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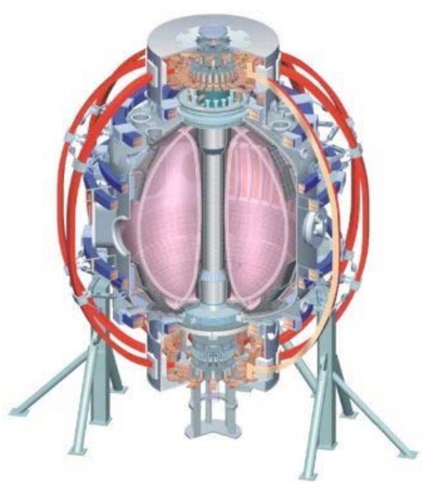
Design and status of the NSTX beam emission spectroscopy (BES) diagnostic for ion gyroscale fluctuation measurements

David R. Smith, R. J. Fonck, G. R. McKee, I. Uzun-Kaymak,
G. Winz (*UW-Madison*), H. Feder, R. Feder, G. Labik,
and B. C. Stratton (*PPPL*)

51st Annual Meeting of the APS Division of Plasma Physics
Atlanta, GA
November 2-6, 2009



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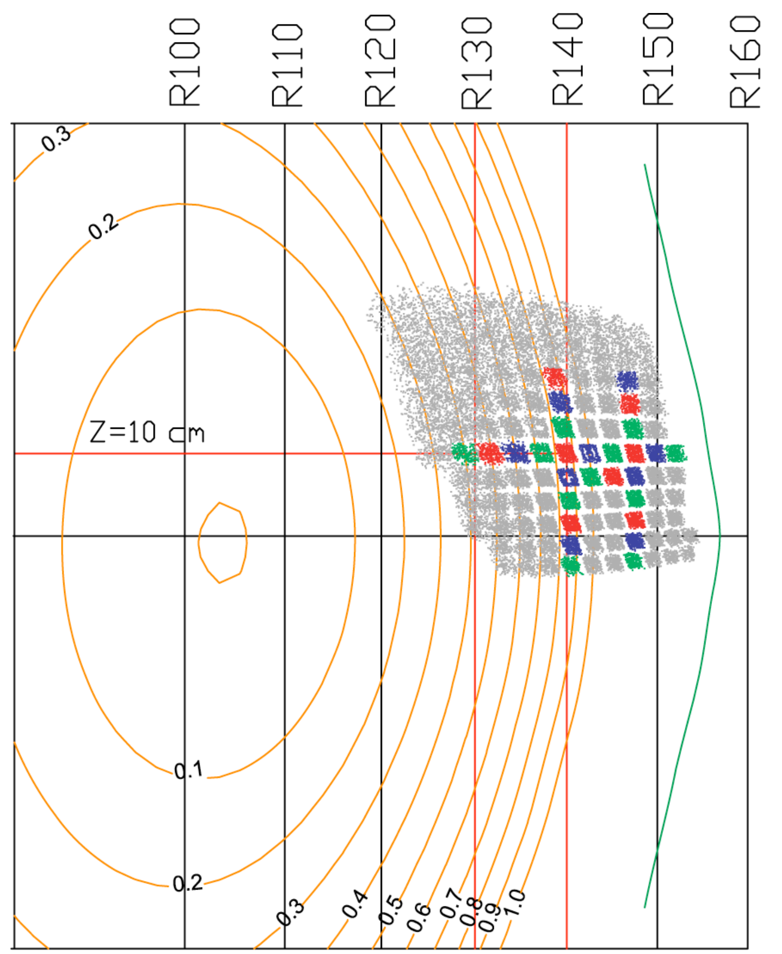
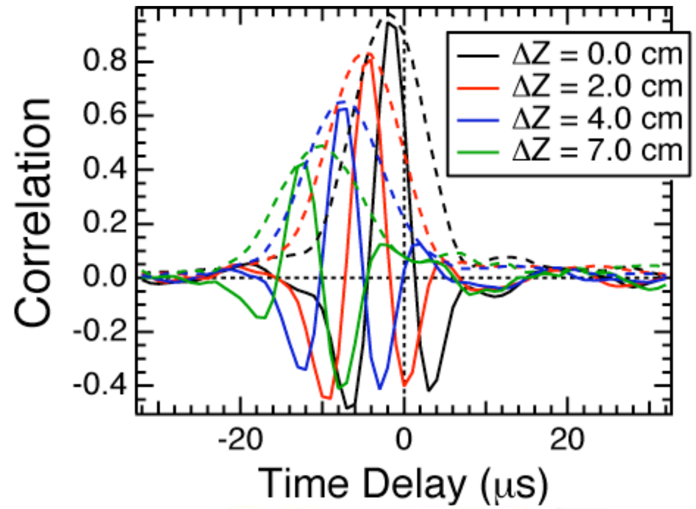
Outline

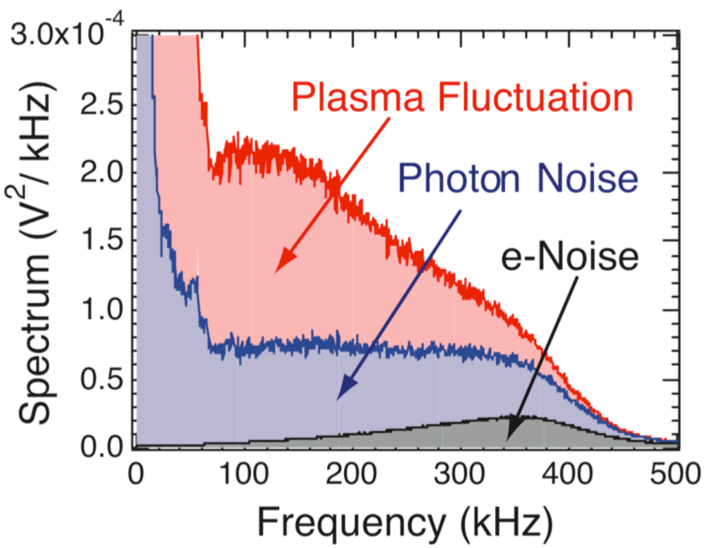
- Motivation
- BES measurement principles
- Optical design
  - Viewing geometry
  - Collection optics
  - Aperture plate
  - Fiber bundles & spot sizes
  - Interference filters
- Detection system design
  - Photodiode & FET preamplifier
  - Photon noise & e-noise
  - Digitizer with true 2 MHz sampling
- Control system design
- Status & plans
- Summary

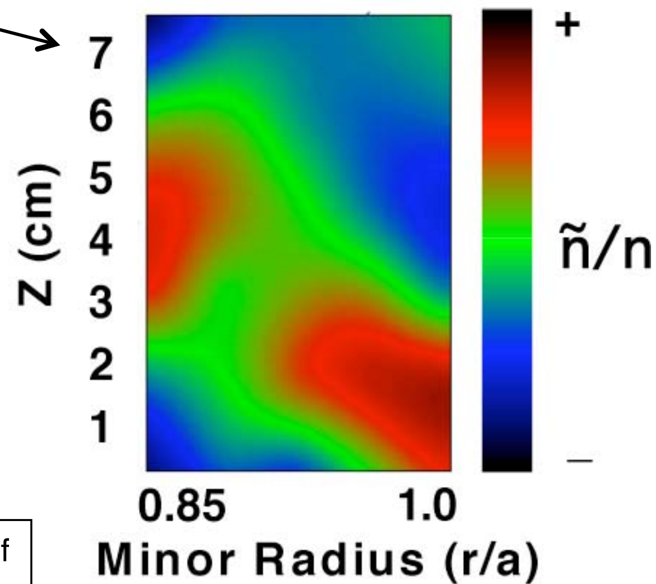


Beam emission spectroscopy (BES) is a diagnostic technique for measuring ion gyroscale fluctuations

- Measured & derived quantities
  - Fluctuation amplitudes
  - Frequency spectra
  - Radial and poloidal correlation lengths
  - Decorrelation times
  - Poloidal flow, flow fluctuations, flow shear, and 2D flow fields
  - 2D fluctuation imaging
  - 3-wave bispectral analysis
  - Particle flux







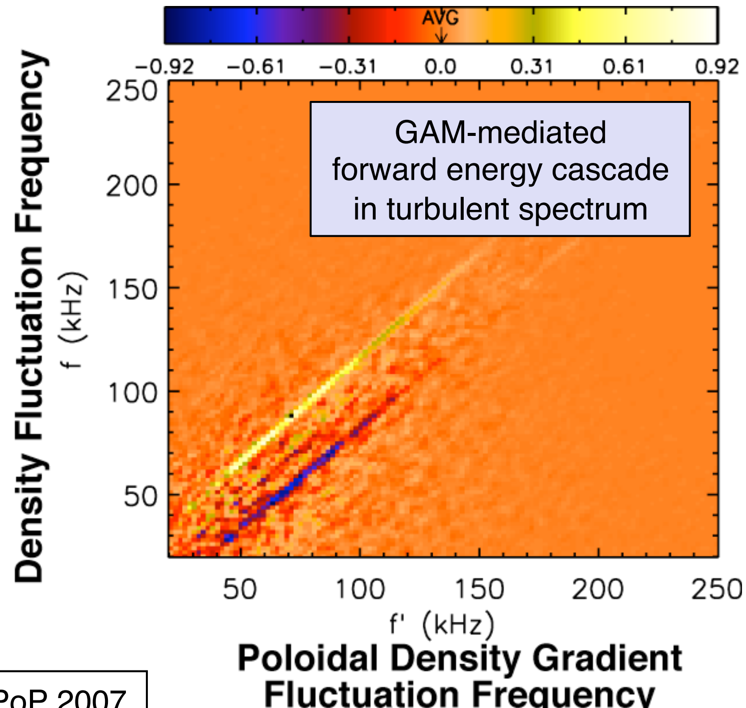
Figures courtesy of DIII-D BES group

BES measurements contribute to many research topics

- Turbulence & transport
  - Momentum transport
  - Transport barriers
  - Flow shear suppression
  - Zonal flows/GAMs
  - Turbulence spreading & nonlocal transport
  - Nonlinear 3-wave mode coupling
  - Turbulence code validation

- Boundary physics
  - LH transition
  - H-mode pedestal
  - ELMs & peeling-ballooning modes

- MHD instabilities
  - Alfven eigenmodes (RSAE, CAE, GAE, TAE, and others)
  - Energetic particle modes
  - Mode structures

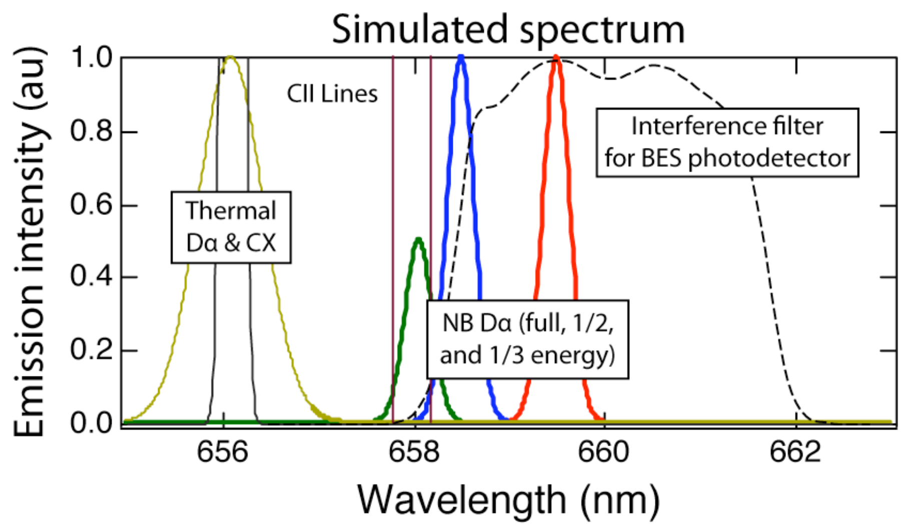


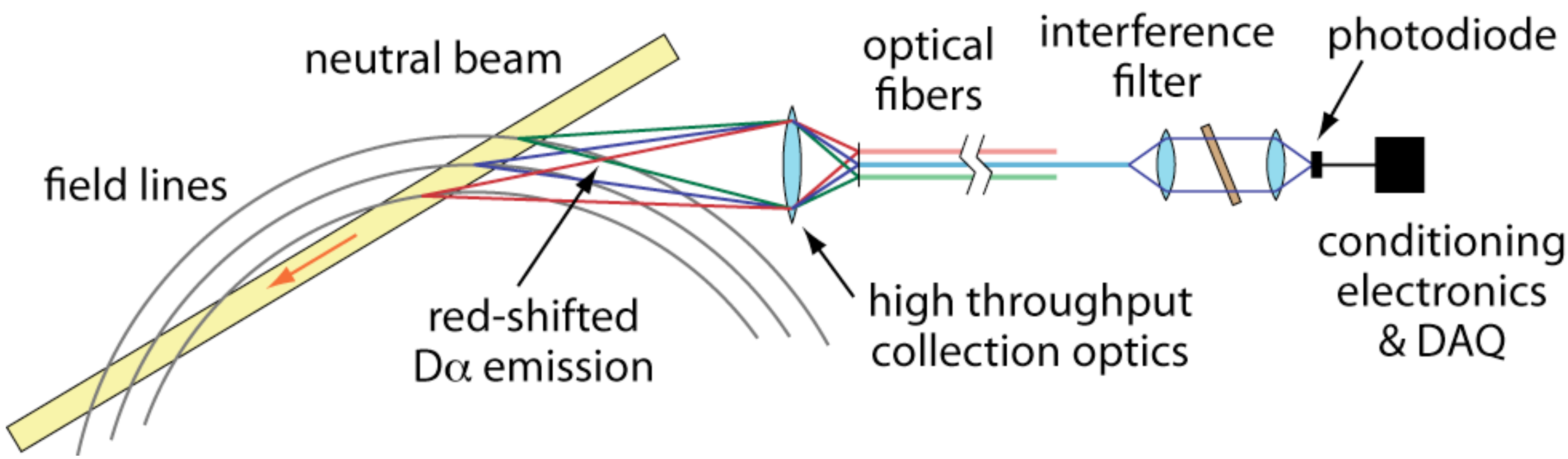
Holland et al, PoP 2007

BES measures Doppler-shifted D_α emission from neutral beam particles to resolve ion gyroscale fluctuations

$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{1}{2} \times \frac{\delta n_i}{n_i} \times C\left(E_{NB}, n_e, T_e, T_i, Z_{eff}\right)$$

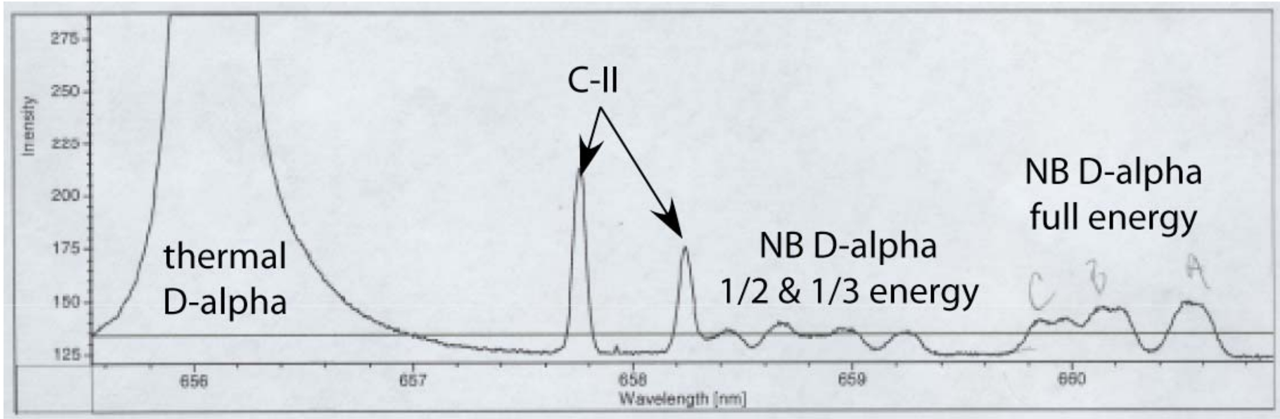
- neutral beam D_α emission
- ion density fluctuation
- weak function





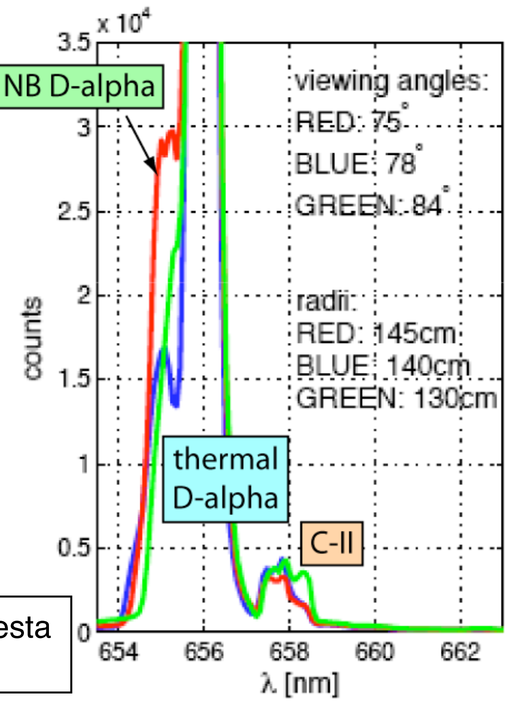
MSE & FIDA measurements on NSTX indicate NB D_α emission is comparable to or greater than C-II emission

MSE spectrum
tangential view with
large red-shift in NB D_α
and long-time integration



Courtesy of H. Yuh & F. Levinton

FIDA spectrum
vertical view with
small blue-shift in NB D_α
and short-time integration



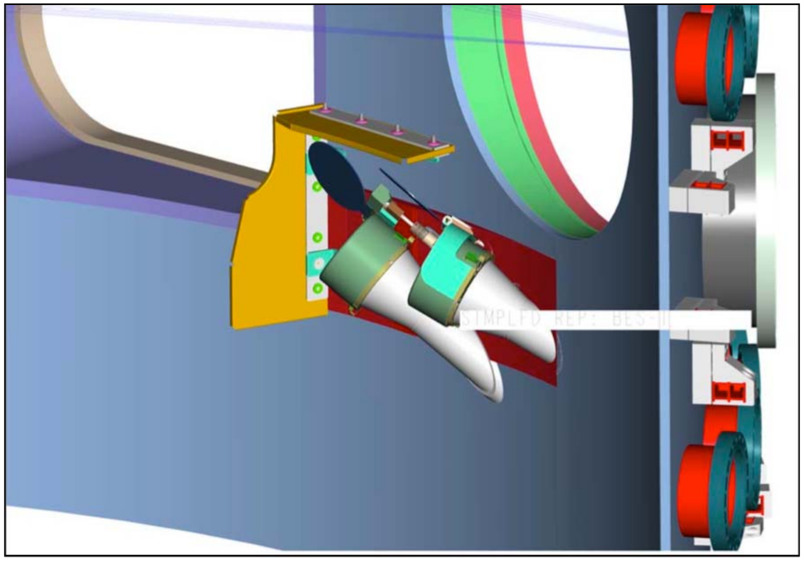
Courtesy of M. Podesta & W. Heidbrink

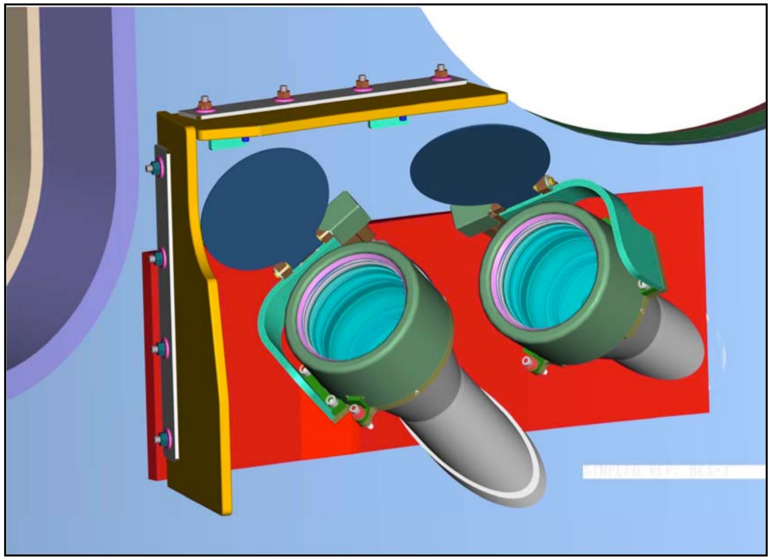
MSE & FIDA spectra indicate:

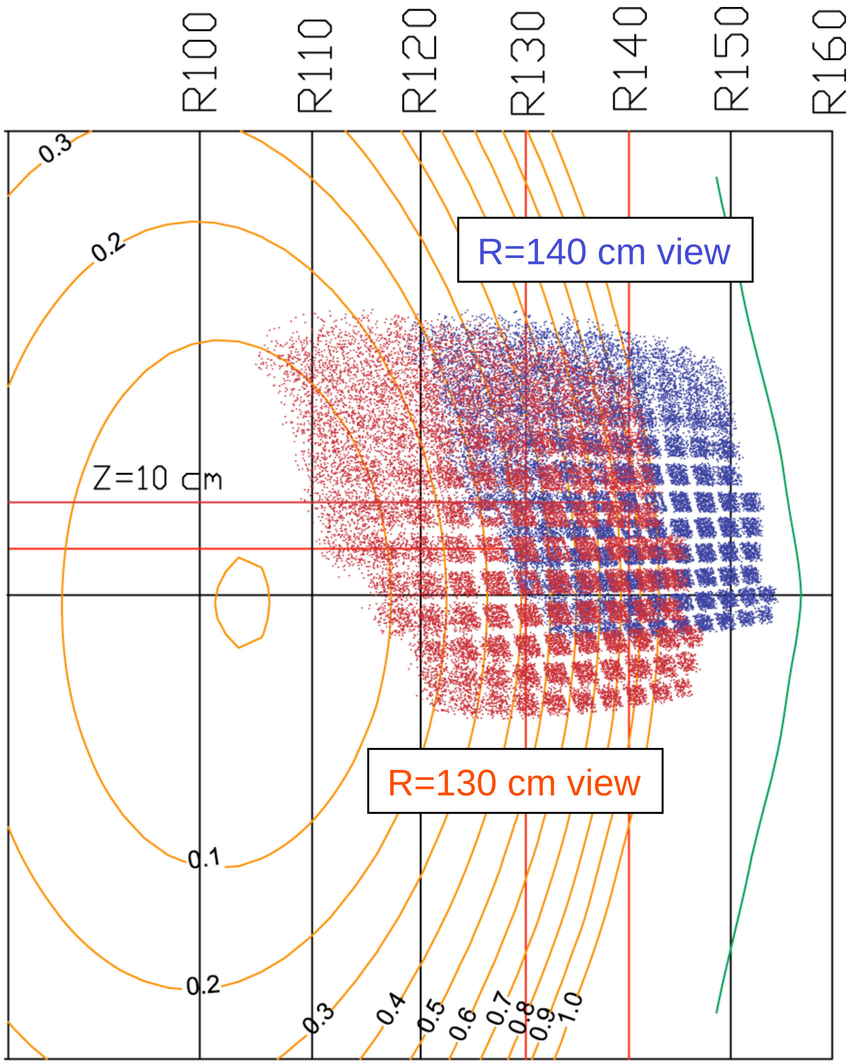
$$\frac{I_{NB\ D\alpha}}{I_{C-II}} \approx 1-10$$

The NSTX BES view is similar to the MSE view

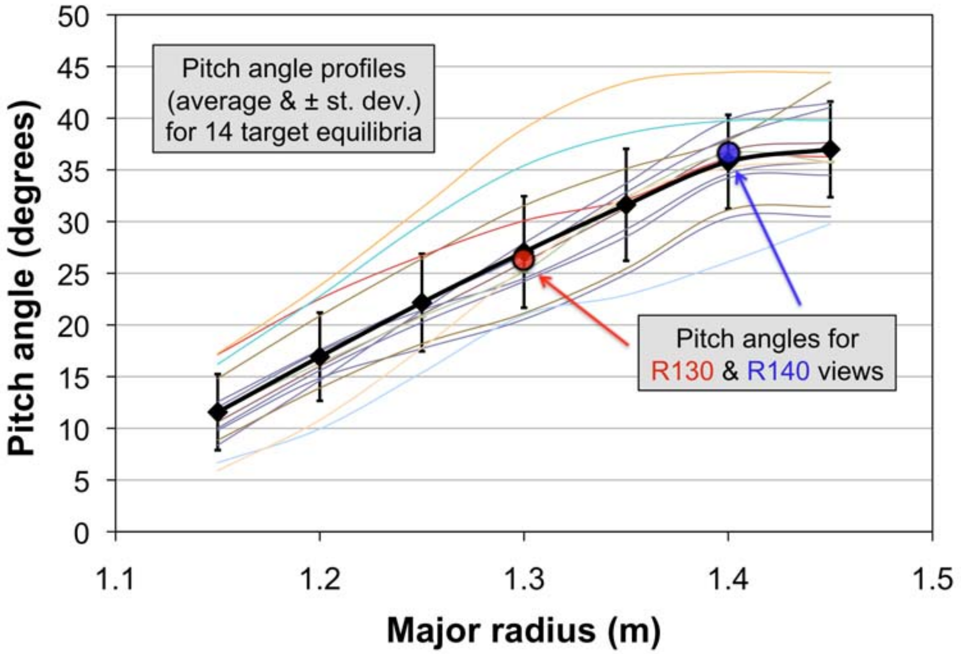
The NSTX BES system includes two optical views centered at R = 130 cm and 140 cm

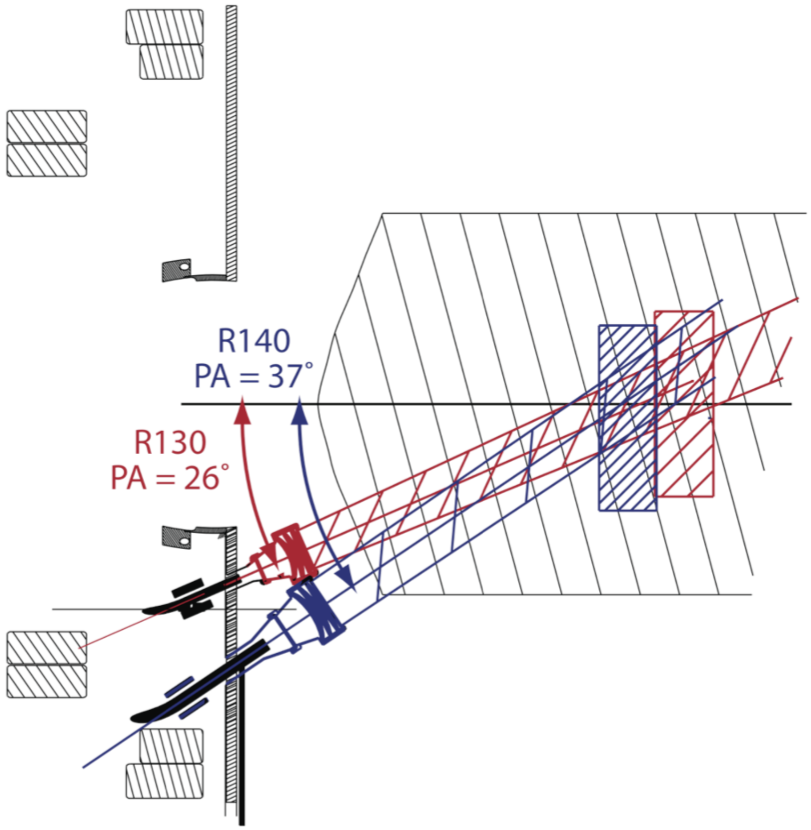




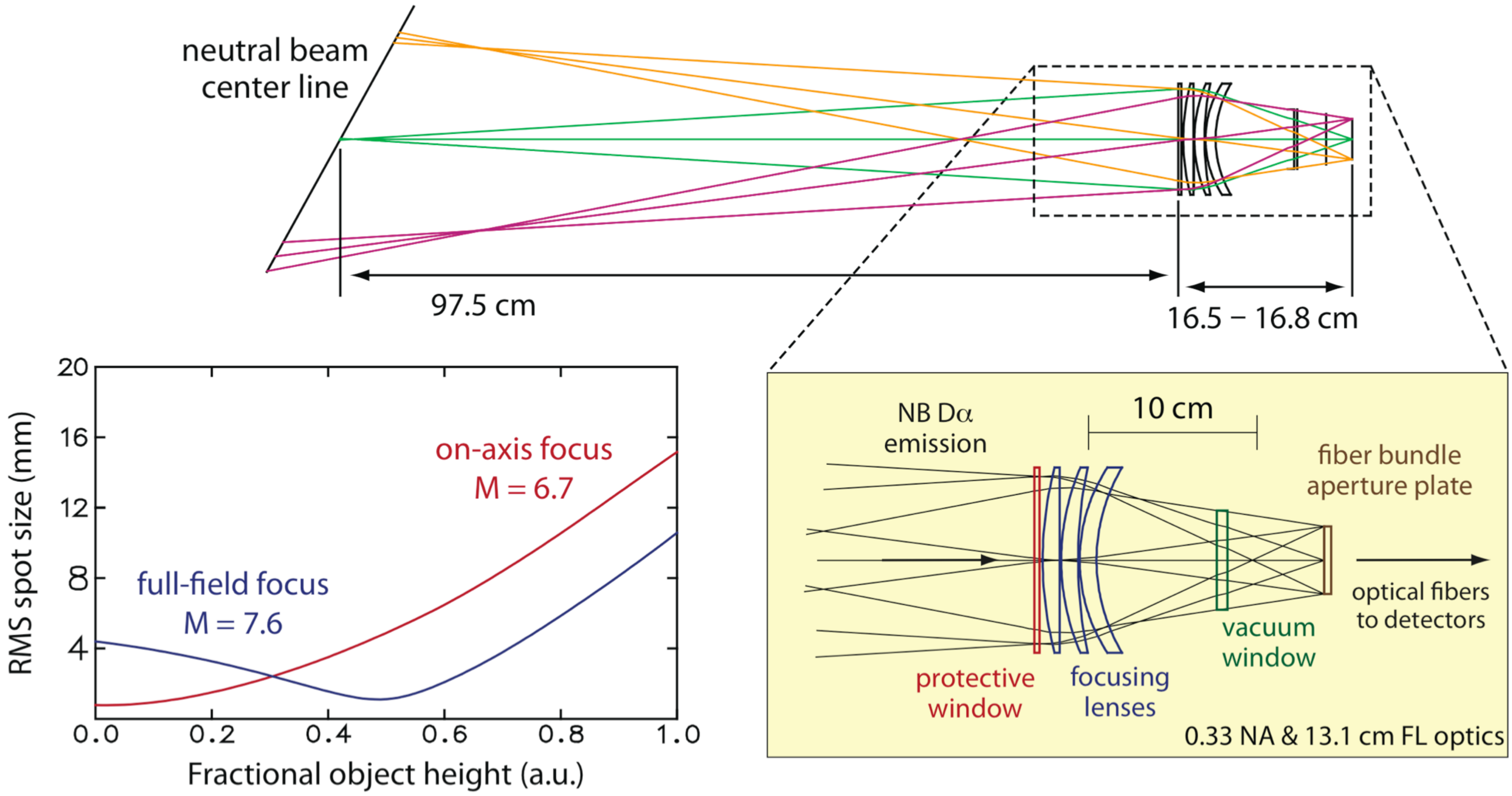


Optical views are aligned to the magnetic field pitch angle within the NB volume to optimize cross-field spatial resolution

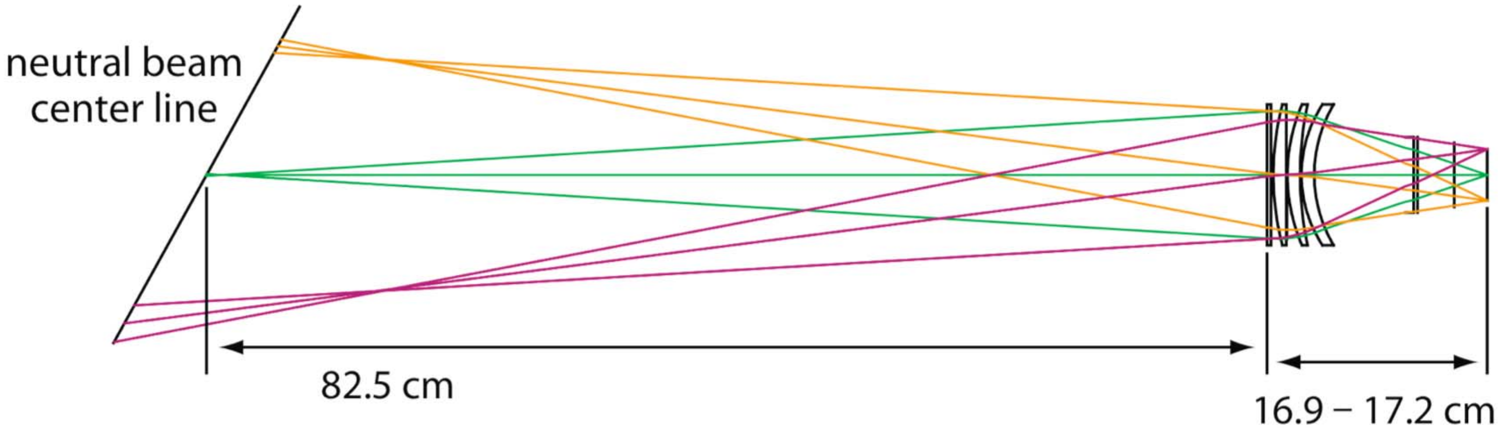


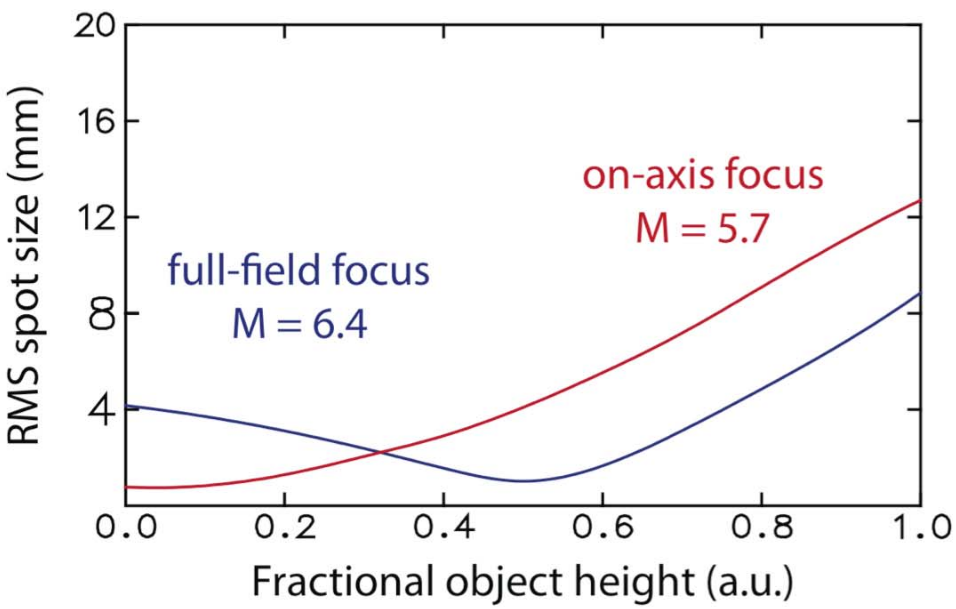


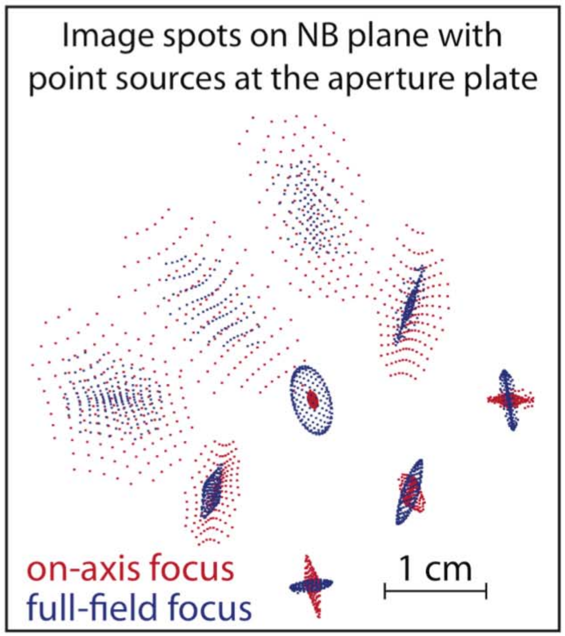
R130 optics provide about ×7 magnification at f/1.5



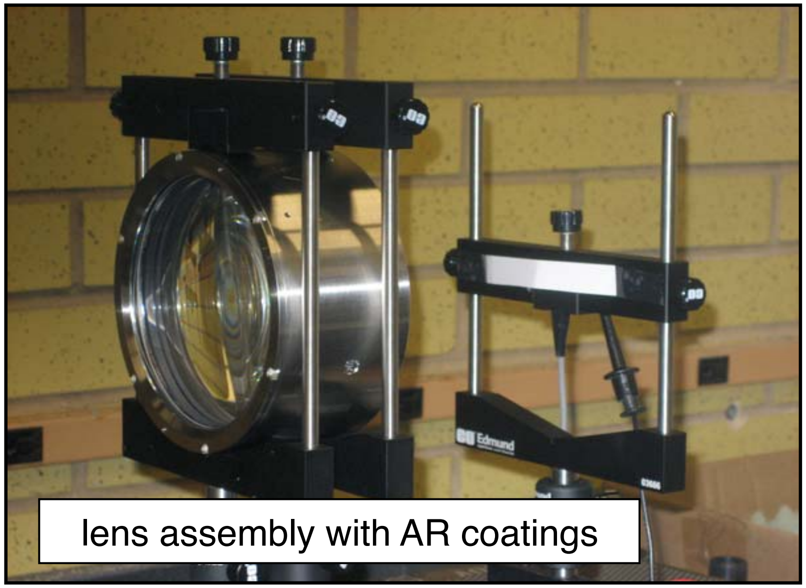
R140 optics provide about ×6 magnification at f/1.5

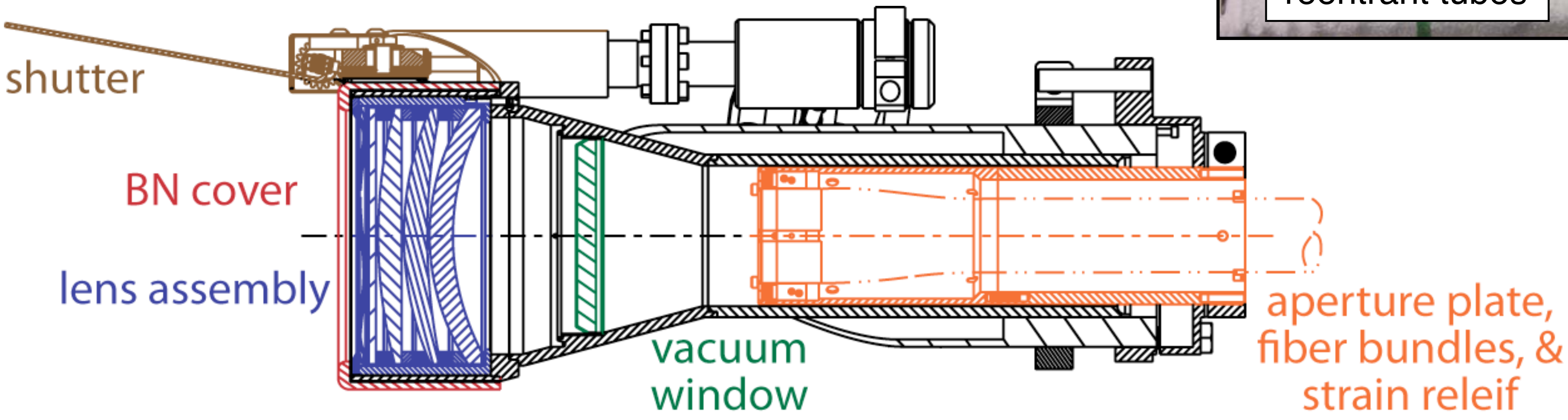




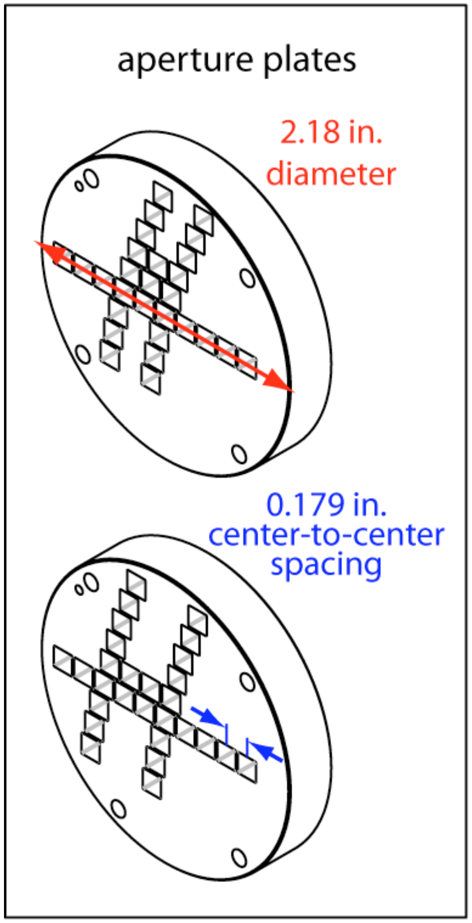


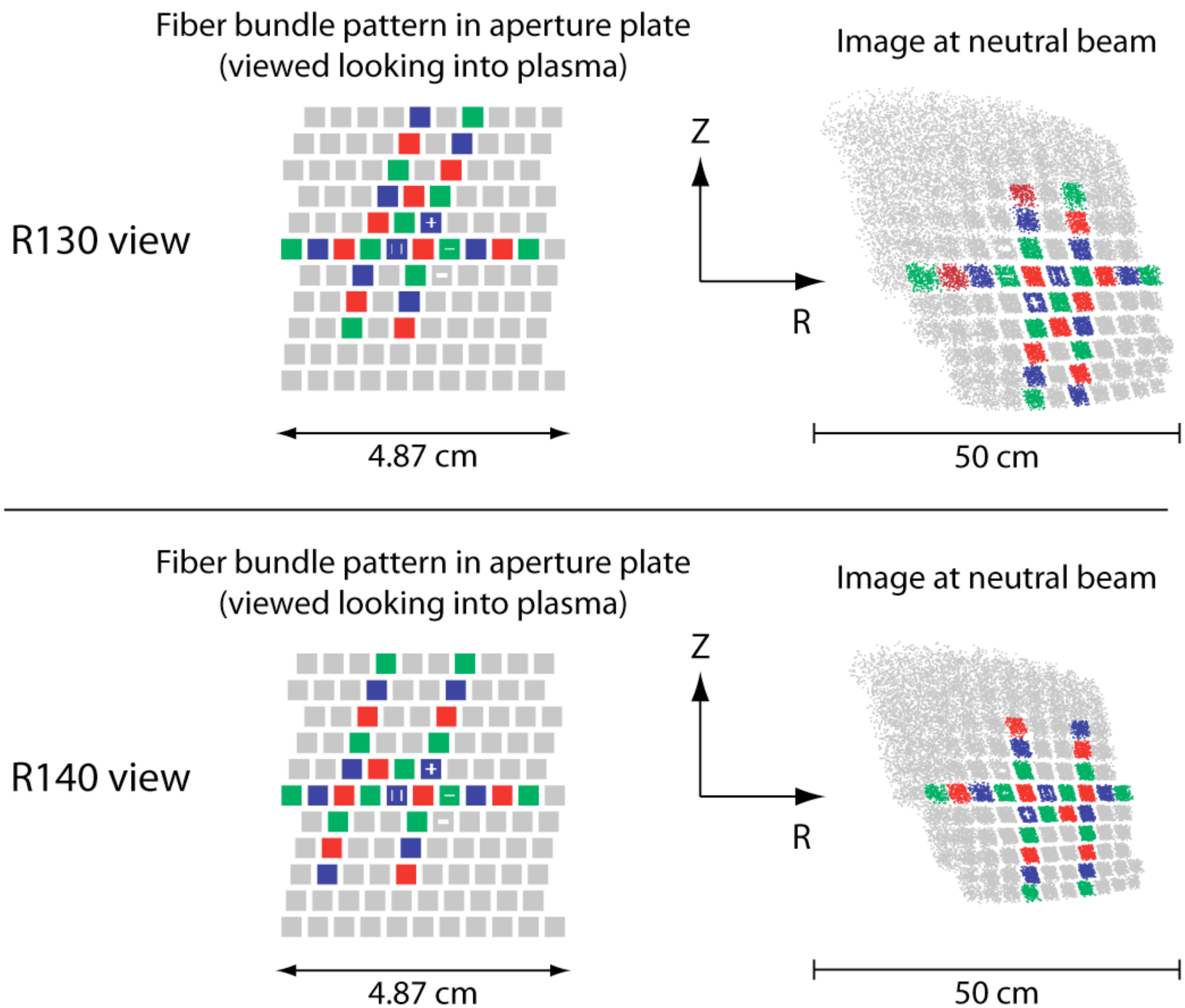
Lens assemblies & reentrant tubes



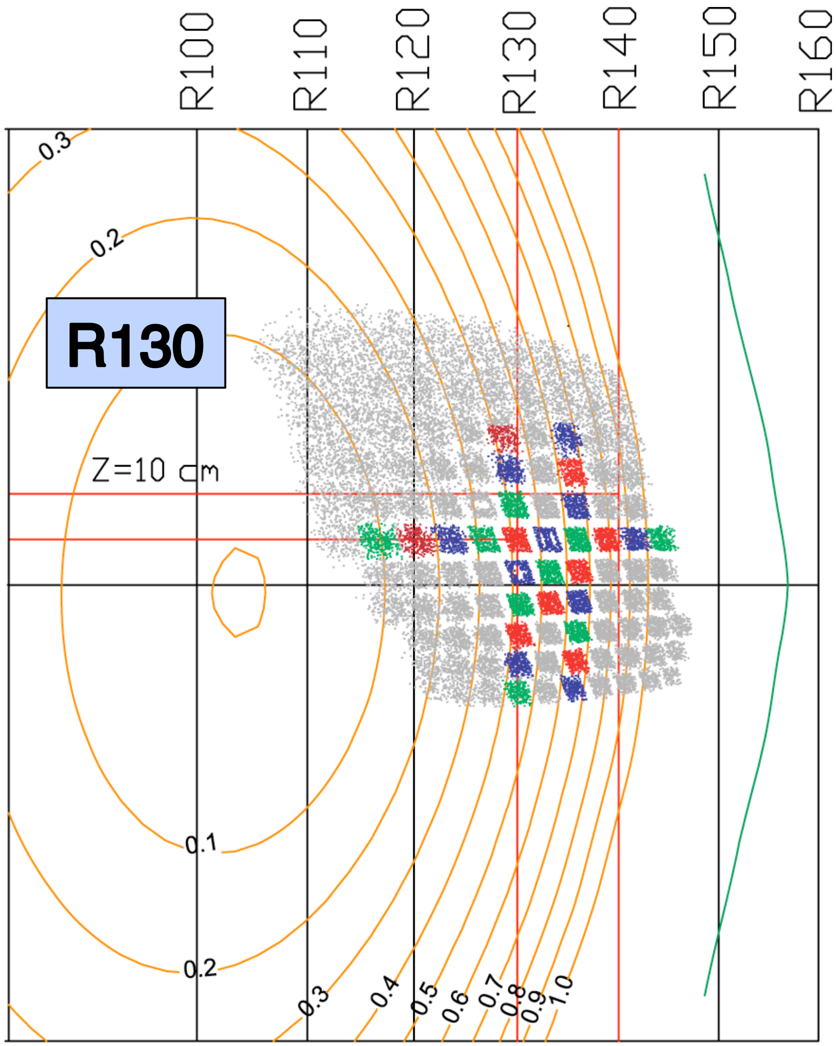


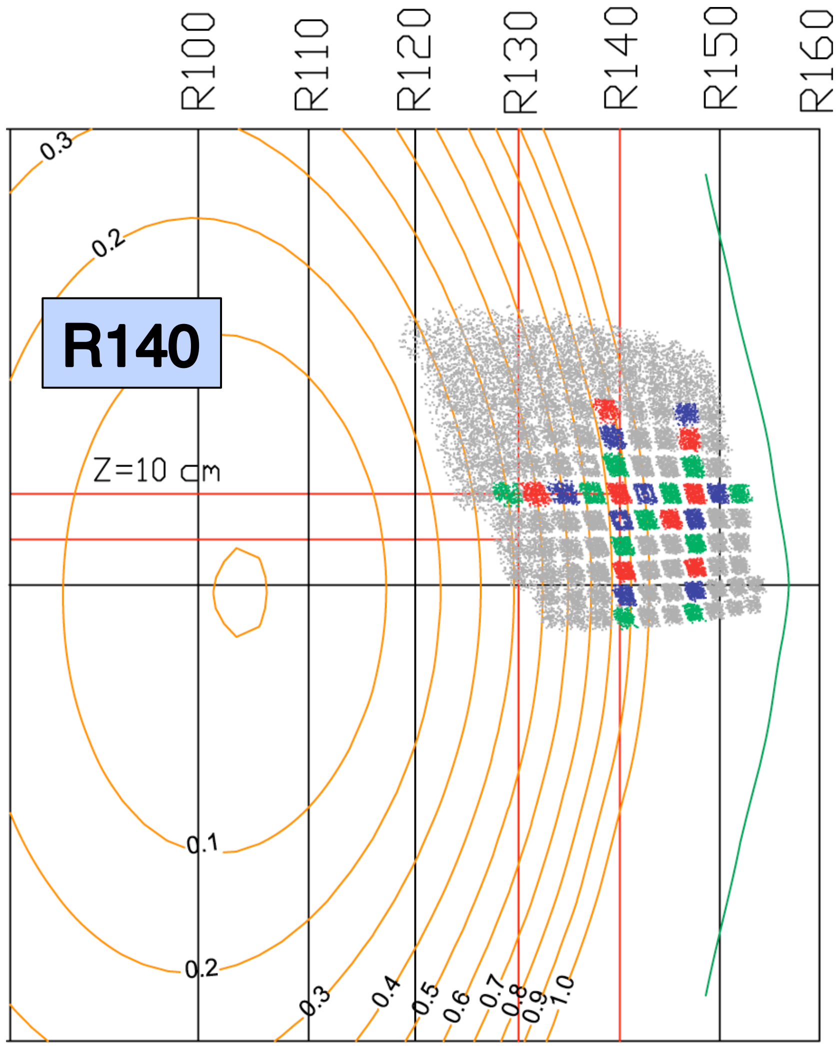
Initial aperture plates include radial arrays, poloidal arrays, and 2D grids



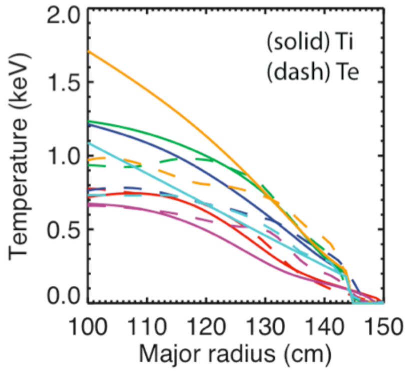


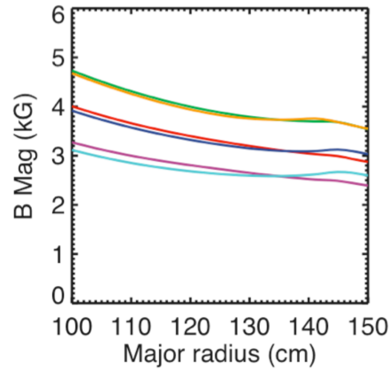
Initial aperture plates provide radial coverage from r/a = 0.1 to beyond the LCFS with 2-3 cm bundle images

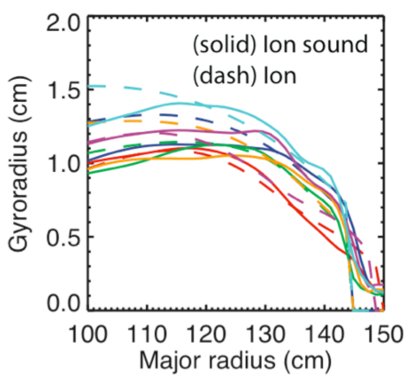


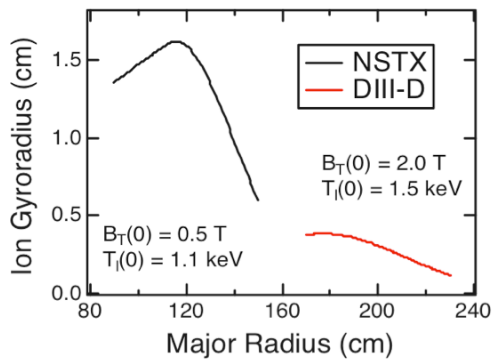


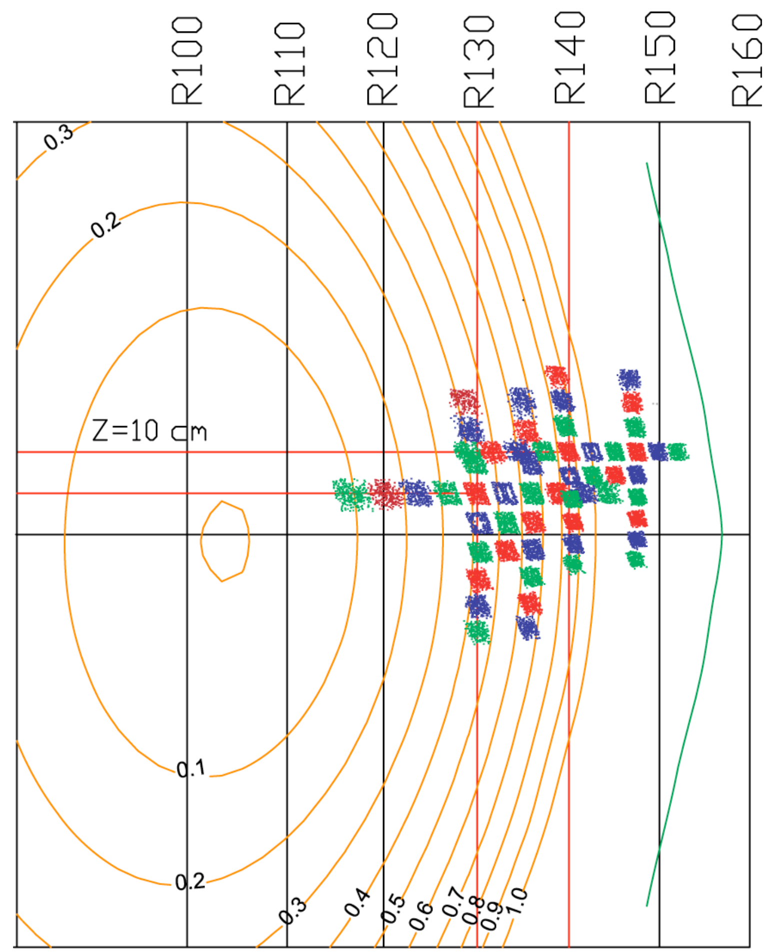
Plasma coverage can sample modes up to $k_{\perp}\rho_i \approx 1.5$



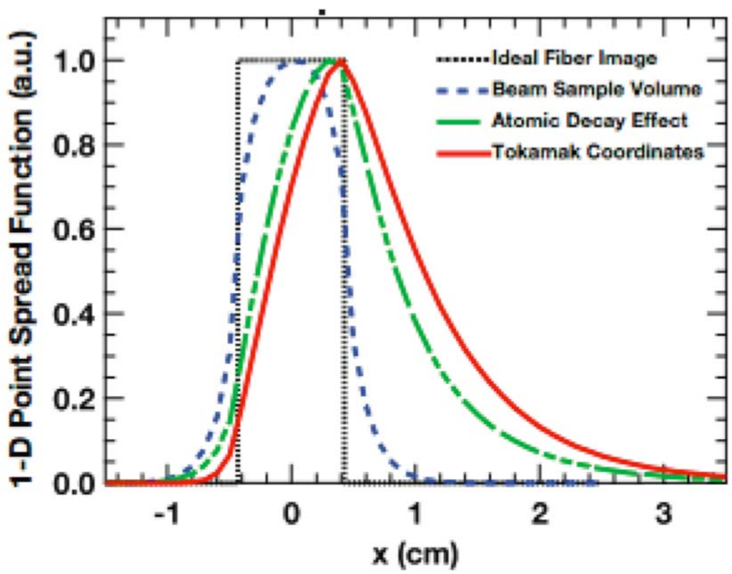






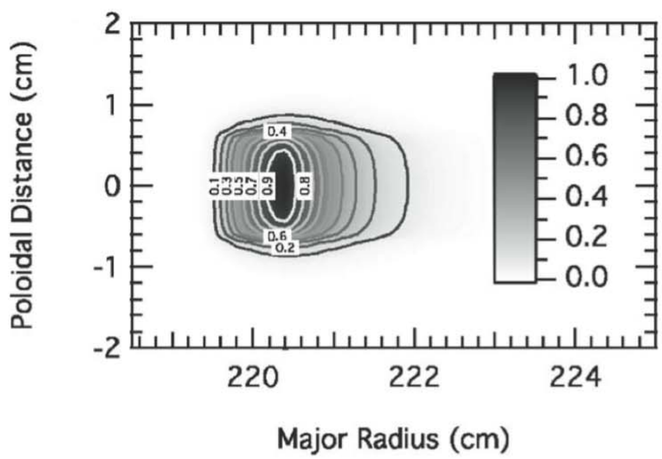


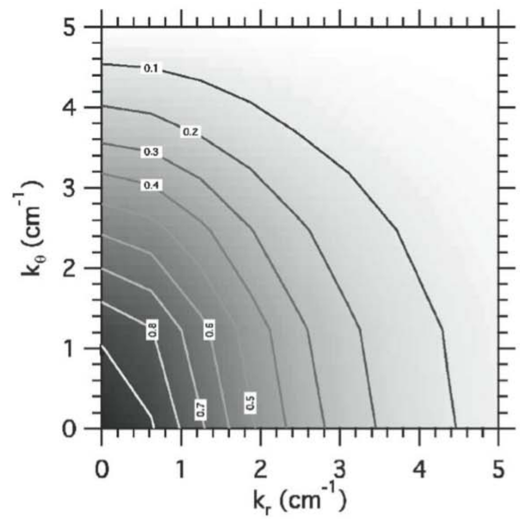
Point-spread-function and spatial-transfer-function calculations will provide spatial and k-space measurement parameters



- Point-spread-function (PSF) specifies the measurement volume taking into account…
  - Viewing optics
  - NB geometry
  - Magnetic equilibrium
  - Atomic physics
- Spatial-transfer-function (STF) specifies the measurement sensitivity in k-space

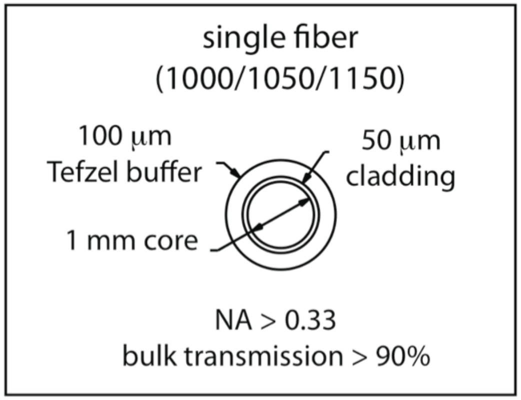
$$\mathrm{STF}\left(\vec{k}\right) = \mathrm{FT}\left(\mathrm{PSF}\left(\vec{x}\right)\right)$$

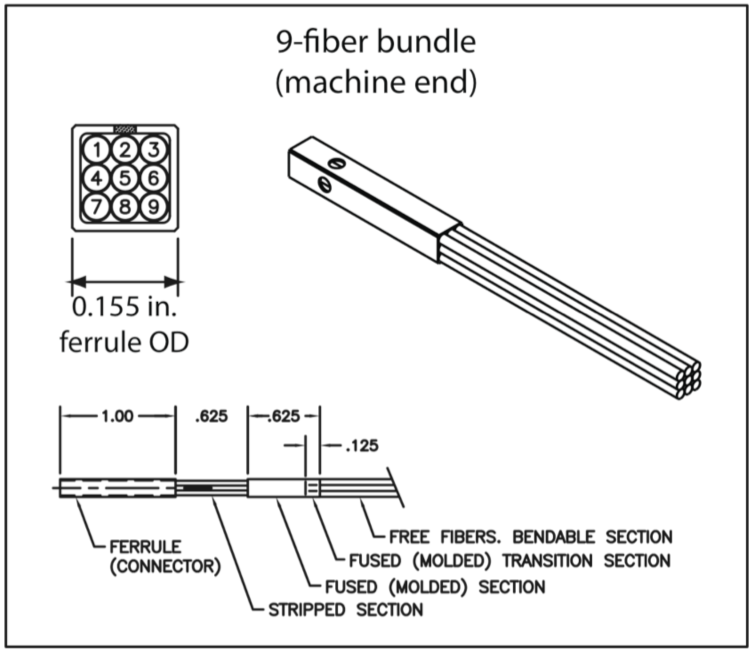


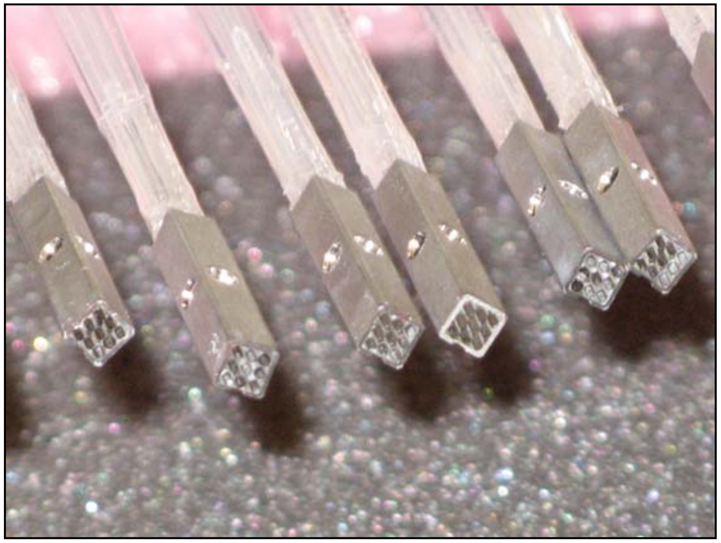


DIII-D BES
PST/STF calculations
Shafer et al, RSI 2006

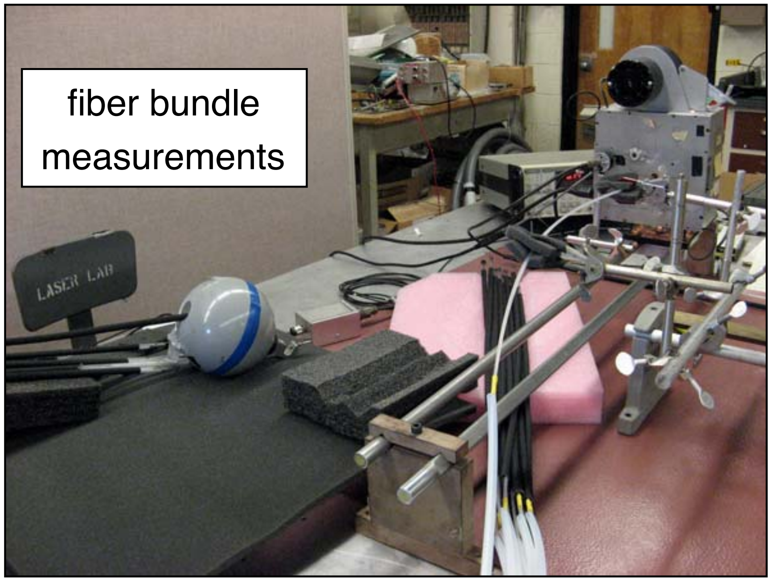
40 meter fiber bundles, each with 9 1-mm fibers, will transmit NB D_α emission from collection optics to photodetectors

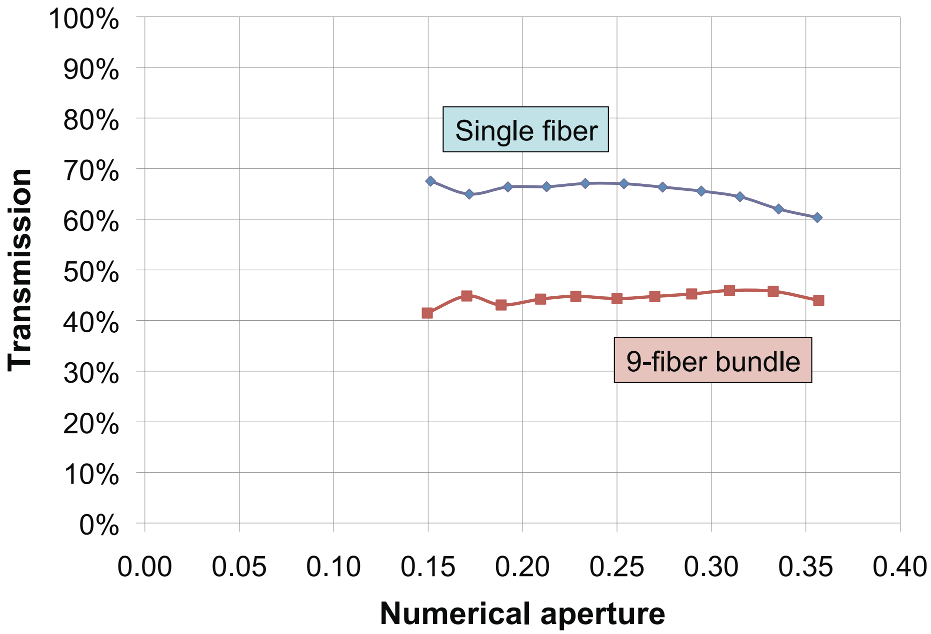


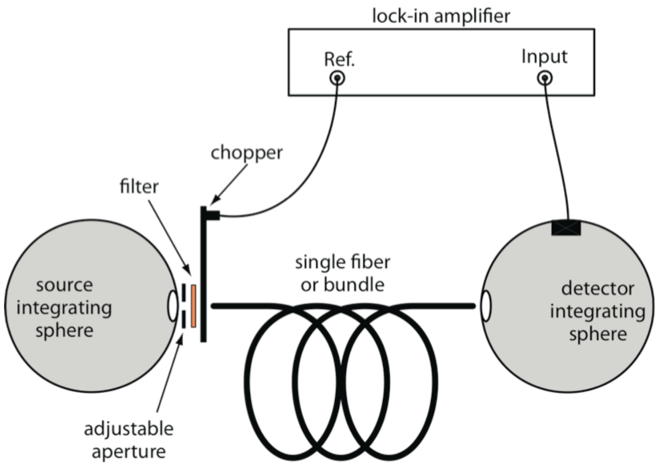


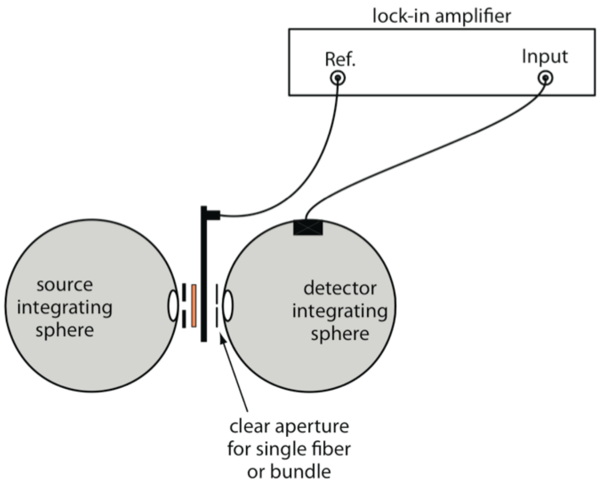


Single fibers achieve 65% transmission & 9-fiber bundles achieve 45% transmission at f/1.5

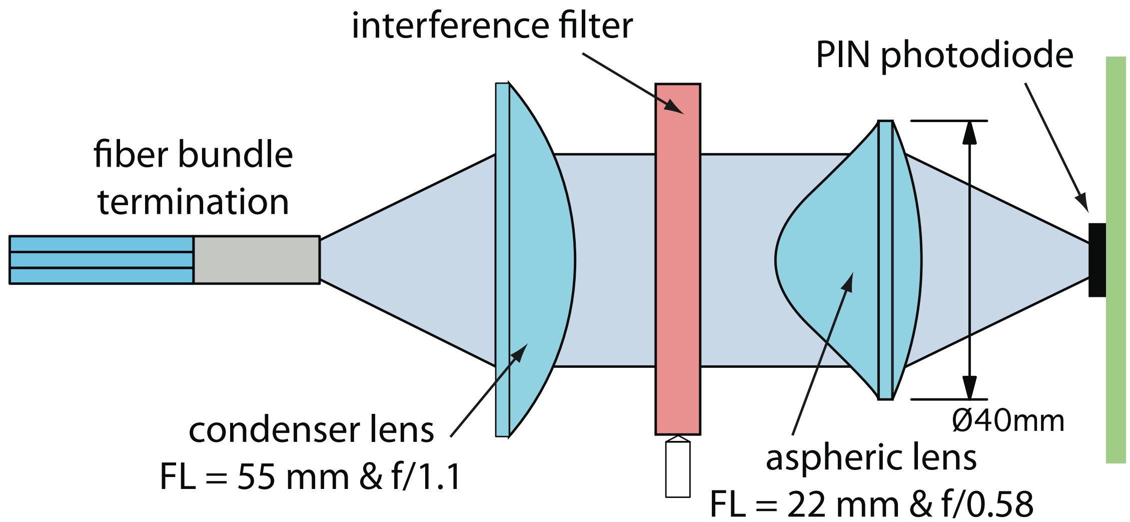


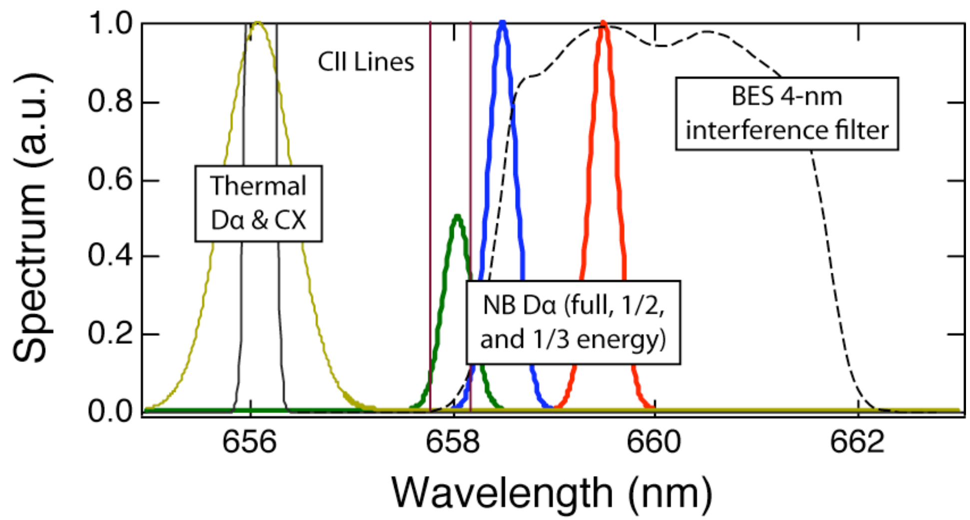


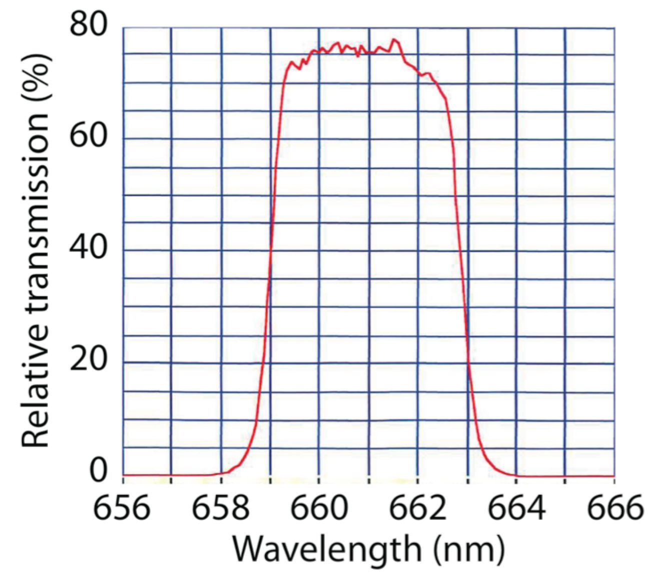




Tilt-tune interference filter provides about 75% transmission in a 4 nm window

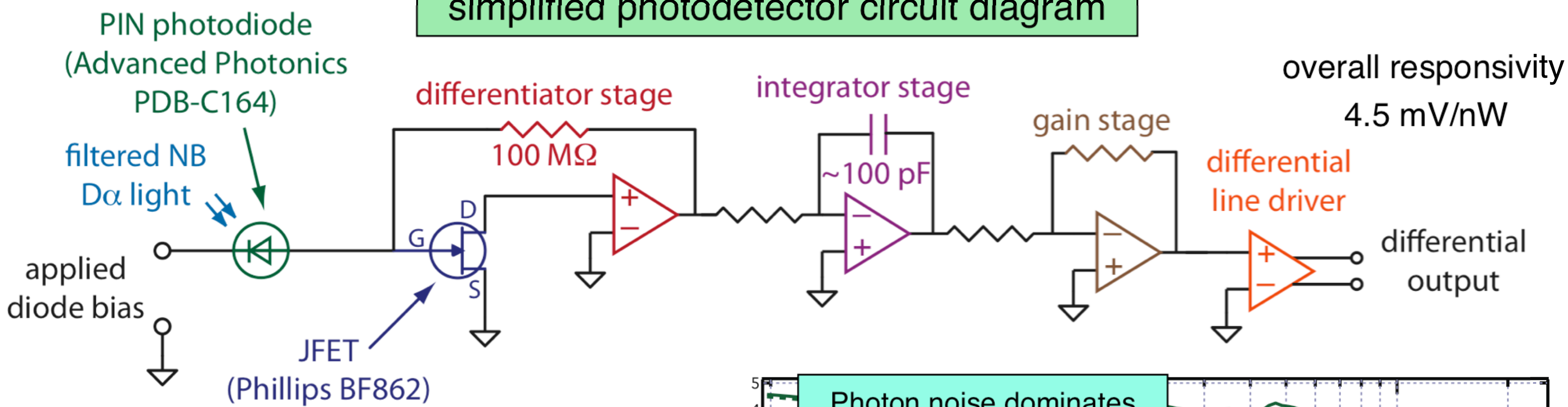






Low-noise, low-capacitance photodiode & FET are key to low-noise, high-responsivity photodetector

simplified photodetector circuit diagram



overall responsivity:
4.5 mV/nW

Noise figure of merit:

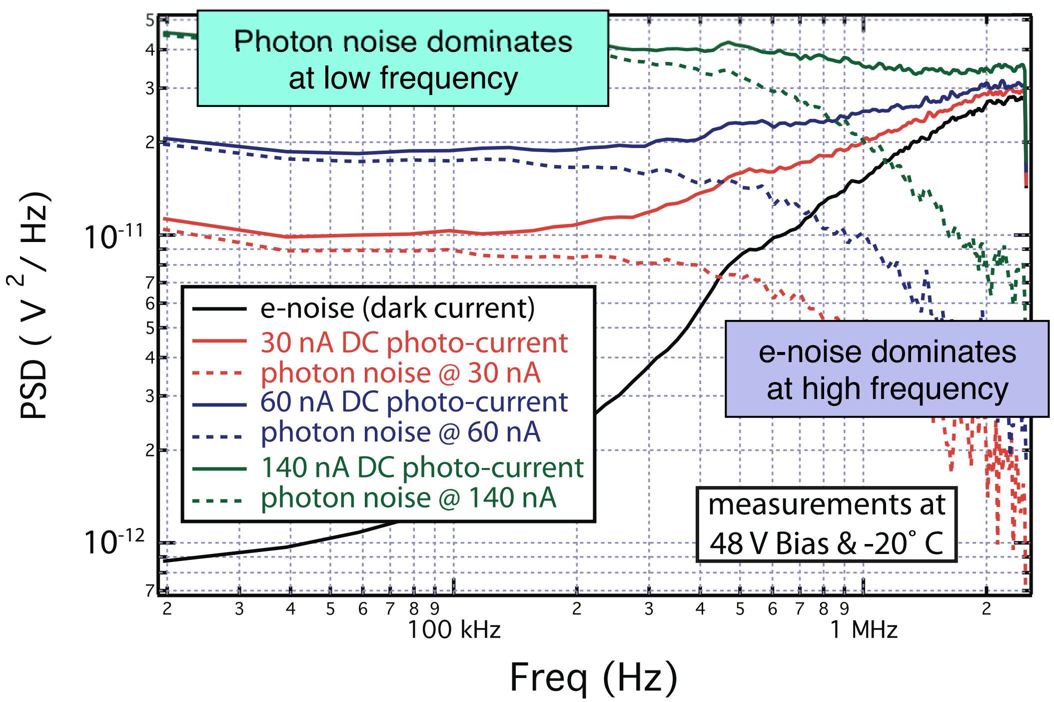
$e_{noise} \times (C_{diode} + C_{FET})$

Design values:

$e_{noise} = 0.8\ nV/Hz^{1/2}$

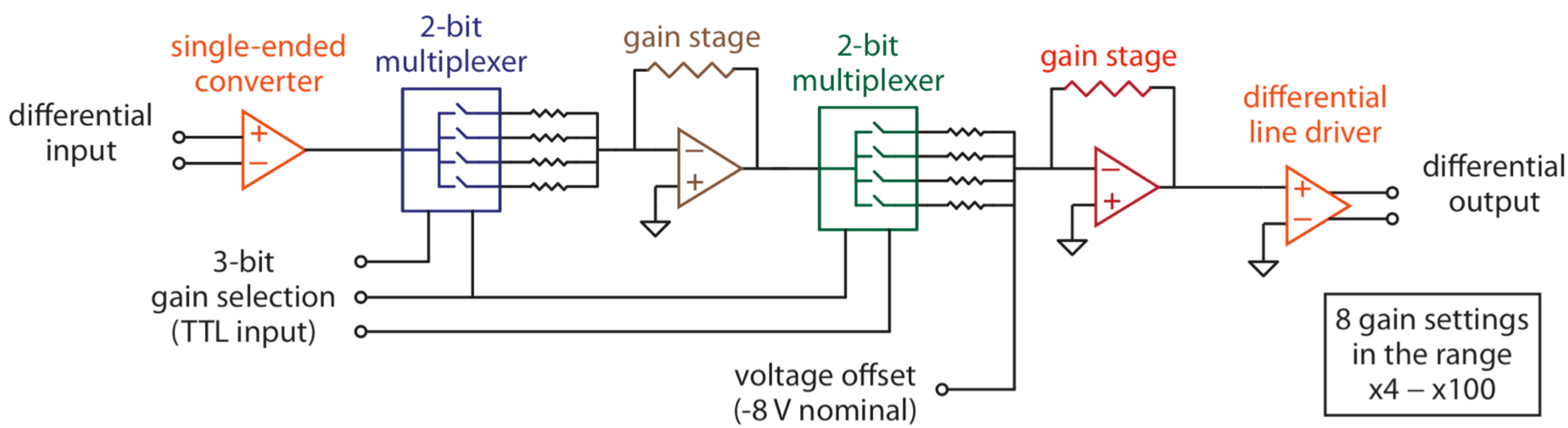
$C_{diode} = 7\ pF$

$C_{FET} = 10\ pF$



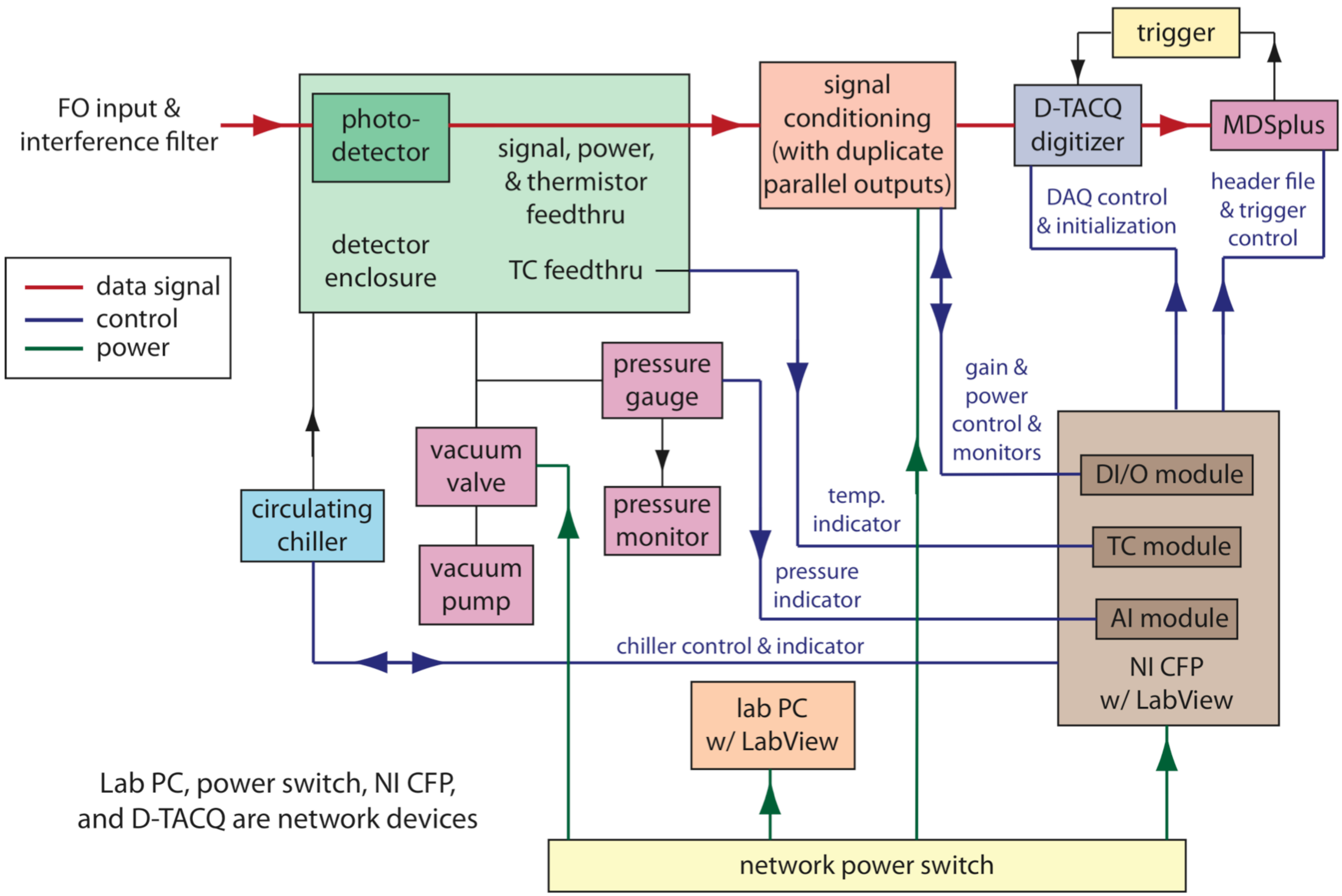
Signal conditioning circuit provides adjustable gain & digitizer with FPGA FIR filter provides true 2 MHz sampling

simplified signal conditioning circuit



- D-TACQ ACQ132 digitizer
  - Simultaneous 32 channel sampling
  - 16-bit digitizer (effective bits with oversampling)
  - ± 10 V differential input
  - 2.5 MHz anti-aliasing filter
  - FPGA with 127-tap FIR filter
  - True 2 MHz output sampling with 32 MHz input sampling

Control system includes vacuum pump, valves, circulating chiller, thermocouples, gain control, and more



Lab PC, power switch, NI CFP, and D-TACQ are network devices

Compared to the DIII-D BES system, the NSTX BES system incorporates new technology and novel design aspects

- Photodetector exhibits lower noise
  - Low-noise, low-capacitance surface-mount photodiode & FET
  - Low-capacitance circuit board layout
- Refrigerant cooling at -20° C
  - DIII-D system uses LN2 cryo-cooling
- Red-shifted viewing geometry aligned to steep NSTX pitch angles
  - DIII-D system uses blue-shifted viewing geometry with shallow pitch angles
- True 2 MHz sampling with FIR and anti-aliasing filters will accommodate large Doppler shifts from strong toroidal rotation and GAE/CAE studies
  - DIII-D system samples at 1 MHz with analog filter
- 9 1-mm fibers per channel at f/1.5 and 2.3 mm^2-ster
  - DIII-D system uses 11 1-mm fibers per channel at f/2 and 1.6 mm^2-ster
- Larger spot sizes (magnification) accommodate larger gyro-radii in NSTX
- Signal and noise levels in the NSTX BES system should be similar to the DIII-D BES system due to multiple offsetting factors

Status & plans: on schedule for first data in FY10

- Lens assemblies, reentrant tubes, 56 fiber bundles, interference filters, control system components, and digitizer have been produced
- Vessel penetrations have been drilled
- Aperture plates, photodetector boxes, and signal conditioning electronics are in fabrication
- Lens assemblies, reentrant tubes, aperture plates, and fiber bundles installed in November 2009
- Photodetector boxes and signal conditioning electronics (16 channels) installed in December 2009
- In-vessel spatial alignment and calibration activities in December 2009
- BES analysis software ported to PPPL in January 2010

Summary

- BES measures Doppler-shifted D_α emission from neutral beam particles to investigate ion gyroscale fluctuations
- The NSTX BES system includes two field-aligned optical views with coverage from r/a~0.1 to beyond the LCFS
- Collection optics provide x5.5 – x8 magnification at 0.33 NA
- 9 1-mm fiber bundles provide 40% relative transmission
- Initial aperture plates include radial arrays, poloidal arrays, and 2D grids
- Low-noise, low-capacitance photodiode & FET enable photodetectors with low-noise and high-sensitivity without cryo-cooling
- Digitizer with anti-aliasing FPGA filter provides true 2 MHz sampling can accommodate large Doppler shifts from strong toroidal rotation in NSTX
- On schedule for first data in FY10

Supported by US DOE Contract No DE-AC02-76CH03073