Physics and Engineering Goals for a Beam Emission Spectroscopy Density Fluctuation Diagnostic on NSTX

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Conceptual Design Review
Princeton Plasma Physics Laboratory
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NSTX

MOTIVATION TO IMPLEMENT A BES SYSTEM ON NSTX

- **NSTX provides unique opportunity for advanced studies of Turbulence & Transport in the ST regime:**
  - Numerous modes of operation: L, H, EP-H, RS modes
  - Array of profile diagnostics
  - Mature suite of fluctuation diagnostics (Scattering, GPI, Reflectometry, probes)
- **Intriguing observations on NSTX:**
  - Near neoclassical ion confinement in some regimes (H-mode)
  - Clearly non-neoclassical in L-mode
  - Differences in χ_I and χ_{MOM}
- **Unique opportunity to study underlying turbulent transport processes in ST**
  - Predicted inherent stability against longer-wavelength modes from high β' and high magnetic shear (C. Bourdelle)
- **BES will complement available fluctuation diagnostics and provide added long-wavelength, 2D capability**
  - *Wide fluctuation phase space to be investigated:*
    low-k, high-k, core, edge, n, T, B, f fluctuations
- **Opportunity to compare and contrast turbulence behavior in ST and Tokamak**
  - Extend dimensionless scaling studies (Aspect ratio, β)
- **Longer-Term: Contribute to the validation of turbulence simulations**

SPECIFIC CHALLENGES AND AN OPPORTUNITY FOR BES ON NSTX

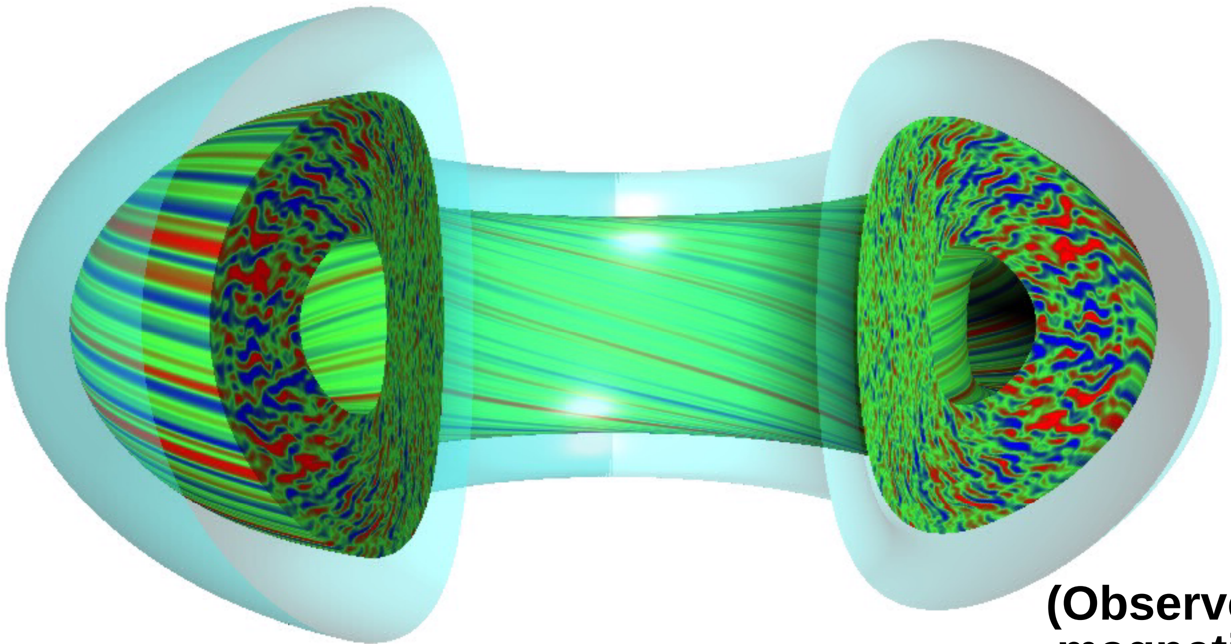
CHALLENGES

- *Viewing geometry: pitch angle, radial variation*
- *Carbon II emission lines near 658 nm (in desired spectral band)*
- *Limited access (coils, other diagnostics)*

OPPORTUNITY

- *Large ρ_I on NSTX (low B_T): access to higher normalized wavenumber*

BES Sight Lines Should be Aligned Nearly Tangent to Local Field Line at Intersection of Sight Line & NB

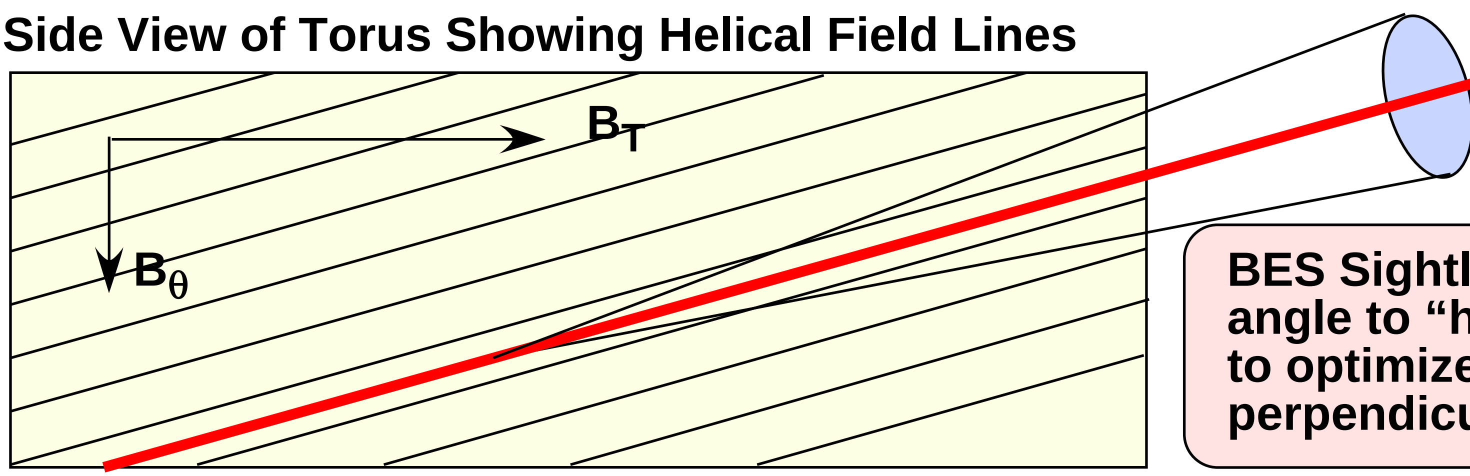


GYRO Simulation of Turbulence illustrate how eddy structures are aligned with magnetic field lines ($k_{||} << k_{\perp}$)

(Courtesy J. Candy, R. Waltz, GA)

(Observed experimentally on various magnetic confinement experiments)

Side View of Torus Showing Helical Field Lines



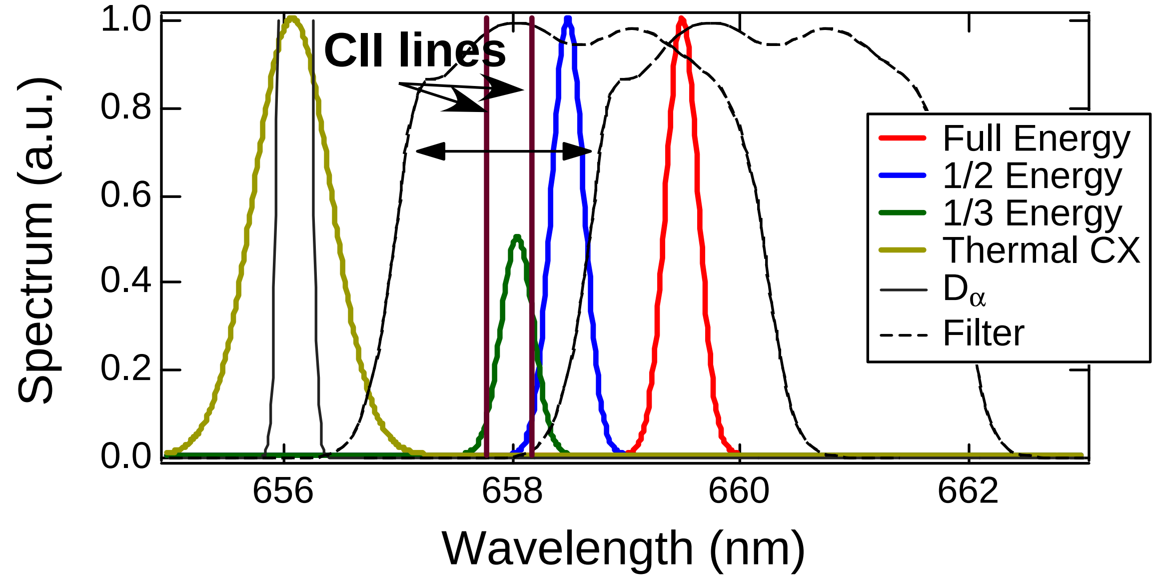
BES Sightlines at finite angle to "horizontal" to optimize spatial resolution perpendicular to *total* field

Makes BES on ST *INTERESTING*!

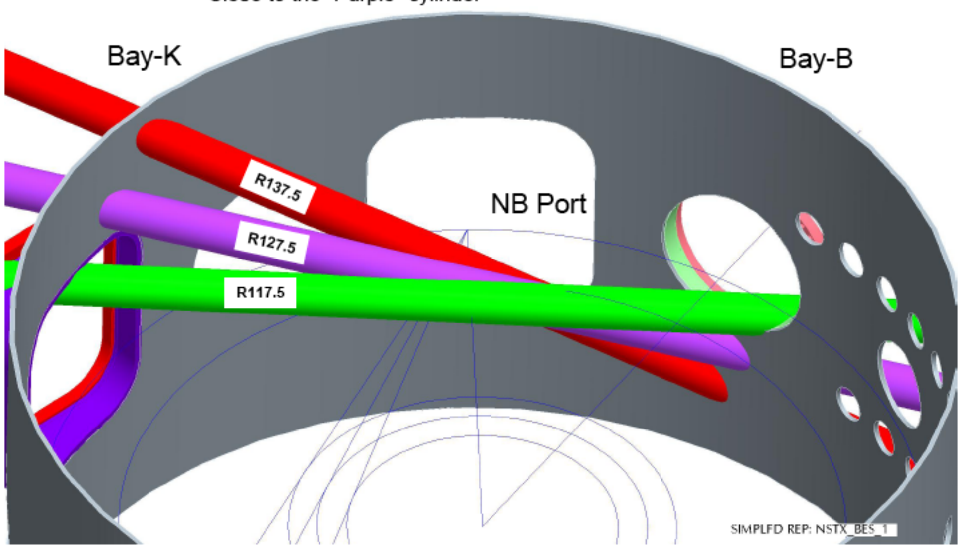
Observe Red-Shifted Beam Emission

- **Improved spatial resolution relative to blue-shifted view**
- **Access to view ports on machine (Bay-K virtually accessible)**

Simulated Beam Emission Spectrum
- 90 kV Deuterium beams
- Viewing Geometry/Angles



View of Z=50 mm optimal lines with a 6” cylinders
In the previous studies we were looking at an 8” bore
Close to the “Purple” cylinder



Edge Carbon lines potentially problematic:

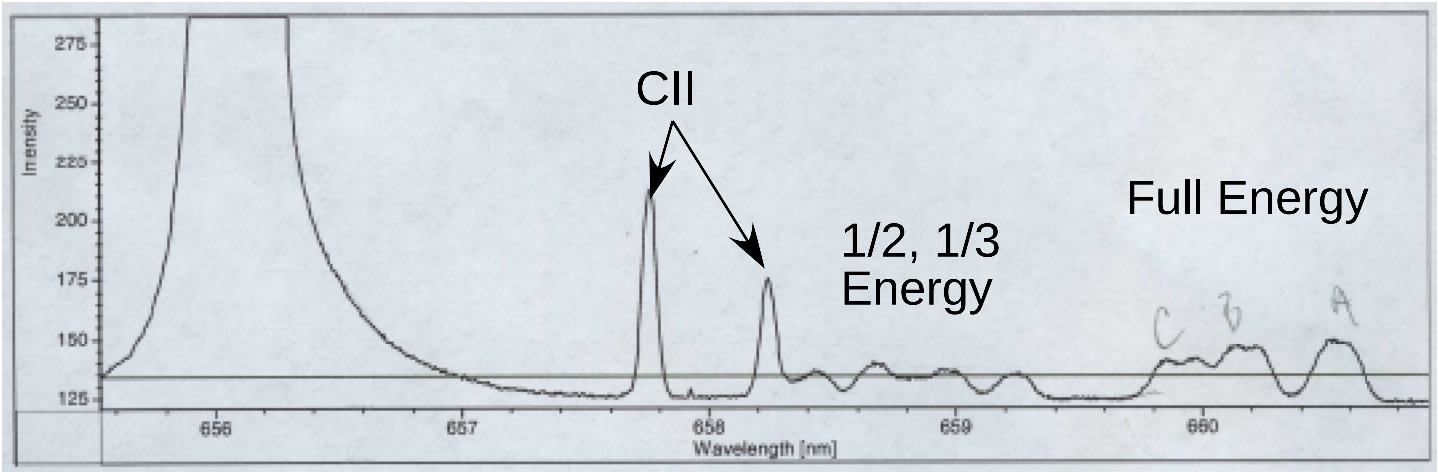
- Extra photon noise
- Delocalized fluctuation signal
- Error to normalization, $\tilde{n}/n$

Solution (not ideal):

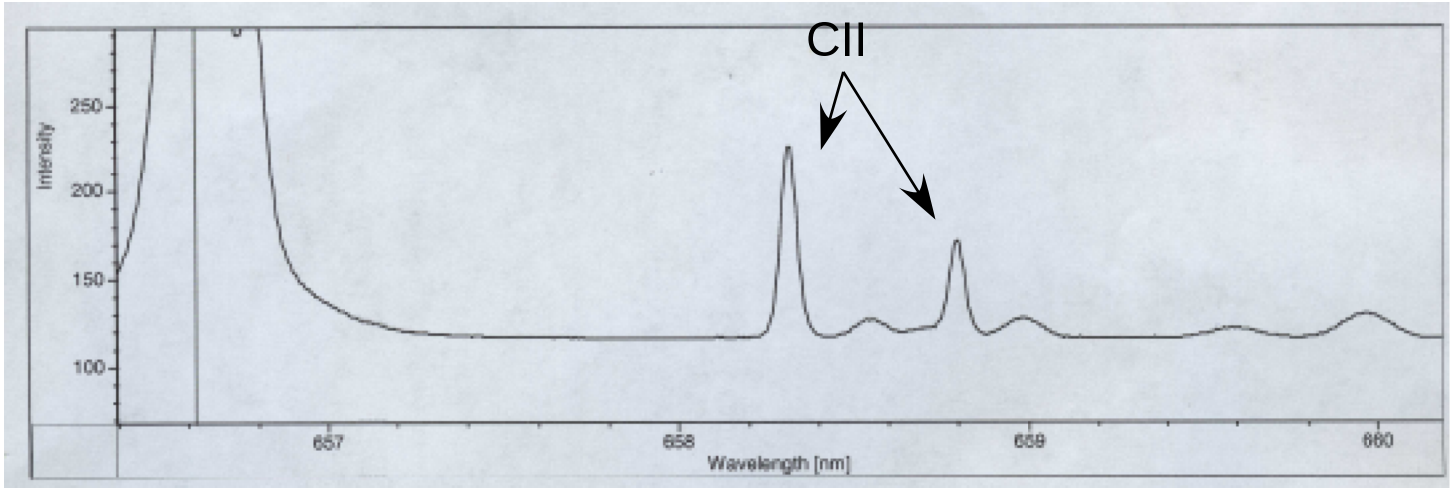
- Angle-tunable filter: design to avoid CII
- tilt-tune to optimize total signal
- small signal: minimal photon noise, low frequency fluctuations

"MSE" Spectra Show CII Lines

- Similar view to BES
- Time-integrated over shot (includes beakdown pulse at startup?)



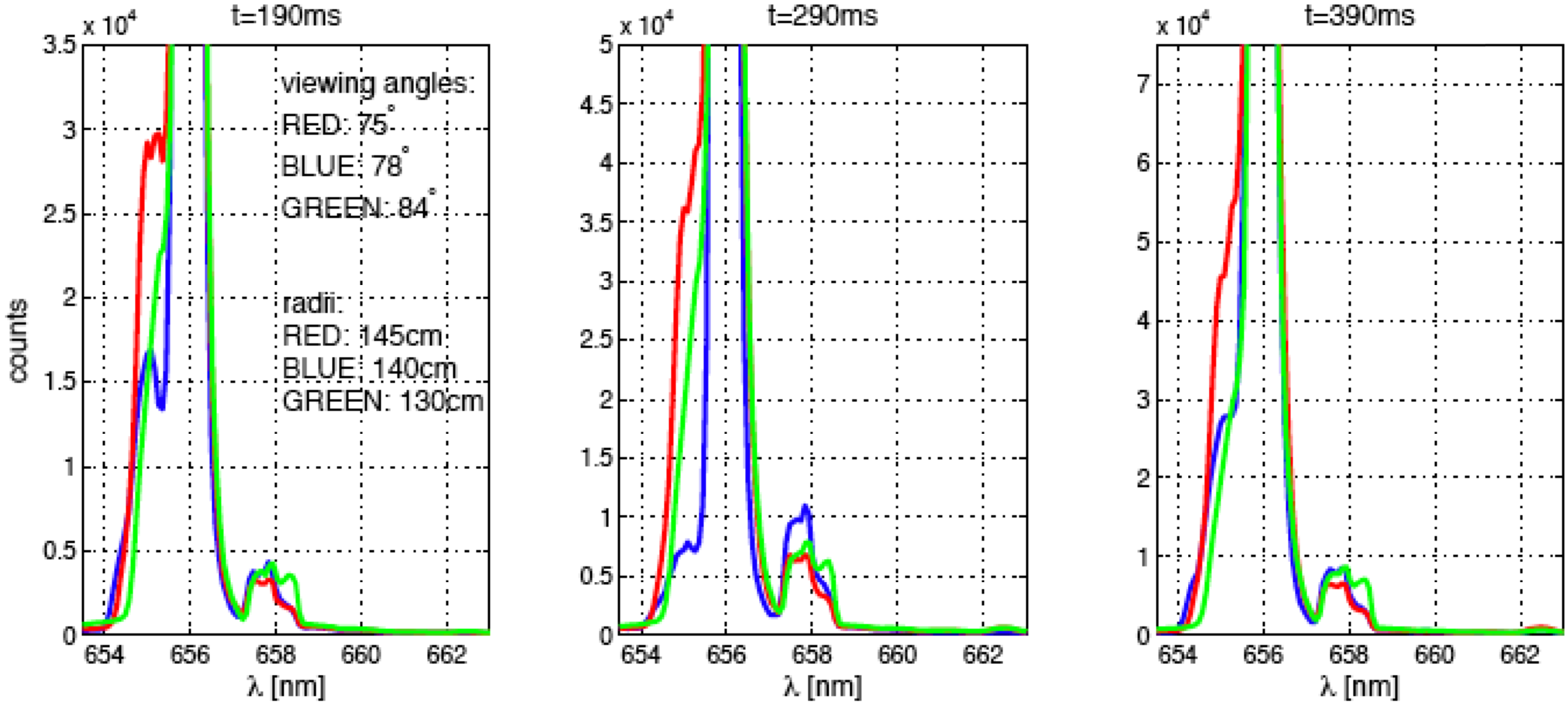
Core Spectrum



Edge Spectrum
(R=136 cm)

FIDA SPECTRA SHOW SMALLER CII LINES

- **Beam Emission appears to be ~10* more intense than CII**
  - *but viewing geometry is different (vertical v. diagonal)*

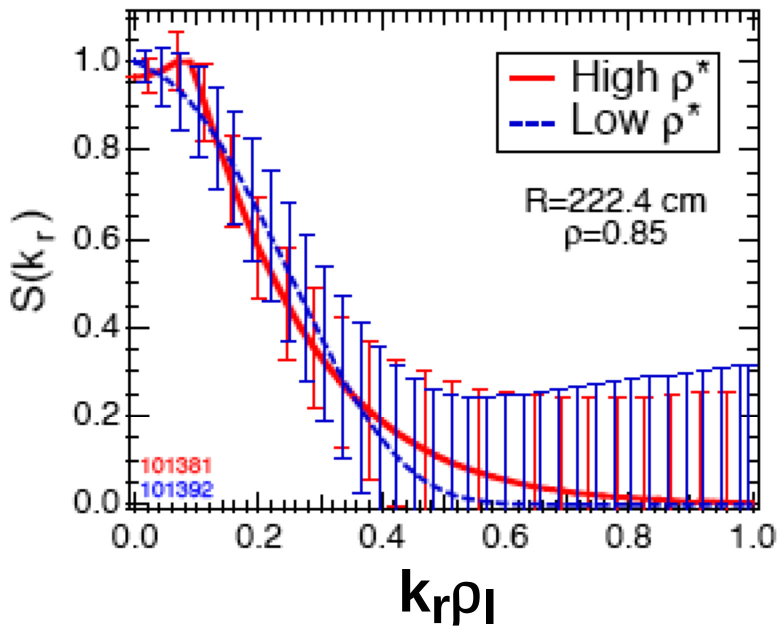


- **If CII intensity ~10% of beam emission, should be OK!**
  - **photon noise contribution minimal**
  - **edge light defocused, very low-k resolution: low frequency, spectral isolation**

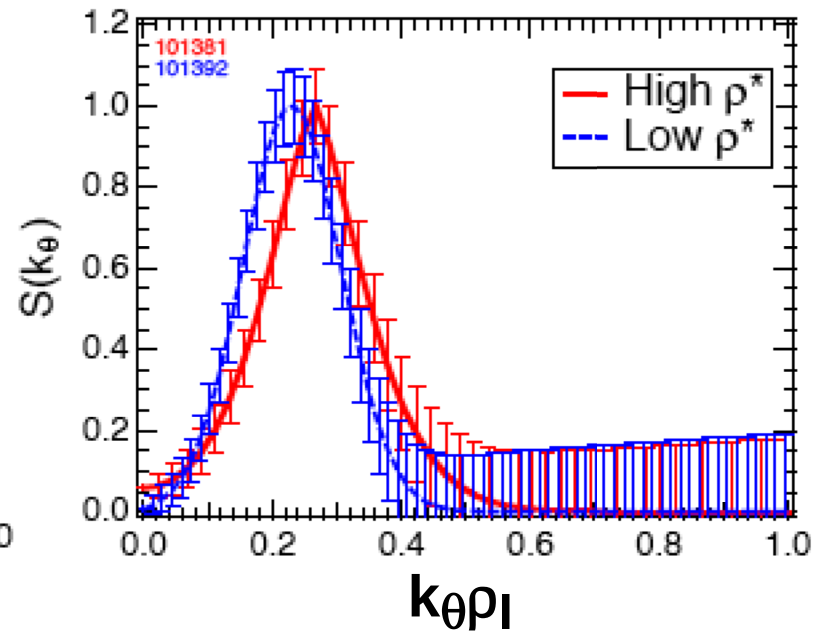
WAVENUMBER RESOLUTION: AIM TO MEASURE TURBULENCE WITH $k_{\perp}\rho_I \sim 1$

Normalized wavenumber spectra from BES@DIII-D:

Radial Spectrum



Poloidal Spectrum



$k_{\perp}\rho_{I(DIII\text{-}D)} \sim 0.3\text{-}0.9$ (spatial resolution limited)

NSTX design goal: $k_{\perp}\rho_I \geq 1$

(large ρ_I offers this opportunity, physics motiviation: ITG + TEM)

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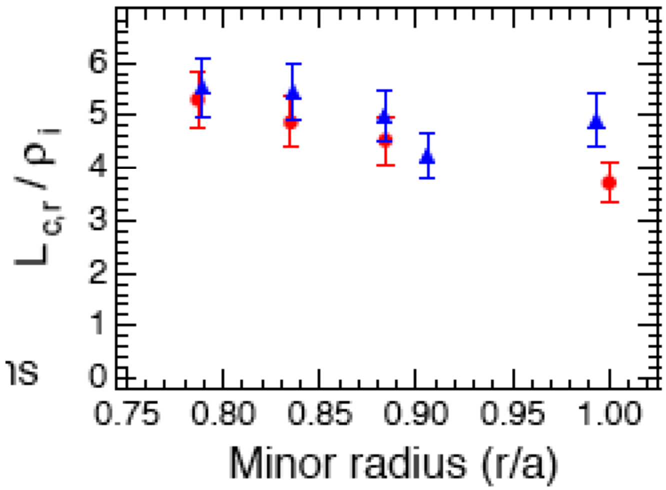
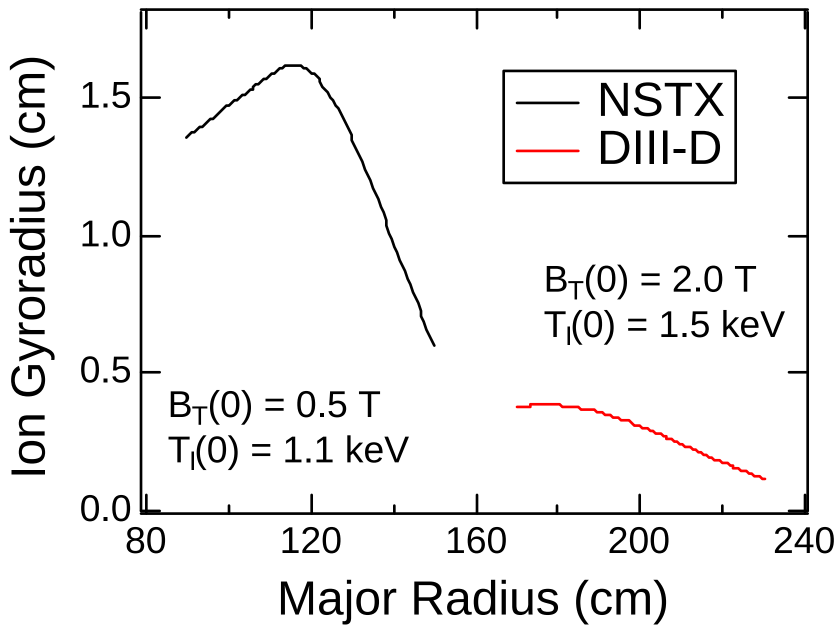
TURBULENT EDDIES SCALE WITH CORRELATION LENGTH: BIG ADVANTAGE FOR NSTX

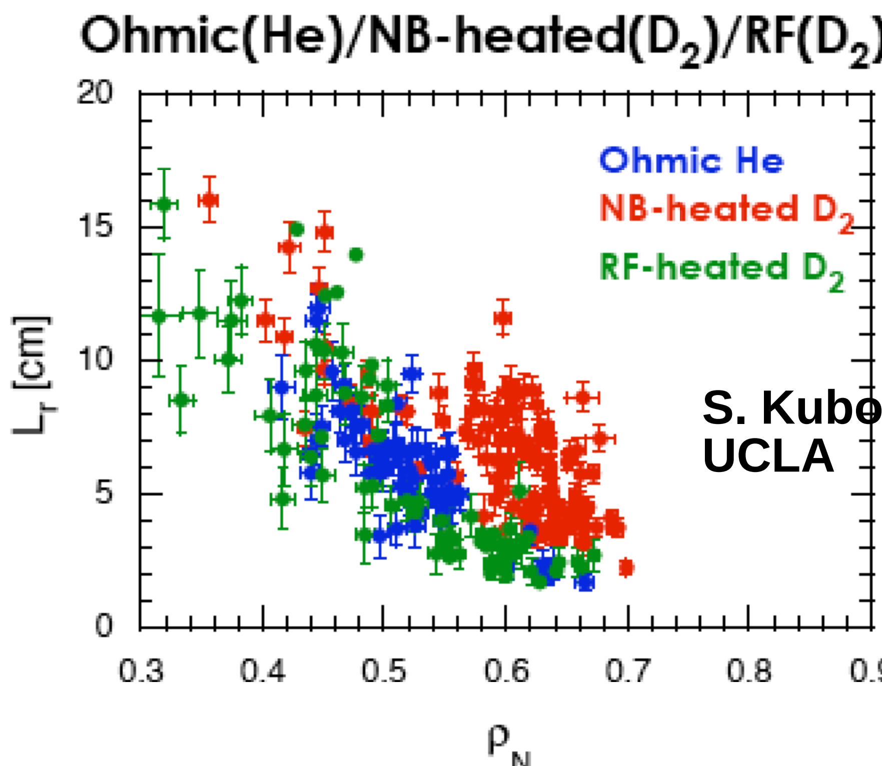


Scaling from previous DIII-D measurements:

$L_{c,r} \sim 5\rho_I$

Expect NSTX to be in this range, $L_{c,r} \sim$ 5-10 cm





S. Kubota, UCLA

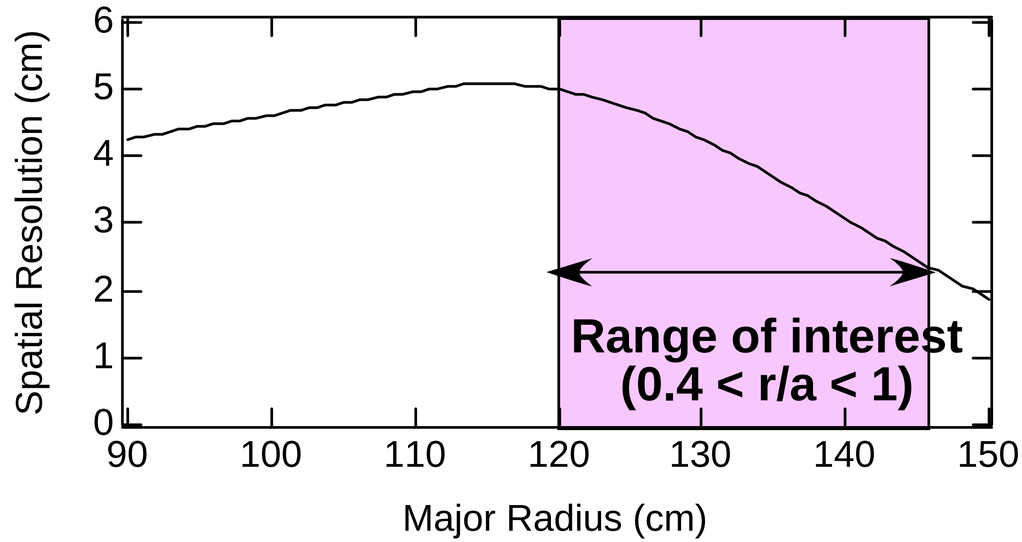
GPI measurements show Lc ~ 4 cm at edge

SPATIAL RESOLUTION TARGETS FOR NSTX BES

$\Delta X = \pi / k_{\perp,max} = \pi \rho_I$

(for $k_{\perp} \rho_I = 1$)

Desired spatial resolution



Reduce spot size for improved spatial resolution to access higher wavenumber turbulence:

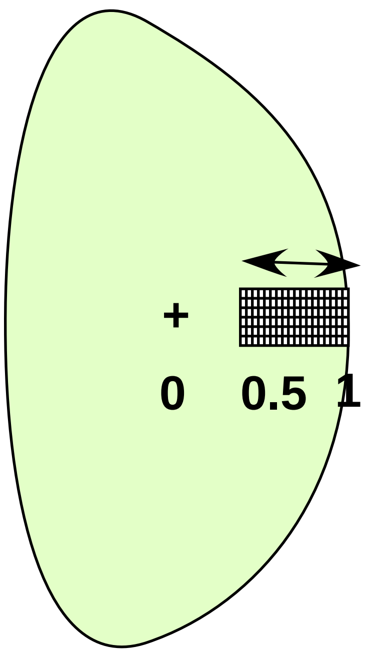
$\Delta X \leq 2$ cm

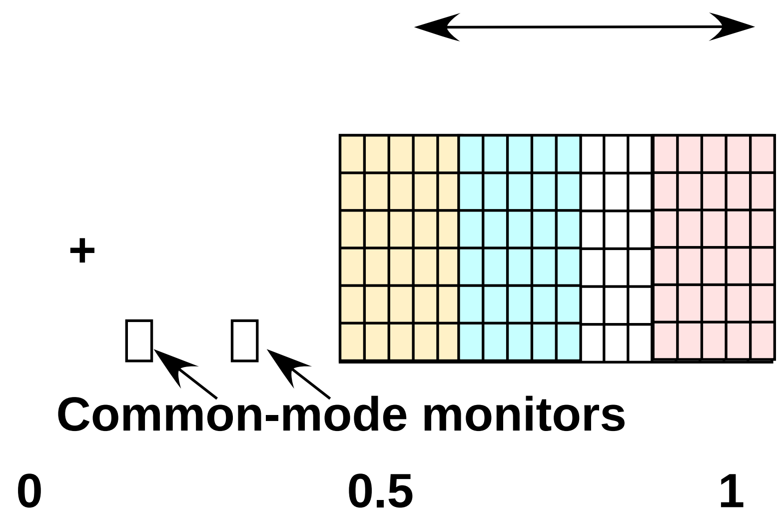
Better resolution near edge beneficial

- **Several factors limit actual spatial/wavenumber resolution:**
  - *Alignment of optical sightline to flux surface/field line*
  - *Helical field lines through sightline/beam intersection (~1-5 cm)*
  - *Finite lifetime of excited neutral beam atoms (~1.5 cm)*
- **Requires full PSF/STF calculation (TBD)**

SPATIAL COVERAGE: SPAN WIDE RADIAL REGION

- **Design goal: 0.4 < r/a < 1.0**
  - *Observe regions of greatest interest to turbulence/transport studies (mid-radius to edge), also of interest to XAE studies*
  - *Seek 32 simultaneous spatial detection channels (optimize physics)*
- **Deploy fiber bundles in image plane to cover much of plasma**





Fiber-scanning optical system in Test Cell

BES REQUIRES HIGH THROUGHPUT (ETENDUE) (LOTTA FIBERS, BIG OPTICS)

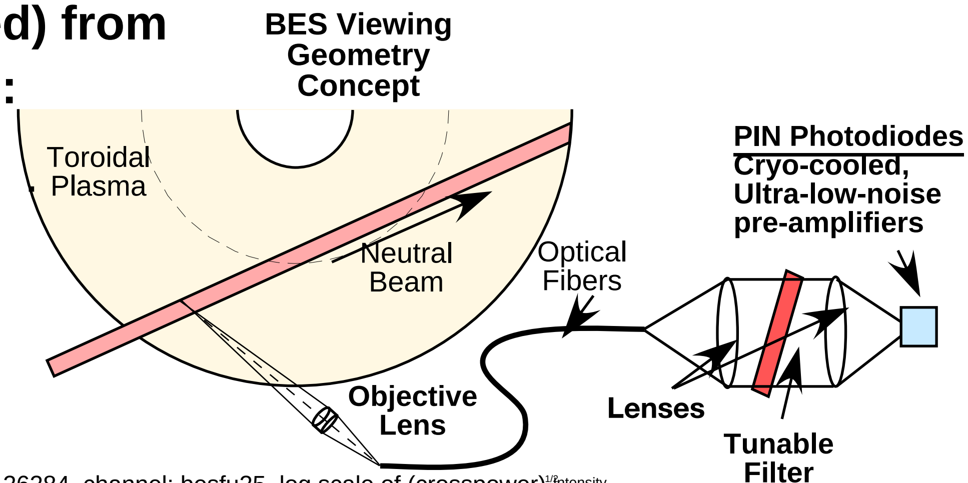
- **Light collection, $E = A * \Omega$, A=collection area, Ω = subtended solid angle**
- **In principle, calculate SNR ratio from beam intensity, plasma density, excitation cross-sections, emission rates, expected turbulence characteristics**
- **In practice, use DIII-D experience as a reference point:**
  - *Beam intensities are very similar*
  - *Plasma densities are similar*
- **$E_{D3D,BES}$ = 1.6 mm^2-ster (11 1-mm fibers, f/2)**
- **NSTX: fill fibers to actual N.A. limit: f/1.3 - f/1.5 (utilize fibers more efficiently)**
  - *verify that fibers can accept this light cone*
  - *observed by various researcher groups*
- **6 fibers/channel, 2(radial) x 3 (poloidal): $E_{NSTX,BES}$ = 1.52 mm^2-ster**
  - *Alternative: 9 fibers/channel: 2.3 mm^2-ster (50% higher throughput)*
- **Optical magnification: (ΔX ~ 2cm), M~7 (midradius), M~5 (edge)**

Summary of Engineering Parameters to Achieve Physics Goals

- **Spectral band: 657-660 nm, but obtain 659-662, angle-tune to proper range**
  - *CII emission lines are a concern*
  - *Blue-shifted viewing geometry not feasible (engineering), would achieve poorer resolution*
- **$k_{\perp}\rho_{I} \geq 1$ ==> ΔX = 2-5 cm, ≤ 2 cm optical resolution**
  - *beam-sightline geometry, optics, helicity, finite lifetime will reduce*
- **Radial range: 0.4 < r/a < 1**
  - *measure edge region: interesting physics (turbulence & XAE), overlap with GPI*
  - *Deeper core (r/a < 0.4) conceivable as future expansion*
- **Etendue: 1.5 mm^2-ster (6 1-mm fibers@f/1.5), up to 9 fibers for 50% increase**
  - *Similar or greater throughput compared with DIII-D BES*
- **Frequency: f_{SAMPLE} = 2 MHz [$f=w/2\pi$, $k_{peak}v_{ExB}/2\pi$], v_{ExB}**
- **Detection System: Employ DIII-D like system: optimized for ultra-low-noise, high light throughput:**
  - *cryogenics necessary? Expensive and difficult, modest gain at high signal*
  - *Avalanche photodiodes vs. PIN/cooled-preamp*
- **Russ will show us how to accomplish this!**

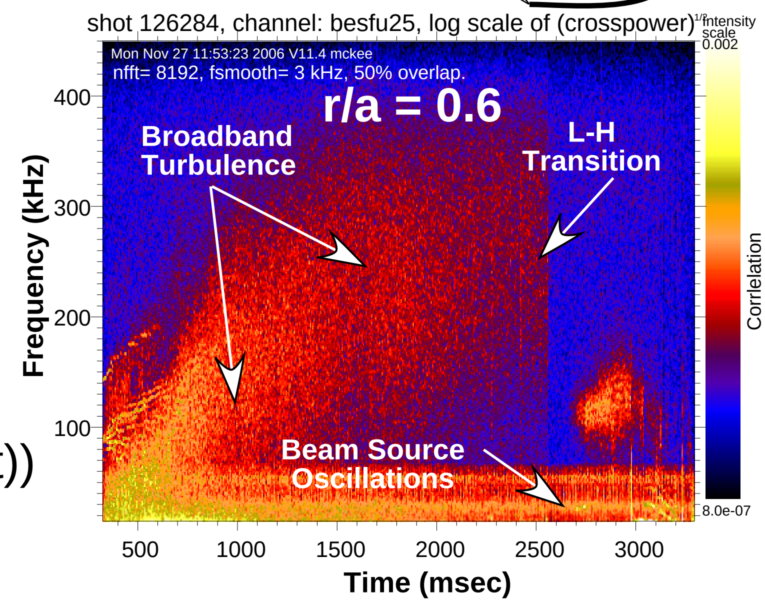
BES Measures Spatio-Temporal Characteristics of "Long-Wavelength" ($k_\perp \rho_I < 1$) Density Fluctuations

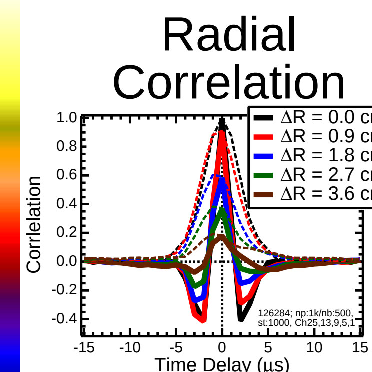
- **Measures intensity of D_α (Doppler-shifted) from collisionally-excited neutral beam atoms:**
  - Relate *I* to *n* (via atomic physics)
  - Core, edge & SOL
  - ΔR, ΔZ ~ 1 cm,
  - Multi-channel (R,Z) ==> 2D imaging

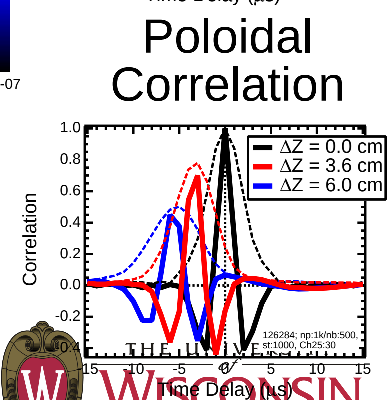


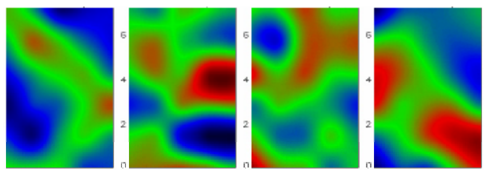
Turbulence Properties Measured:

- Local Turbulence Spectra
- Fluctuation amplitude ($\tilde{n}/n$)
- Correlation Lengths: $L_{c,r}$, $L_{c,\theta}$
- Decorrelation Time, τ_c
- Poloidal advection, v_θ
- Eddy structure via imaging
- Time varying poloidal flows ($\tilde{v}_\theta(t)$) (Zonal Flows, GAMs)
- Bispectra, phase coherence (nonlinear: energy transfer)
- Velocity Field (**v**(r,θ,t) via velocimetry









NSTX

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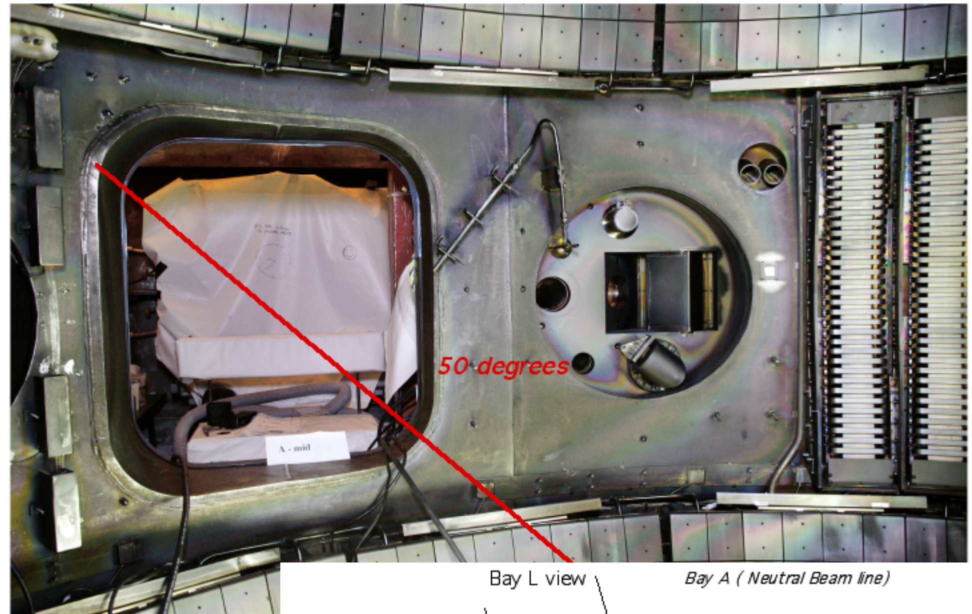
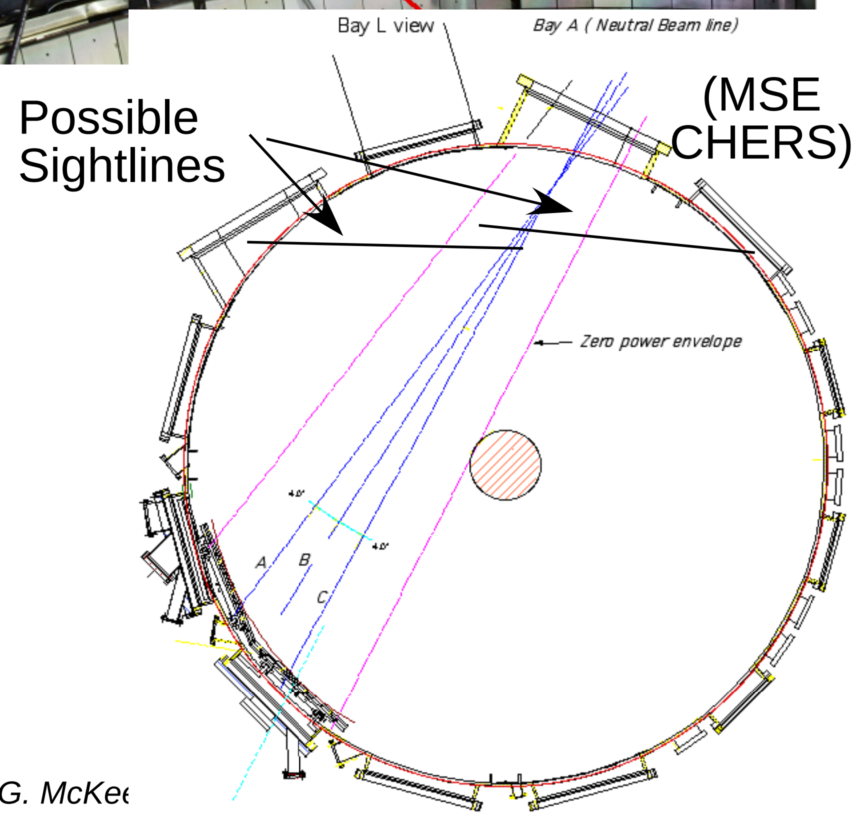
Opportunities and Issues for Consideration

- **High T_I, low B_T ==> Large ρ_I, $L_{c,r}$**
  High spatial resolution and wavenumber sensitivity, $L_{c,r}$: 2-20 cm
  (S. Kubota, APS-06, S. Zweben, GPI)
- **Spatial resolution and radial coverage will depend sensitively on local magnetic field pitch angle:**
  - *3 NB sources*
  - *Viewing geometry considerations*
  - *Core vs. Edge*
  - *Focus on core turbulence?*
    - *Flat q-profile to large radius*
  - *Diagnostic Discussion next week...*
- **Carbon edge lines near 658 nm?**
- **BES can study:**
  - *Alfven eigenmode structure*
  - *Pedestal/ELMs*
  - *MHD structure*





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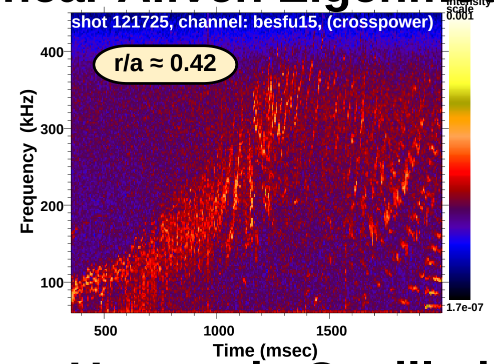
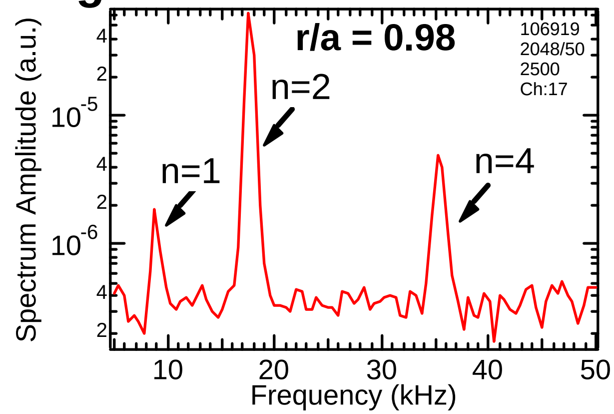
BES Measurements Applicable to Wide Variety of Plasma Instabilities

- **Measurements provide important data on a wide range of phenomena:**
  - *Energetic-particle-driven modes: Alfven Eigenmodes*
  - *Neoclassical Tearing Modes*
  - *Sawtooth interchange effects*
  - *Pedestal dynamics*
  - *Edge Localized Modes*
  - *Edge Harmonic Oscillation (in Quiescent H-mode)*
  - *Quasi-Coherent Mode (in Enhanced D_{α} H-mode)*
  - *Resonant Magnetic Perturbation Effects*
  - *Edge - Scrape Off Layer interaction: "blob" generation*

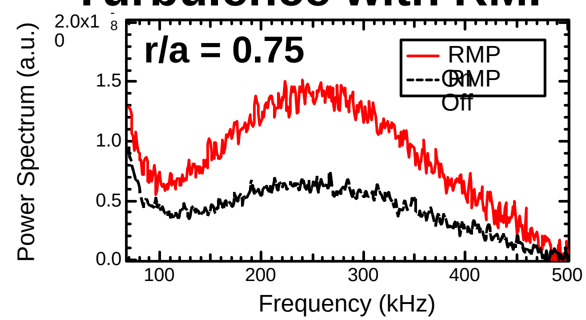
Reversed-Shear Alfven Eigenmodes



Edge Harmonic Oscillation



Turbulence with RMP

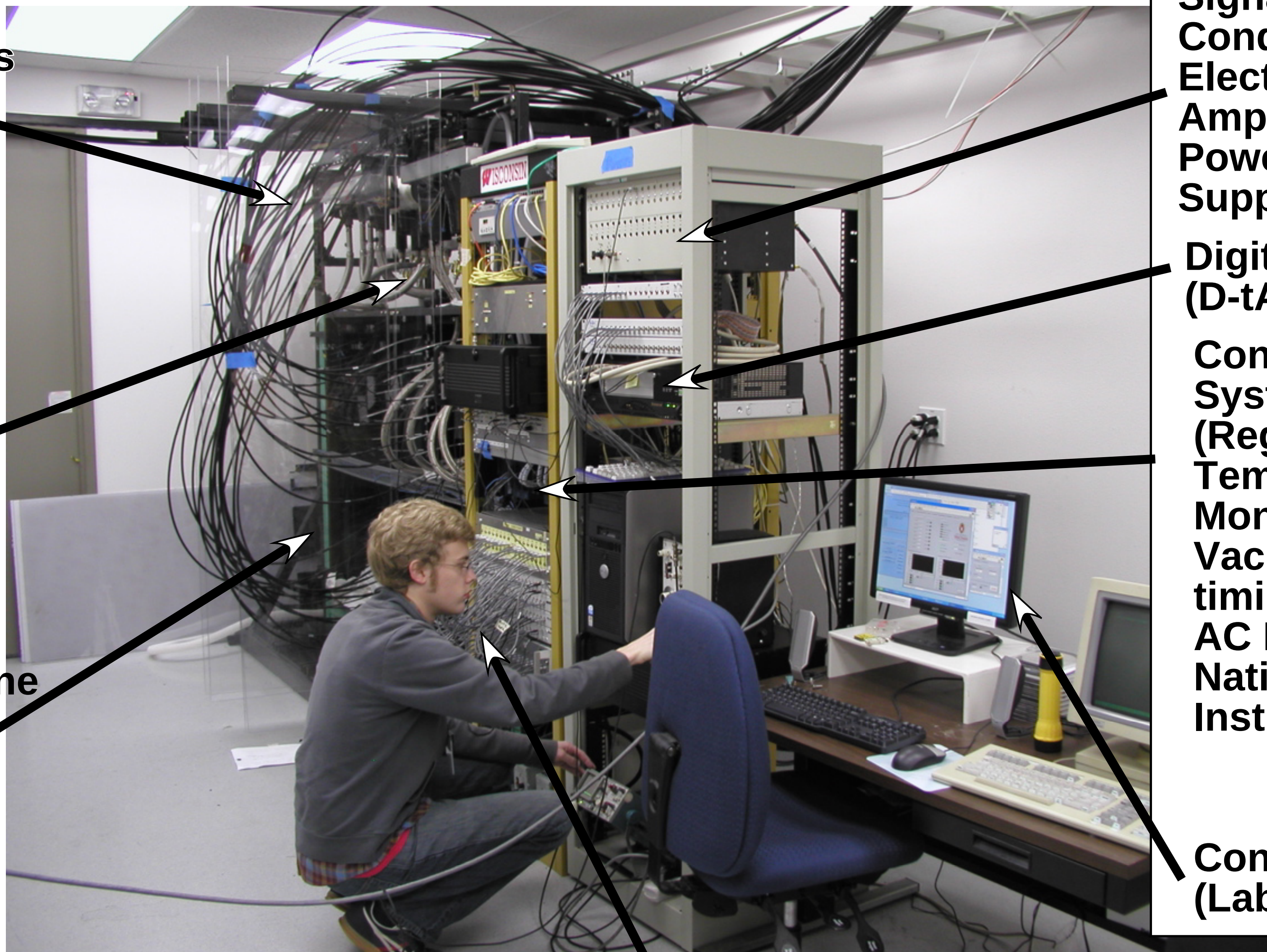


Overview of the Beam Emission Spectroscopy System at DIII-D

Fiber Optics

Cryogenic Lines, Manifold, Transfer Lines

5-ton Pb & Borated Polyethylene Radiation Shield



Signal Conditioning Electronics, Amplifiers, Power Supplies

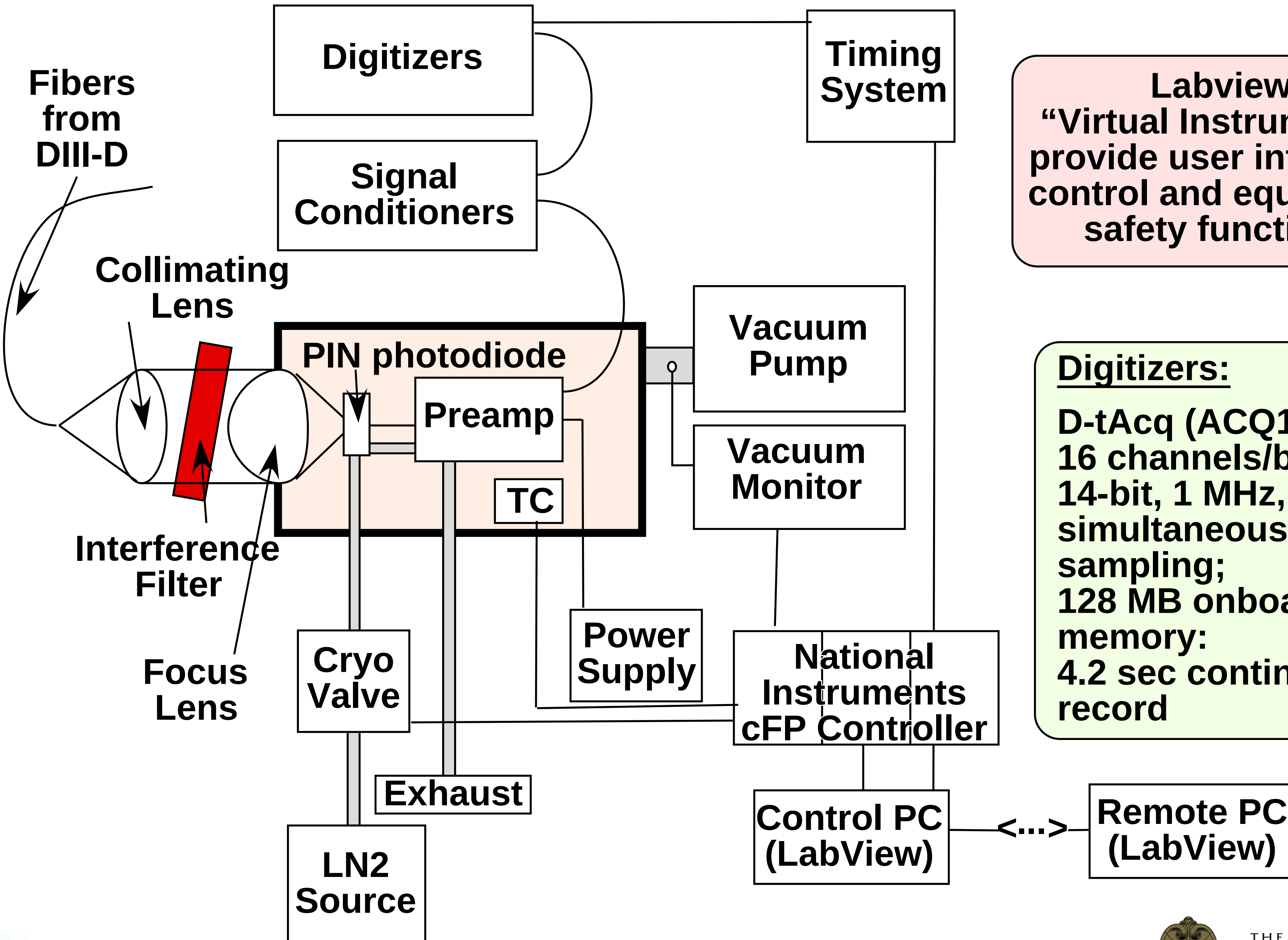
Digitizer (D-tAcq)

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

Control PC (Labview)

Morgan, the Graduate Student

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

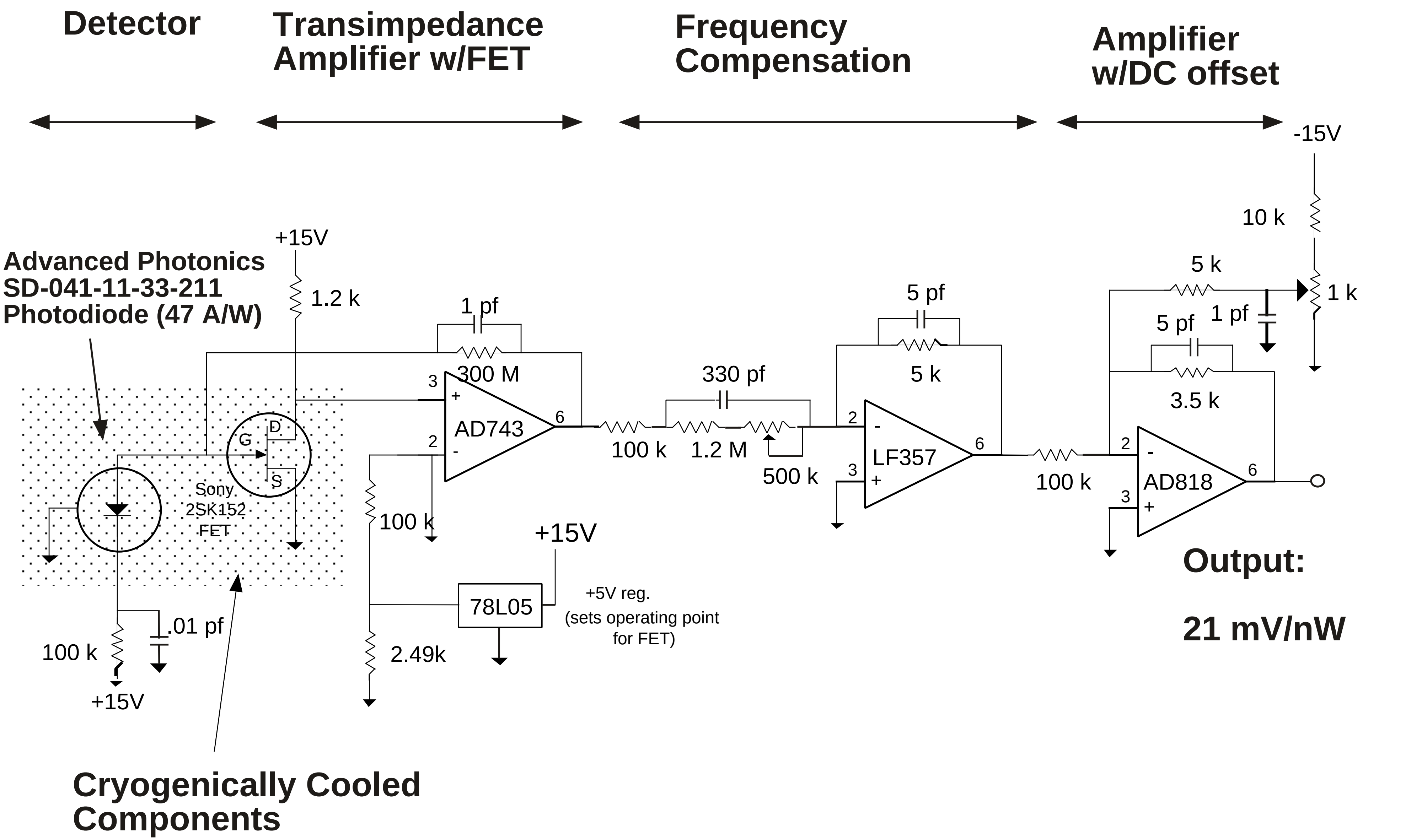


Labview "Virtual Instruments" provide user interface, control and equipment safety functions

Digitizers:

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

CUSTOMIZED, CRYOGENICALLY-COOLED TRANSIMPEDANCE PREAMPLIFIER PROVIDES ULTRA-LOW-NOISE SIGNAL AMPLIFICATION



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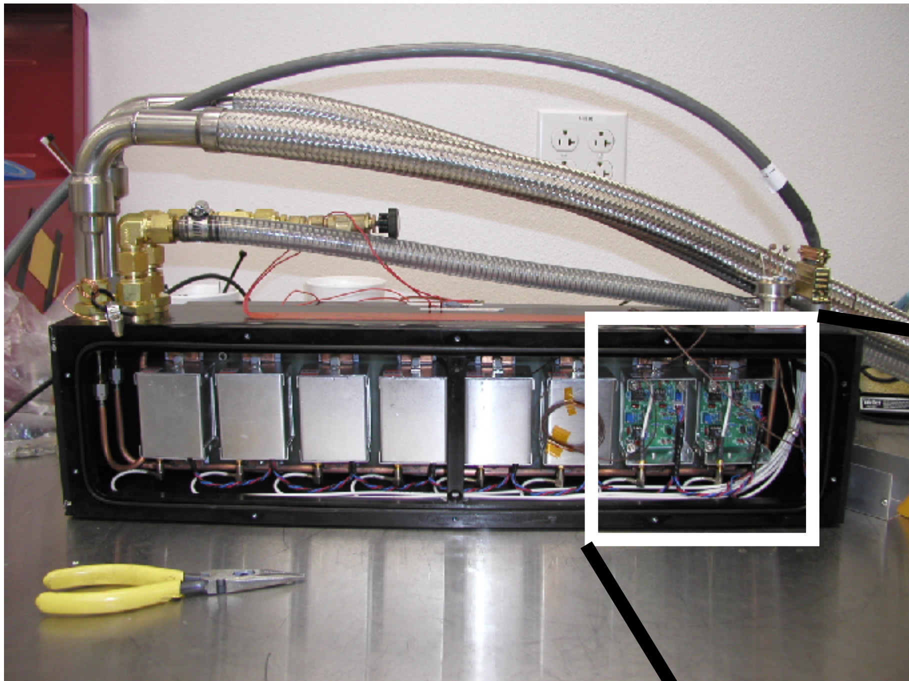
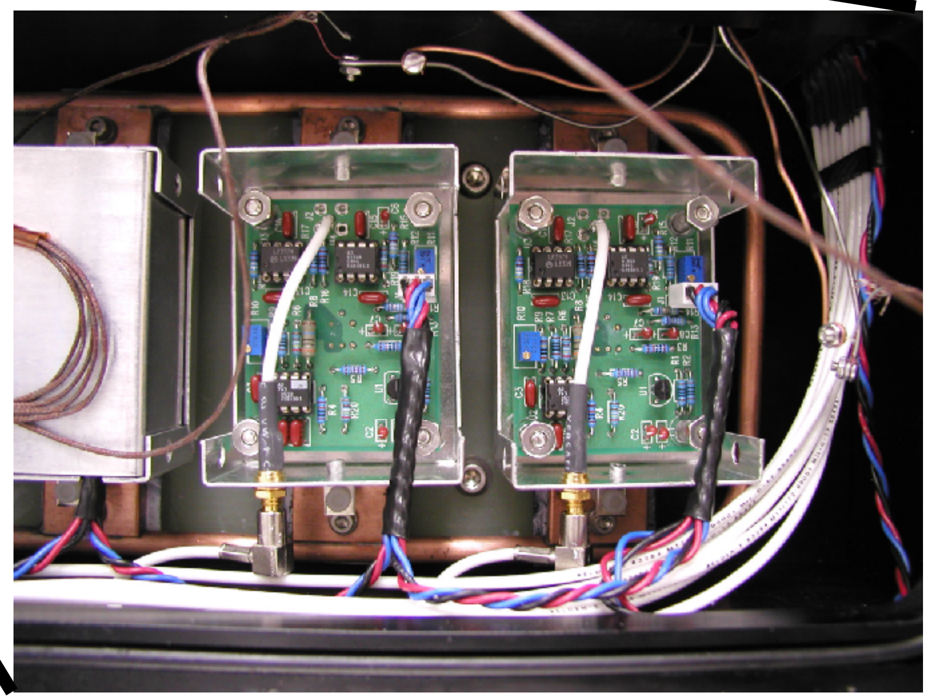
Customized Detector Module and Preamplifier Provide Ultra Low-Noise Signal Detection



Input/Exhaust Vacuum-jacked LN2 lines

Vacuum pump lines (operated near 30 mTorr)



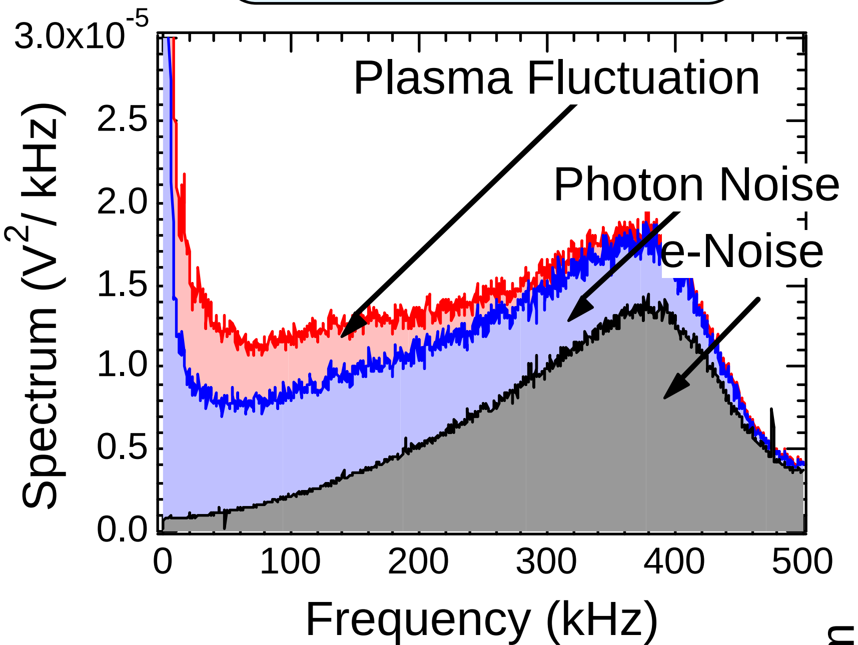
Copper LN2 line provides thermal transfer to PIN photodioes and first-stage FET

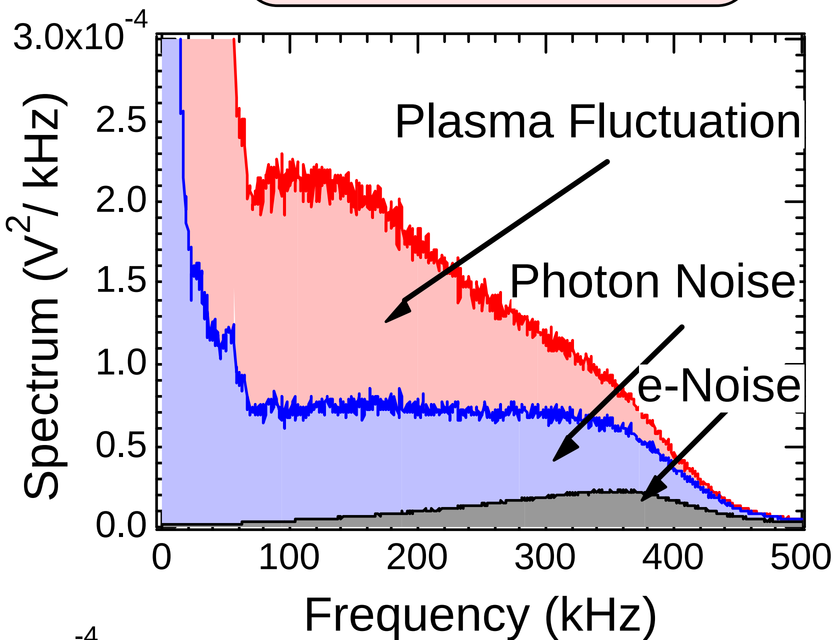
Factor of 30-50 Increase in Sensitivity to Plasma Density Fluctuation Power with Upgraded BES System

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