Design of the NSTX beam emission spectroscopy system

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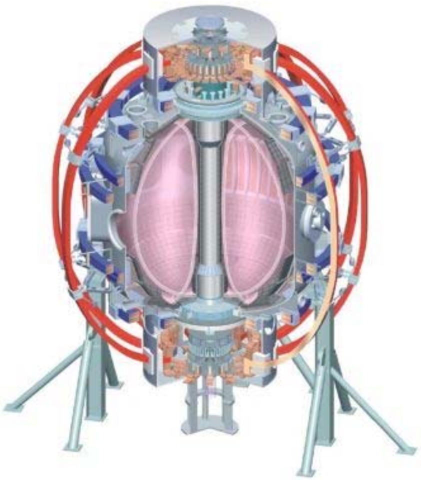

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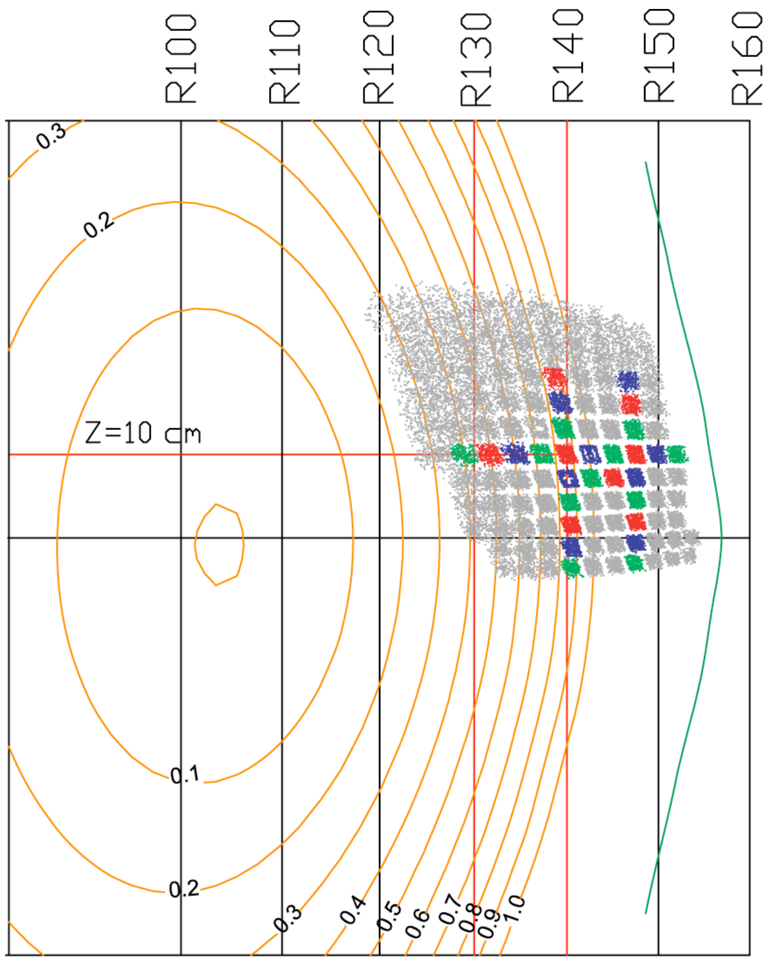
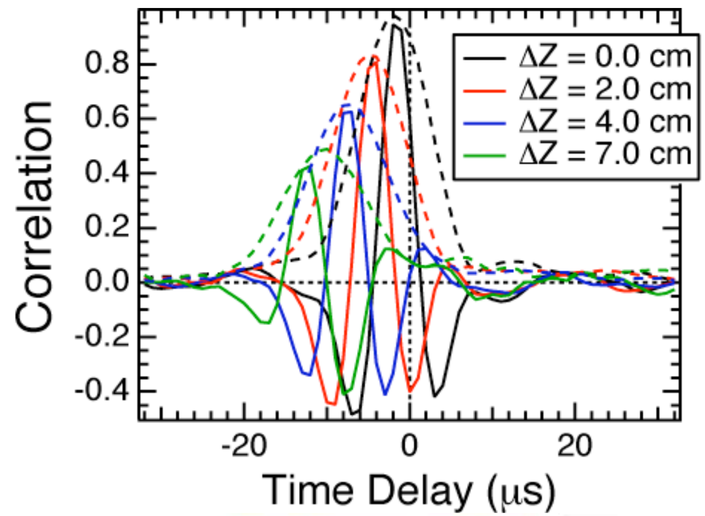
Outline

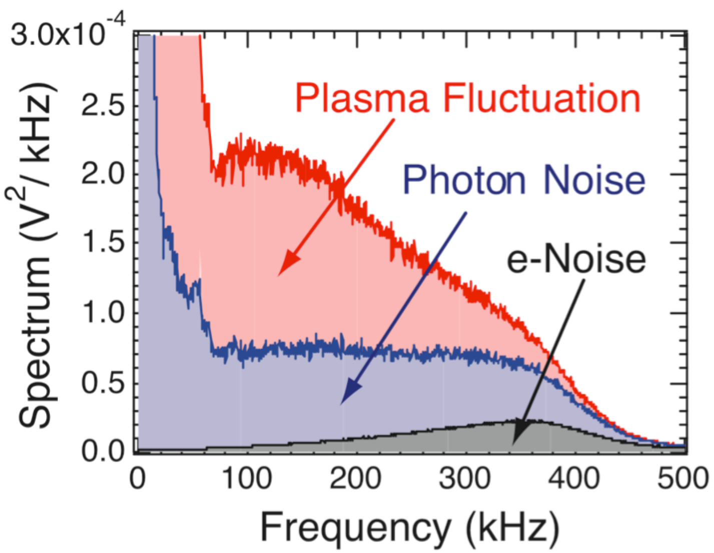
- Motivation
- BES measurement principles
- Optical design
  - Viewing geometry
  - Collection optics
  - Aperture plate
  - Fiber bundles & spot sizes
  - Interference filters
- Detection system design
  - Photodiode & FET preamplifier
  - Photon noise & e-noise
  - Digitizer with FIR filter
- Status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

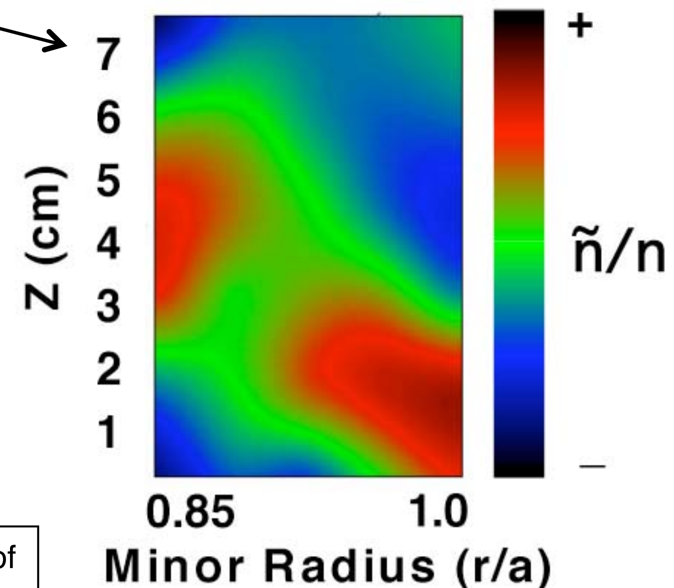


Beam emission spectroscopy (BES) is a diagnostic technique for measuring ion gyroscale ($k_\perp \rho_i < 1$) density fluctuations

- 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







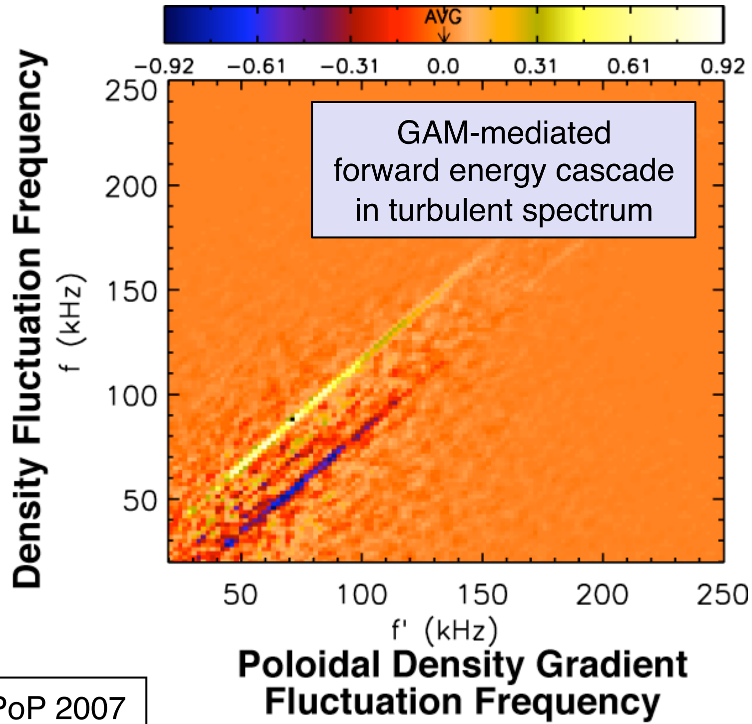
Figures courtesy of DIII-D BES group

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

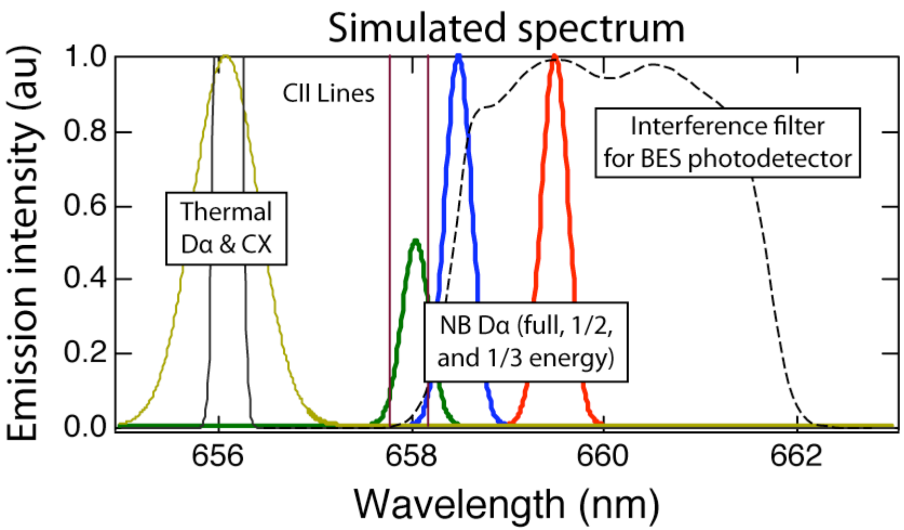


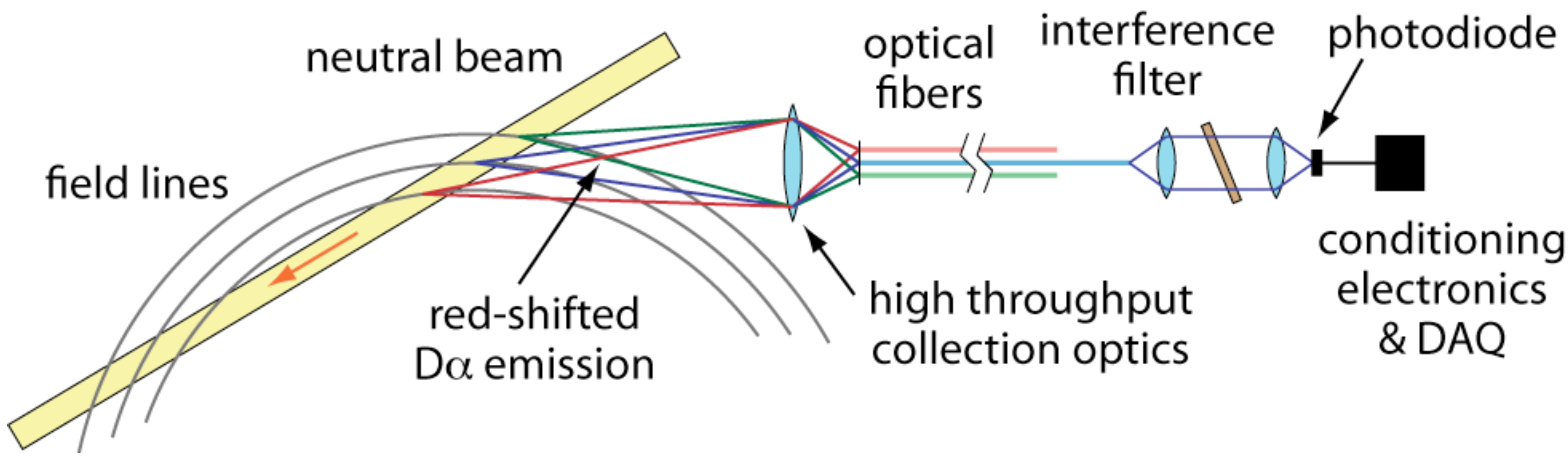
Holland et al, PoP 2007

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

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

neutral beam D_α emission — ion density fluctuation — $C \approx 1/2$

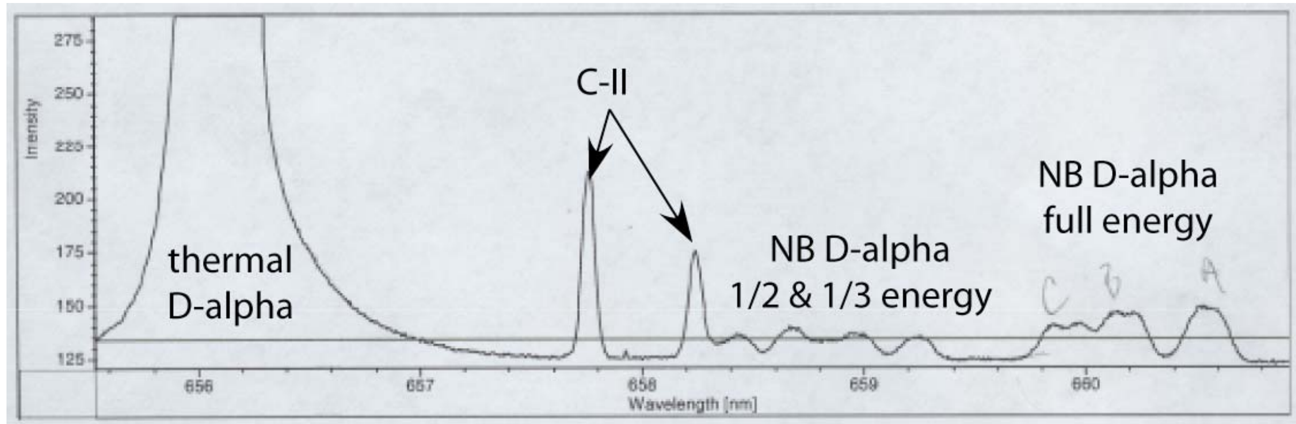




MSE & FIDA measurements on NSTX indicate NB D_α emission is comparable to or greater than C-II emission

MSE spectrum

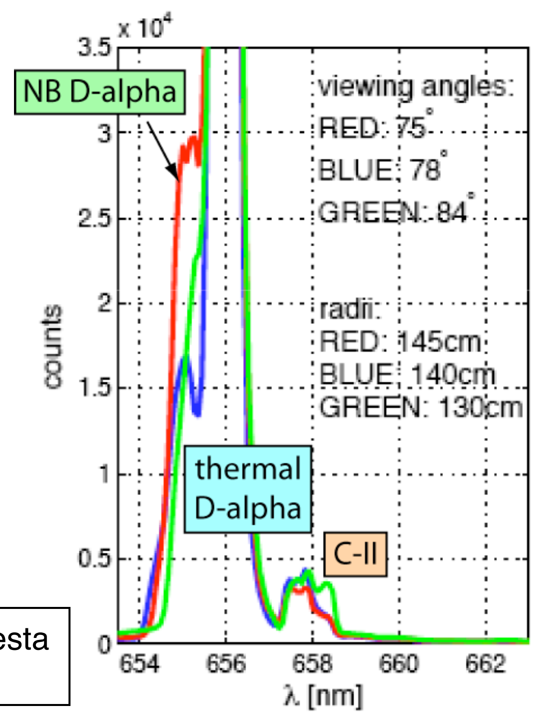
tangential view with
large red-shift in NB D_α
and long-time integration



Courtesy of H. Yuh & F. Levinton

FIDA spectrum

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



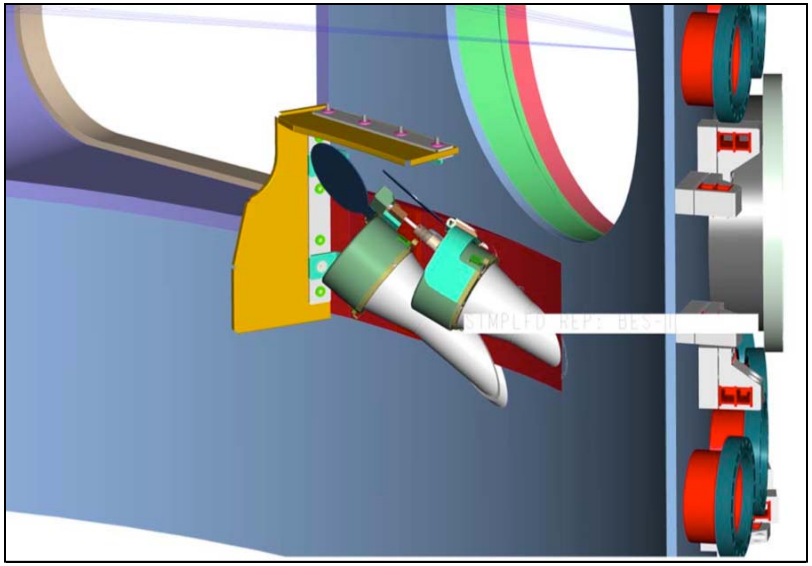
Courtesy of M. Podesta & W. Heidbrink

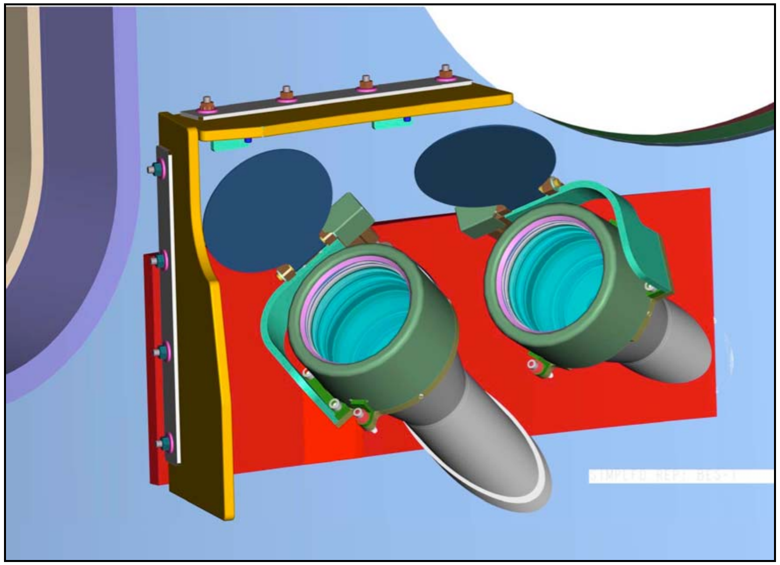
MSE & FIDA spectra indicate:

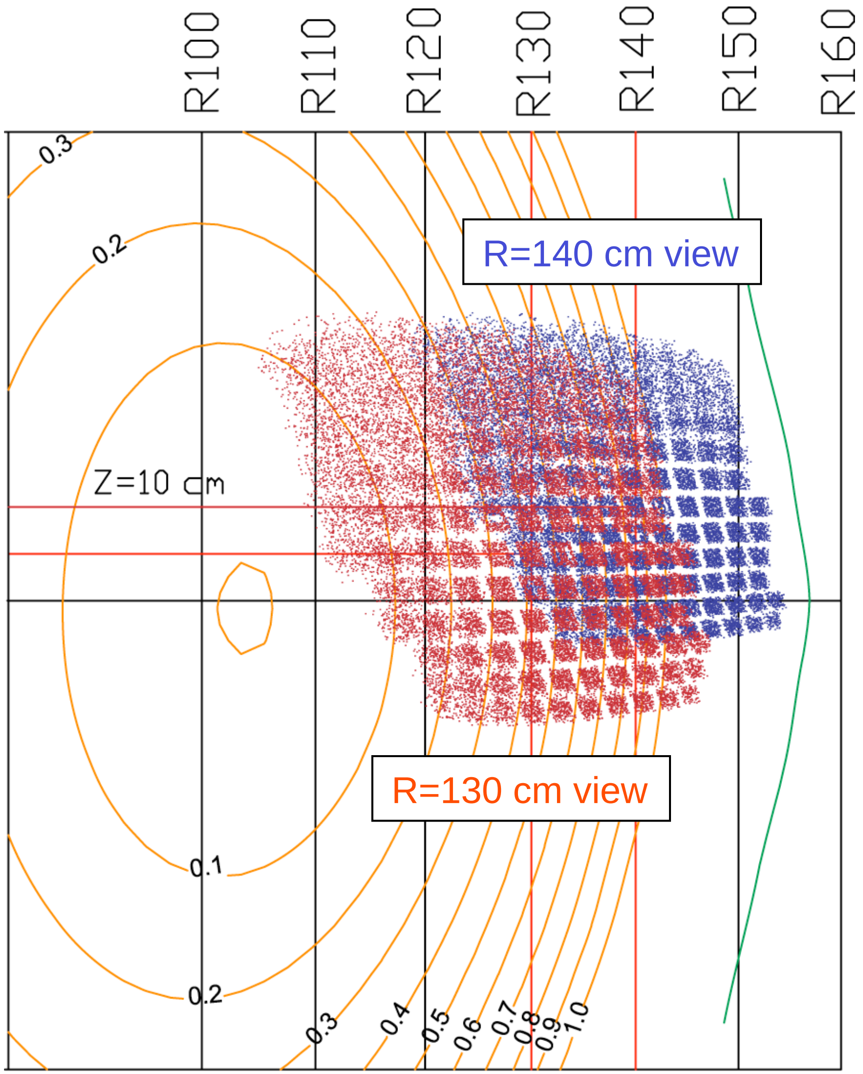
$$\frac{I_{NB\ D\alpha}}{I_{C-II}} \approx 1-10$$

Also, C-II fluctuations should average out due to large C-II sampling volume.

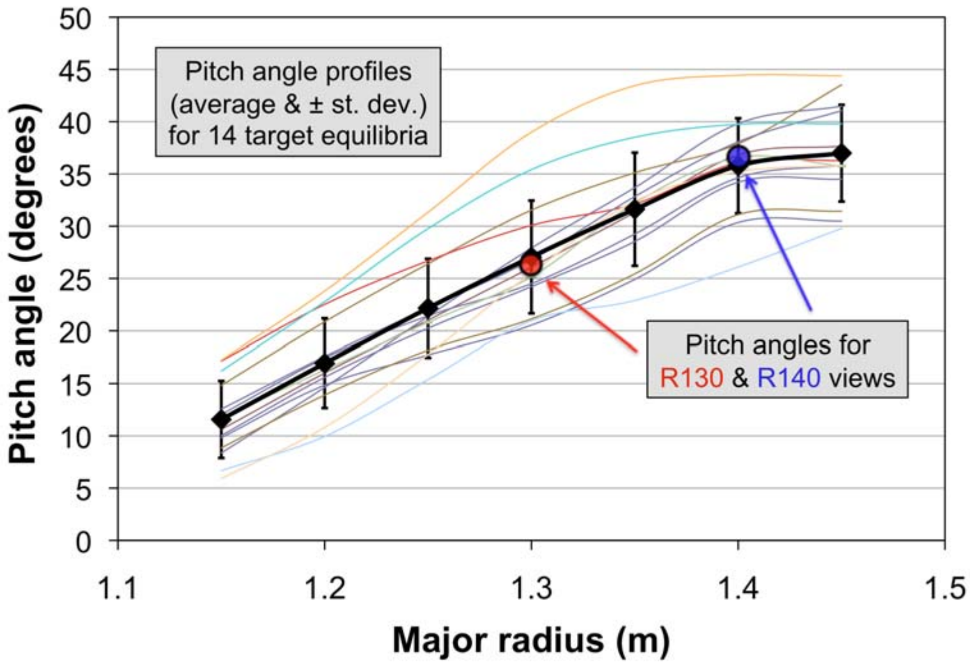
The NSTX BES system includes two optical views centered at R = 130 cm and 140 cm

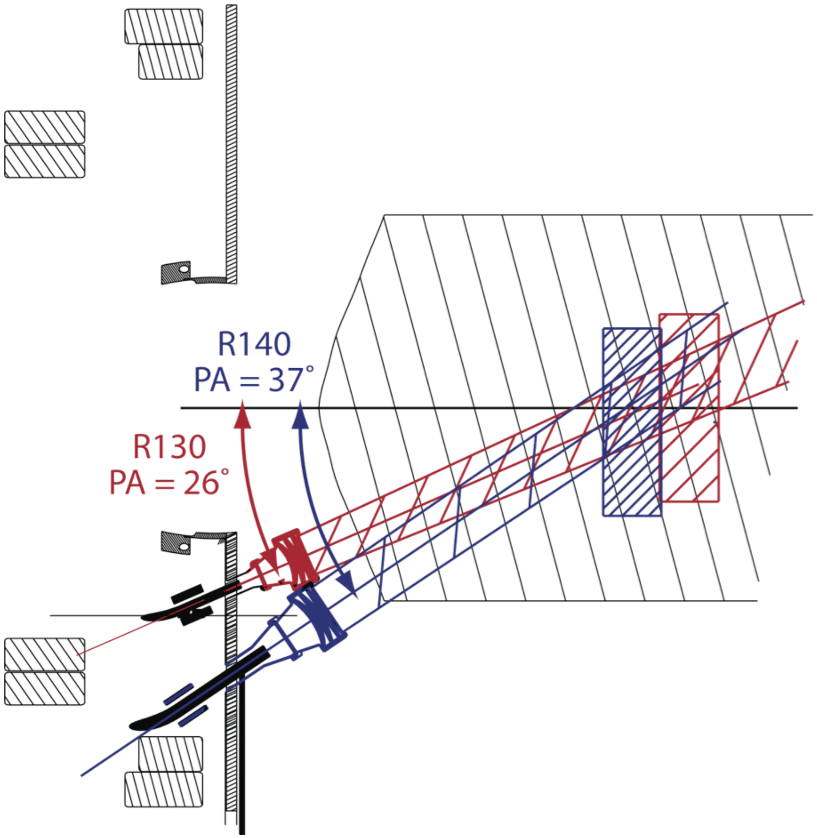




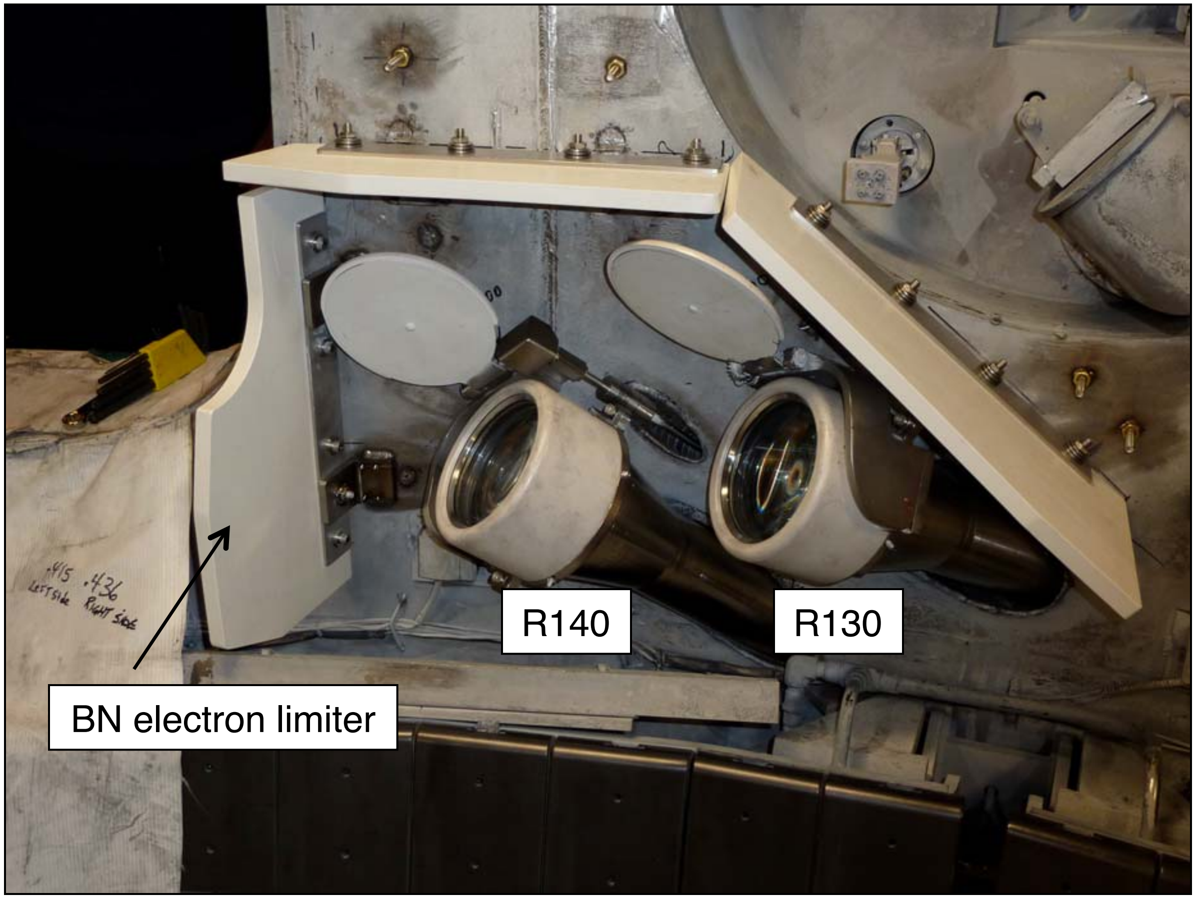


Optical views are aligned to the magnetic field pitch angle within the NB volume to optimize cross-field spatial resolution

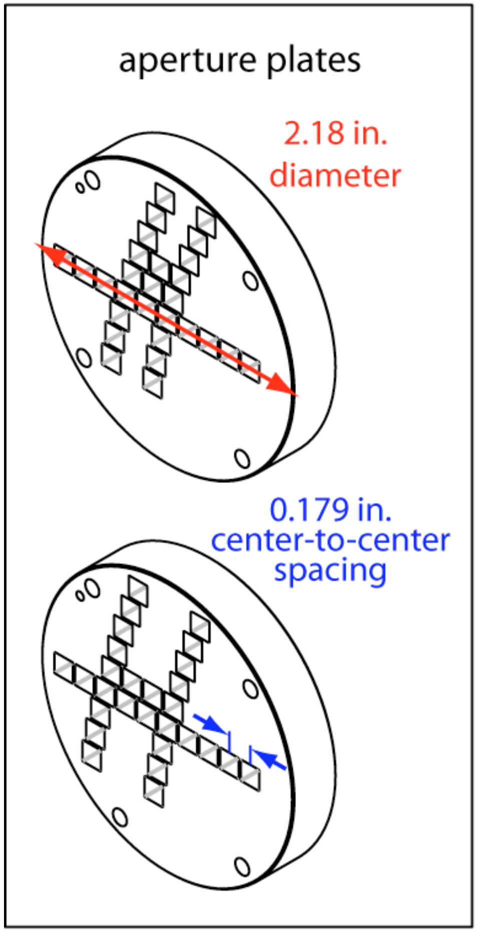


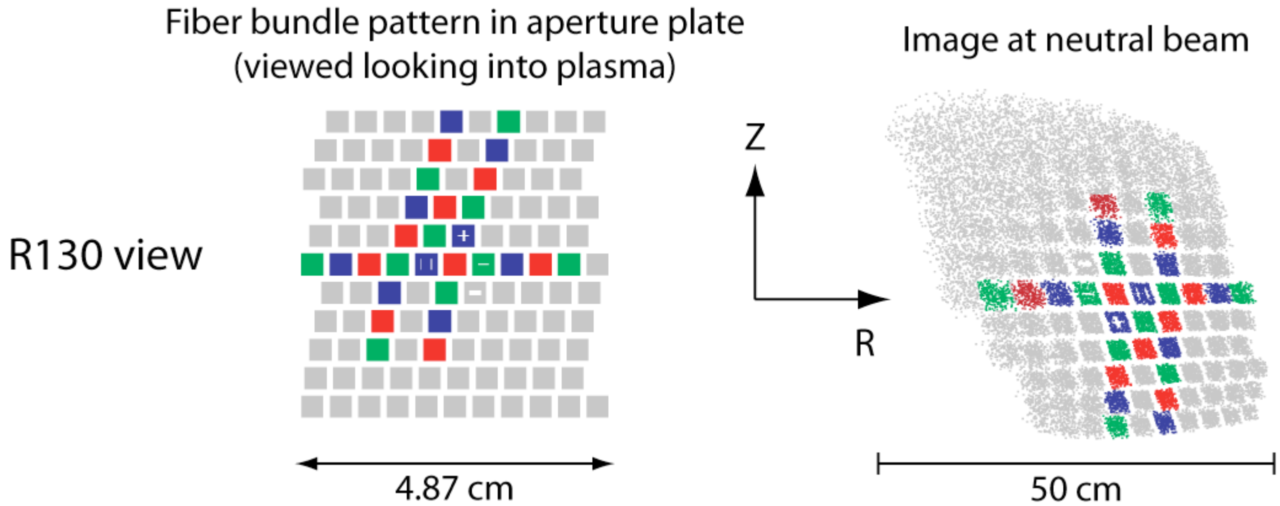


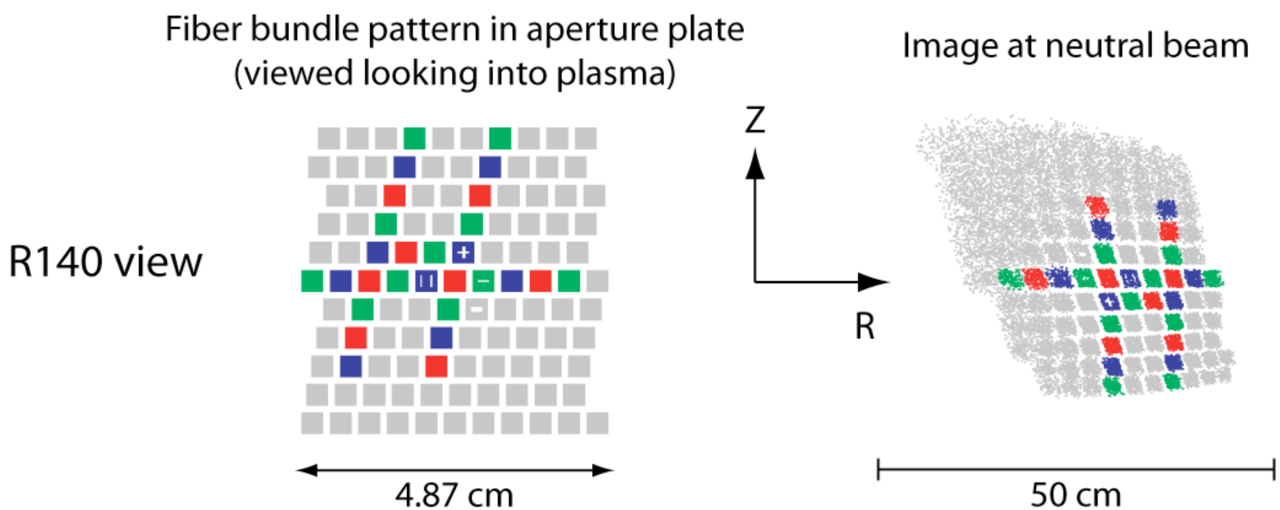
Collection optics installed in Fall 2009



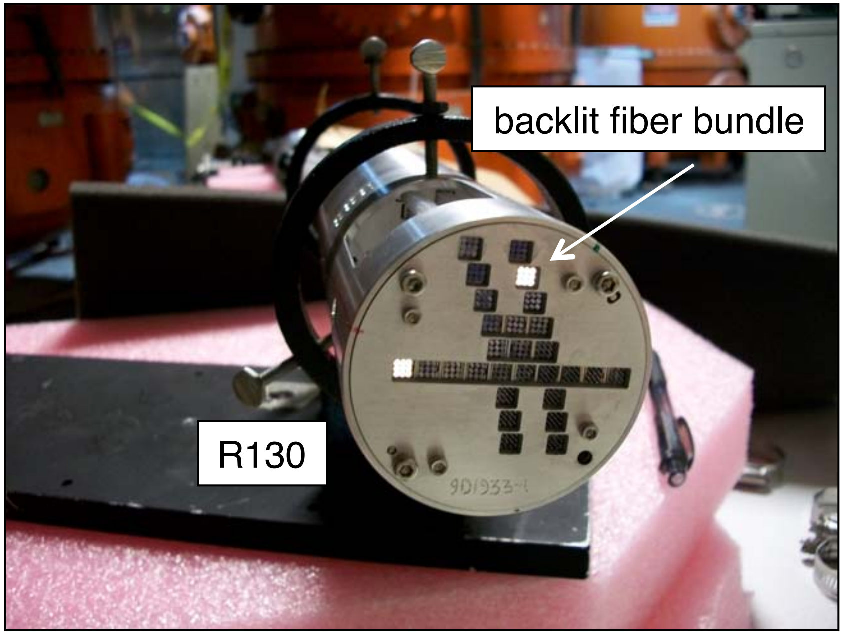
Initial aperture plates include radial arrays, poloidal arrays, and 2D grids

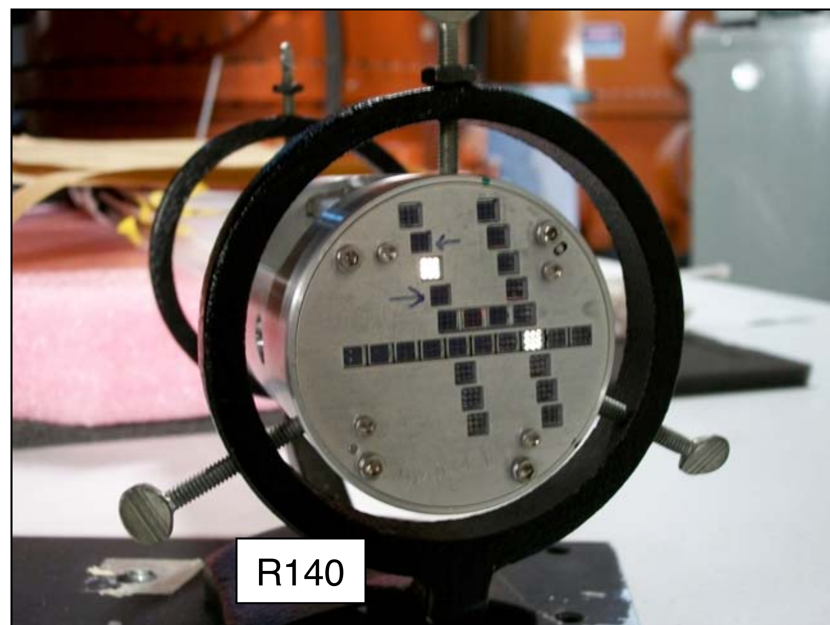




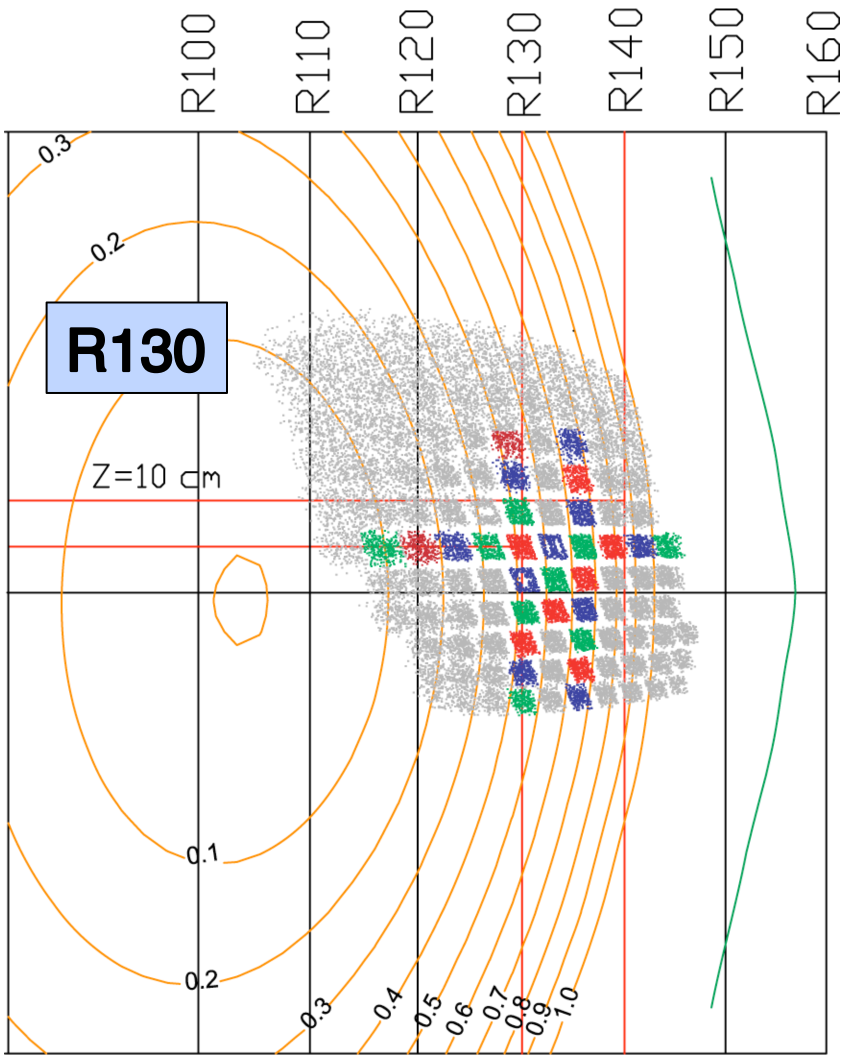


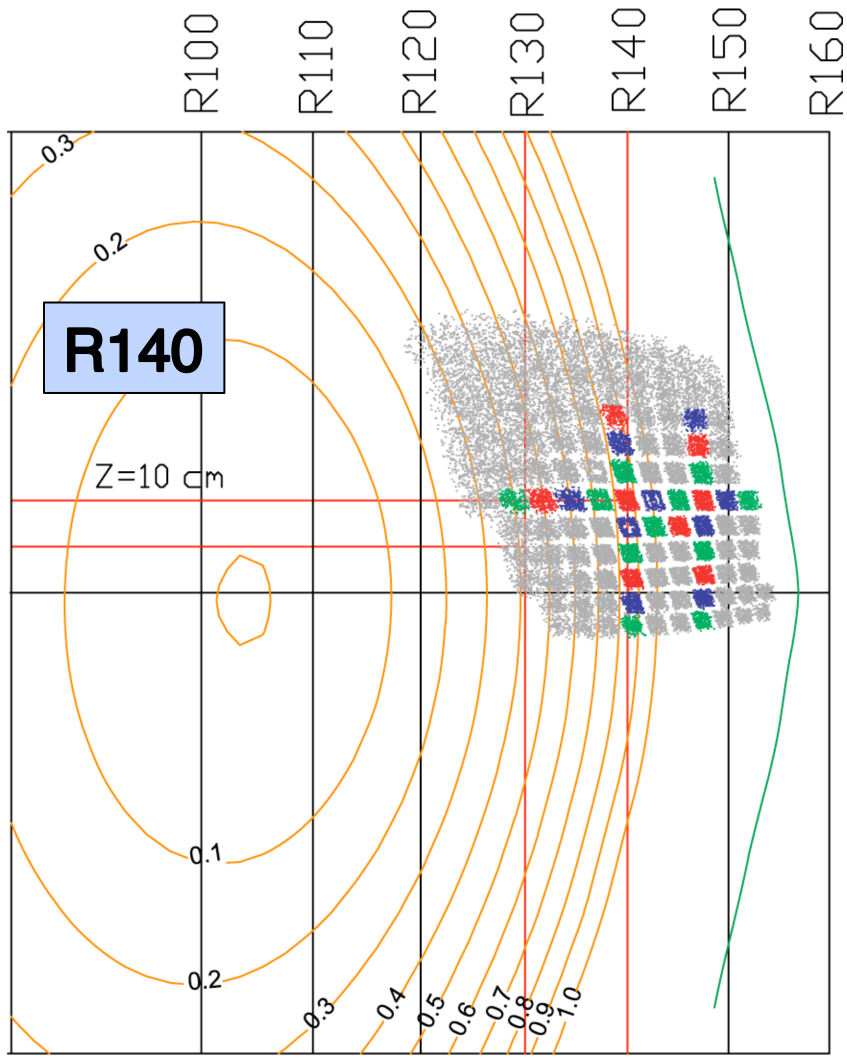
Aperture plates and strain reliefs assembled and installed



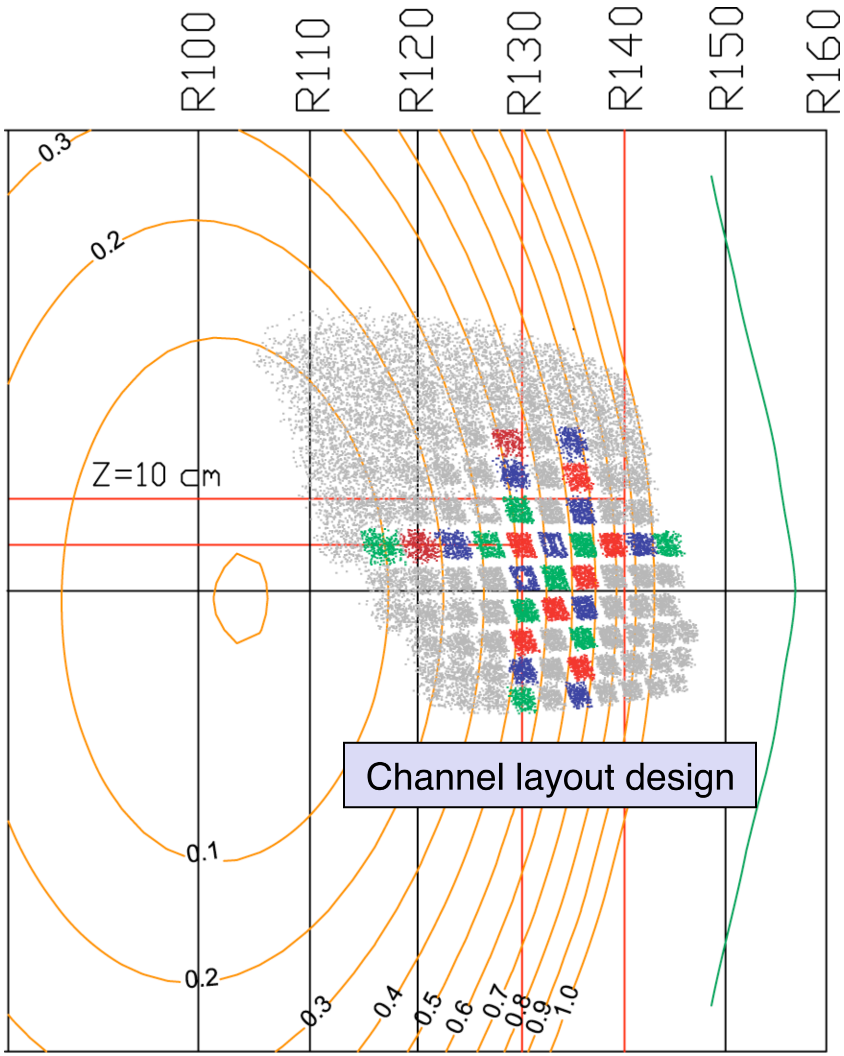


Initial aperture plates provide radial coverage from r/a = 0.1 to beyond the LCFS with 2-3 cm bundle images

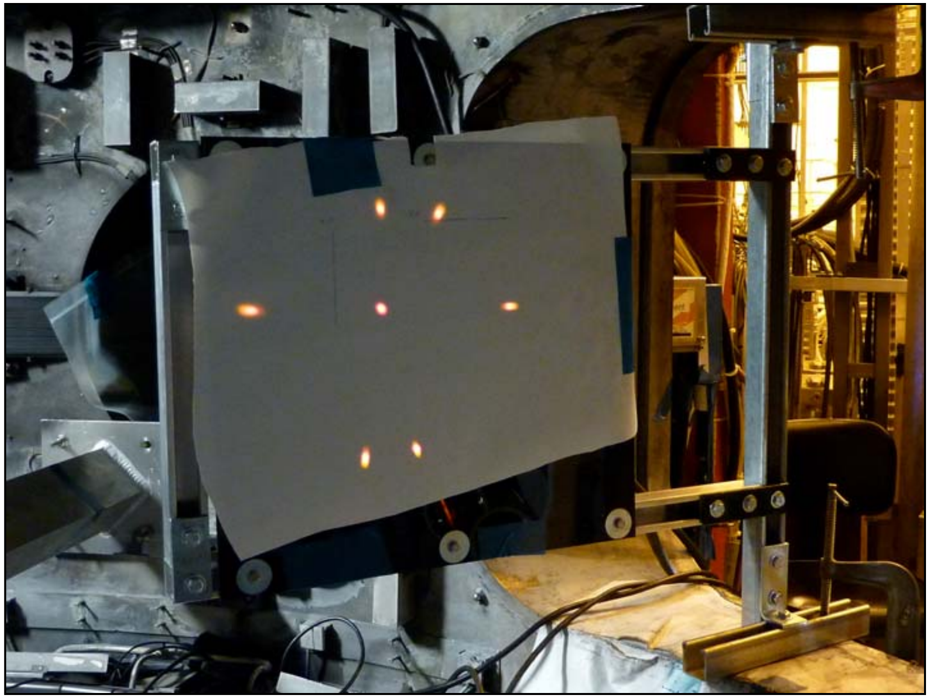




Spatial calibration performed in Fall 2009

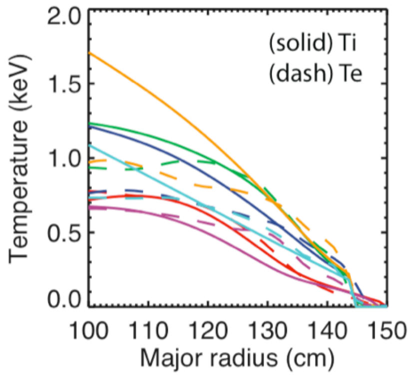


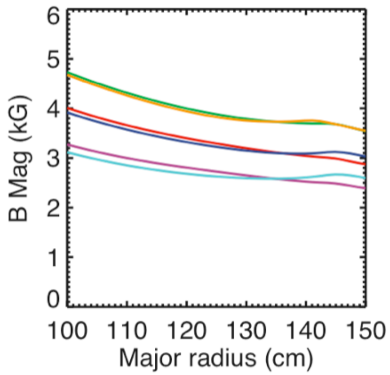
Channel layout design

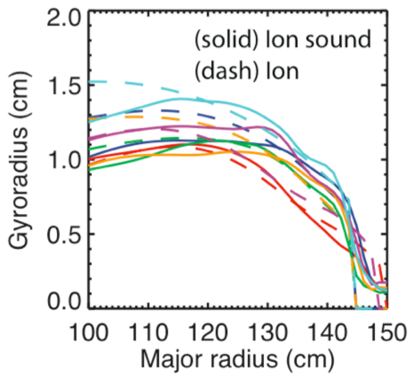


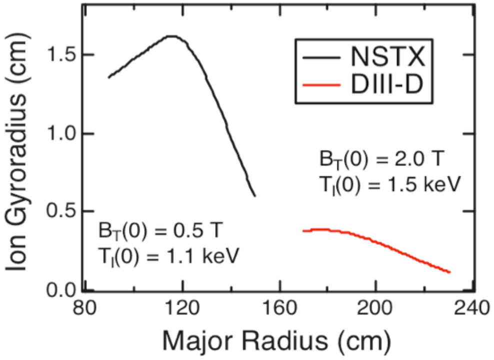
Backlit single-fiber images are within 1 cm of design values

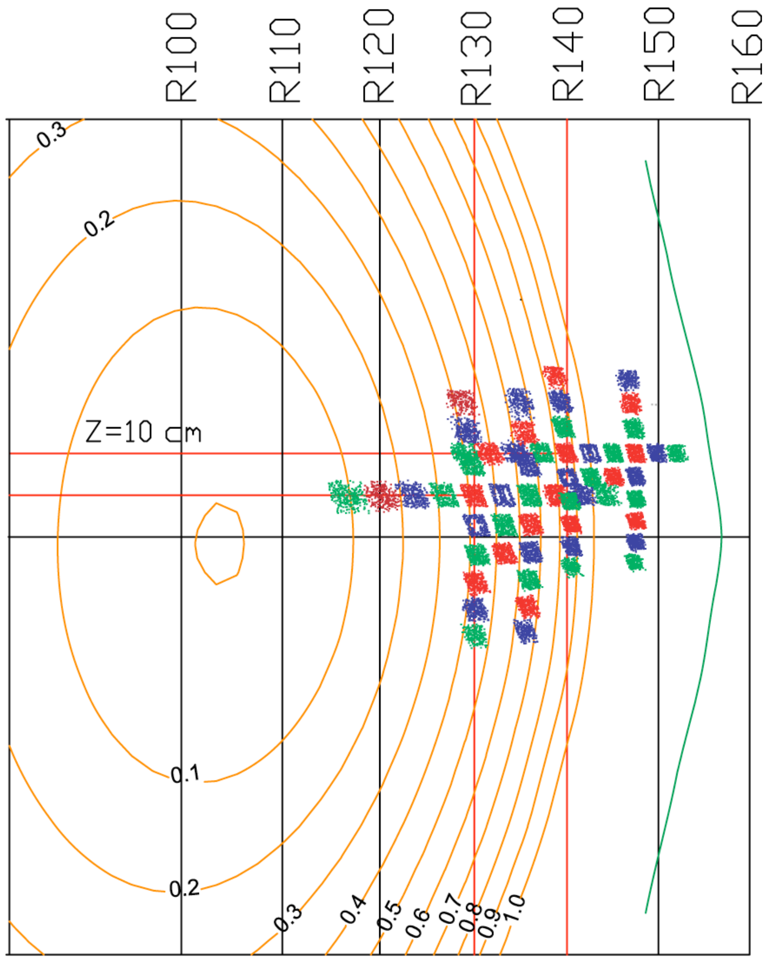
Plasma coverage can sample modes up to $k_\perp \rho_i \approx 1.5$



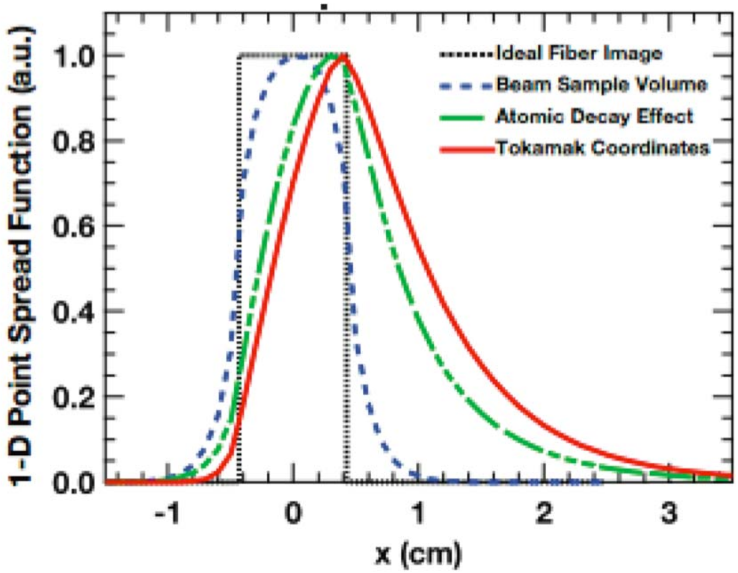






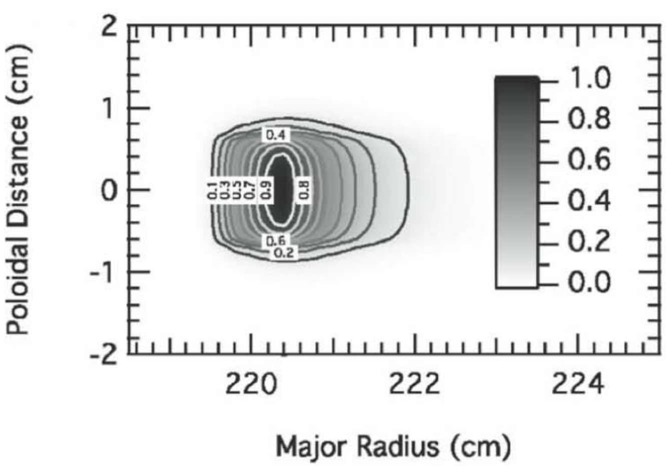


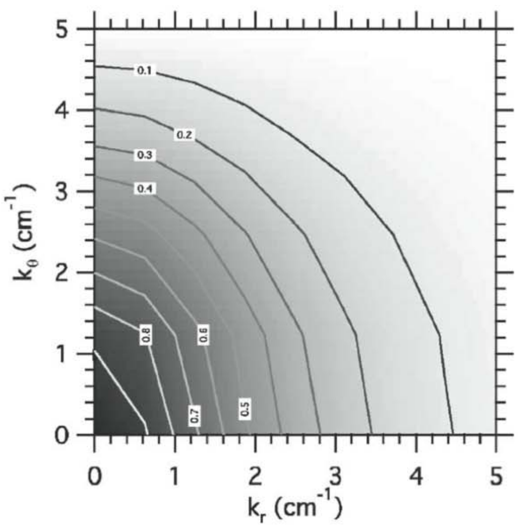
Point-spread-function and spatial-transfer-function calculations will provide spatial and k-space measurement parameters



- 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

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

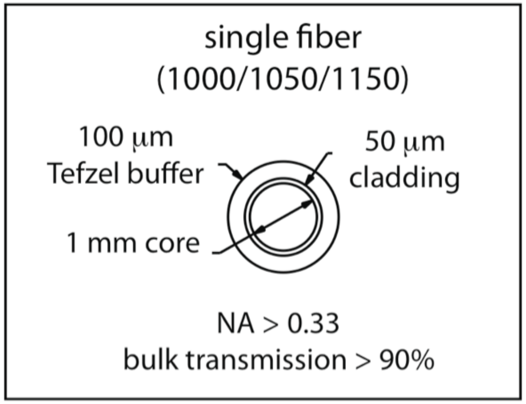


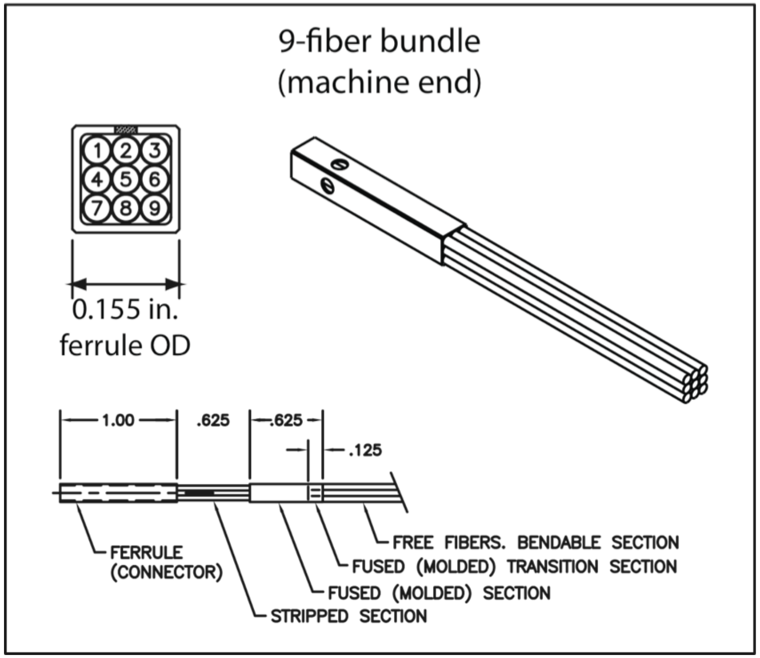


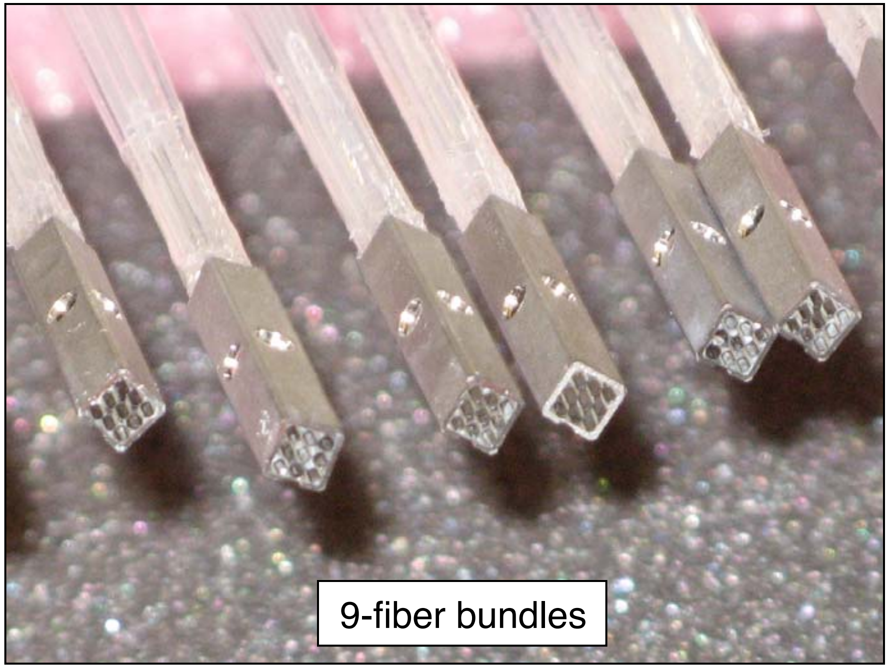
DIII-D BES PST/STF calculations from Shafer et al, RSI 2006

Similar calculations for NSTX will be performed.

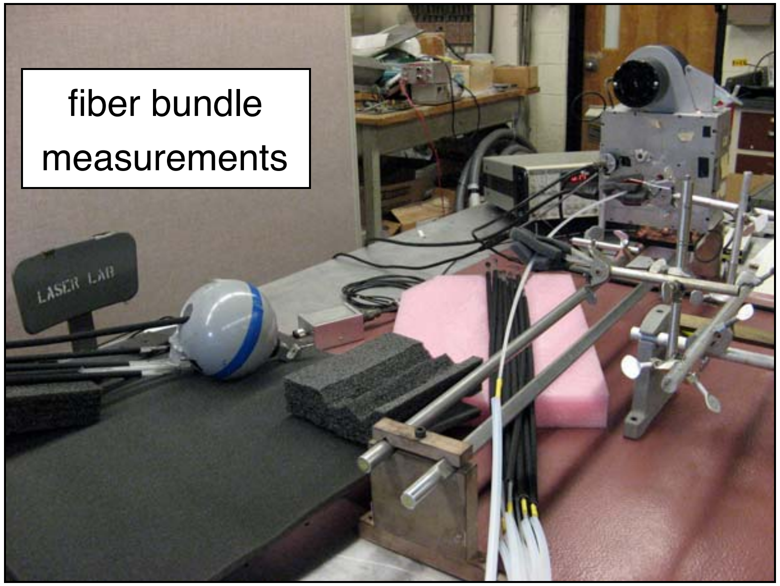
40 meter fiber bundles, each with 9 1-mm fibers, will transmit NB D_α emission from collection optics to photodetectors

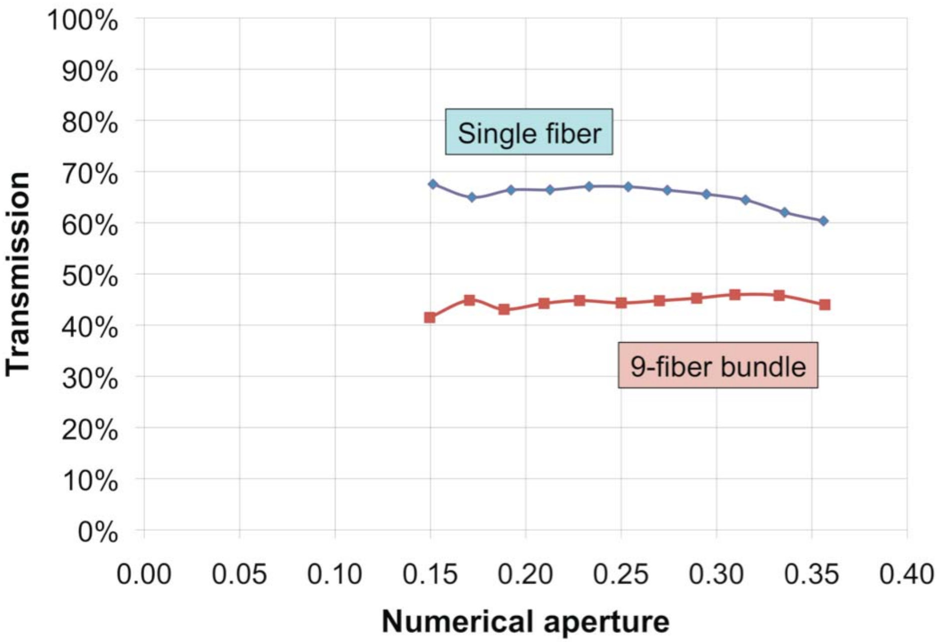


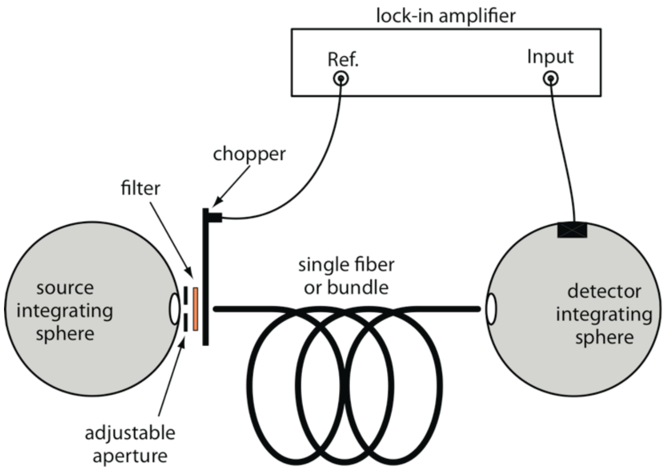


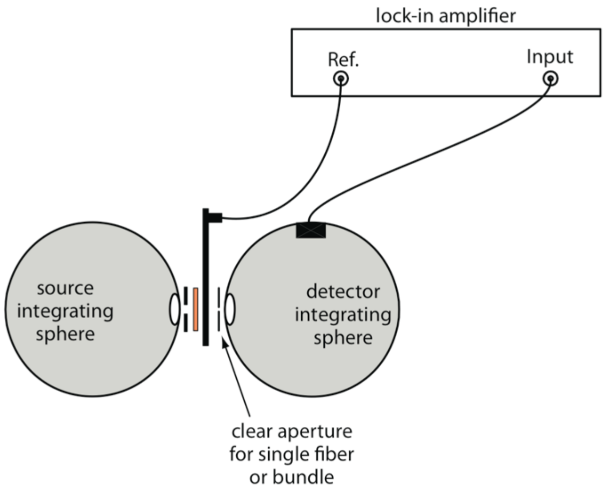


Single fibers achieve 65% transmission & 9-fiber bundles achieve 45% transmission at f/1.5 and NA= 0.33

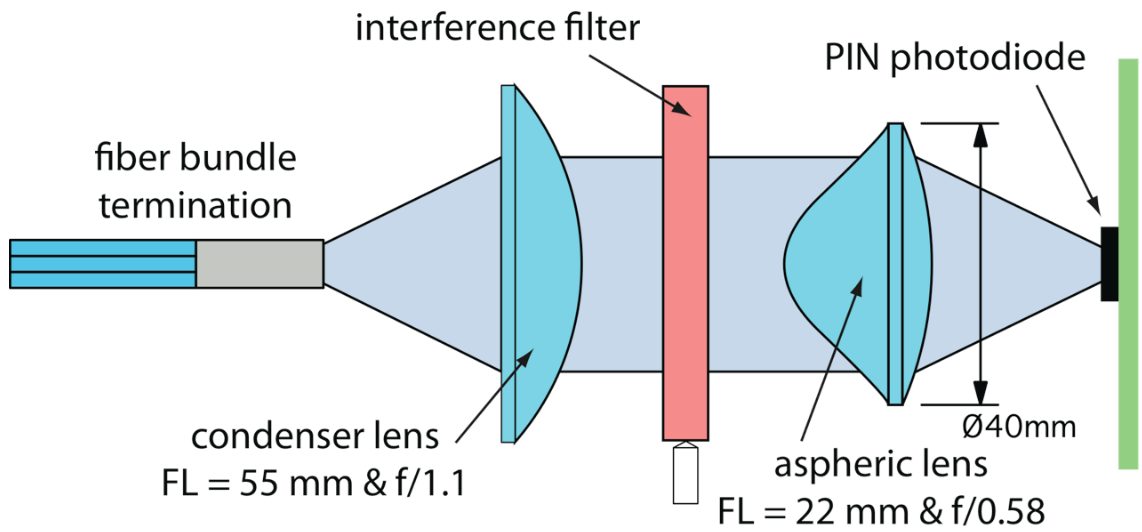


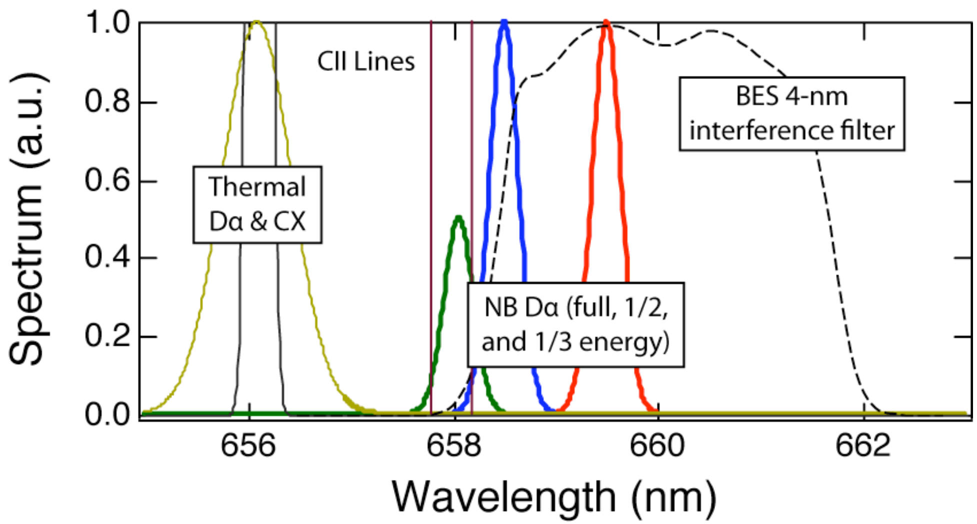


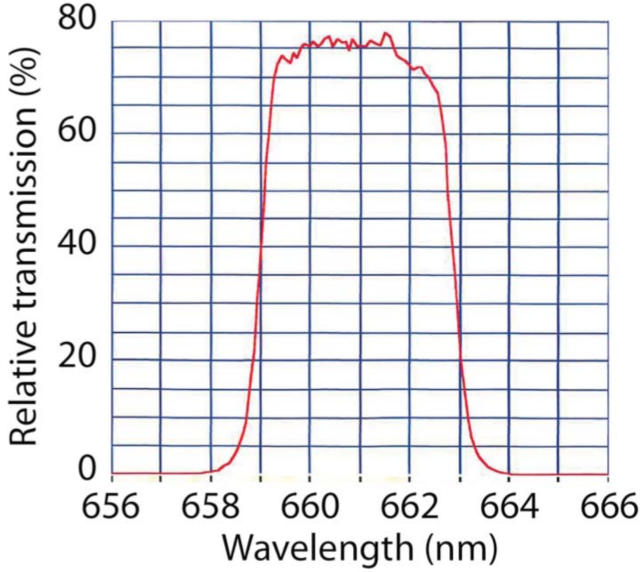




Tilt-tune interference filter provides about 75% transmission in a 4 nm window

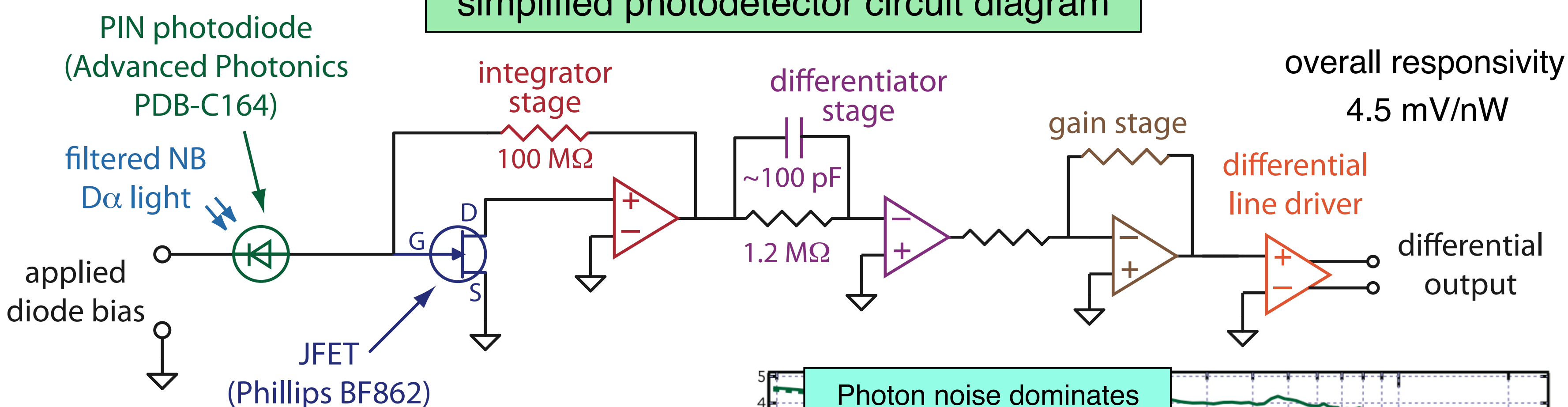






Low-noise, low-capacitance photodiode & FET are key to low-noise, high-responsivity photodetector

simplified photodetector circuit diagram



overall responsivity:
4.5 mV/nW

Noise figure of merit:

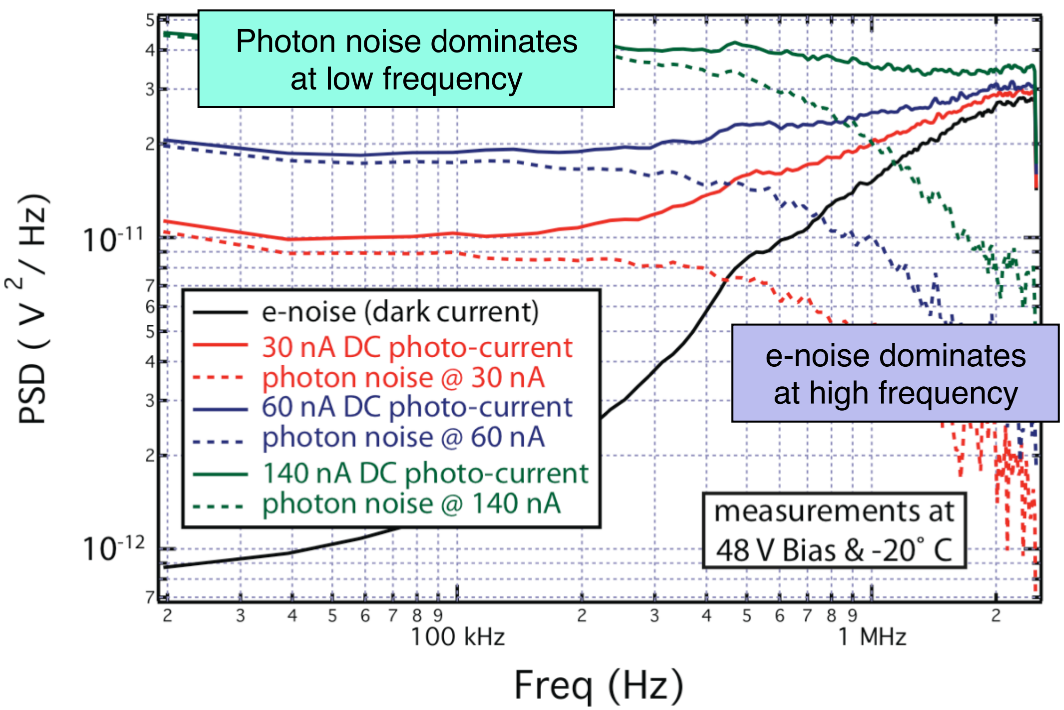
$$e_{noise} \times (C_{diode} + C_{FET})$$

Design values:

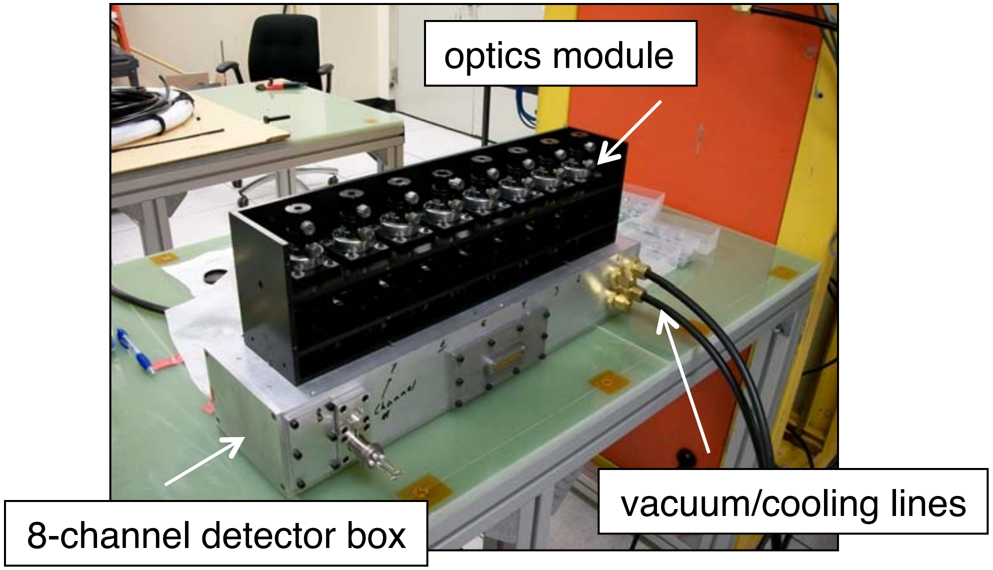
$$e_{noise} = 0.8\ nV/Hz^{1/2}$$

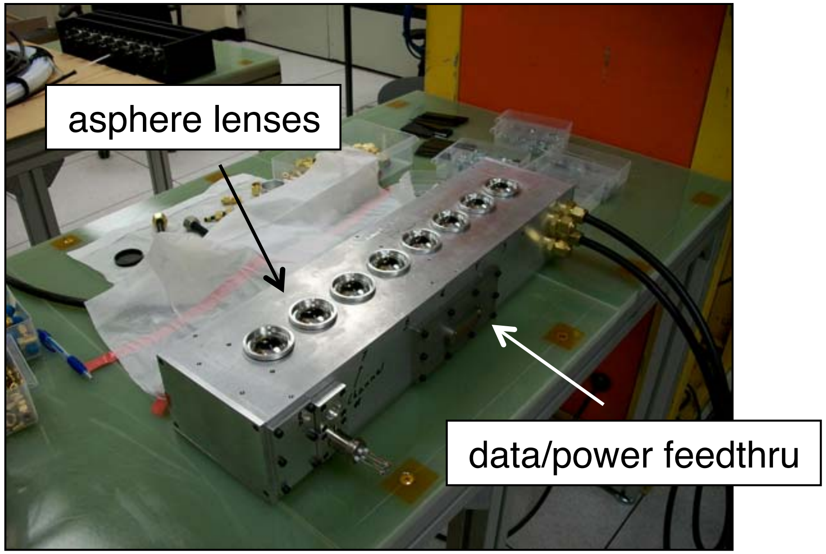
$$C_{diode} = 7\ pF$$

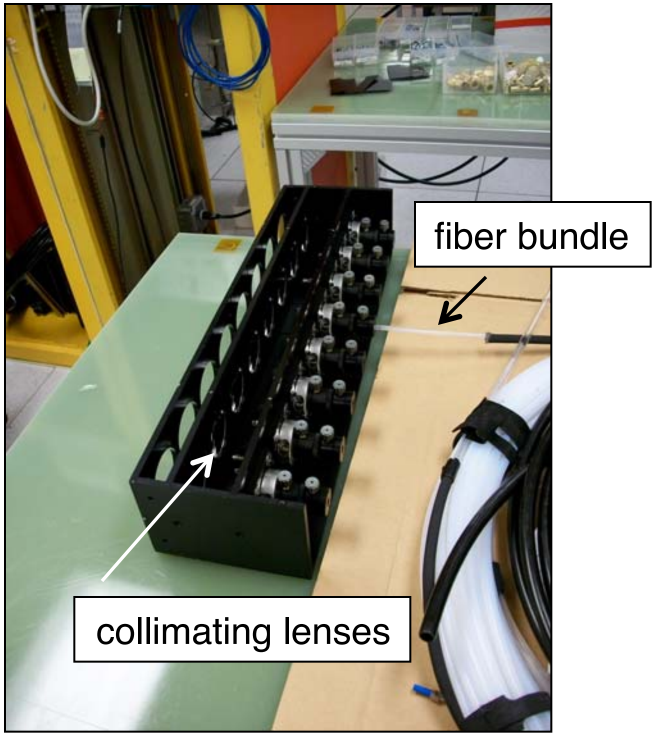
$$C_{FET} = 10\ pF$$

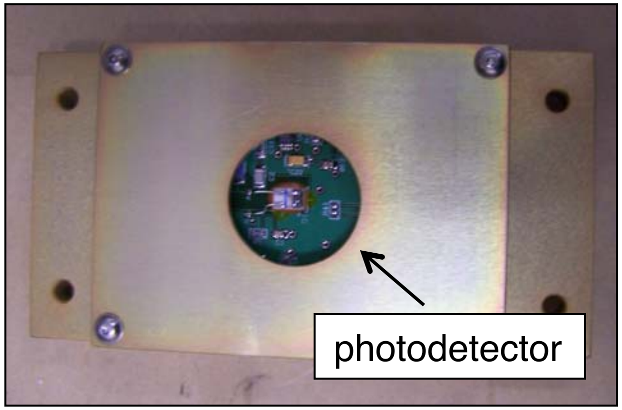


Photodetectors, 8-channel detector box, and optics module



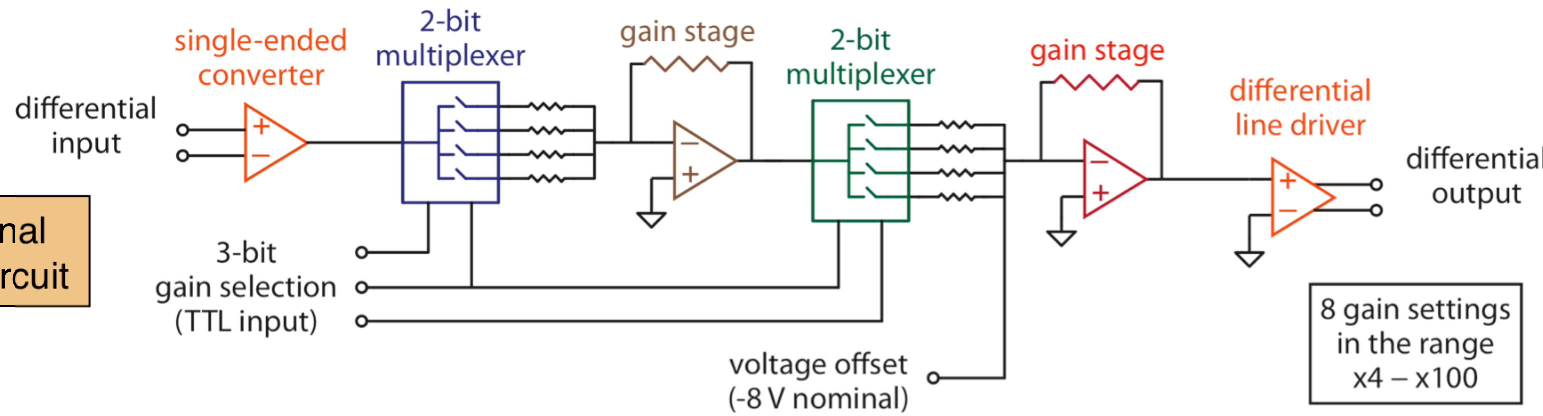




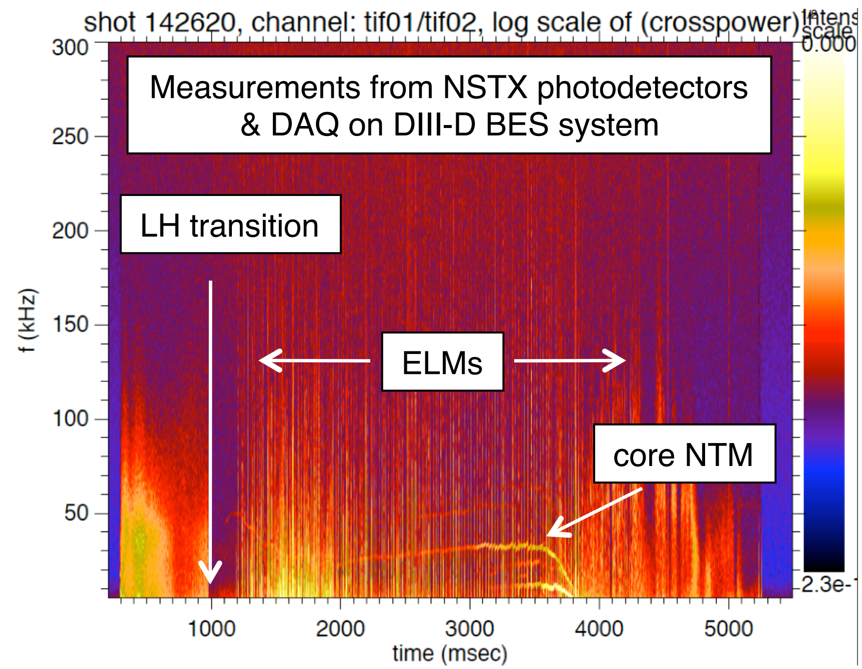


Signal conditioning circuit provides adjustable gain & digitizer with FPGA FIR filter provides 2 MHz sampling

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
  - Filtered 2 MHz output sampling with 32 MHz input sampling



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
- 1 MHz Nyquist with FIR and anti-aliasing filters will accommodate large Doppler shifts from toroidal rotation and GAE/CAE studies
  - DIII-D system samples at 500 kHz Nyquist 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/2.7 and 1.1 mm^2-ster
- Larger spot sizes (magnification) accommodate larger gyro-radii in NSTX
  - NSTX system will access slightly higher $k_\perp \rho_i$
- Signal and noise levels in the NSTX BES system should be similar to the DIII-D BES system due to multiple offsetting factors
  - NSTX photodetectors show similar SNR as DIII-D photodetectors on DIII-D BES system

Status & plans: on schedule for first data in Spring 2010

- Invessel collection optics installed & spatial calibration performed
- Fiber bundle transmission and f/# have been measured
- Fiber bundles (56) and aperture plates installed
- 2 detector boxes (16 channels total) installed
  - 2 additional detector boxes will come online soon for a total of 32 channels
- DAQ and essential control equipment installed
  - Remote control & monitoring capabilities will come online in Spring 2010
- BES analysis software ported to PPPL in Spring 2010
- Shakedown and commissioning in Spring 2010
- Possible experiments in Summer 2010:
  - Anomalous momentum transport driven by low-k fluctuations
  - Characterization of pedestal fluctuations
  - Edge fluctuations and the LH transition
  - TAE & GAE mode structure measurements

Summary

- BES measures Doppler-shifted D_α emission from neutral beam particles to investigate ion gyroscale ($k_\perp \rho_i < 1$) density 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 FIR filter provides 1 MHz Nyquist sampling to accom-modate large Doppler shifts from strong toroidal rotation in NSTX
- On schedule for first data in Spring 2010, and experiments are planned

*Supported by US DOE Contract Nos. DE-AC02-09CH11466 and DE-FG02-89ER53296