Plasma Turbulence Imaging Via Beam Emission Spectroscopy in the Core of the DIII-D Tokamak

George R. McKee

R. J. Fonck, D. Gupta, D.J. Schlossberg, M.W. Shafer

University of Wisconsin-Madison

R. Boivin

General Atomics

W. Solomon

Princeton Plasma Physics Laboratory

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THE UNIVERSITY of WISCONSIN MADISON

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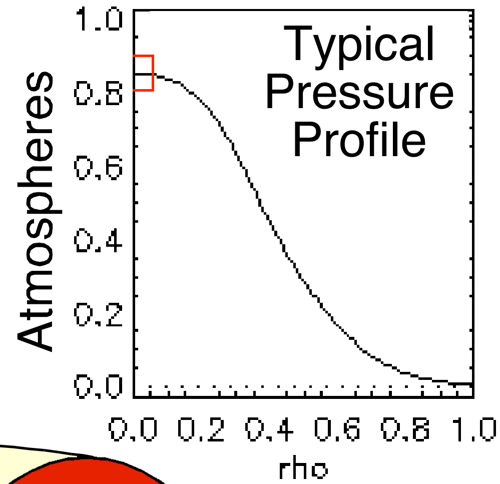
OUTLINE

- **Role of Turbulence in Magnetically-Confined Plasmas**
- **Motivation to Design, Build and Implement a Higher Sensitivity BES**
- **Overview of Beam Emission Spectroscopy Diagnostic for 2D Density Fluctuation Measurements**
- **Design concepts employed for upgraded BES**
  - *Optics*
  - *Configuration*
  - *Filters*
  - *Detectors*
  - *Data Acquisition*
- **Noise Considerations & Measurements**
- **Example density fluctuation measurements with upgraded BES system**
- **Visualizations of core turbulence**
- **Applications: Time-Resolved Velocimetry Analysis**
- **Summary & Future directions**

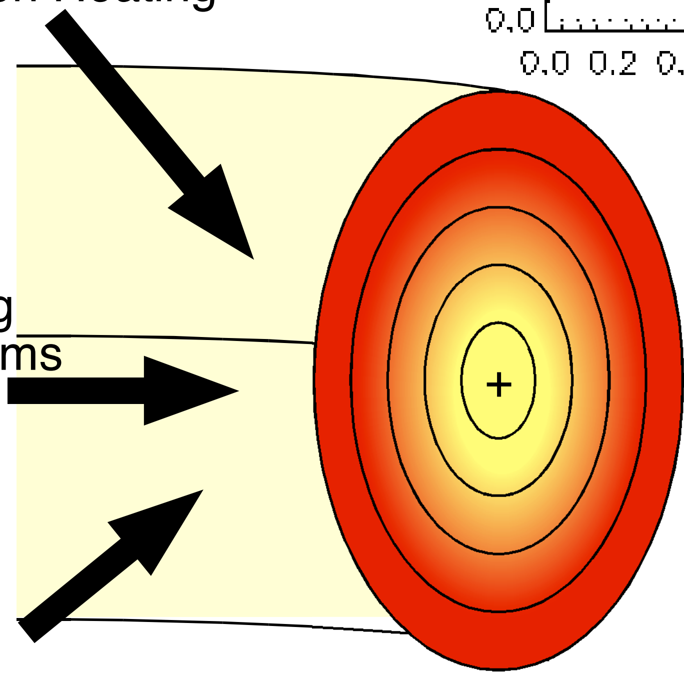
Turbulence Drives Cross-Field Transport of Particles, Energy and Momentum in a Magnetically-Confined Plasma

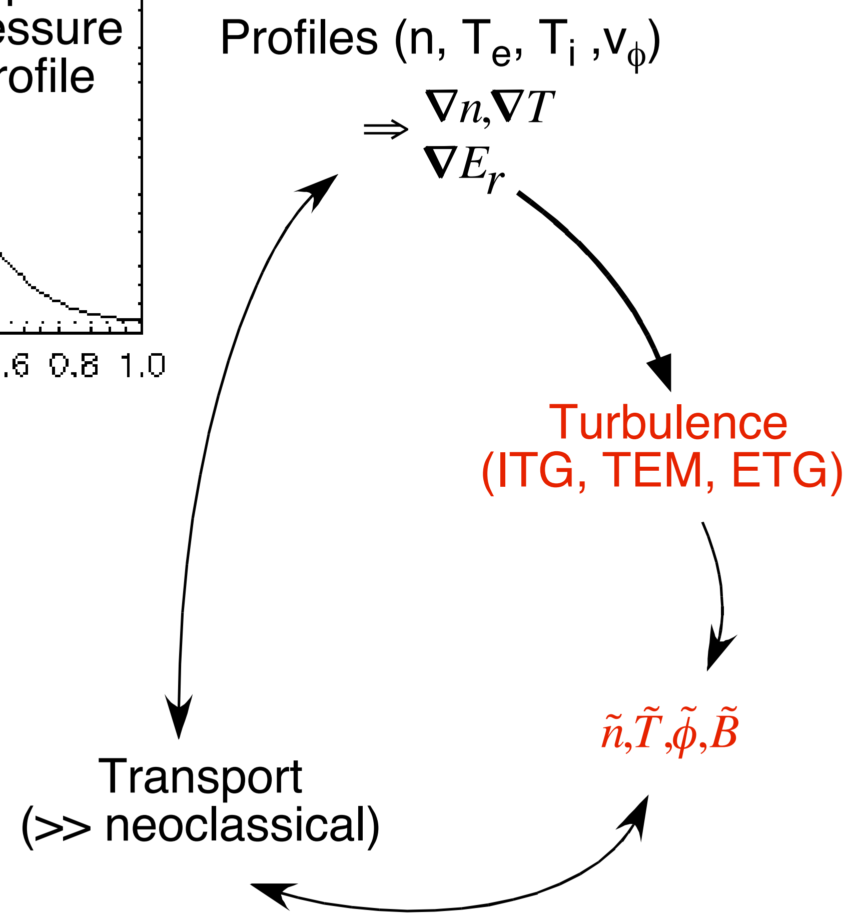


Energy
- Ohmic
- Neutral Beams
- Electron Cyclotron Heating
- Ion Cyclotron Heating

Particles
- Gas Fuelling
- Neutral Beams
- Pellets

Momentum
- Neutral Beams
- ICRF





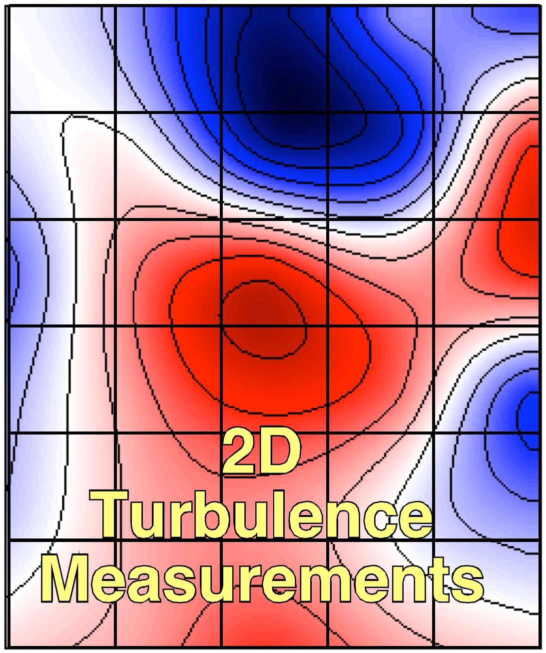
$$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle$$

$$Q = n\langle \tilde{v}_r \tilde{T} \rangle + T\langle \tilde{n}\tilde{v}_r \rangle$$

Complex, Highly Nonlinear, Self-Regulating System

WHY MEASURE 2D DENSITY FLUCTUATION CHARACTERISTICS?

Strong Physics Need for Higher Sensitivity 2D Fluctuation Measurements ($k_{||} \ll k_{\perp}$)



Z (cm)

R (cm)

Upgraded BES provides:

$\tilde{n}(r,Z,t), \tilde{v}(r,Z,t)$

at high sensitivity in core regions of high performance discharges

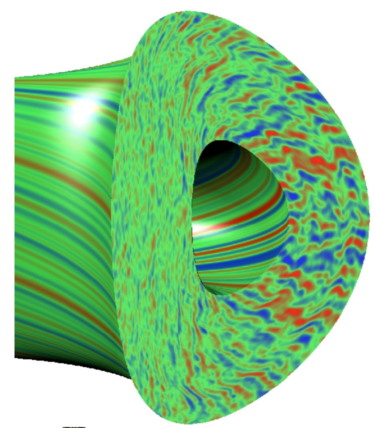
Physics Topics

Turbulence Imaging
- Eddy visualization
- Velocity field turbulence

Nonlinear Physics:
- Energy cascade
- Growth rate
- Reynolds Stress

Zonal Flows:
- Core Zonal Flow Identification
- Geodesic Acoustic Mode
- Generation & Interaction

Validation of Nonlinear 3D Simulations (e.g., GYRO)



Turbulent Particle Flux

$$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle$$

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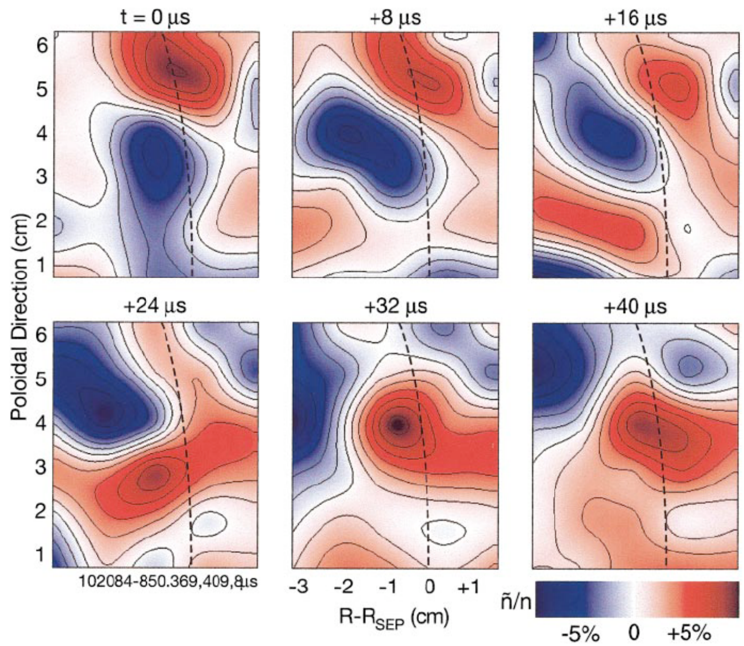
Several Approaches to 2D Turbulence Diagnostics Have Been Successfully Deployed on Plasma Experiments

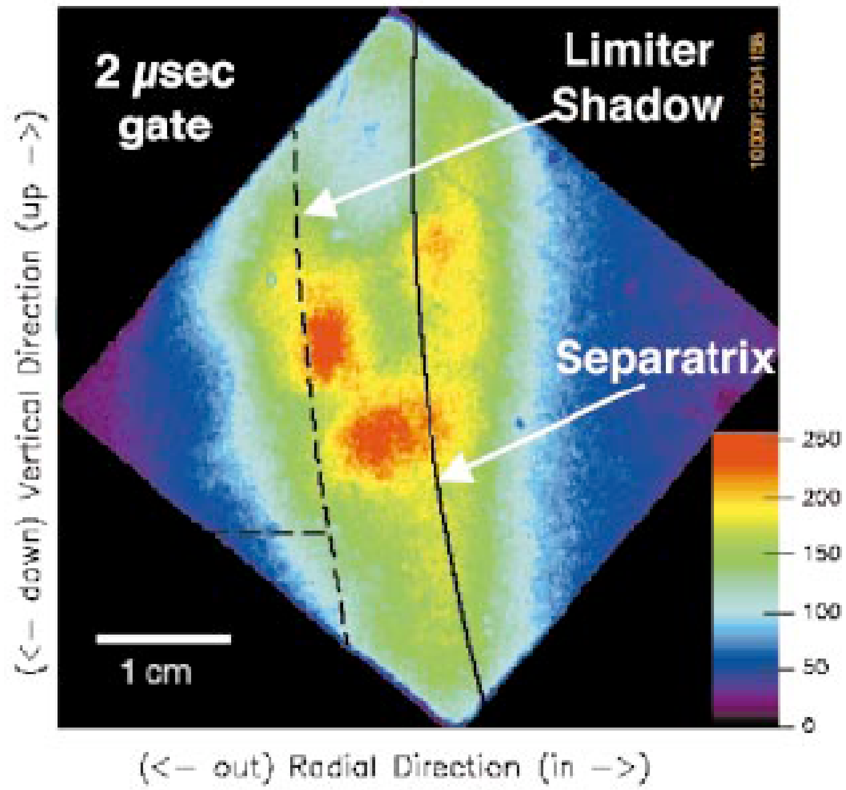
BES@DIII-D



C. Fenzi *et al.*, Rev. Sci. Instrum. **72**, 988 (2001).
G. McKee *et al.*, Rev. Sci. Instrum. **74**, 2014 (2003).

Imaged edge region due to signal to noise

Gas Puff Imaging @ NSTX, CMOD



S. Zweben *et al.*, Phys. Plasmas 9, 1981 (2002).
J. Terry *et al.,* Phys. 10, 1739 (2003).

Views emission shell near plasma edge

Core Plasma Turbulence Imaging capability is needed!

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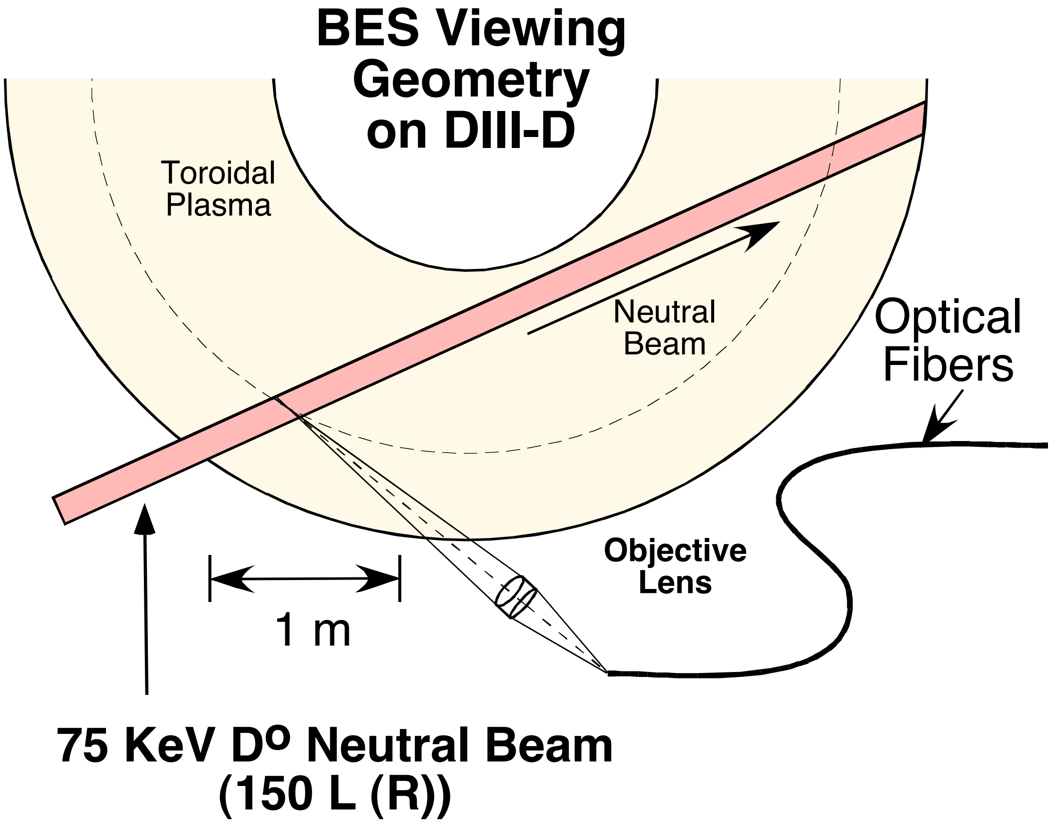
Beam Emission Spectroscopy Measures Spatially Localized, Long-Wavelength ($k_\perp \rho_I < 1$) Density Fluctuations

Collisionally-excited, Doppler-shifted neutral beam fluorescence

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



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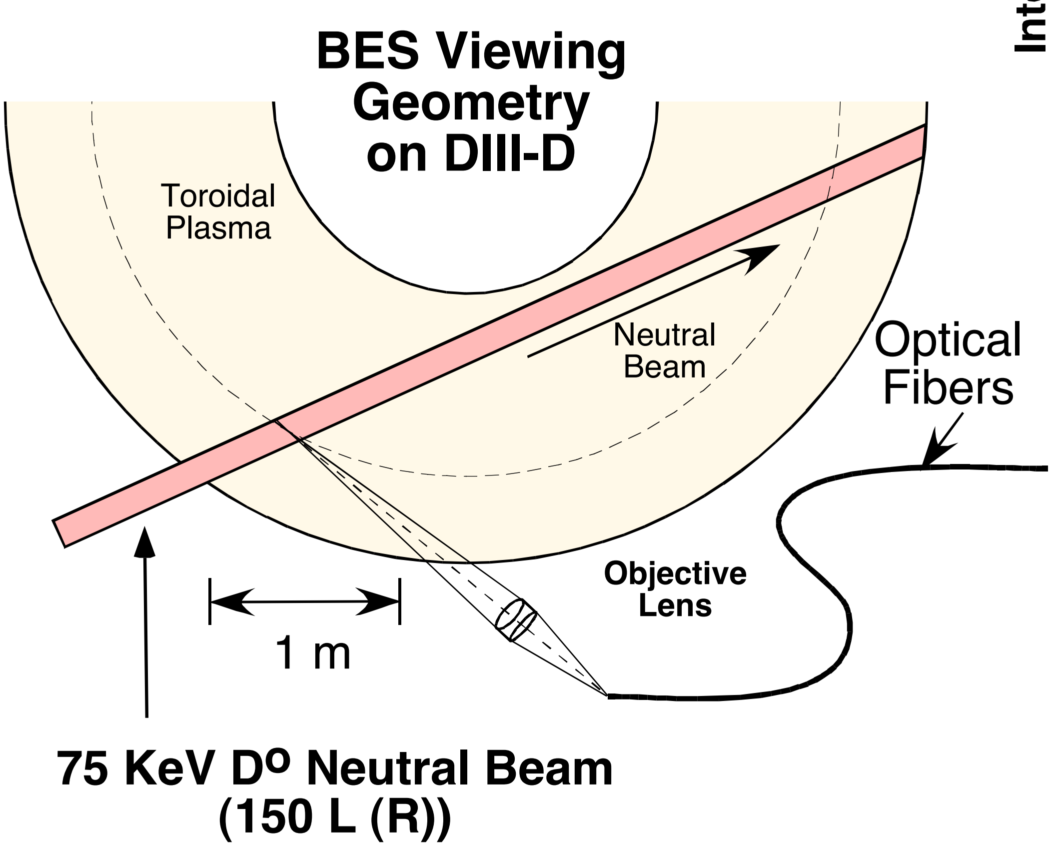

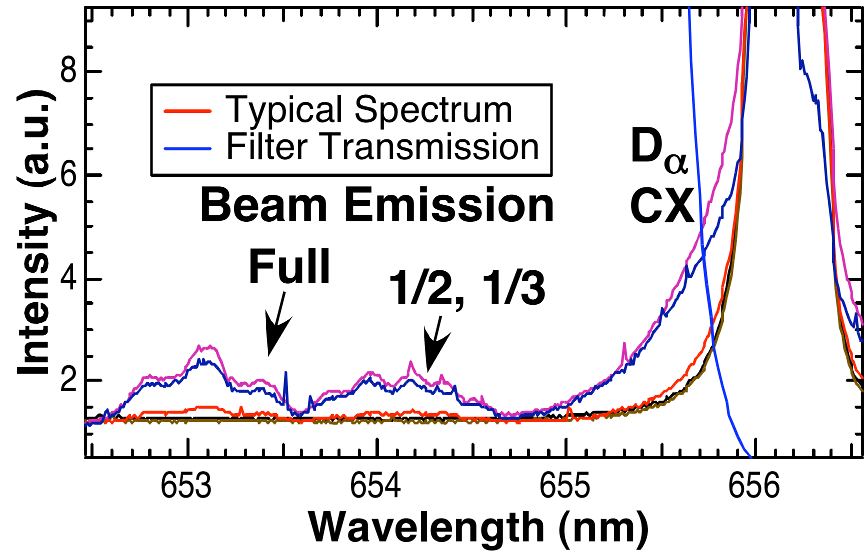

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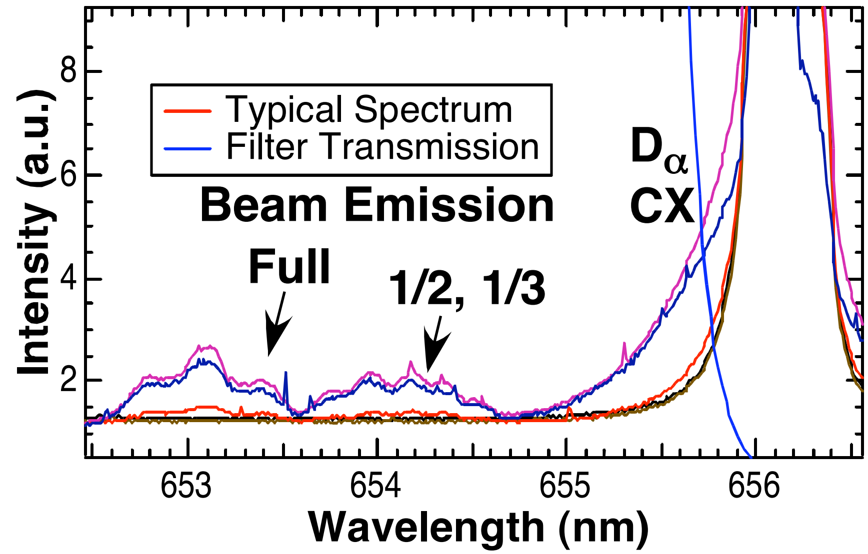

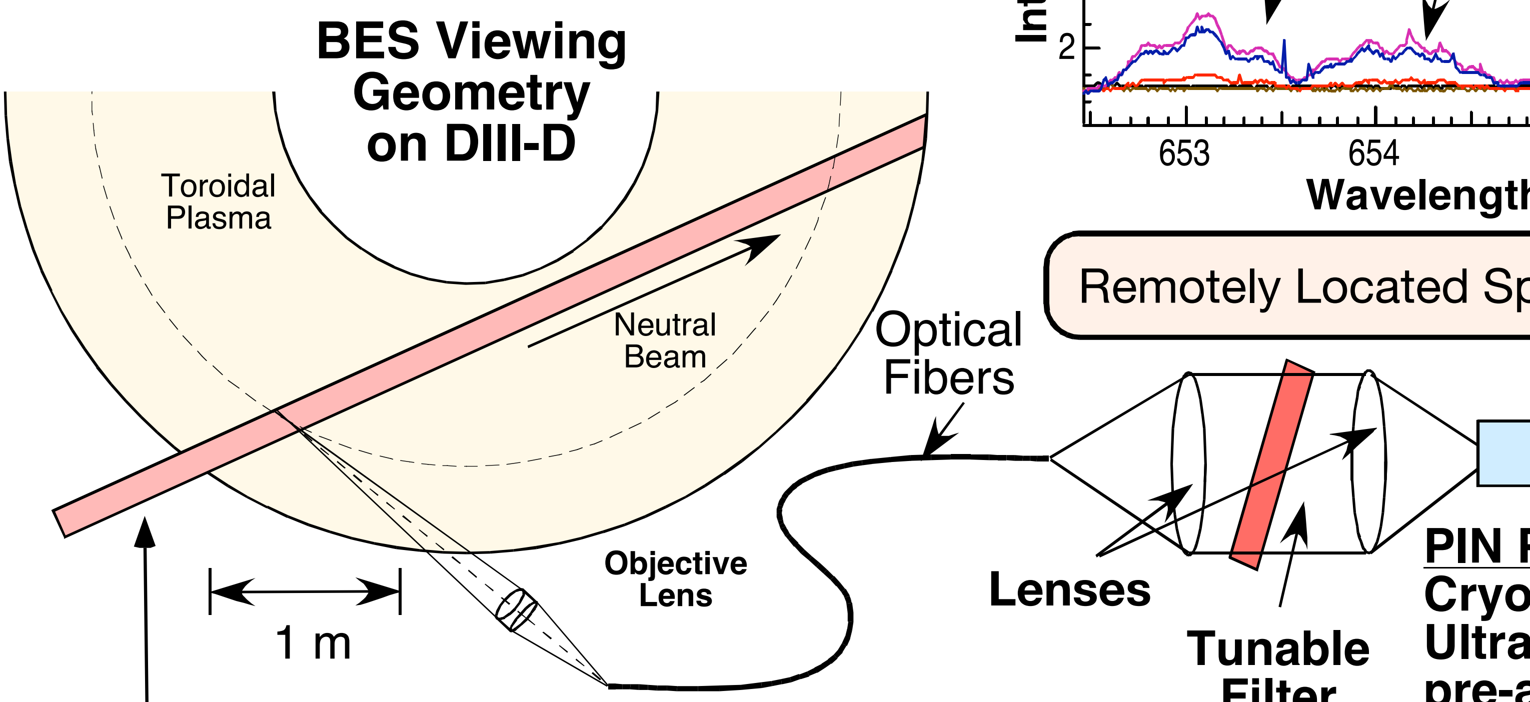

75 KeV D^o Neutral Beam (150 L (R))

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

$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$

(via Atomic Physics)

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

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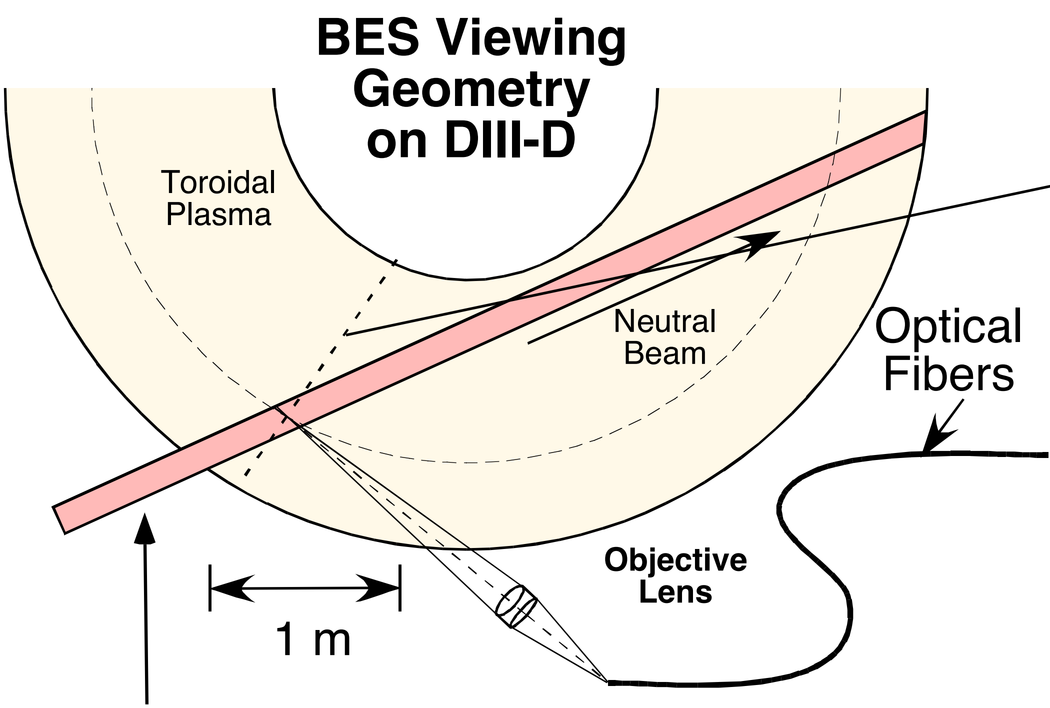
BEAM EMISSION SPECTROSCOPY MEASUREMENT OF LOCALIZED, LONG-WAVELENGTH ($k_{\perp}\rho_{I} < 1$) DENSITY FLUCTUATIONS

Collisionally-excited, Doppler-shifted neutral beam fluorescence

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



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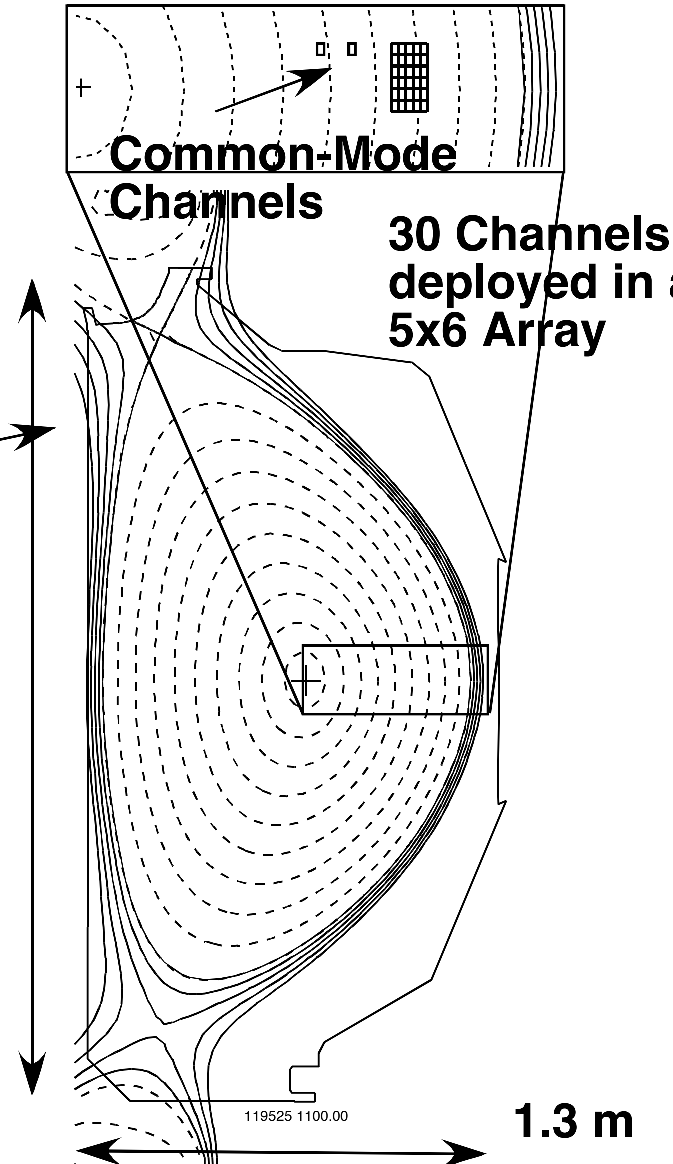

$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$

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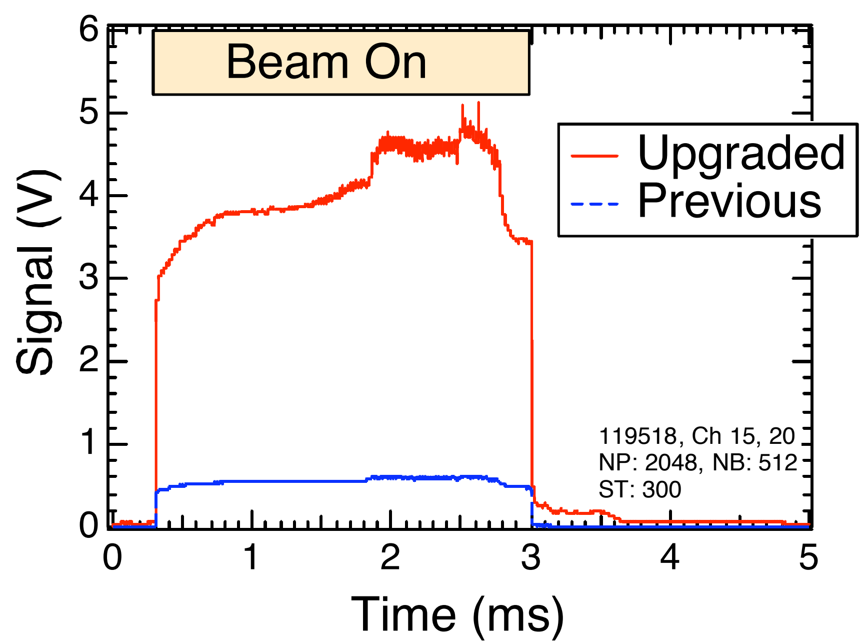
Numerous Diagnostic Enhancements Yield Significant Gain in Measured Signal

	Parameter	Previous	Upgraded	Gain
1)	Increased light collection:	0.59 mm^2-ster	1.62 mm^2-ster	2.75
2)	Increased filter transmission	1.0	1.5 (w/D_α CX)	1.5
3)	Larger photodiode detector	0.85 mm^2	2.9 mm^2	1.4
4)	Higher reflectivity mirrors	0.94	0.98	1.05
				Total 6+



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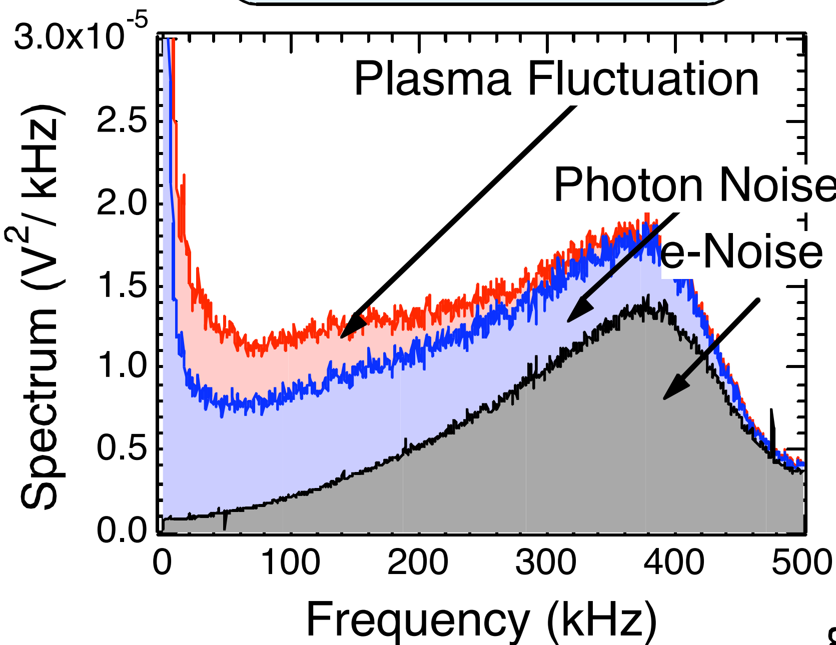
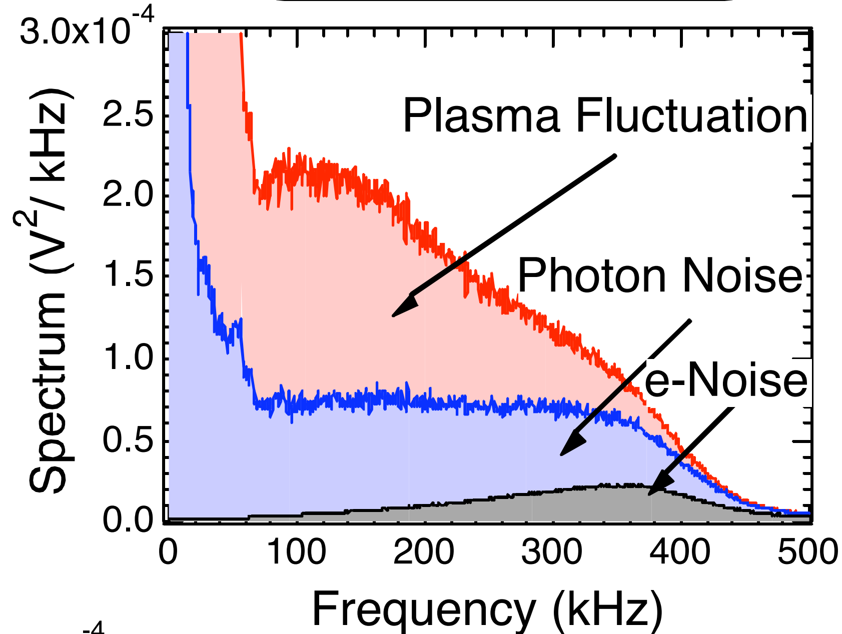
Factor of 30-50 Increase in Sensitivity to Plasma Density Fluctuation Power with Upgraded BES System

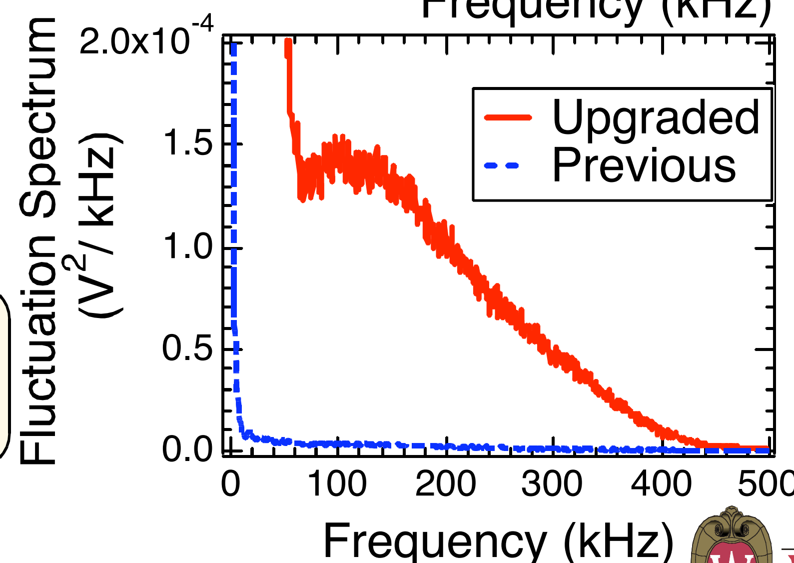
Previous BES **r/a ~ 0.7** **Upgraded BES**



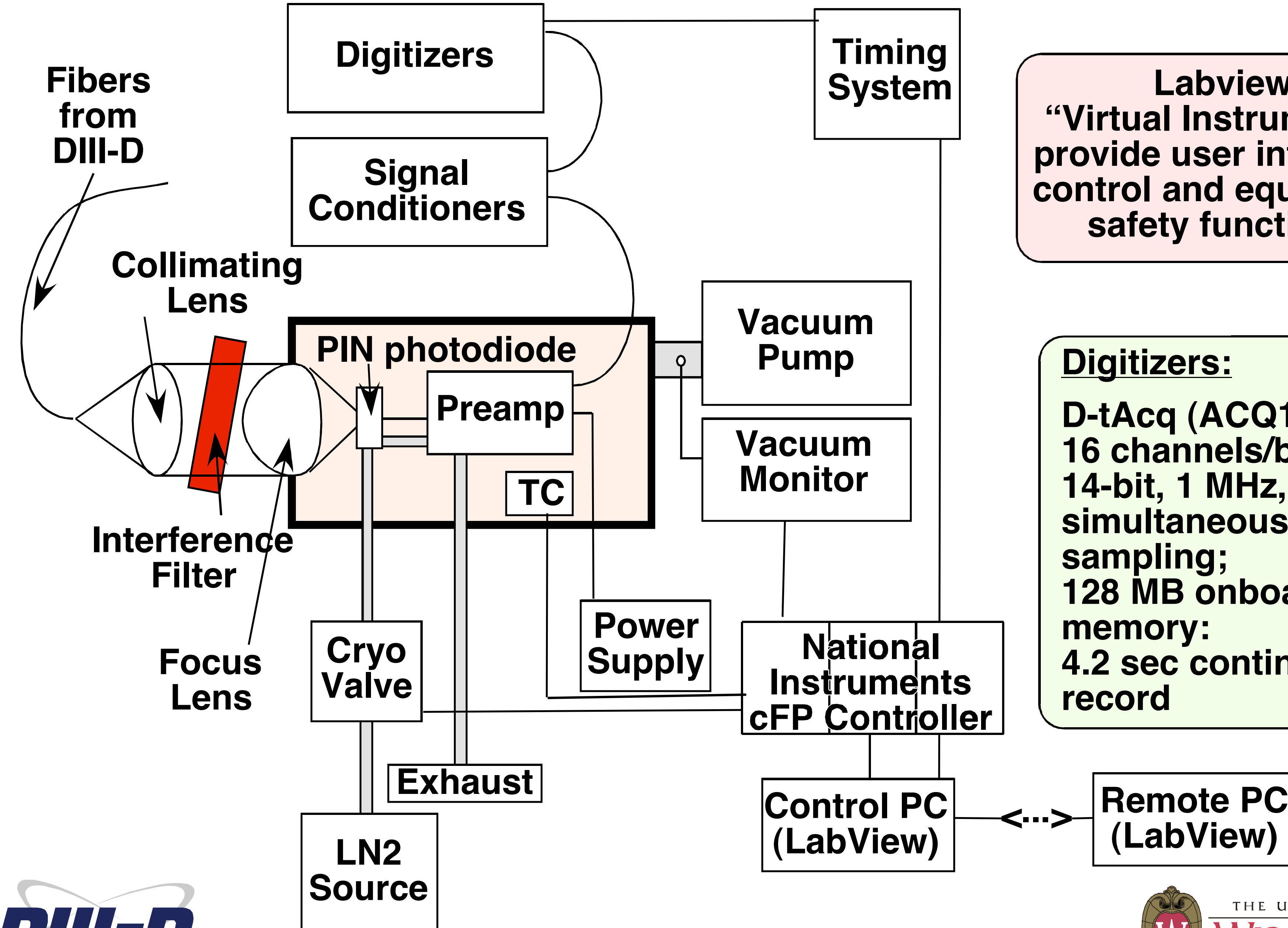


- **e-Noise: x 1.7**
- **Photon Noise: x ~10**
- **Plasma Fluctuation: x ~40**

Huge increase in plasma fluctuation power greatly facilitating studies of small-amplitude density fluctuations



BES Detector and Control System Provides Integrated Control and Fully Remote Operations



Labview "Virtual Instruments" provide user interface, control and equipment safety functions

Digitizers:

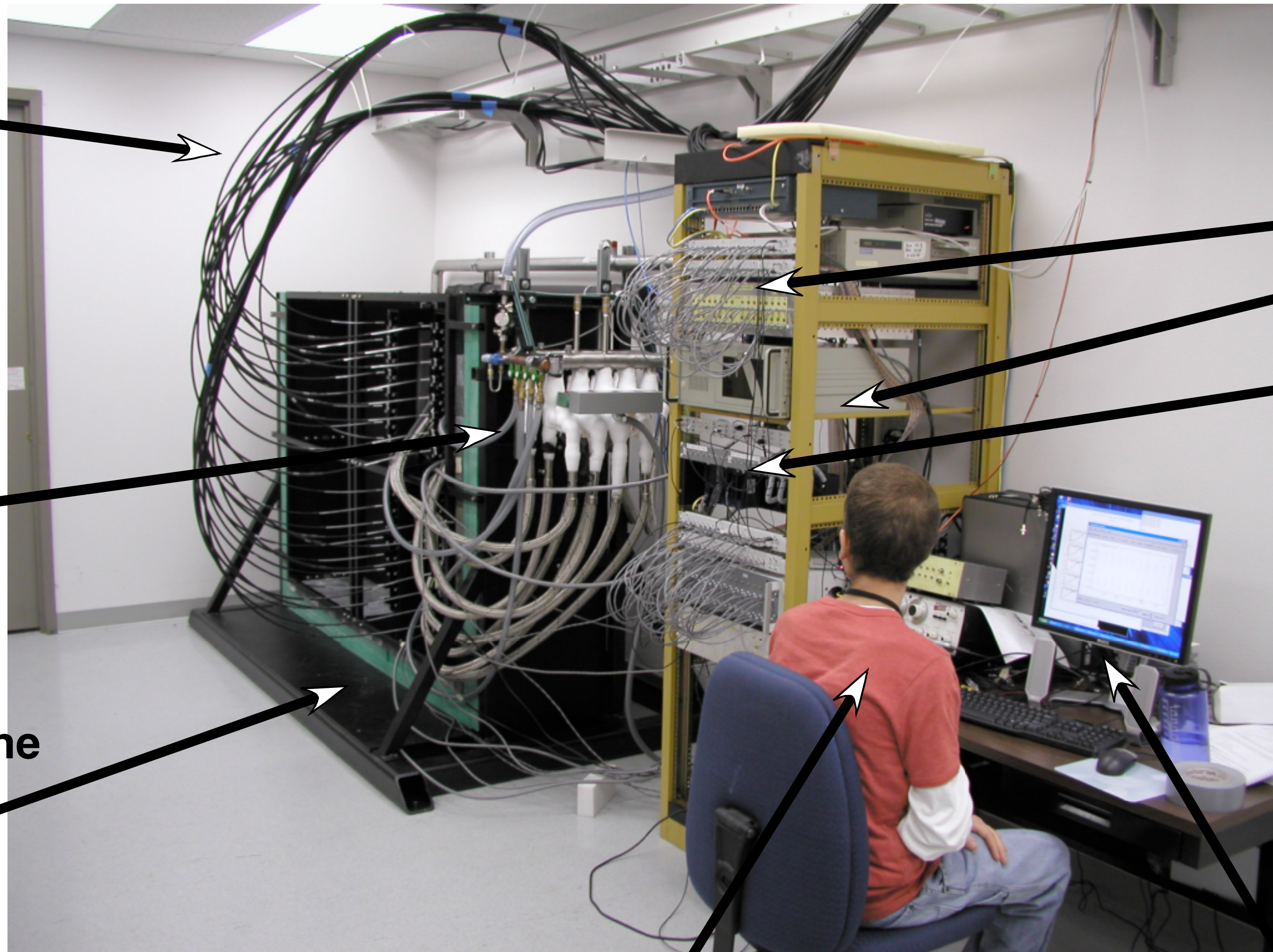
D-tAcq (ACQ16PCI):
16 channels/board
14-bit, 1 MHz, simultaneous sampling;
128 MB onboard memory:
4.2 sec continuous record

Overview of the Beam Emission Spectroscopy System

Fiber Optics

Cryogenic Lines, Manifold, Transfer Lines

5-ton Pb & Borated Polyethylene Radiation Shield



Signal Conditioning Electronics, Amplifiers, Power Supplies

Digitizer (D-tAcq)

Control System (Regulates Temperature Monitors Vacuum, timing, AC Power National Instruments)

Control PC (Labview)

Dave, the Graduate Student

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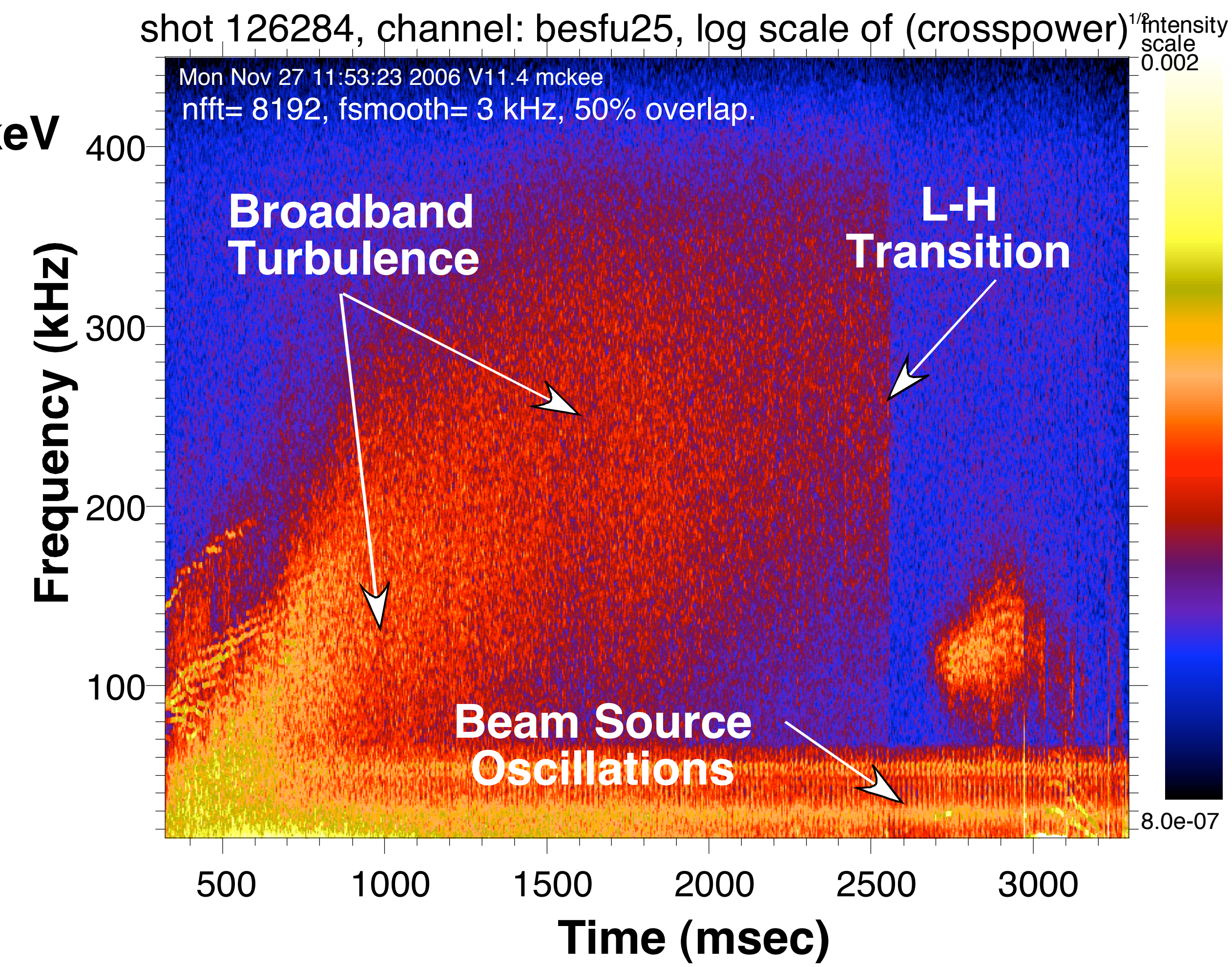
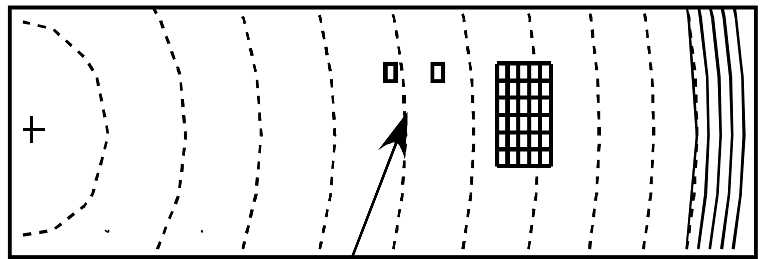
FLUCTUATION SPECTRUM EVOLVES DYNAMICALLY THROUGHOUT DISCHARGE

- Measurements obtained in L-mode Discharges:
  I_p=1 MA, B_T = -2.0 T
  P_{inj} = 5 MW,
  $n_{e,o}$=3x10^{19} m^{-3}, Te,o=2.2 keV
  $T_{i,o}$=2.7 keV
- Beam source oscillations arise from current or voltage noise in neutral beam source, small amplitude:
  $\tilde{n}_{BEAM}/n < 1\%$
- Common-mode rejection procedures can isolate and subtract

Cross-Power Spectrum
at r/a=0.64 (ΔZ=1.2 cm)

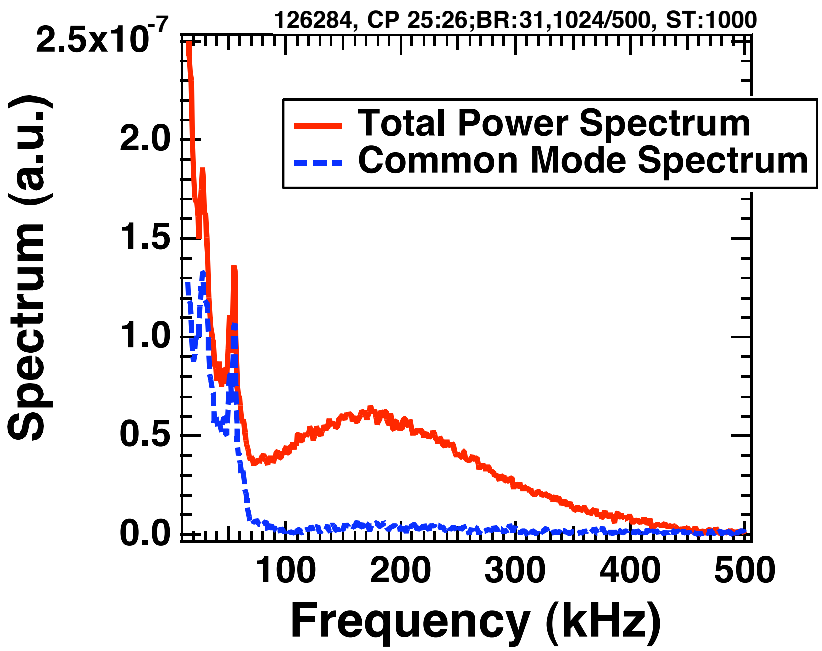


COMMON-MODE FLUCTUATIONS ARE MEASURED AND SUBTRACTED

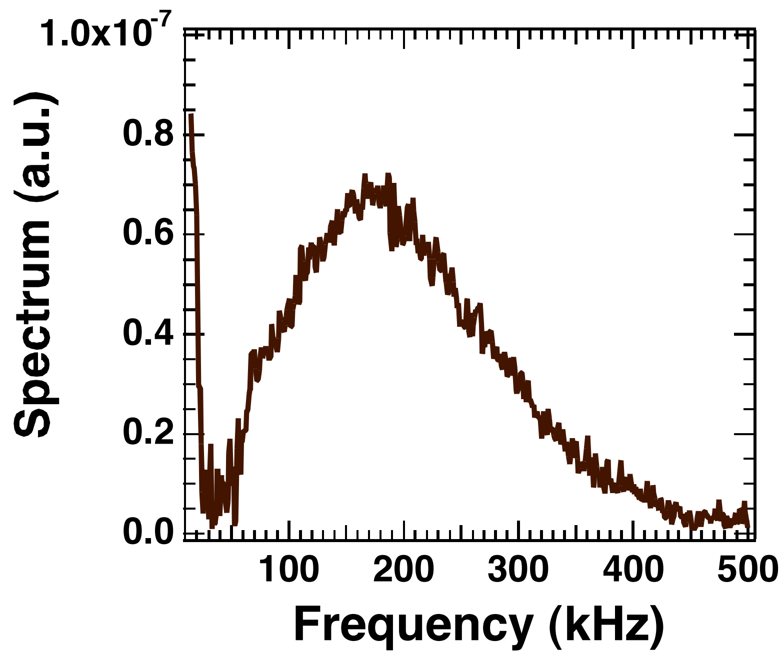


Common-Mode Channels

Power Spectrum has both local fluctuations and common-mode components



Local Spectrum after Subtraction of Common-Mode Signal



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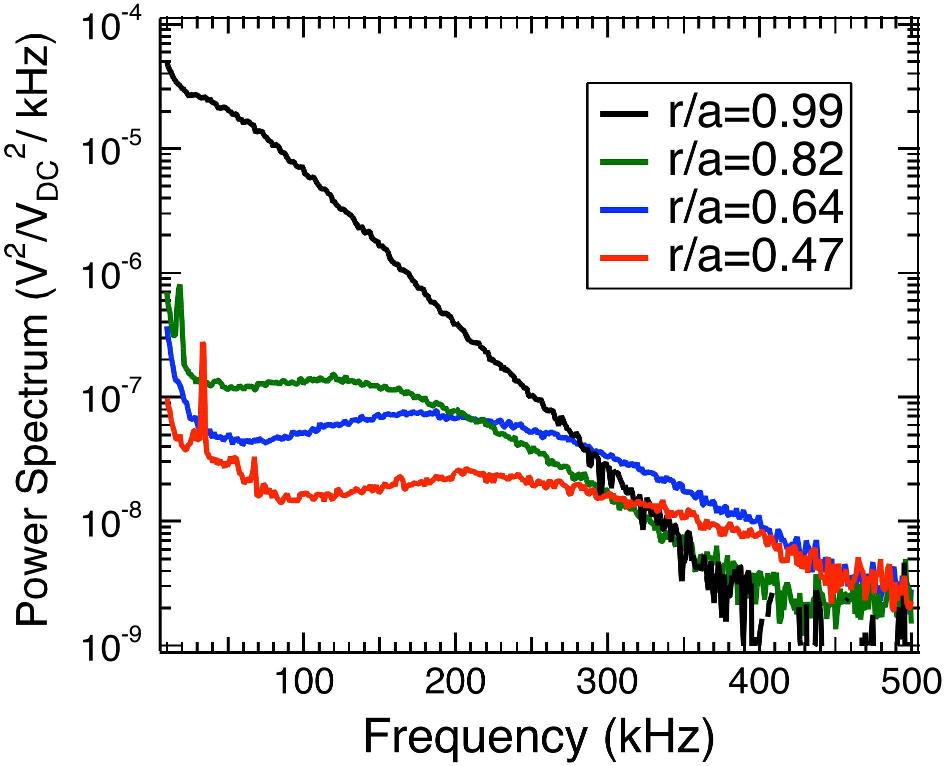
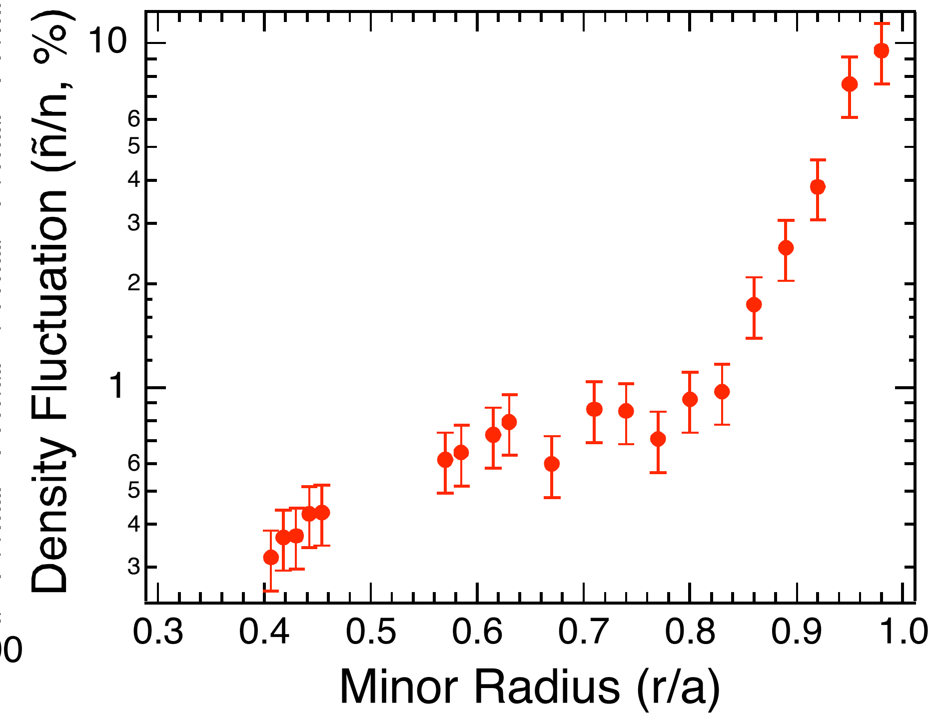
FLUCTUATION SPECTRA AND AMPLITUDE VARY STRONGLY WITH RADIUS

Fluctuation Spectra at Several Radii



Density Fluctuation Amplitude Profile



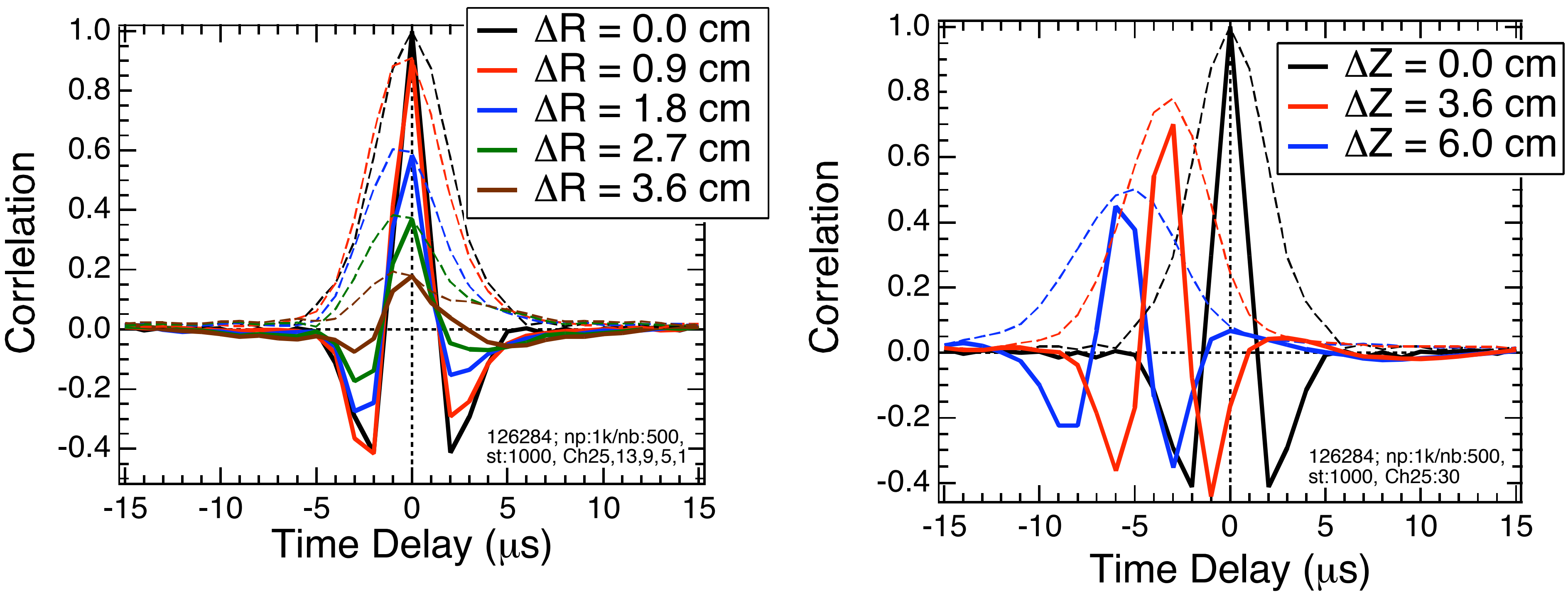
- **Density fluctuation amplitude in L-mode discharges shows wide dynamic range across plasma radius**
- **Spectra strongly Doppler-shifted to higher frequency towards core**

TIME-LAG CROSS CORRELATIONS EXHIBIT STRONG SPATIAL ASYMMETRY

Radial Cross Correlation Function

r/a = 0.64

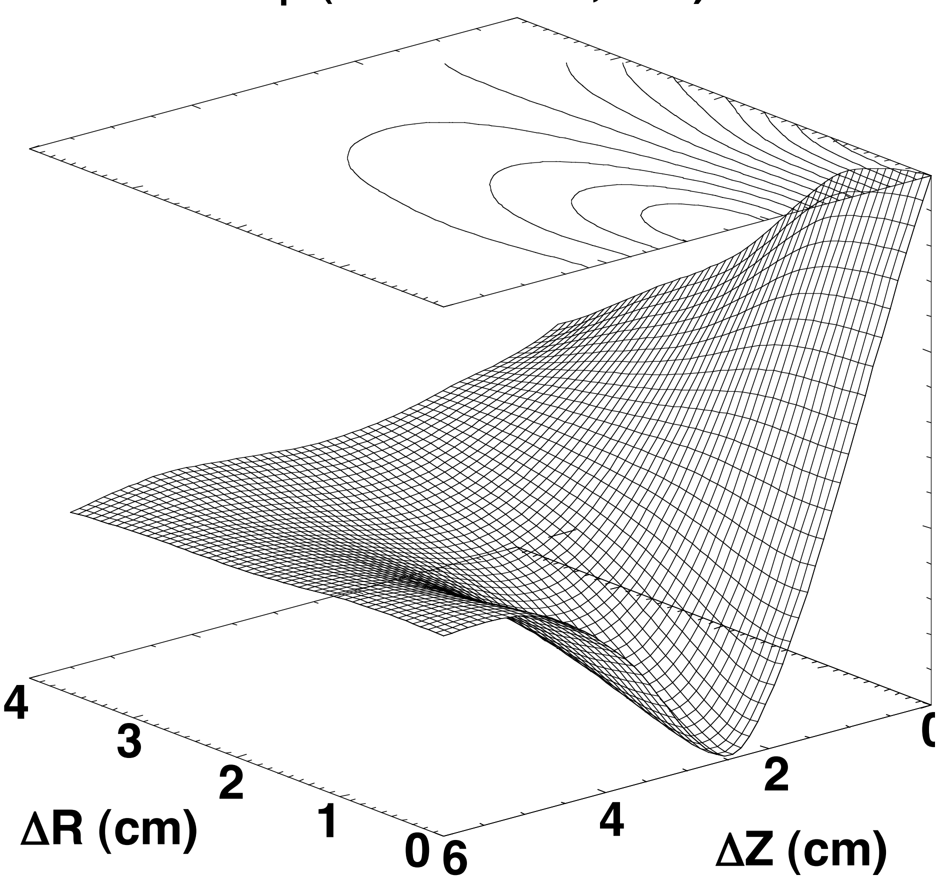
Poloidal Cross Correlation Function

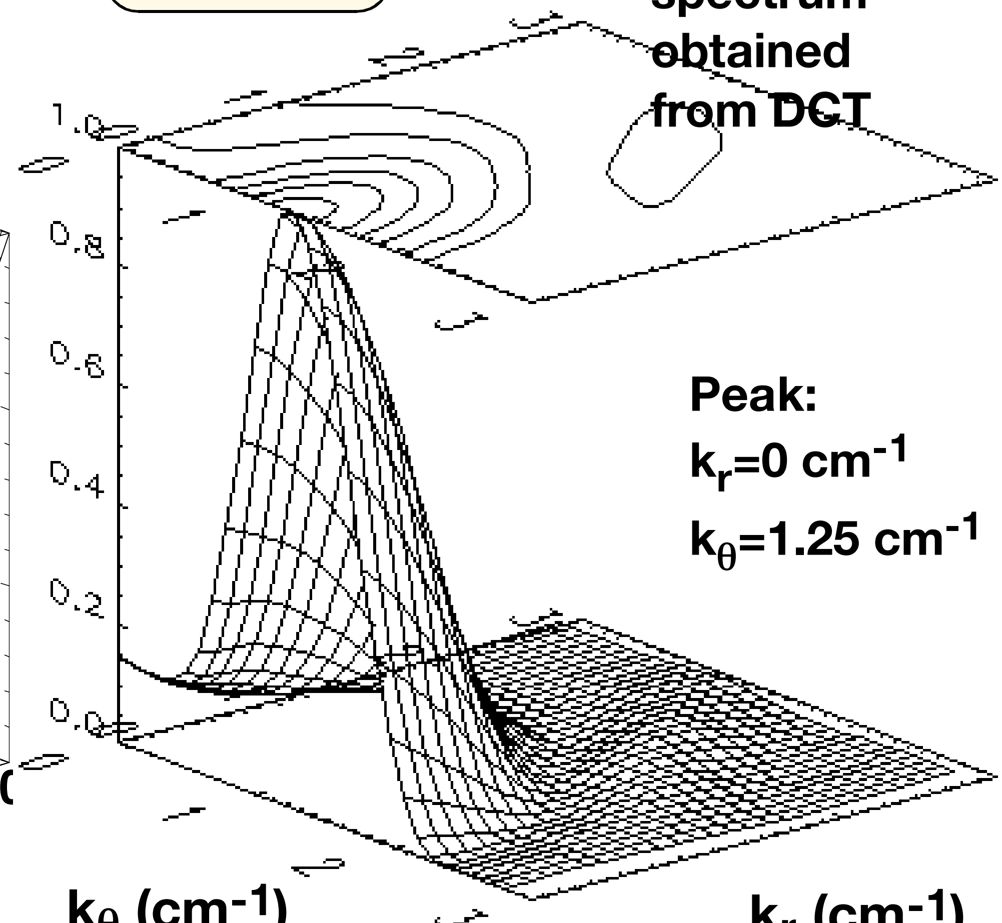


- **Turbulence has no time-averaged radial propagation, but strong poloidal propagation**
- **Poloidal correlation length slightly larger than radial:**

$$L_{c,\theta} \approx 3.0 \text{ cm}, \; L_{c,r} \approx 2.5 \text{ cm}$$

2D Correlation and $S(k_r, k_\theta)$ Spectra Confirm Spatial Asymmetry

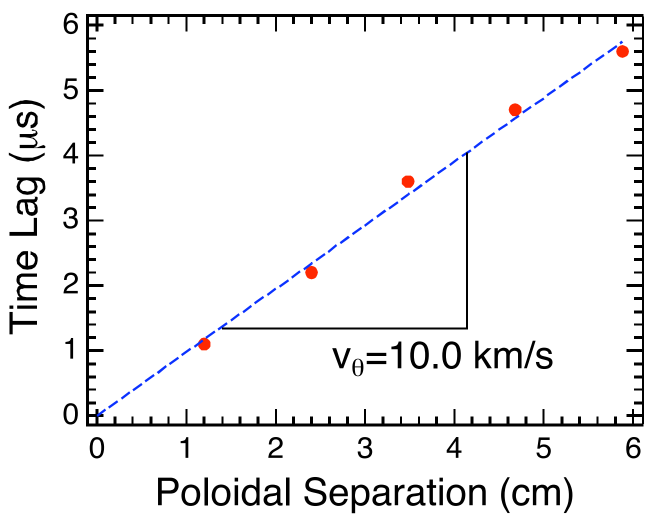




- Exhibits radially decaying, poloidally wavelike structure, $L_{c,\theta} > L_{c,r}$
- Wavenumber spectra can be compared with turbulence simulations

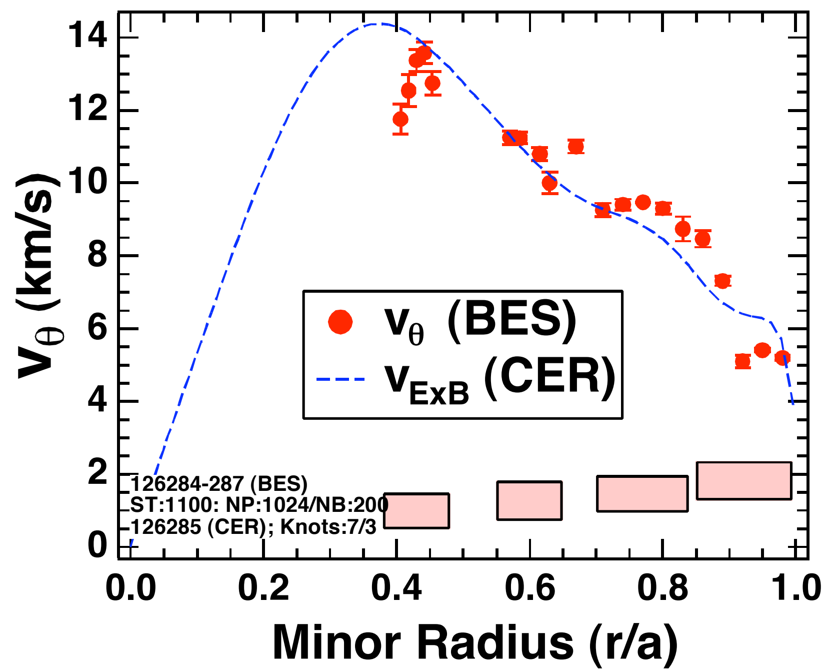
TURBULENCE ADVECTS POLOIDALLY AT LOCAL E_rxB_T VELOCITY

- **Turbulence Velocity determined from poloidal cross-correlation time-lag analysis from BES**



- **V_{ExB} determined from ion radial force balance equation and Charge Exchange Recombination Spectroscopy measurements of carbon impurity toroidal and poloidal rotation, temperature and density**

Poloidal Velocity from BES compared to V_{ExB} from CER



- **Excellent agreement between independent measurements confirms that turbulence advection at ExB velocity**

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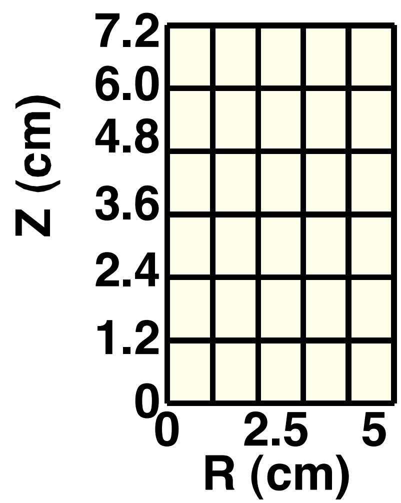
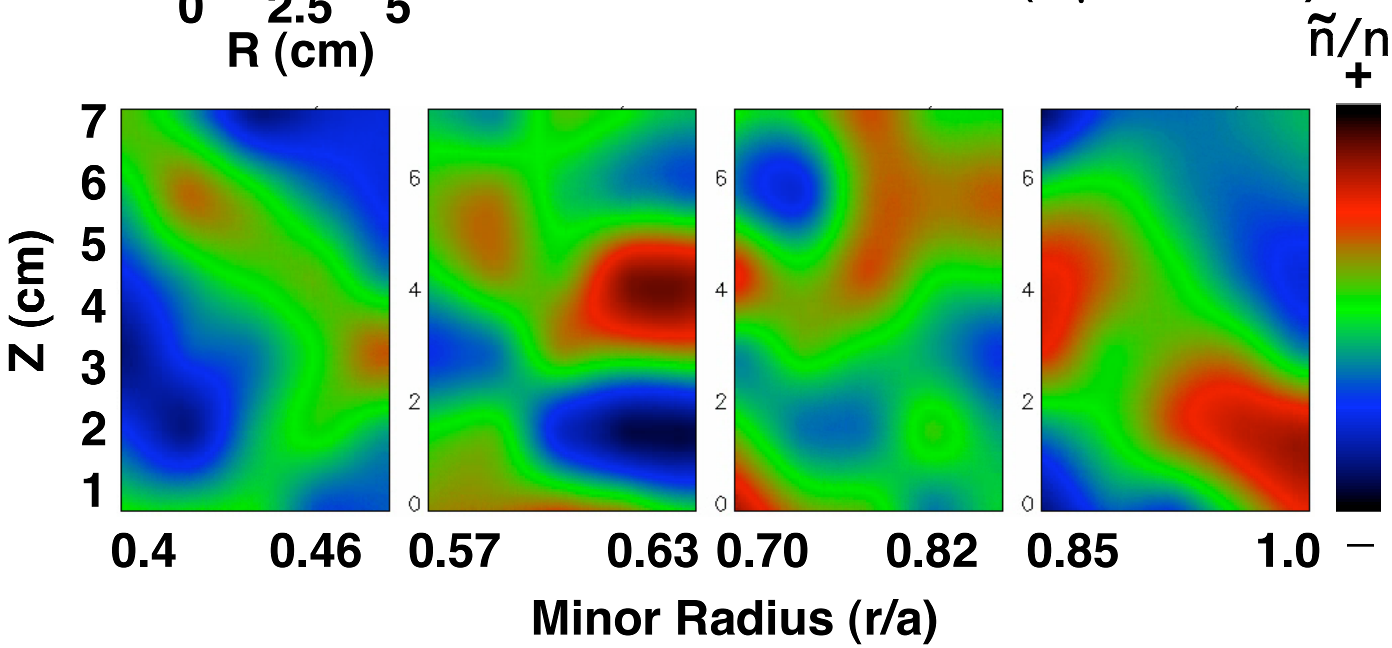
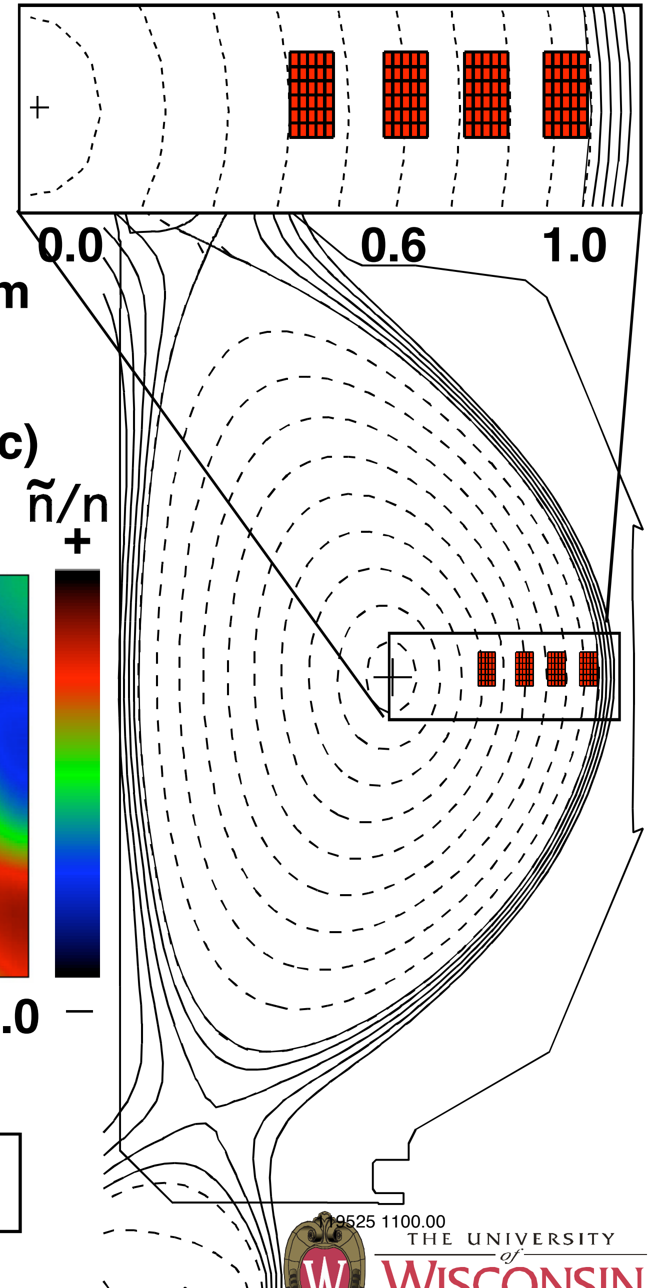
Visualizations of Core Plasma Turbulence Obtained with High-Sensitivity BES System Across Minor Radius



- 1 MHz sampling
- L-mode discharges (1.2 MA, 2.0 T, 5 MW NBI)
- Frequency-filtered per spectrum
- 2D spline
- 2×10^5 time dilation (5 μs = 1 sec)





ñ/n	0.4%	0.7%	0.9%	2-10%

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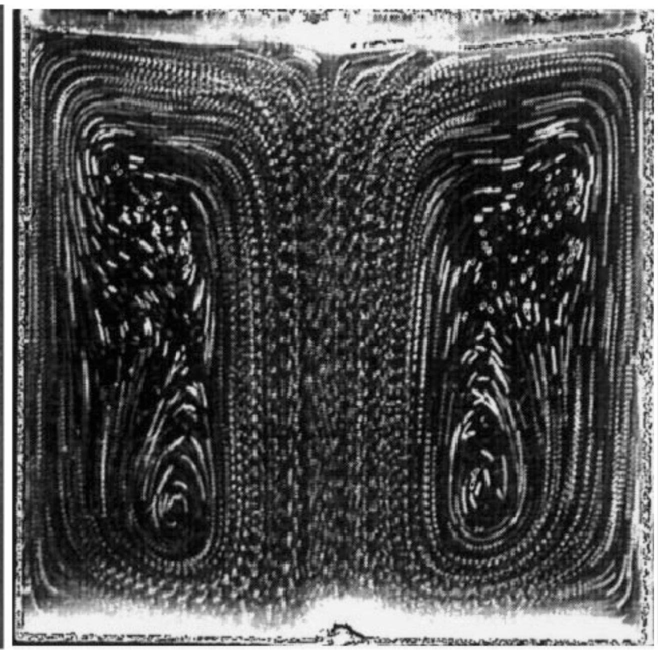
TIME-RESOLVED EDDY VELOCITY FIELD CAN BE DERIVED FROM MULTI-FRAME SPATIOTEMPORAL ANALYSIS

- **Adapt technique from in fluid dynamics: *Orthogonal Dynamic Programming***
  - *Reduces 2D problem to a set of selected 1D vector-matching problems*
  - *Utilizes "dynamic programming" to match patterns in related data sets*
  - *ODP then applies successive 1D matching techniques to full 2D data set, first in one dimension, then the other*
  - *Various optimization and tuning parameters*

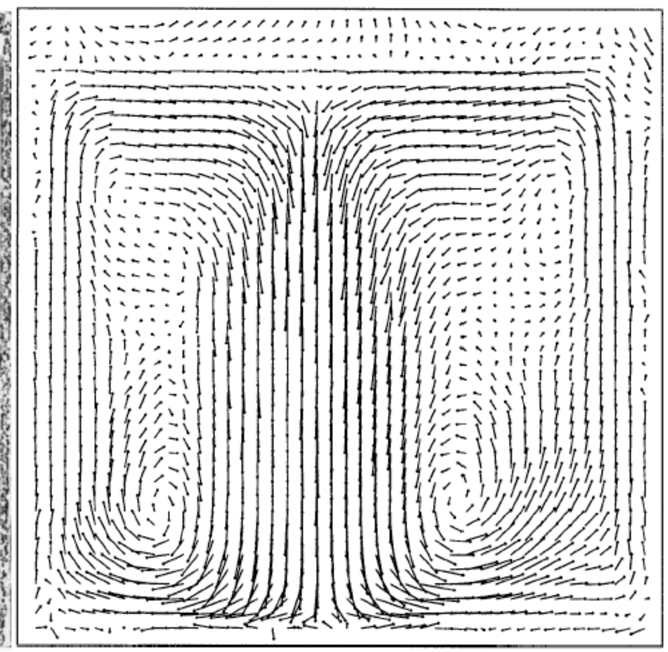
- **Example output from application to PIV [1]:**

Single Image

Time-averaged Image



Calculated Flow Field



[1] G. M. Quenot *et al.*, Exp. in Fluids **25**, 177 (1998)

Example Sequence of Time-Resolved 2D Turbulence Flow Field

Analysis Provides:

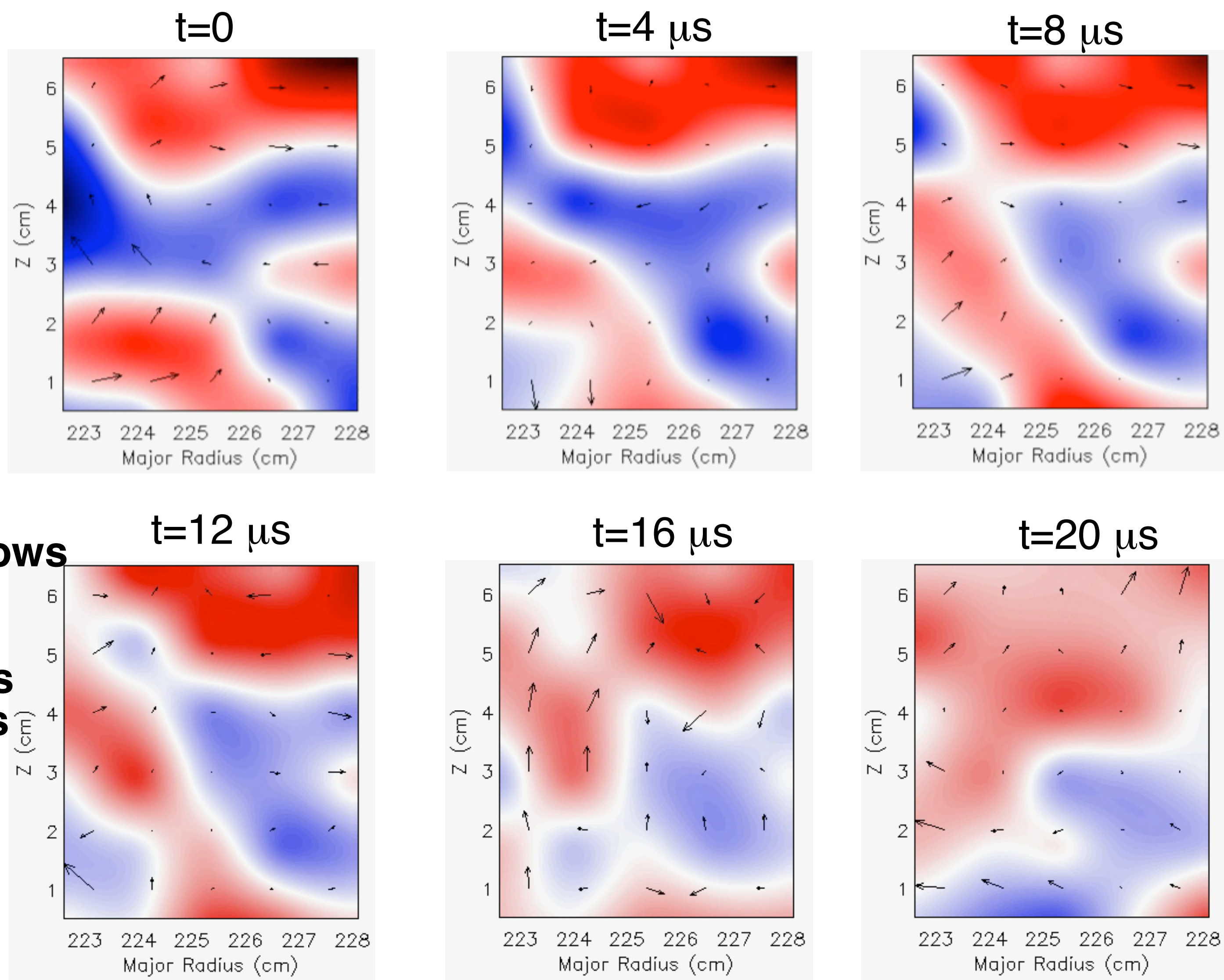
v_r (R, Z, t)

- **Flux**

v_θ(R, Z, t)

- **Zonal Flows**

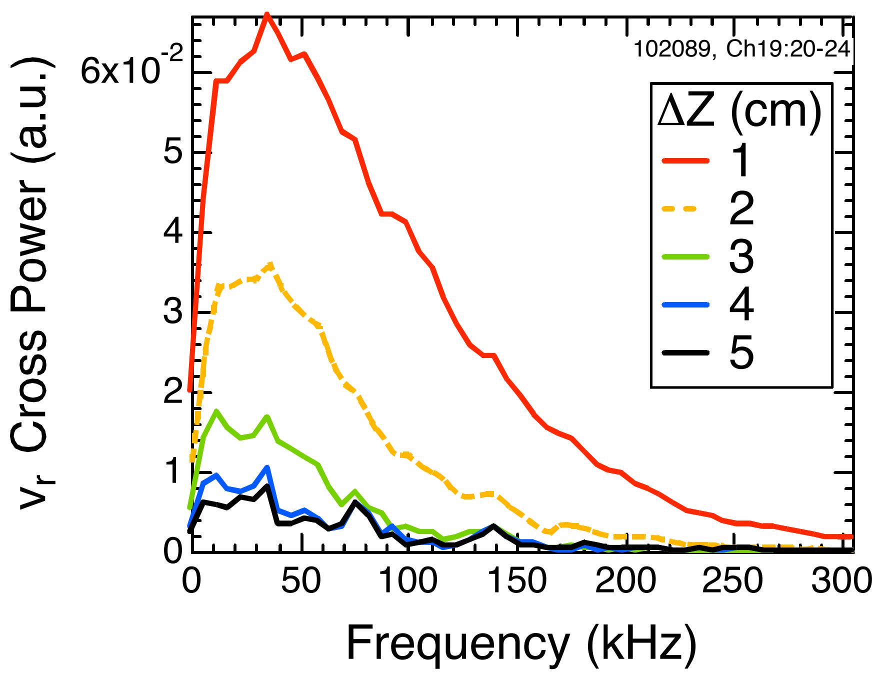
R - 5 channels
Z - 6 channels
t - 1000 μs



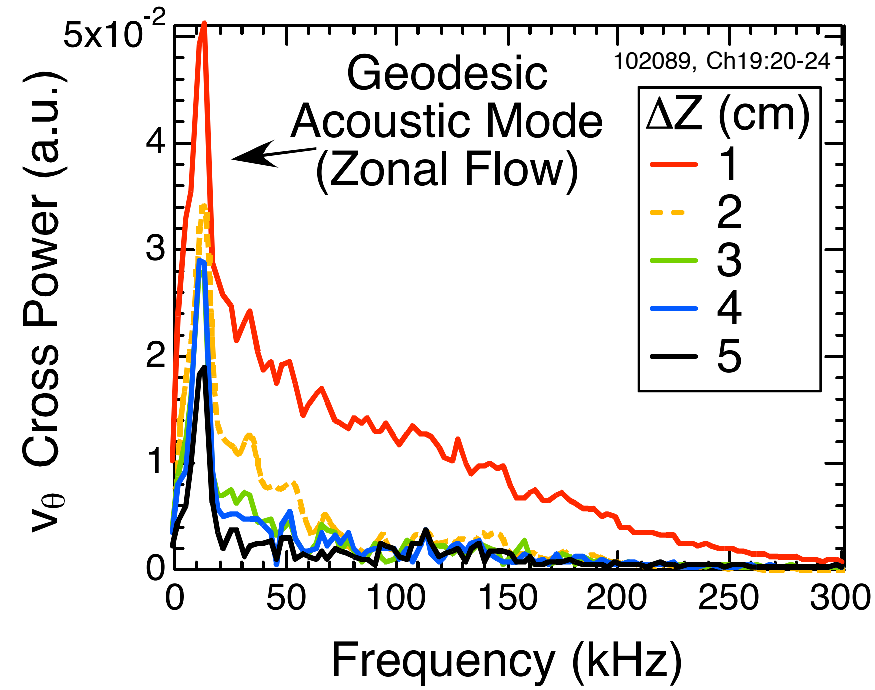
Vectors represent local velocity field (scaled by image)

RADIAL AND POLOIDAL VELOCITY FLUCTUATIONS EXHIBIT DISTINCT BROADBAND SPECTRA

Radial Velocity Spectra



Poloidal Velocity Spectra



- **Decaying spatial coherence indicates velocity fluctuations have few cm correlation length, similar to density fluctuations**
- **Spatially increasing phase shift suggests poloidal advection (not shown)**
- **GAM shows clearly in v_θ, not in v_r: zero poloidal phase shift, $2\pi f = c_s/R$**

How are $\tilde{v}$ related to $\tilde{\phi}$ (through $\tilde{E}$xB)?

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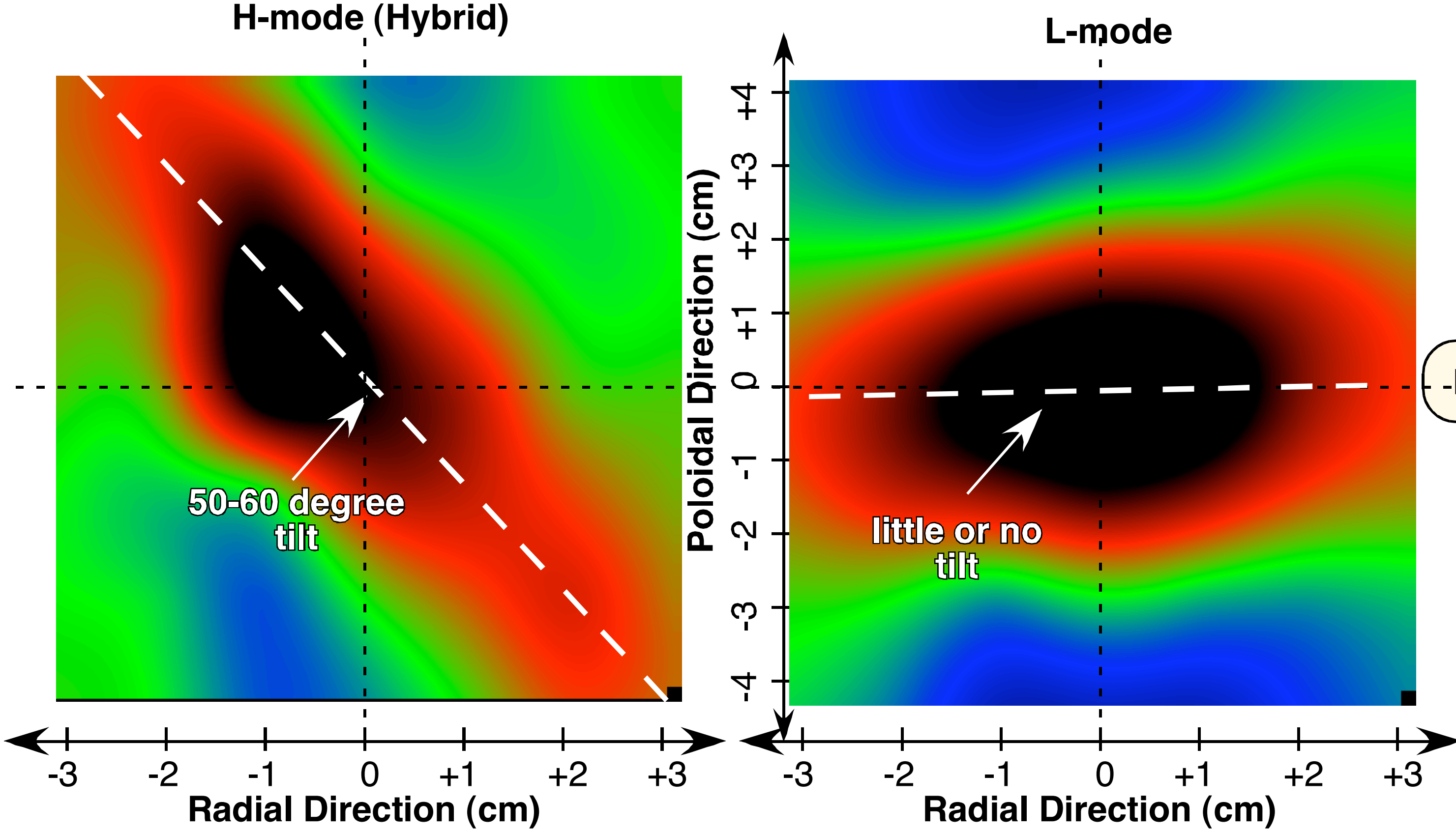
Spatiotemporal Cross-Correlations reveal Significant Differences in L-mode & H-mode Turbulence Structures

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

Time-resolved correlation function: $\rho(\Delta r, \Delta\theta, \Delta\tau)$



- **Suggests core H-mode turbulence subject to stronger flow shear: amplitude is significantly lower (~*10)**

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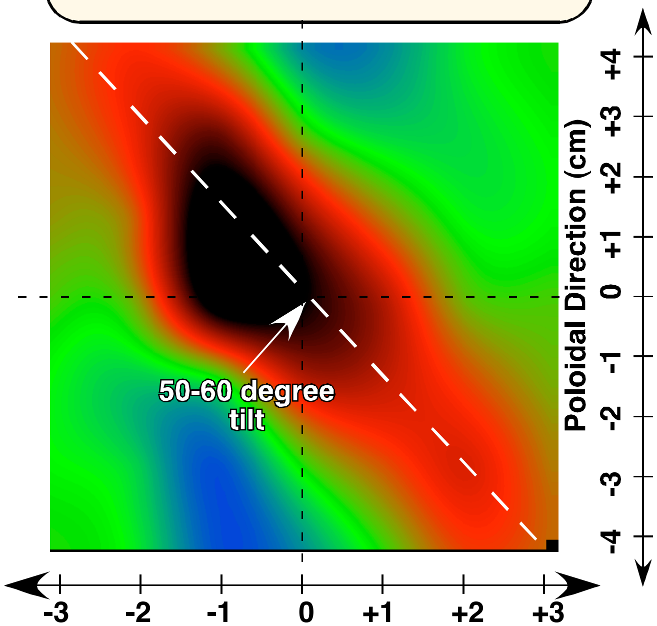
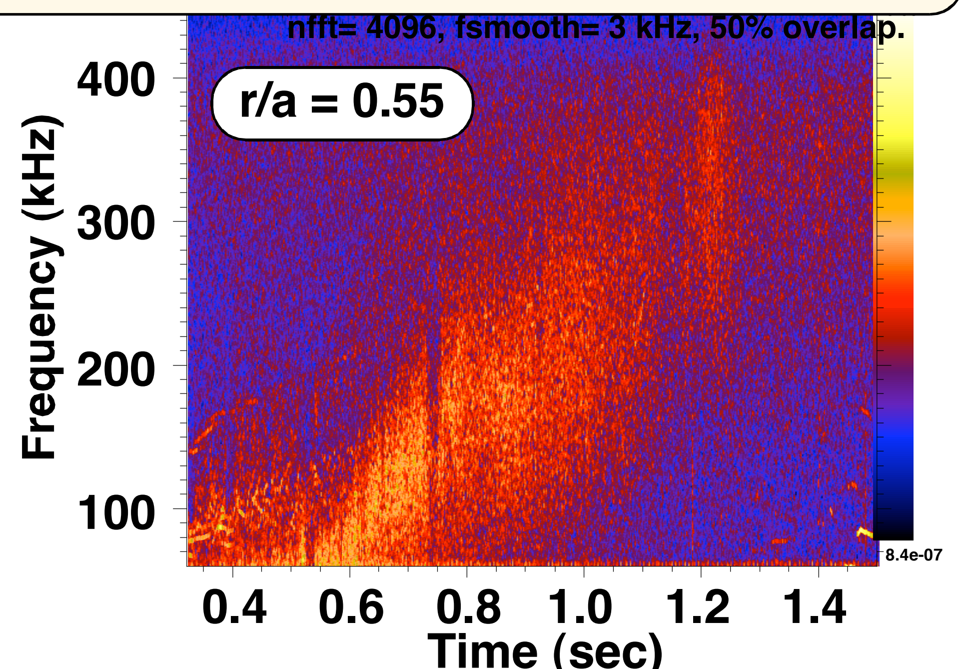
Studies of Small-Scale, Low-Amplitude Plasma Instabilities Benefit from Local, High-Sensitivity Fluctuation Measurements

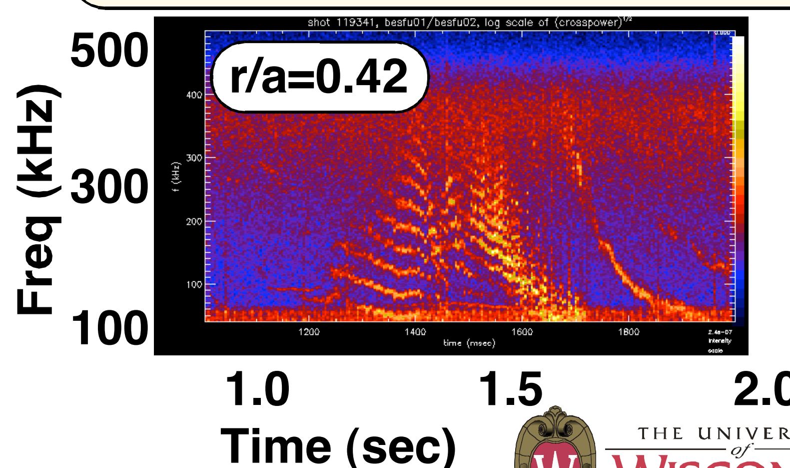
Turbulent Eddy Spatial Correlation in H-mode Plasmas



Turbulence Dynamics During ITB Formation



Energetic Particle-Driven Modes



Example measurements obtained in the core of DIII-D Tokamak Plasmas with the upgraded High-Sensitivity Beam Emission Spectroscopy System

$\tilde{n}/n < 1\%$

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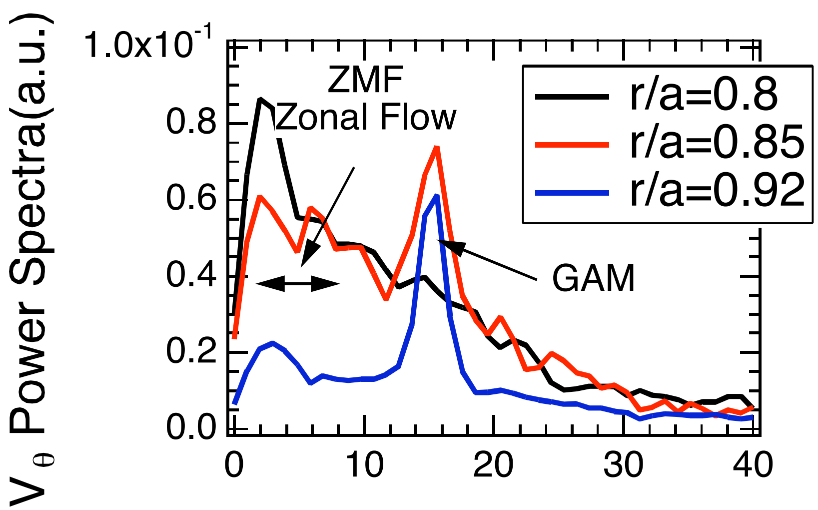
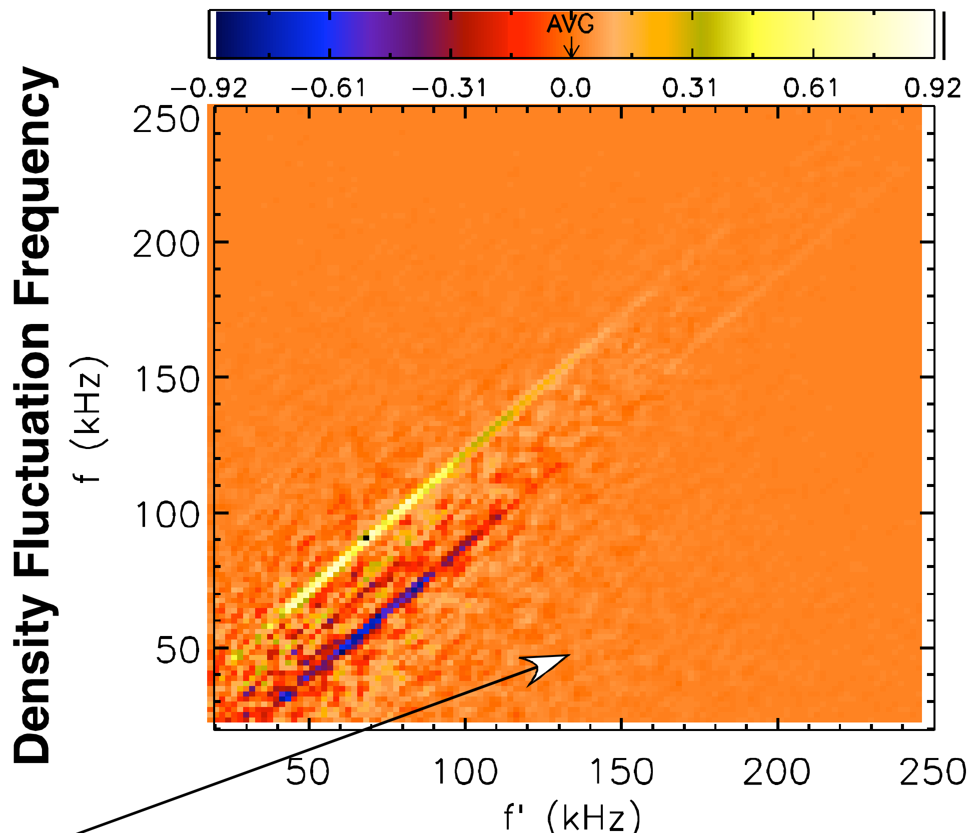
ANALYSIS OF 2D TURBULENCE MEASUREMENTS ALLOWS FOR INVESTIGATION OF COMPLEX AND NONLINEAR DYNAMICS

$$T_n^Y(f',f) = -\mathrm{Re}\left\langle n^*(f)V_y(f-f')\frac{\partial n}{\partial y}(f')\right\rangle$$

Zonal Flows, include Geodesic Acoustic Modes are manifest in high frequency poloidal velocity fluctuations, measured via application of "Time-Delay-Estimation" methods to BES data





Poloidal Density Gradient Fluctuation Frequency

GAM mediates nonlinear transfer of energy from low frequencies to high frequencies in tokamak edge plasma

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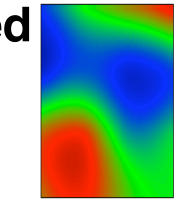
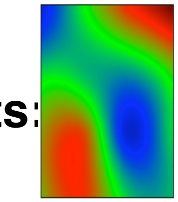
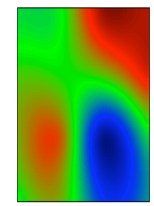
Conclusions & Future Directions



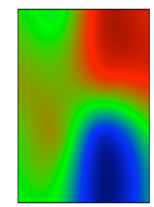
- **Beam Emission Spectroscopy deployed at DIII-D provides time-resolved visualizations of plasma turbulence in the R-Z plane**
  - *Allowing for detailed characterization of inherently 2D turbulence in magnetically-confined plasmas*



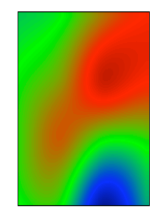
- **Beam Emission Spectroscopy at DIII-D has been redesigned, component-by-component to provide high-sensitivity 2D measurements:**
    - *Increased light collection*
    - *Higher transmission filter*
    - *Larger area photodiode*
    - *Net* ***5-10**** *increase in measured signal*
    - *Advanced control system, expanded lab facility*



- **Sensitivity to small-amplitude fluctuation power increased by 30-50**



- **Now provides density fluctuation measurements in the core region (0.25 < r/a < 1.0) of L & H modes (L, H-mode, QH, QDB, Hybrid, AT)**
  - *Turbulence and energetic particle-driven modes*



- **High SNR data and advanced analysis enables study of:**
  - *Zonal flow/Geodesic Acoustic Mode (GAM)*
  - *Velocimetry (potential fluctuations, turbulent particle flux)*
  - *Nonlinear: energy transfer, cascades*