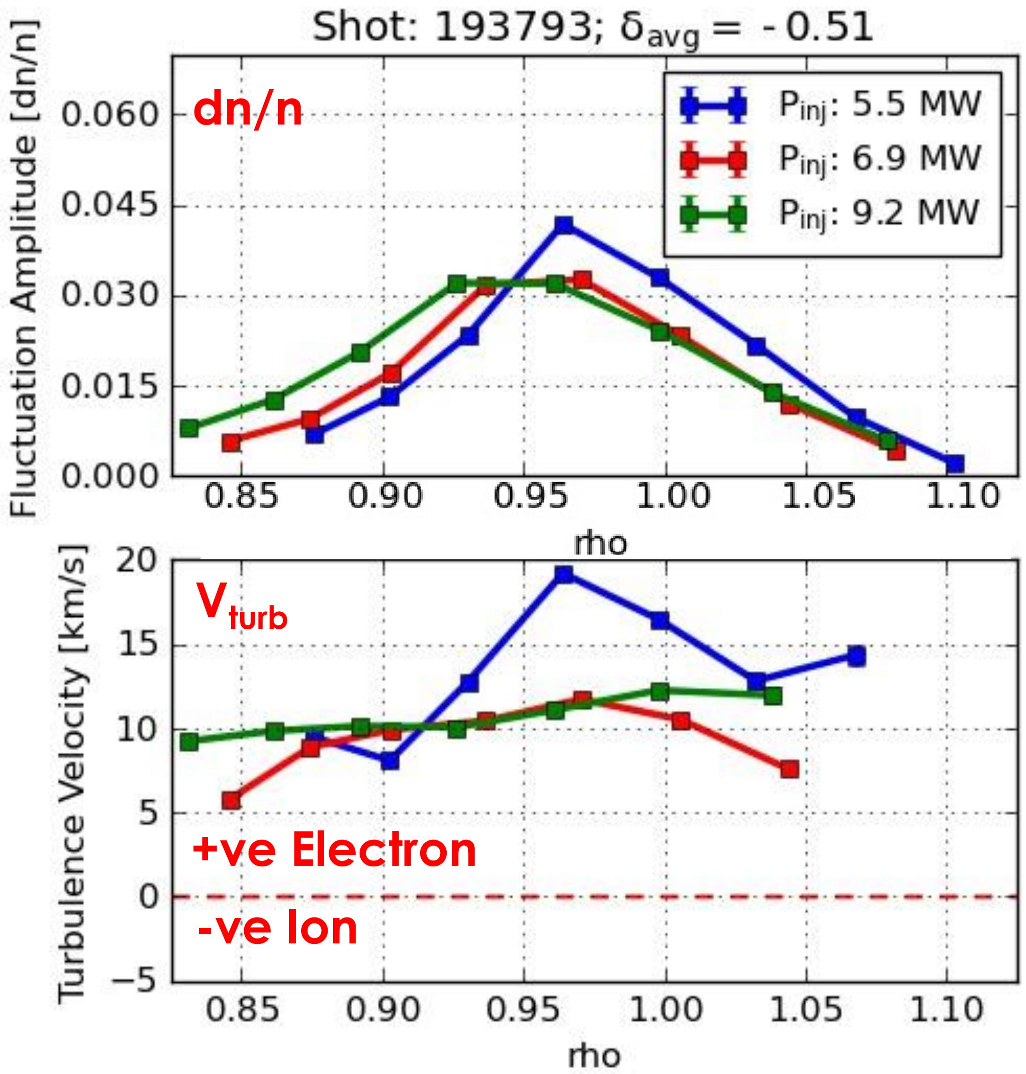
[1]Y. Martin, J. of Phys. (2008)

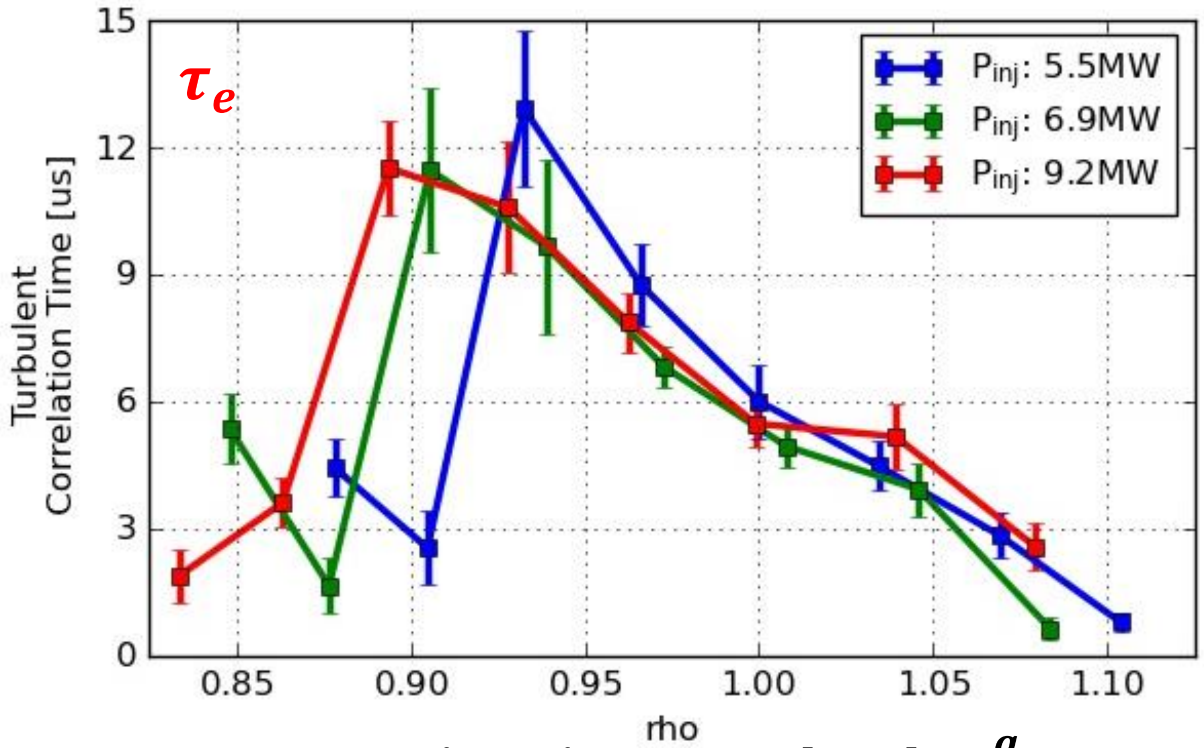
Low-k broadband density turbulence amplitude peaks near separatrix

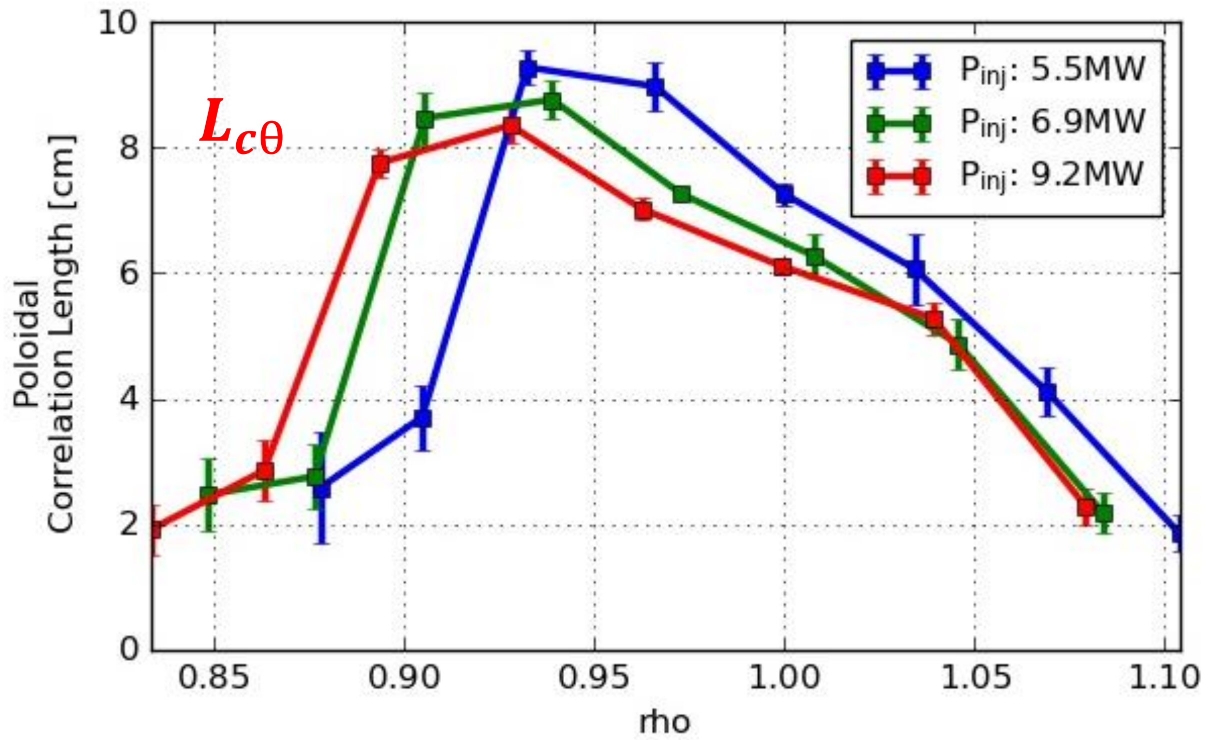
- **Broadband Electron Diamagnetic Directed mode described by single power law (broad k-spectra)**
- **Amplitudes profiles peak inside the separatrix**
- **Velocity profiles show low shear**
- **Power flattens amplitude and velocity profiles**





Poloidal Correlation Lengths larger than PT





- **Peak correlation time τ_e~ (3-5) * $\frac{a}{c_s}$**
  - Typical in PT: τ_e~1* $\frac{a}{c_s}$
  - $\frac{a}{c_s}$ ~ 2.5-3.5 μs
  - Falls off to ~ (0.5-2) * $\frac{a}{c_s}$ in outer core (typical)
- **Peak correlation length $L_{c\theta}$~ (20-40)* ρ_i**
  - Typical in PT: $L_{c\theta}$ ~(5-10)* ρ_i
  - ρ_i ~ 0.23-0.35 cm
  - Falls off to ~(6-12)* ρ_i in outer core (typical)

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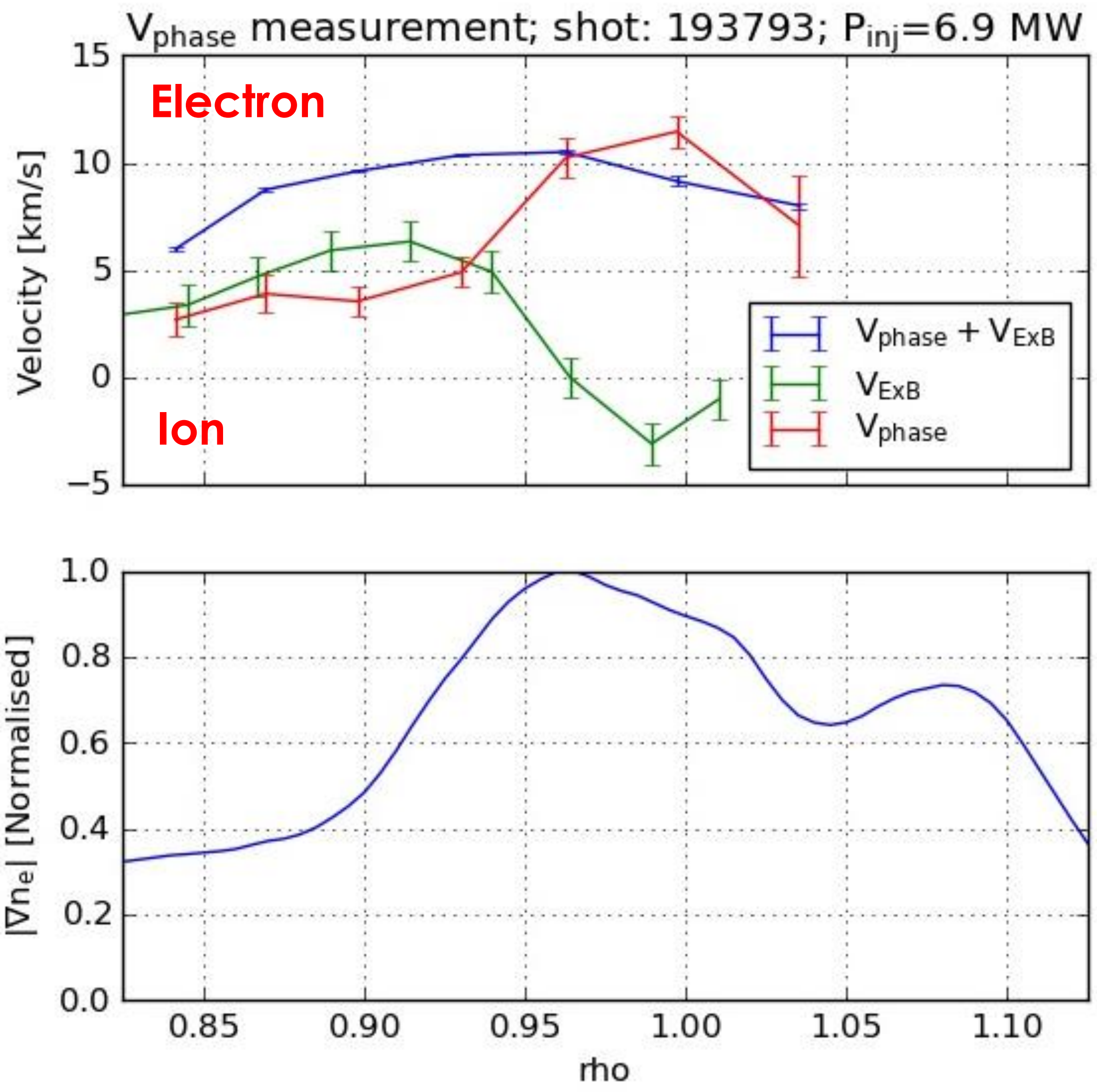
Phase velocity correlated to diamagnetic velocity

- **Compare BES and CER measurements:**

$$V_{BES} = V_{ExB} + V_{phase}$$
$$V_{phase} \approx V_{BES} - V_{ExB}$$

  - **V_{ExB} from CER-informed ion force balance**
- **Phase velocity Electron Diamagnetic directed**
- **Phase velocity larger than V_{ExB} and correlated to ∇n_e**
- **∇n-TEM phase velocity correlated to diamagnetic velocity (∇n_e)**



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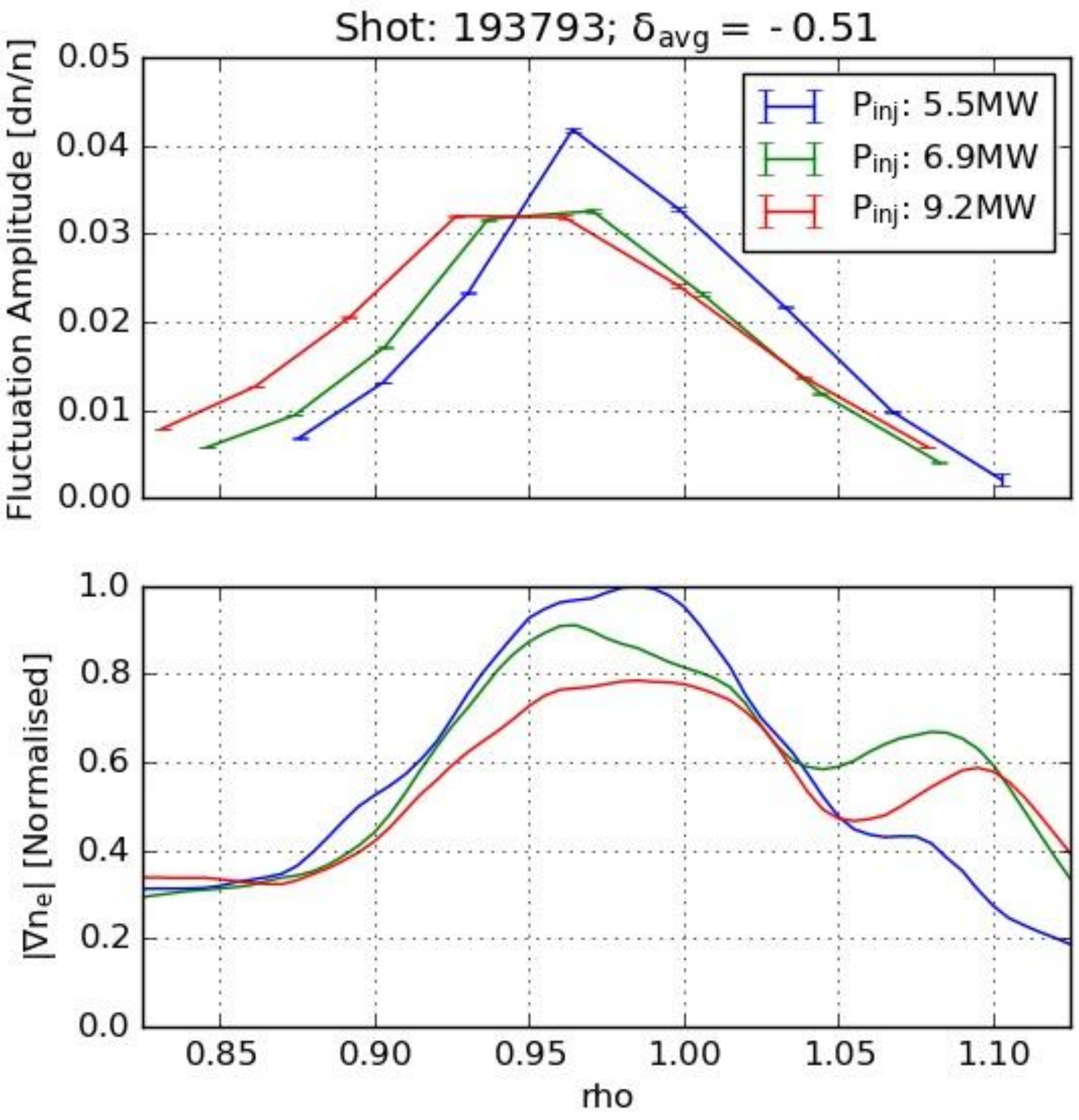
Observed mode consistent with ∇n-branch TEM

- **Amplitude correlated with ∇n**
  - Linear TEM drive expected to be correlated to ∇n
- **Electron Mode Direction:**
  - TEM in electron direction
- **Phase velocity correlated with ∇n**
  - TEM velocity expected to be correlated to ∇n
- **Other possible modes:**
  - Micro tearing Modes (MTM)
  - Other Electromagnetic modes
- **Further gyrokinetic analysis required**



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Introduction and Motivation

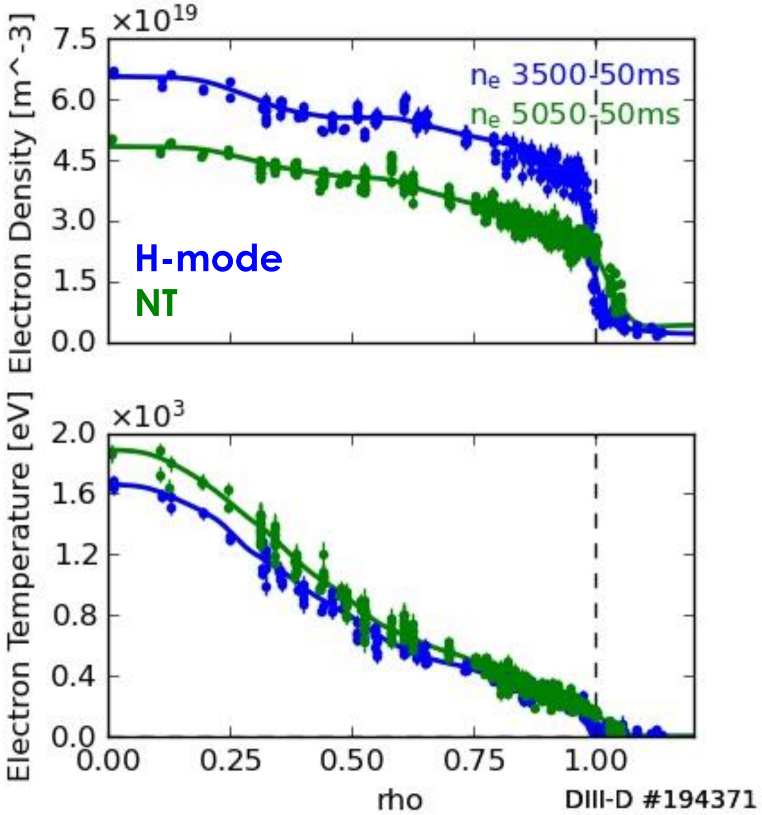
What are the unique turbulence properties of Negative Triangularity (NT) that impact confinement?

- **Methodology**
- **Reactor Relevant Triangularity**
  - Identify net turbulent properties
  - Turbulence consistent with ∇n-TEM
- **H-mode to NT-mode Transition**
  - Effect of triangularity on net properties
  - Suppression of ion-directed mode
  - Turbulent particle flux follows gradients

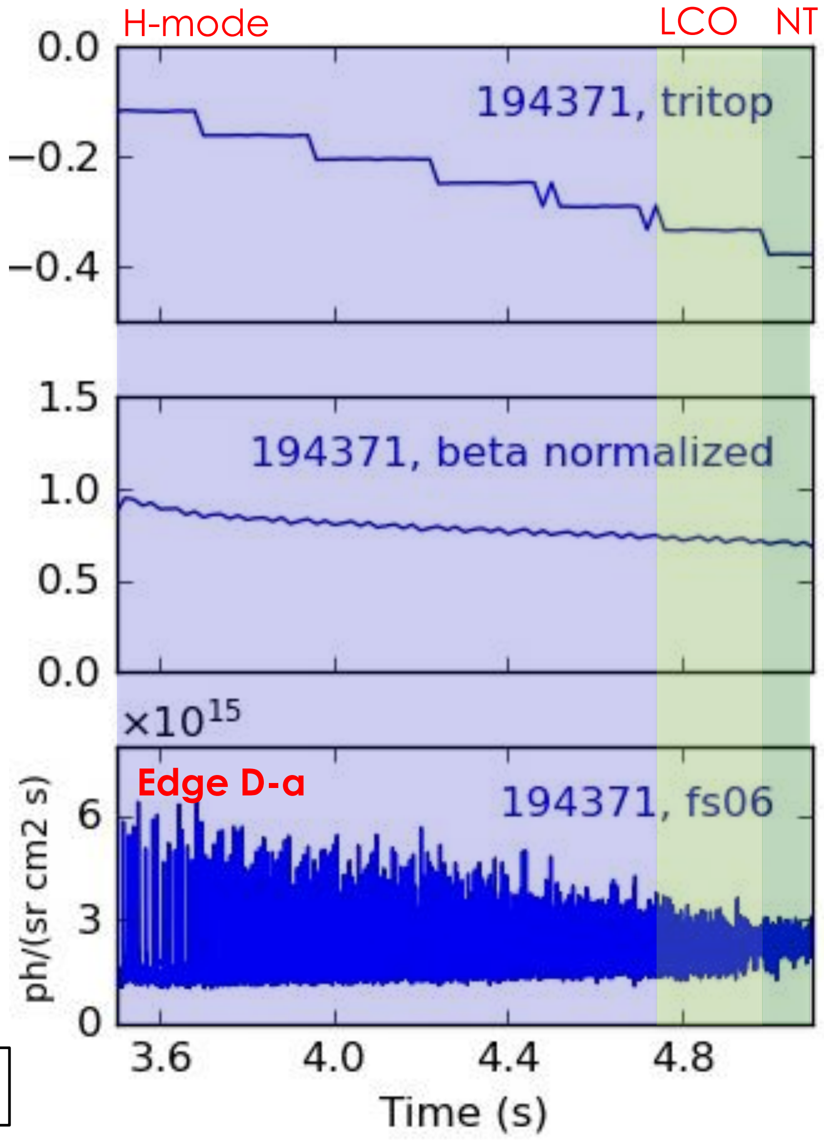
H-mode to NT experiment: H-mode suppression

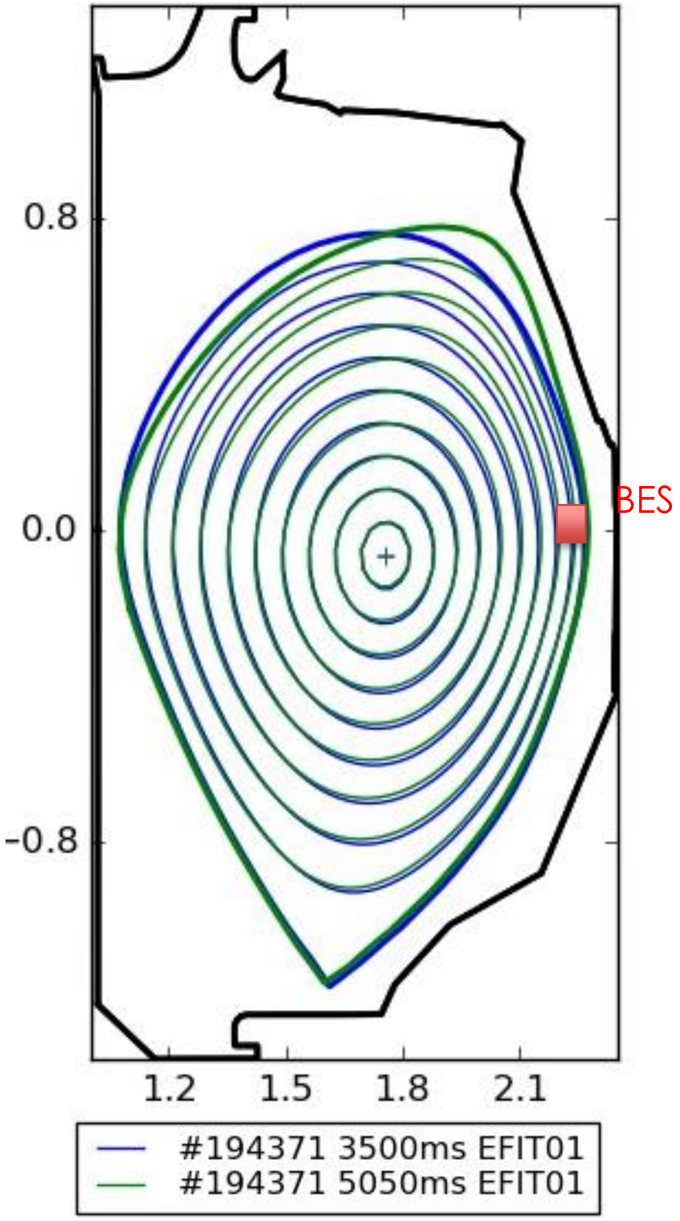
Shot: 194371 [3400-5100 ms]

- I_p = 0.9 MA, q_{95} = 4.3, B_T = -2 T,
- P_{inj} = 1.4 MW (NBI only)



Steeper core ∇T_e in NT





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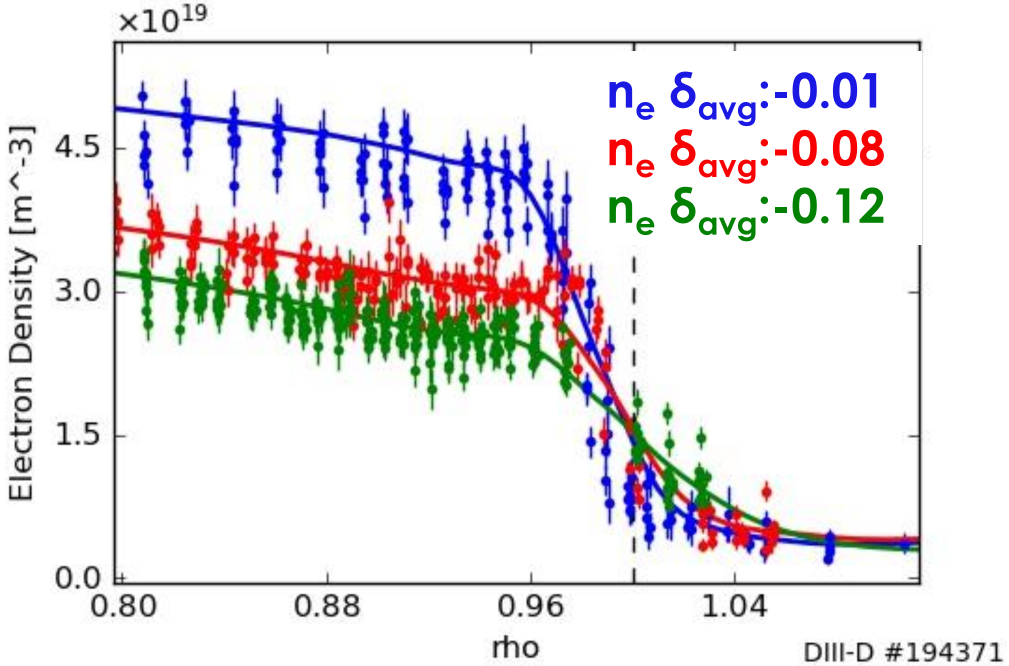
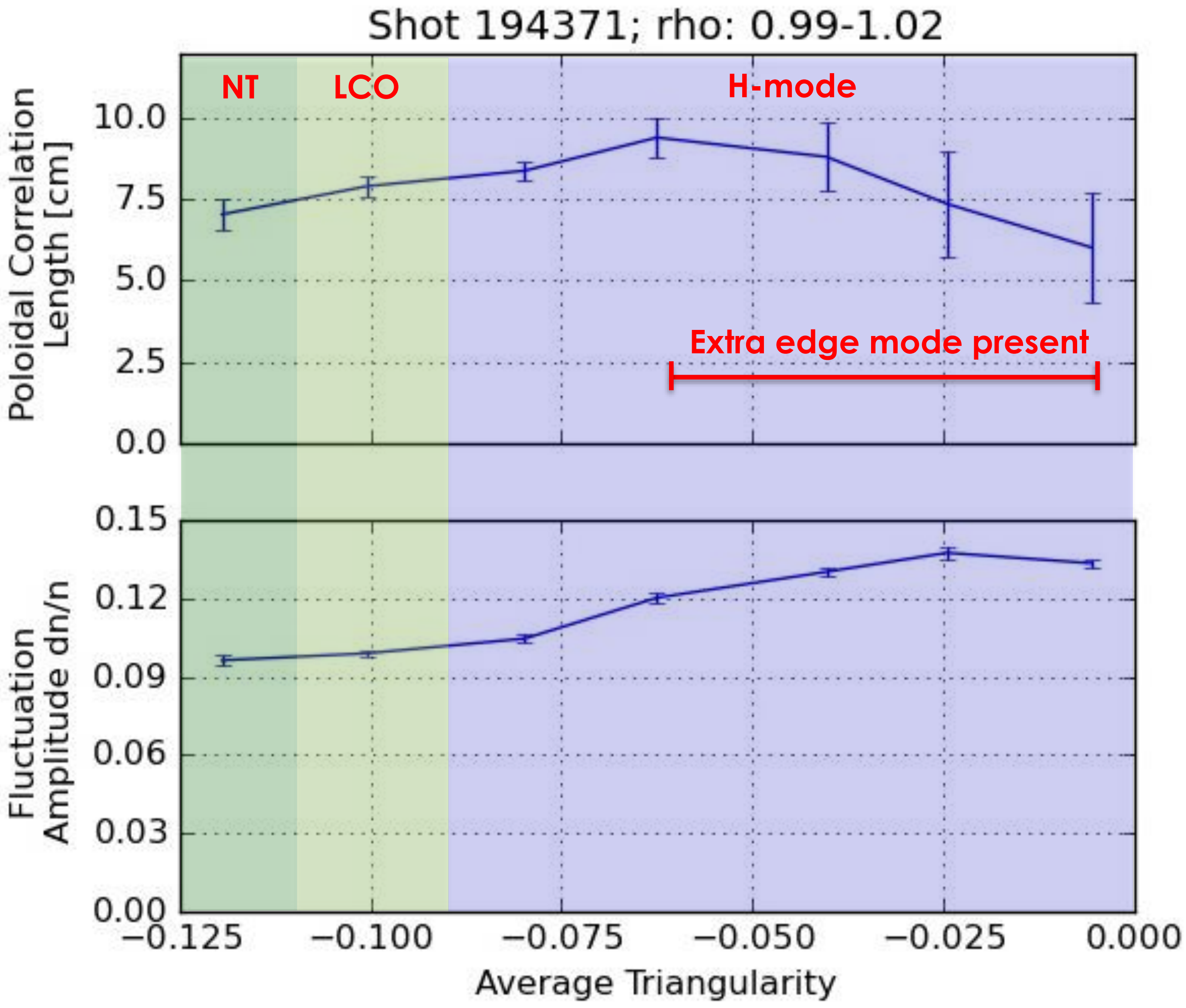
Turbulence properties vary with triangularity





- Similar Electron Diamagnetic directed mode localized in the edge (TEM-like)

- With Stronger NT:
  - Edge ∇n (-60 %) ↓
  - Edge Turbulence Amplitude (-30%) ↓
  - Poloidal correlation length (-25%) ↓

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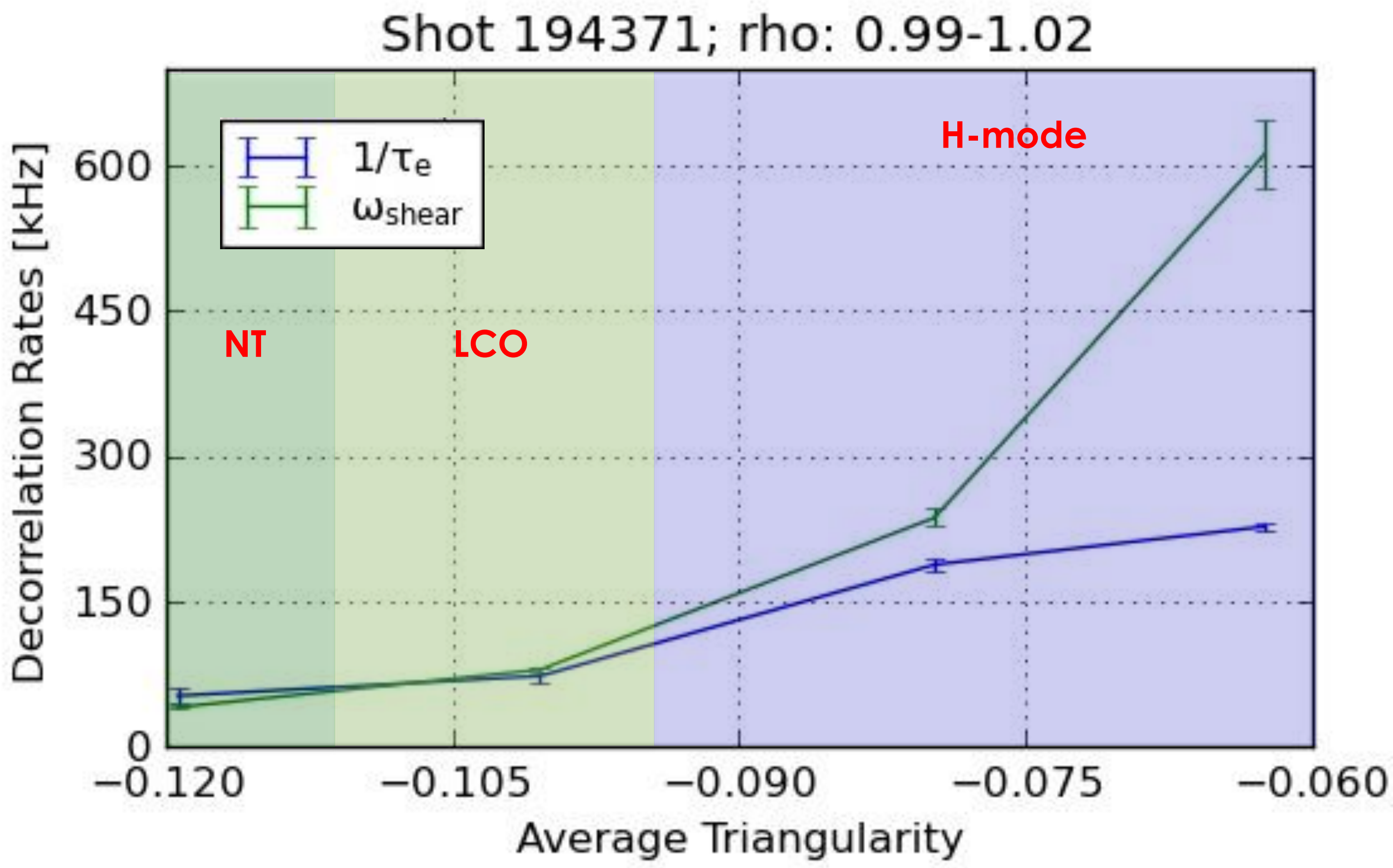
Turbulence nonlinear saturation not exclusively shear

- **Saturation not exclusively from mean velocity shear as in H-mode**

$$\omega_{decorr} = \frac{1}{\tau_e}$$

H-mode Pedestal: $\frac{\omega_{shear}}{\omega_{decorr}} > 1$

NT-edge: $\frac{\omega_{shear}}{\omega_{decorr}} < 1$



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Particle fluxes reduced with stronger NT

- **Turbulent fluxes estimated to decrease across H-NT transition**

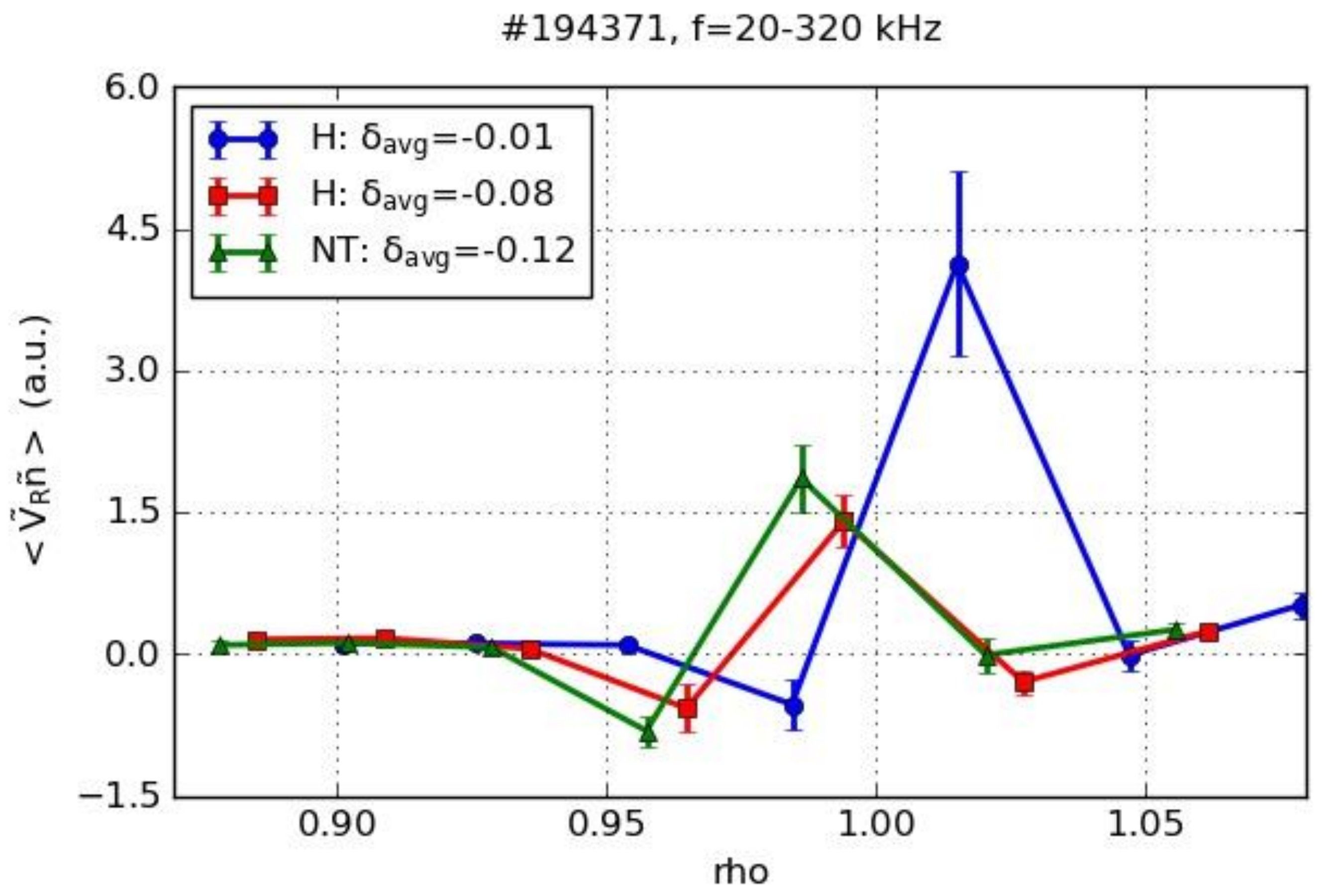
  $L_{c\theta}$: Poloidal Correlation Length ↓

  $\omega_{decorr} \sim \frac{1}{\tau_e}$: Turbulent Decorrelation Rate ↓

  $$\Gamma \sim D \sim \frac{L_{cr}^2}{\tau_e} \sim \frac{L_{c\theta}^2}{\tau_e}$$ ↓ ↓

- **As density gradient decrease Turbulent particle fluxes decrease**

- **Further studies to investigate what sets the edge gradients**



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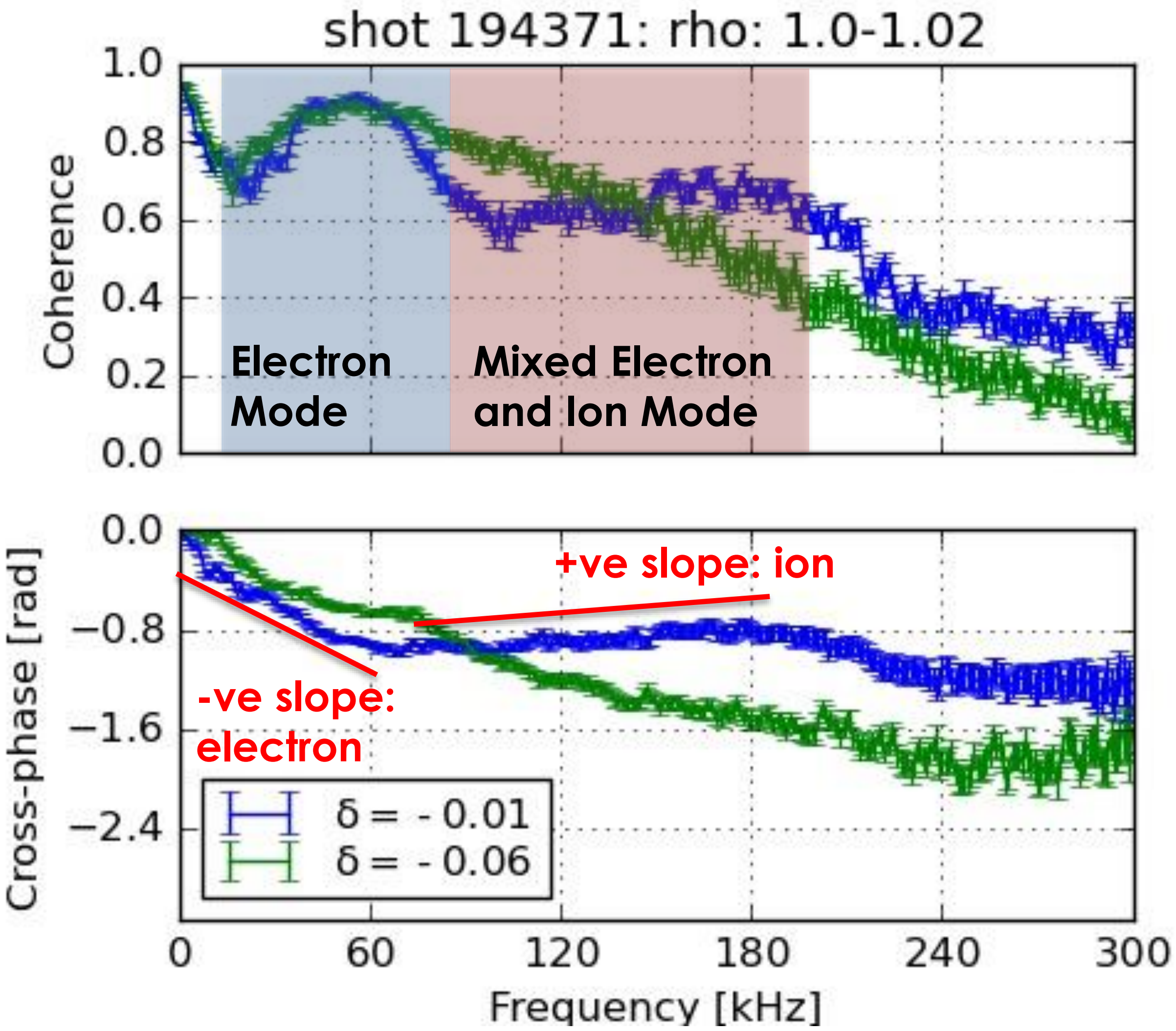
Ion-directed edge mode suppressed by NT

- For δ_{avg} <-0.06 ion diamagnetic directed edge mode suppressed
- Frequency varies between 80-200 kHz
- Radially localized to rho: 0.98-1.04
- Further analysis of edge mode required



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Negative Triangularity exhibits promising edge turbulence

- **Turbulent Properties:**
  - Electron directed broadband mode
  - Localized to the edge region
  - Large poloidal structure
  - Long correlation times
  - Mode correlated to ∇n_e consistent with ∇n-branch TEM

- **Effect of NT on Edge Turbulence:**
  - Particle Flux ↓
  - ∇n_e TEM drive ↓
  - Velocity shear ↓
  - Edge Ion-directed mode ↓

- **Future Work:**
  - Analyze core turbulence data
  - Analyze L-H transition precursors (Turbulent Reynolds stress)
  - Use UF-CHERS (fast ion-temperature measurement) to measure heat flux
  - Confirm ∇n-branch TEM as dominant instability using gyrokinetics
  - Analyze ion-directed edge mode using gyrokinetics

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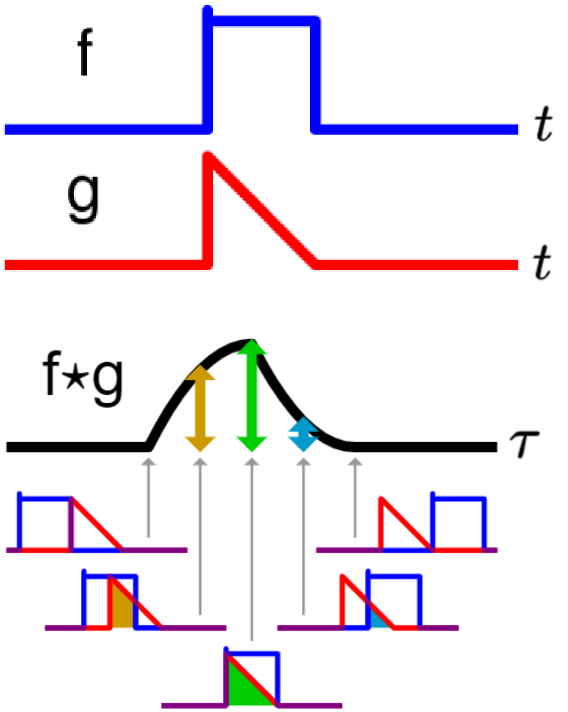
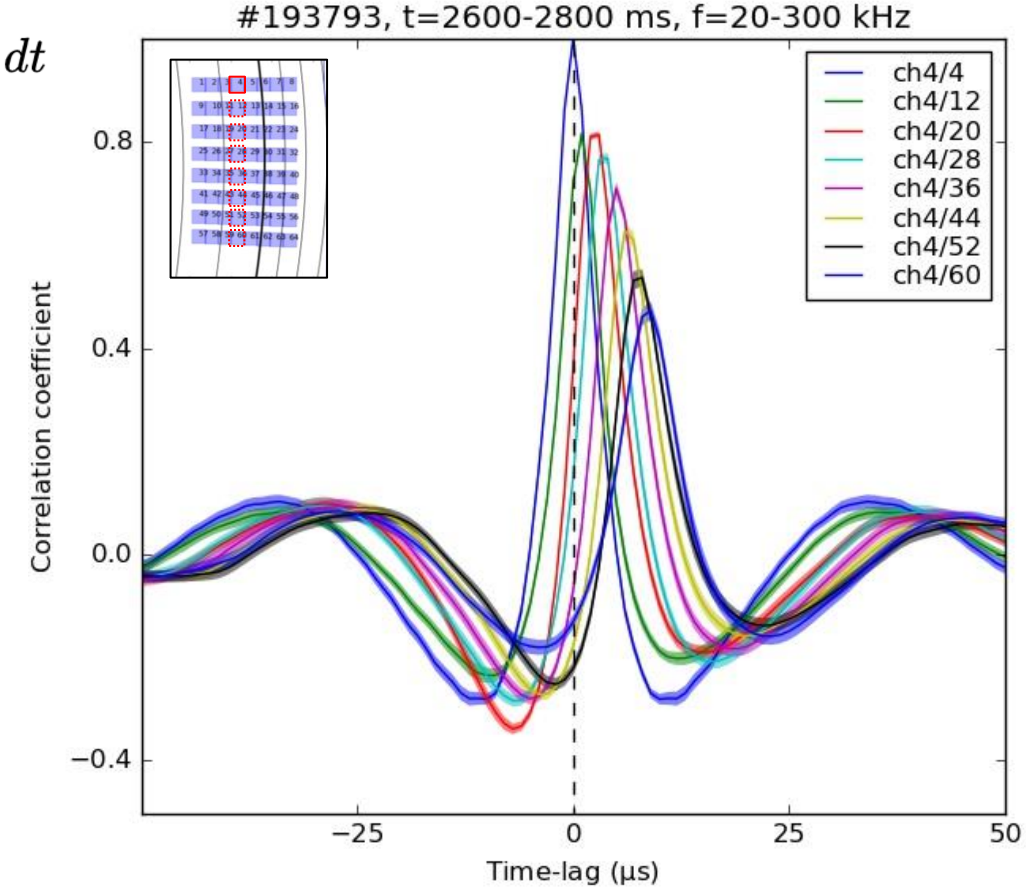
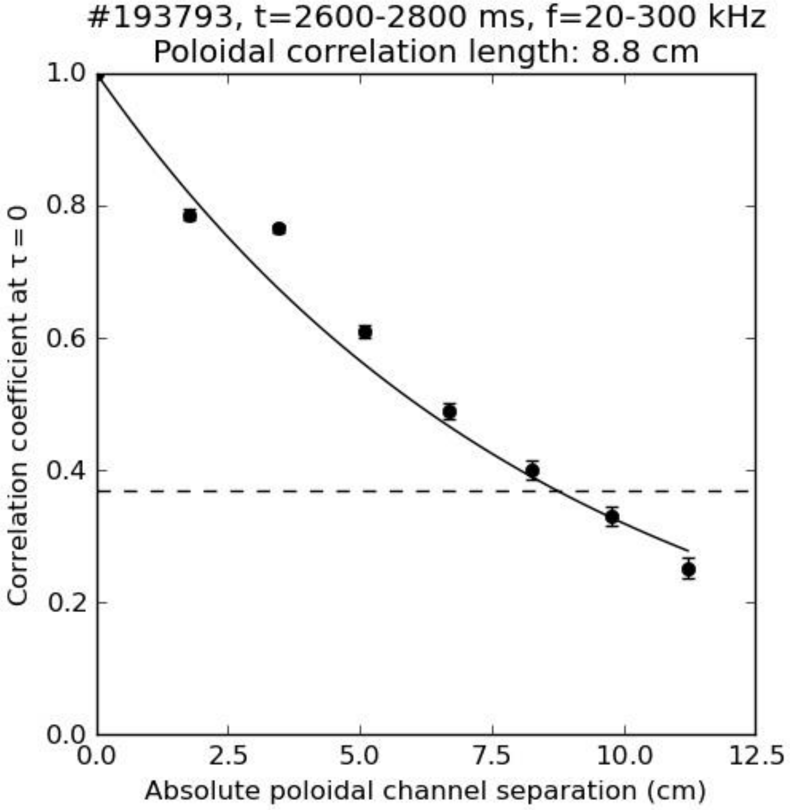
Correlation Functions Probe Statistical Properties

Correlation Function:

$$(f \star g)(\tau) \triangleq \int_{-\infty}^{\infty} \overline{f(t)} g(t+\tau)\, dt$$







Orthogonal Dynamic Programming used to determine Velocity

STEP 1. Split image into strips of decreasing size to compare neighboring time slices

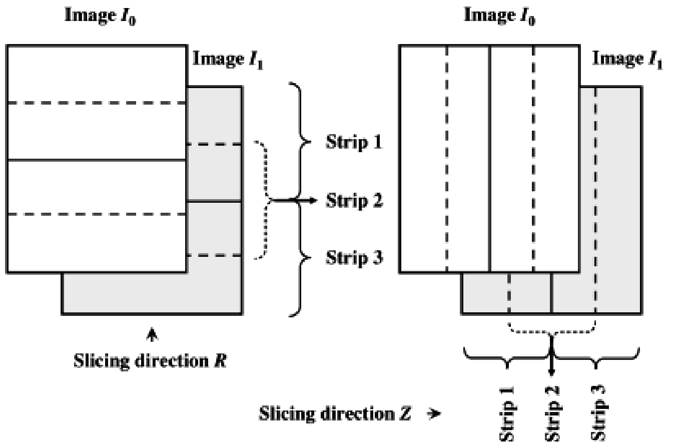


FIG. 1. Overlapping image strips are shown when the slicing is done in the R and Z directions in the first horizontal-vertical (R-Z) iterative step. Width of the strips and the corresponding overlaps are reduced by about $\sqrt{2}$ in each iteration.

STEP 2. Find path of minimal distance correlating the strips to indicate velocity at scale of strip

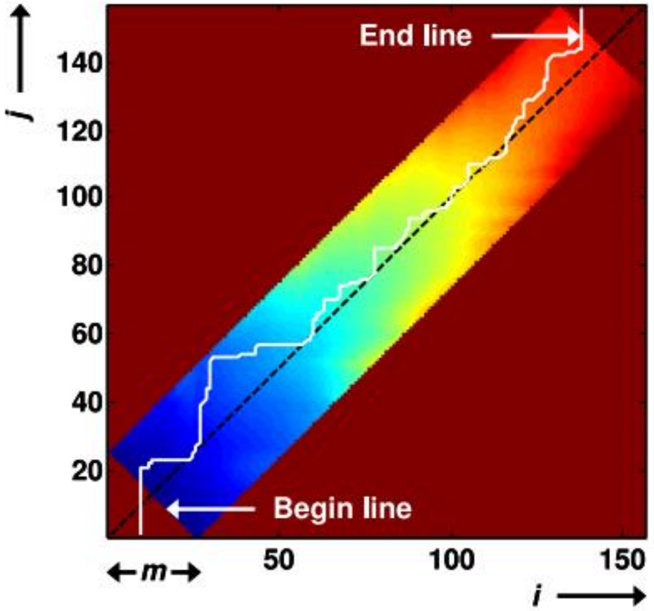
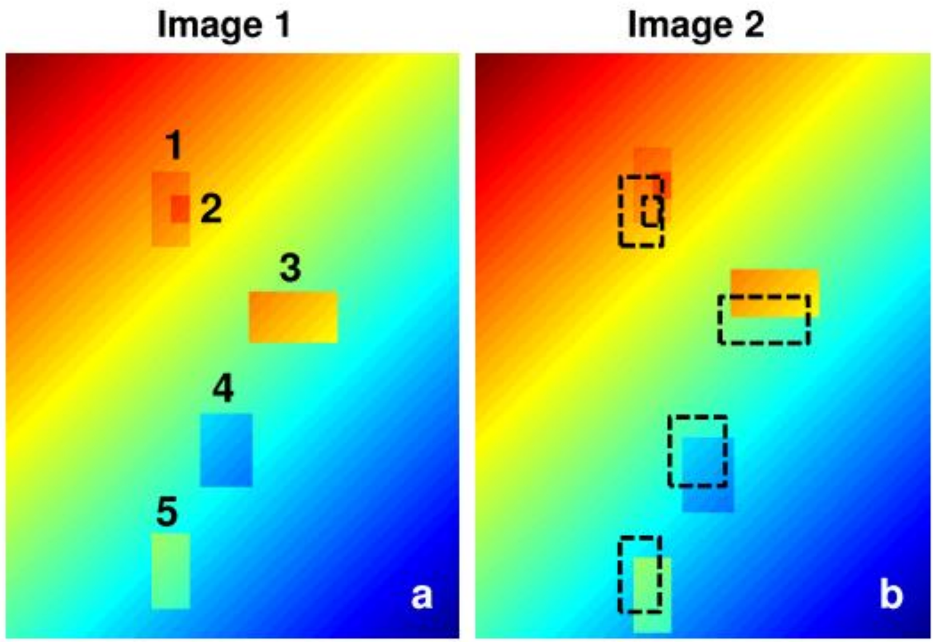


FIG. 2. Disparity matrix for a pair of image strips in one of the orthogonal iteration steps. The $i = j$ condition (diagonal) is shown as black broken line and the matching path is shown as the solid white line, respectively.

STEP 3. Combining mappings indicates pixel shift of "features" to determine velocity



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Dynamical programming based turbulence velocimetry for fast visible imaging of tokamak plasma - Santanu Banerjee, H. Zushi, N. Nishino, et al. [2015]