New instrumentation and analysis for particle transport and fast ion measurements in Alcator C-Mod

Abstract: UP9.00027

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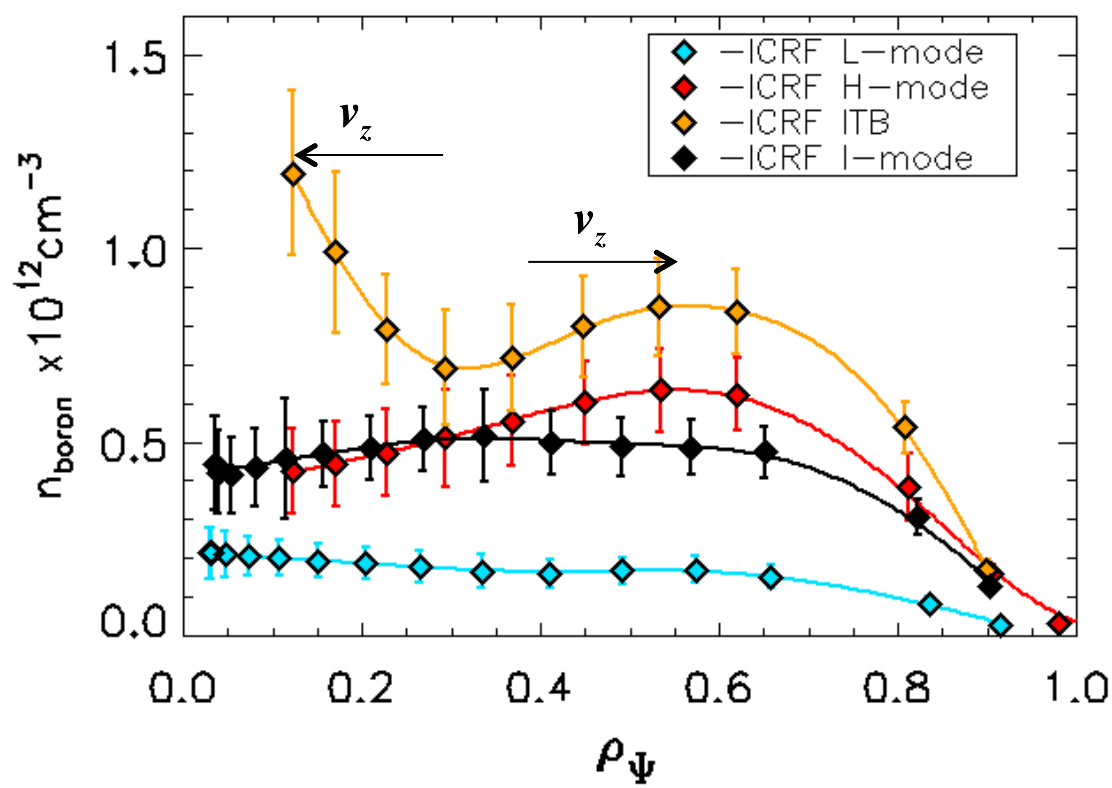
Summary

- **Recent results motivated new instrumentation and techniques.**
- **Impurity profile measurements identified peaked and hollow profiles. Identification of these features requires good spatial resolution. Measurement of the impurity density requires that the density profile of the diagnostic neutral beam be known. Simulation of the beam penetration is the primary tool for this. A direct measurement of the beam density profile is being developed.**
- **Fast ion measurements in helium motivated profile measurements of *thermal* helium. The successful measurement of fast helium ions in D(^{3}He) heated plasmas opened up the possibility for new experiments in which the deposition of the RF and its effect on the plasma will be studied as a function of ^{3}He content and profile. As the ^{3}He content is increased from a few percent, minority heating is replaced by mode conversion. This measurement of ^{3}He profile required implementation of new tools for calibration of the diagnostic.**

Outline

- Summary of recent results
- Overview of the Core CXRS diagnostic
- CXRS particle measurements require detailed DNB profiles
  - Improved simulation tools provide profiles based on measured beam profiles
  - New beam profile diagnostics are in place or in progress
  - Beam emission measurements will be substituted for beam density simulation
  - The use of beam emission requires calibration of the polarization sensitivity of our in-vessel, metal optics
  - Beam width affects radial resolution
- Fast ion measurements
  - New calibration techniques were applied for thermal helium density measurement
  - Isolation of relevant spectra will be changed from interference filters to a mechanical blocking bar.

Recent Results
Identification of Impurity Pinches



- **Flat/hollow regions indicate particle pinches**

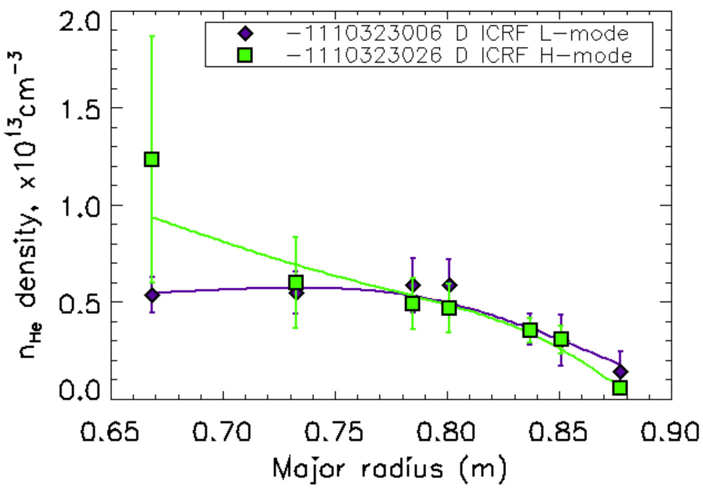
$$\Gamma_z = -D_z \frac{\partial n_z}{\partial r} + v n_z$$

pinch

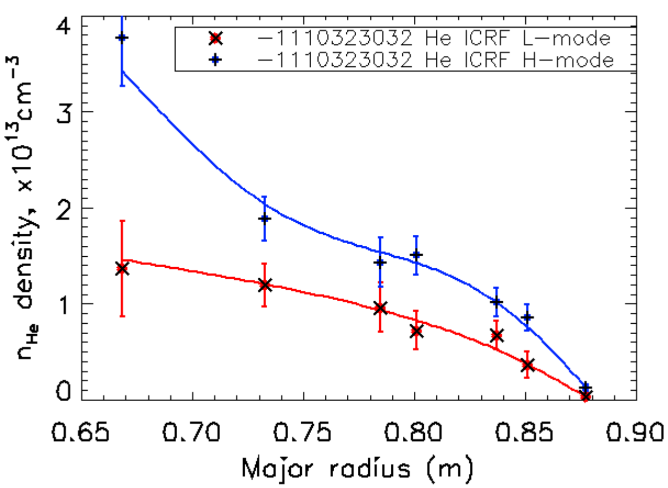
- **Measurement of spatial variation**
  - **Requirement on spatial resolution**
  - **Requirement on uncertainty**
- **Note: displayed data analyzed to emphacize flat and hollow regions.**

Recent Results
Measurement of Helium Profiles

Trace Impurity

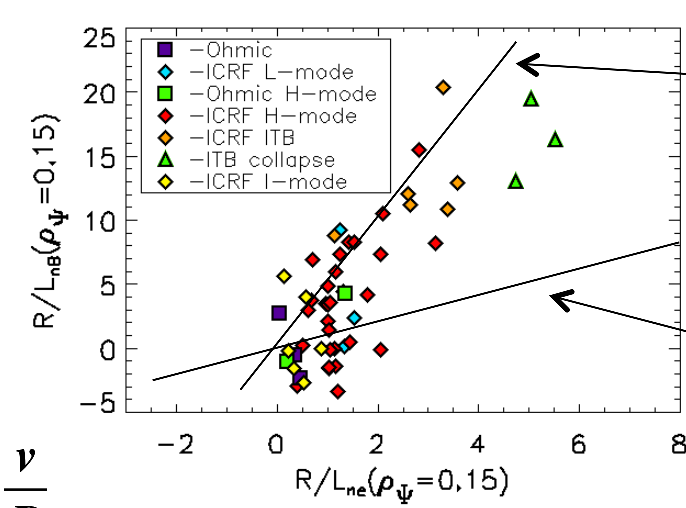


Main Ion



- **Helium profiles**
  - **Helium trace/impurity**
  - **Helium main ion**
- **Required for interpretation of fast ion measurements: As the ^{3}He content is increased from a few percent, minority heating is replaced by mode conversion.**
- **Required improvements – mostly completed**
  - **New methods for calibration to acquire profiles**
  - **Improved optical throughput for reduction of error bars**
  - **Increased spatial resolution Improved scale lengths**

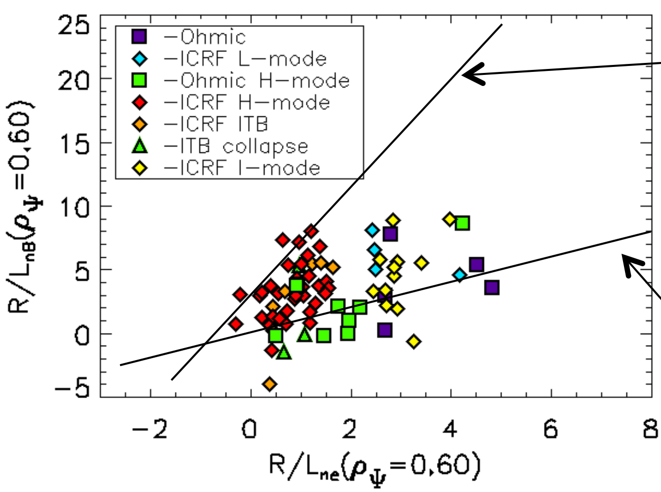
Recent Results
Scaling of Light Impurity Profiles for Transport Investigations



$$\left.\frac{R}{L_{nB}}\right|_{neocl}$$

$$\frac{R}{L_{ne}} = \frac{R}{L_{nB}}$$

$$R\frac{v}{D}$$



$$\left.\frac{R}{L_{nB}}\right|_{neocl}$$

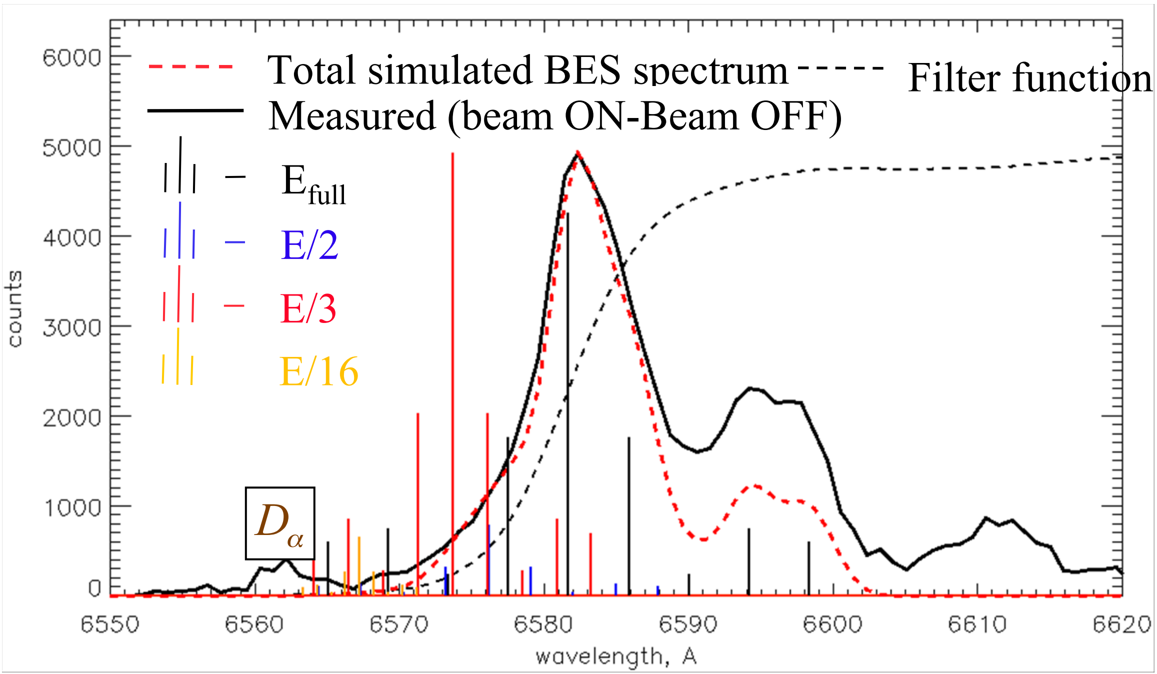
$$\frac{R}{L_{ne}} = \frac{R}{L_{nB}}$$

- **Typical scaling parameters (scale lengths in the case) give immediate access to impurity transport information.**

$$\frac{v_z}{D_z} = \frac{1}{n_z}\frac{\partial n_z}{\partial r} = \left(-L_n\right)^{-1}$$

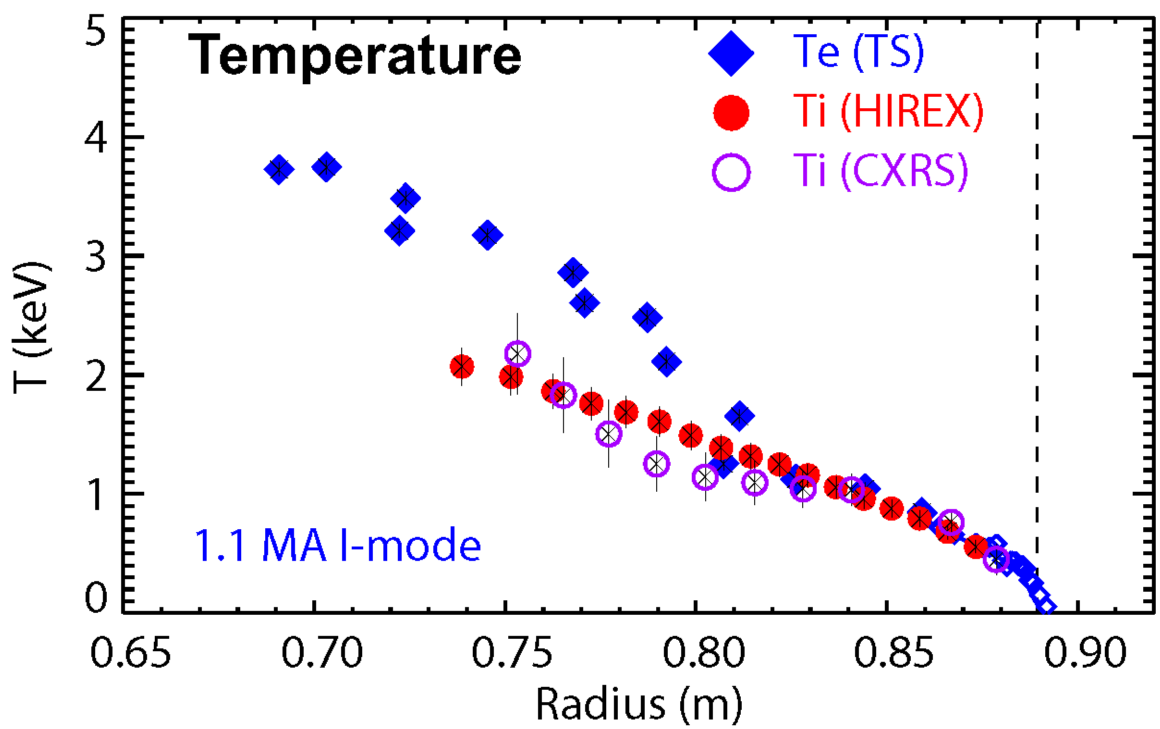
- **Scalings valuable: here they show general departure from neoclassical theory and thus demonstrate an opportunity for investigation of turbulent transport**
- **Inference of scale lengths requires places stringent requirements on both resolution and impurity density uncertainty**

Recent Results
Neutral Beam Emission Spectrum Measurement and Simulation



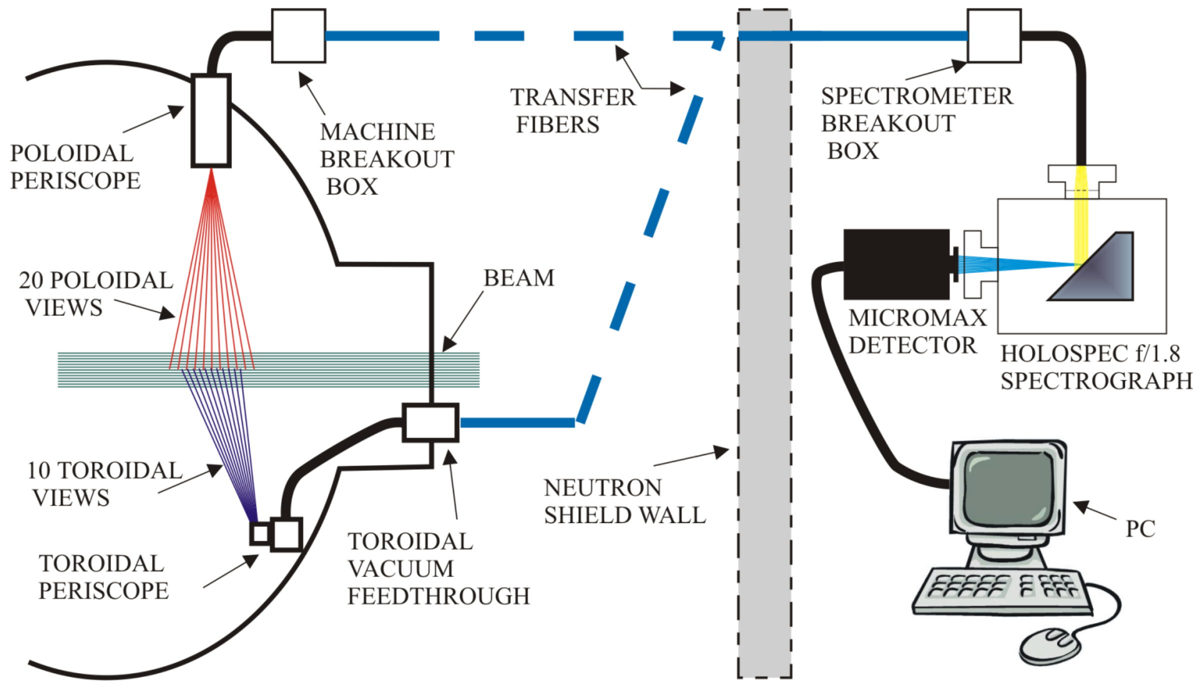
- **BES spectrum required for new beam density measurement**
- **BES spectrum computation required for background subtraction in fast ion measurement**
- **Require improved resolution – just narrower slits**
- **Require polarization calibration for optics since the spectrum is polarized and metal mirrors are in use.**

Recent Results
Ion Temperature measurements benefit from general improvements in the diagnostic



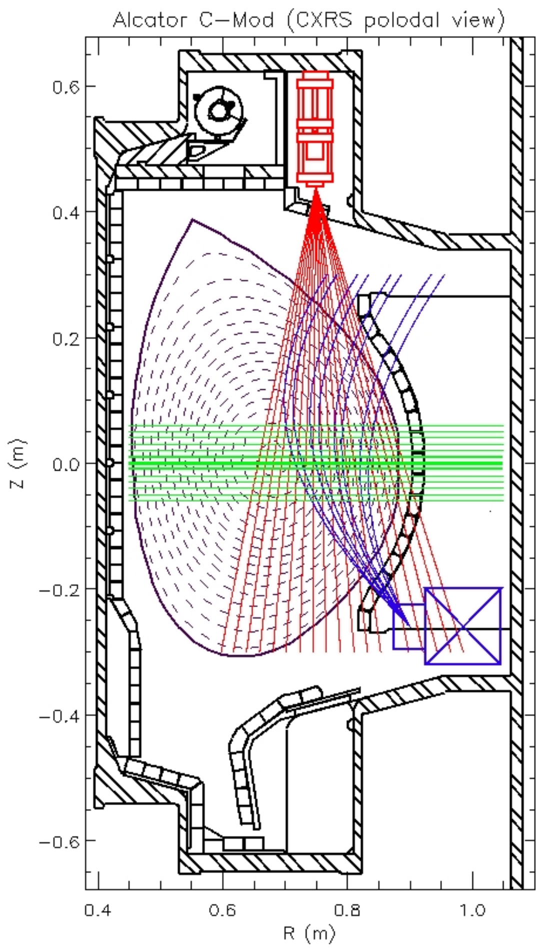
- Comparison of T_e and T_i in a 1.1 MA I-Mode discharge
- High spatial resolution made possible by high throughput
- Beam optimization will improve the measurement

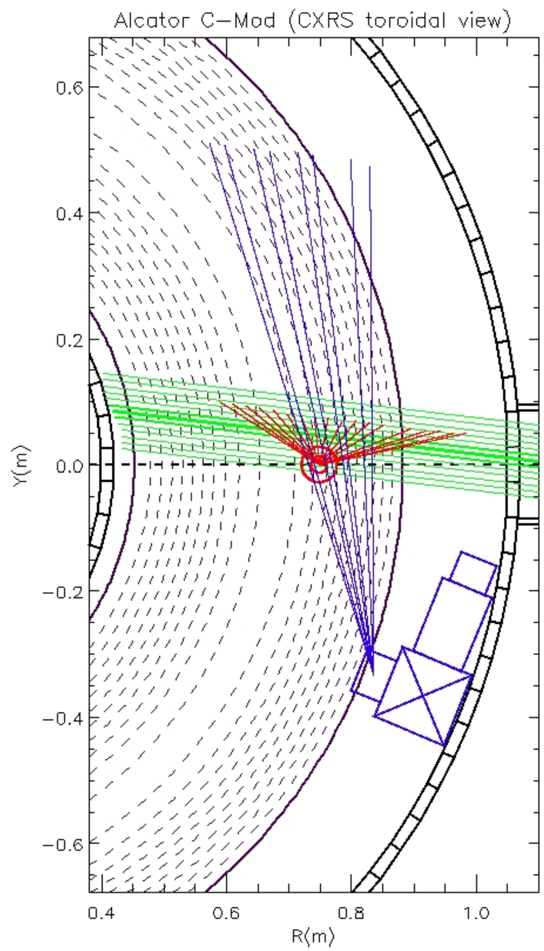
Overview of the Core CXRS Diagnostic at Alcator C-Mod



- **The light is collected by two optical periscopes (red and blue chords) and transmitted through two fiber bundles to holographic imaging spectrograph.**
- **Spectrograph is set up to accept the light from up to 45 spatial channels and spectrally disperse them onto the CCD detector, while keeping them spatially separated**

Overview of the Core CXRS Diagnostic at Alcator C-Mod





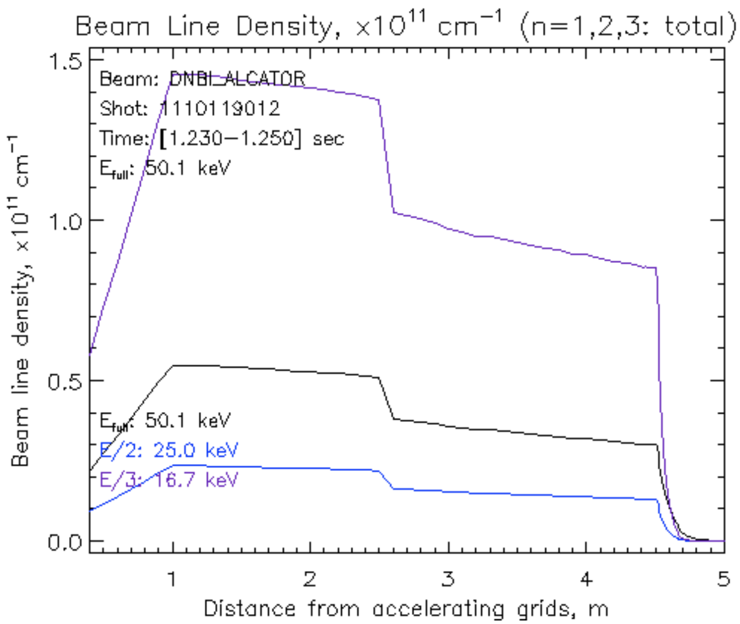
- DNB (green) is injected in the midplane of the tokamak
- Observe its interaction with the B^{+5} and He^{+2}
- Poloidal optical views
  - 20 chords (red)
  - Mainly poloidal
- Toroidal optical views
  - 20 chords (blue)
  - Mainly toroidal
- Chord separation for system is 1.2 cm

CXRS Particle Measurements Require Detailed DNB Profiles

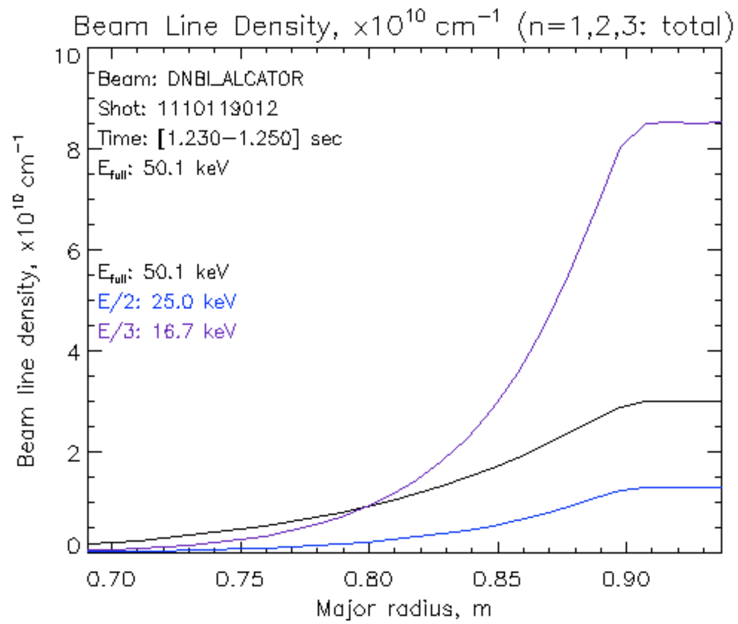
- Simulation tools: ALCBEAM developed specifically to fully describe a DNB, as a tool for optimization, and to support beam-based diagnostics
- Beam profiles are measured to benchmark ALCBEAM. New measurements upstream of plasma will help optimize beam formation
- Beam emission measurements that are simultaneous in space and time with the CXRS measurements may provide the beam density with greater reliability than beam attenuation calculations
- Beam emission is polarized. Application as a replacement for beam attenuation simulation requires calibration of polarization sensitivity of optics.
- Larger beam width reduces the radial localization of the CXRS measurements. In C-Mod, this is estimated by analysis of the CXRS emission distribution along the intersection of viewchord and beam and ultimately included as an uncertainty.

Simulation of Neutral Beam ALCBEAM

- **ALCBEAM is a new three-dimensional neutral beam formation and propagation code. It was developed to support the beam-based diagnostics installed on the Alcator C-Mod tokamak**



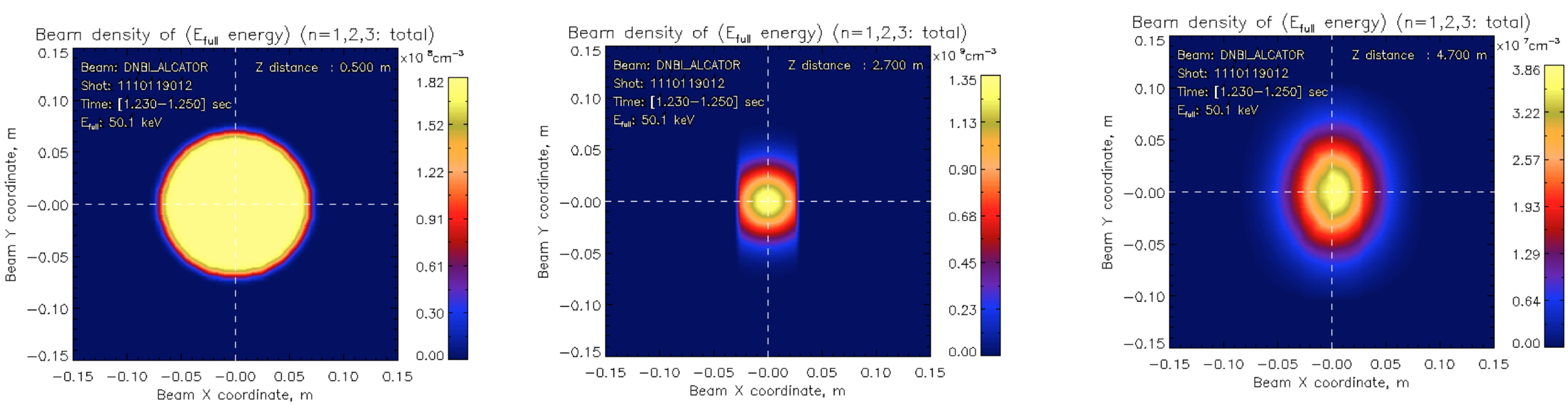
Follows beam along full trajectory
Allows use of upstream measurements as constraints



Tracks all beam energy components whether there are one or four or ...

Simulation of Neutral Beam ALCBEAM

- **Beam parameters can be followed in cross section throughout the trajectory from extraction through the plasma**



z = 0.5
Extraction

z = 2.7
Near aperture

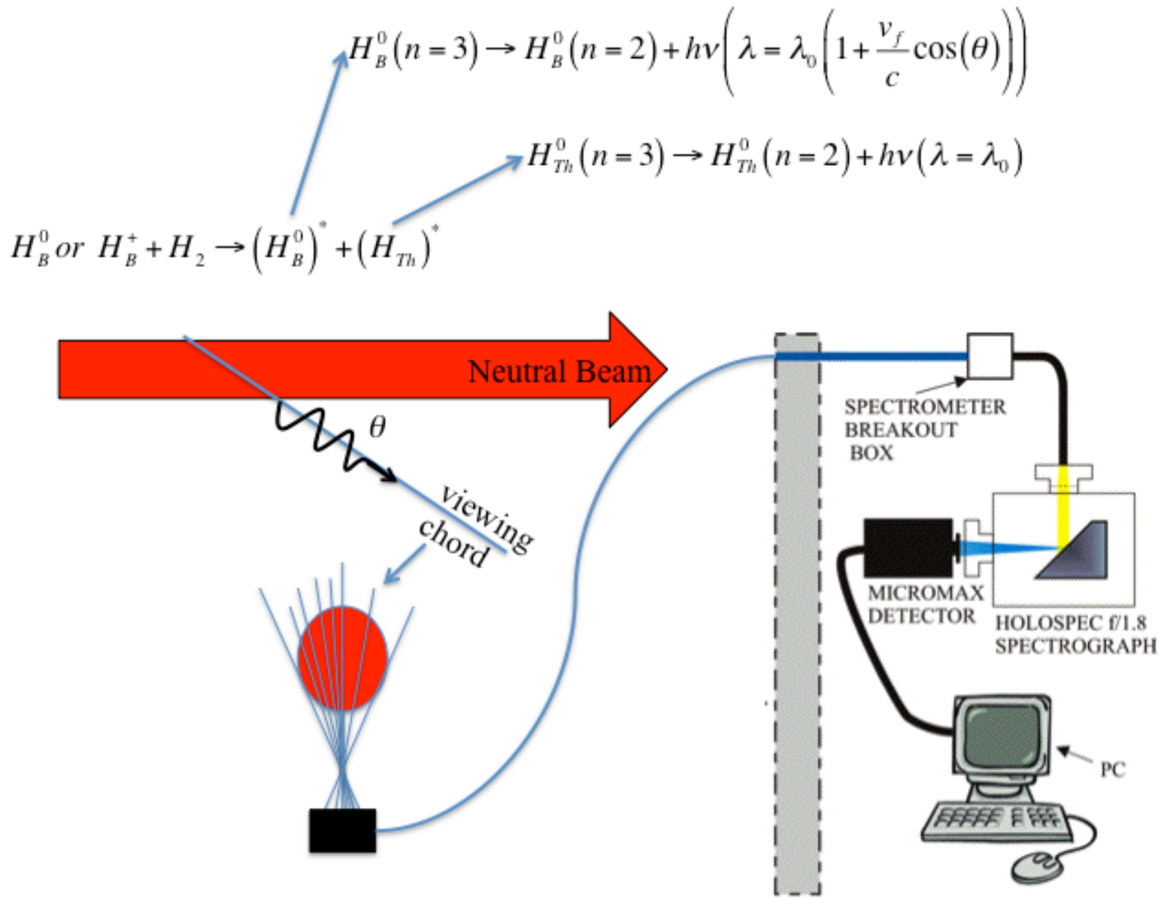
z= 4.7
Near beam focus

Beam Profile Measurement Benchmarking and DNB Optimization

- Optical diagnostic for measurement of the radial profile of the diagnostic neutral beam where the neutral beam is injected into the duct leading from the DNBI to C-Mod.
- As a benchmark for ALCBEAM, it supplements a calorimeter and measurements in the plasma.
- Designed to optimize the beam performance
  - Measure the profile of each of the energy components of the beam. The profile of the beam will betray grid alignment problems which can be examined with ALCBEAM
  - Measure the Fulcher spectrum (570 to 640 nm) emitted by the H_2 in the beam neutralizer. Infer temperature of the neutralize gas and efficiency of neutralization.

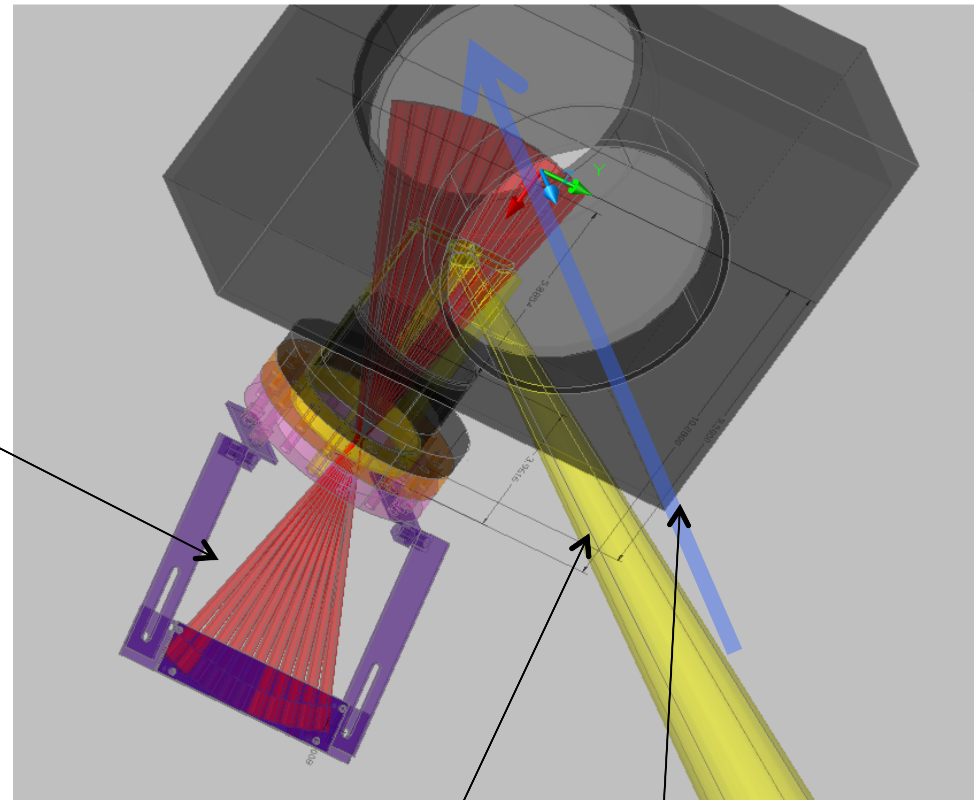
Beam Profile Measurement Benchmarking and DNB Optimization

- **Optical diagnostic for measurement of the radial profile of the diagnostic neutral beam where the neutral beam is injected into the duct leading from the DNBI to C-Mod.**
- **Beam is observed in the duct. Beam and background gas emit radiation which is used to to infer beam energy and density.**



Design of the Beam Profile Diagnostic

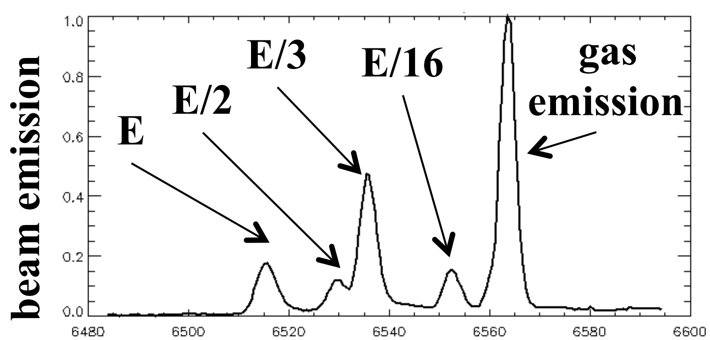
view chords
for beam profile



view of
neutralizer

neutral beam

Typical Beam Spectrum

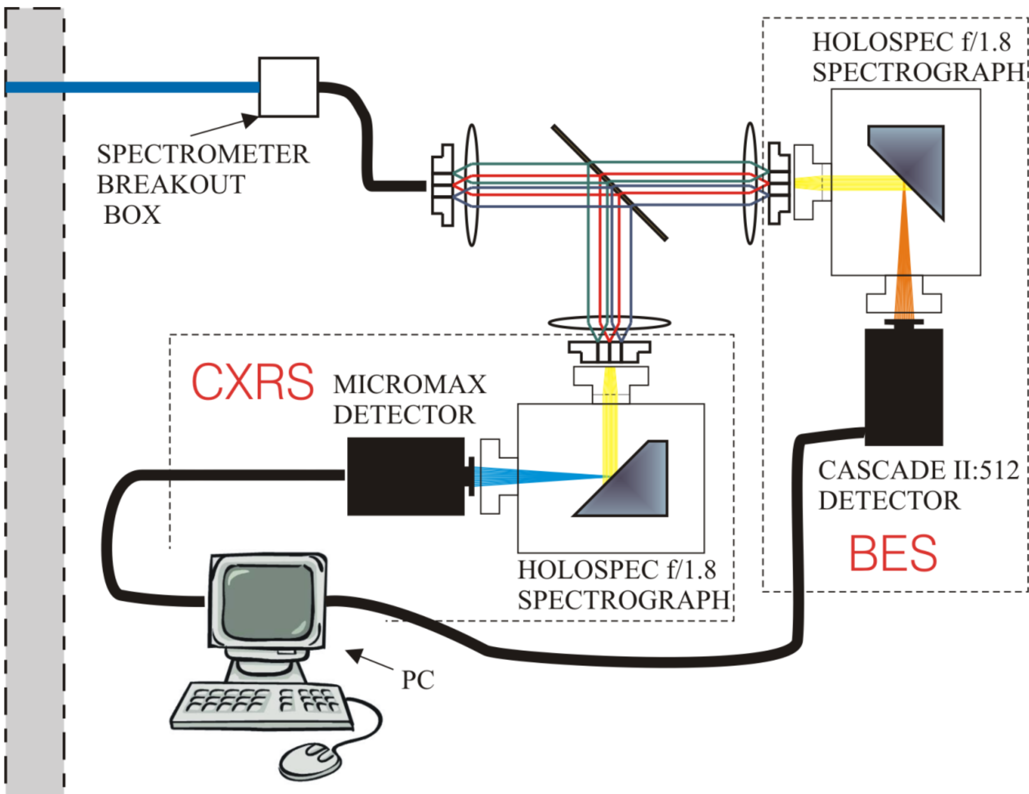


relative wavelength (A)

New Measurement of Neutral Beam Density

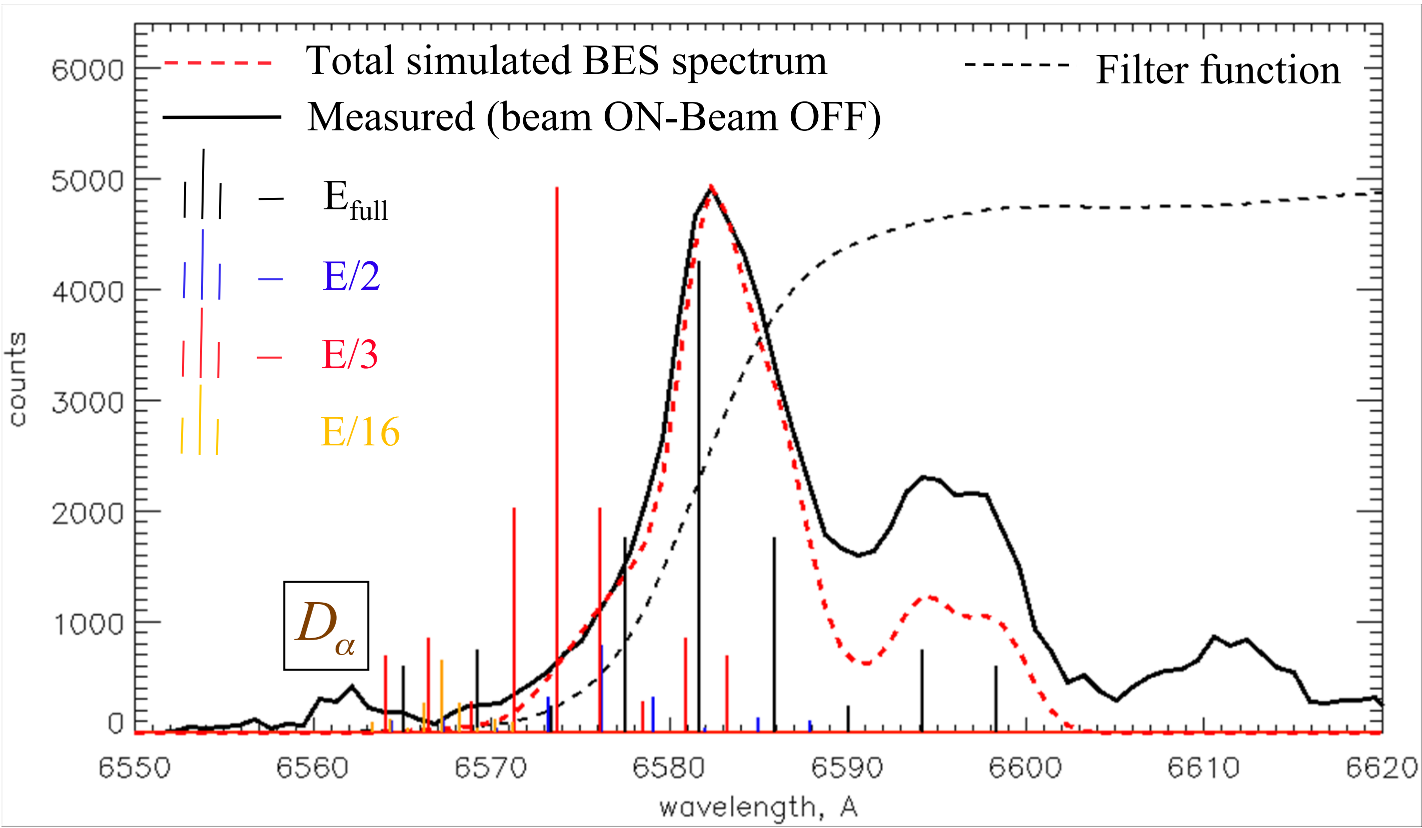
- Measurement of absolute density of boron or helium density requires measurement of the neutral beam density although the relative profile requires only the much more accessible relative neutral beam attenuation.
- The new upgrade -- Integrated CXRS/BES System -- is a new optical system which simultaneously measures the CXRS spectrum and the beam emission spectrum using the same viewing geometry. The beam emission then substitutes for the beam density to yield impurity density.
- It is based on a method proposed for ash measurement via CXRS proposed for ITER

Upgrade to combine CXRS and BES systems

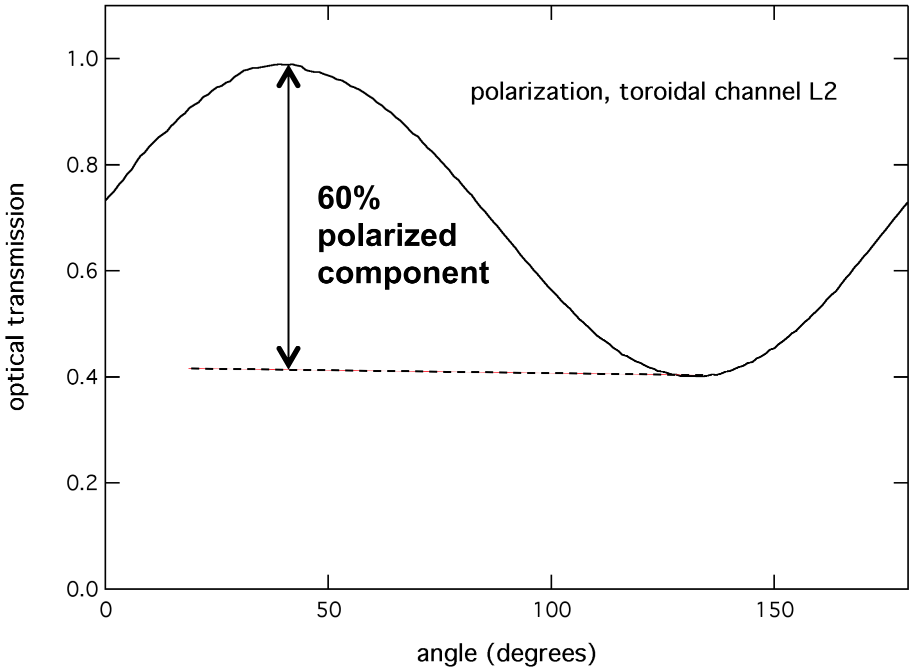


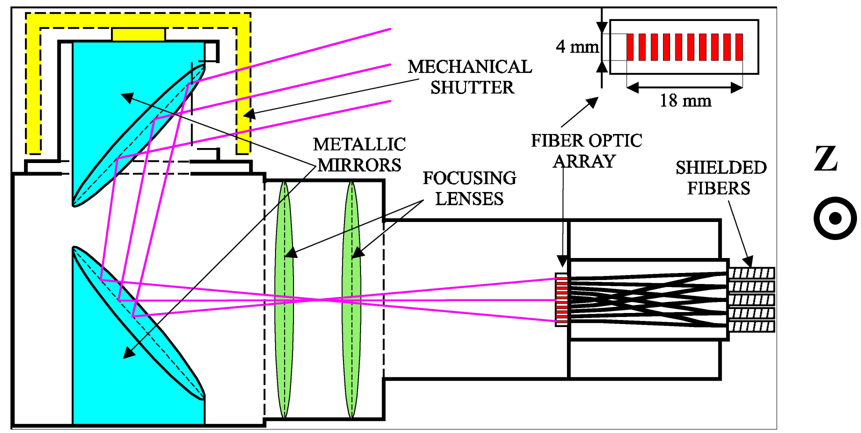
- A multi-channel optical splitter diverts the CXRS emission (4945 B^{+4} or 4949 H^{+}) into one spectrometer and allows the beam emission (Doppler shifted H_a) to pass through to a different spectrometer
- Two high resolution (~0.1 nm) high throughput holographic imaging spectrographs (Kaiser Holospec f/1.8) and two high speed, low noise CCD cameras - (Princeton Instruments Micromax and Photometrix Cascade II:512) (512 x 512 pixels) will be used to spectrally analyze the CXRS and BES emission from all 42 optical spatial channels.

BES Spectrum
Measurement and Simulation



Calibration of Polarization Sensitivity





Toroidal Optic Schematic

- **The first optic in the toroidal optical system is a stainless steel mirror which was chosen as a rugged component for invessel use. Reflection from the mirror is expected to be polarized and the optical transmission is expected to be polarization sensitive.**
- **Polarization is shown on the right. Angle in graph on the right is wrt vertical.**

BES Spectrum
Measurement and Simulation

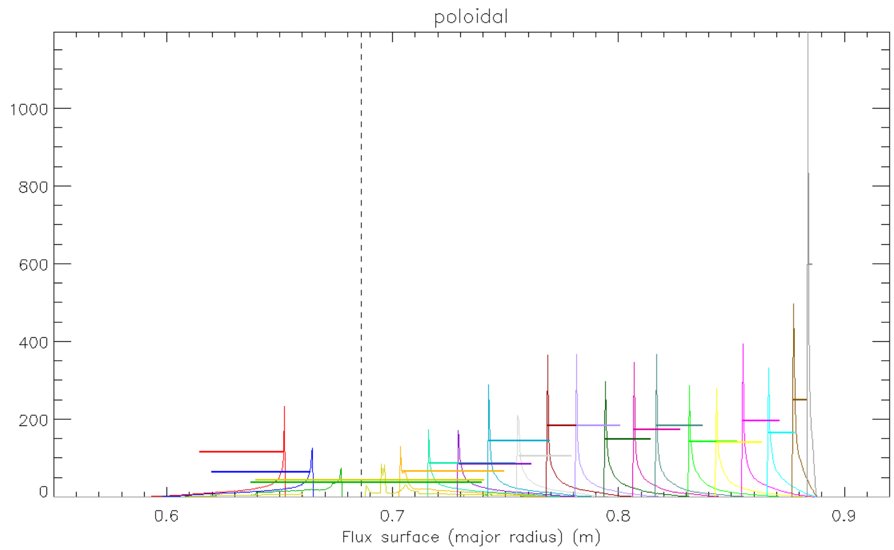
- The spectrum has been observed.
- Beam simulation reproduces the spectrum adequately.
- D_α should be isolated by physical block instead of the bandpass filter
- The revised analysis of the CXRS spectrum for impurity density is straightforward

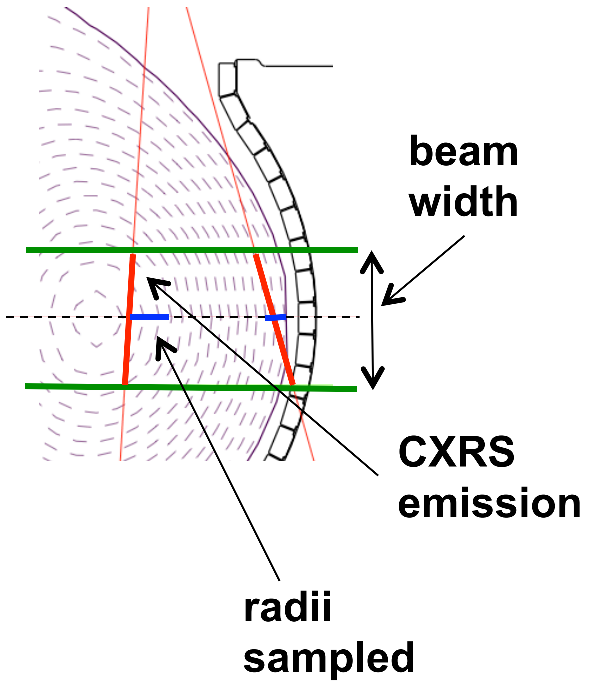
$$N_k\left(B^{+5} or\ He^{+2}\right) = \frac{n_e R^{CXRS}}{\sum_{j=1}^{M} R^{BES}\left(E_j\right)\frac{q_j^{CXRS}\left(n \rightarrow n''\right)}{q_j^{BES}\left(E_j, n_e, T_i, Z_{eff}\right)}}$$

  - R^{BES}, radiance of BES spectrum
  - R^{CXRS}, radiance of CXRS spectrum
- Note that absence of geometrical factors: due to common viewing geometry

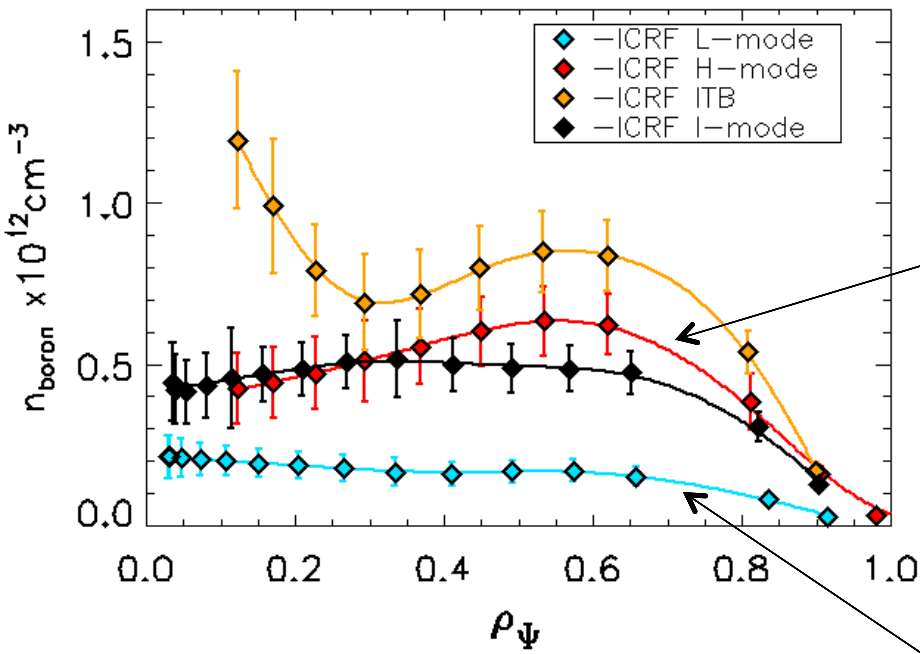
Accounting for the finite width of the beam with an uncertainty in radius

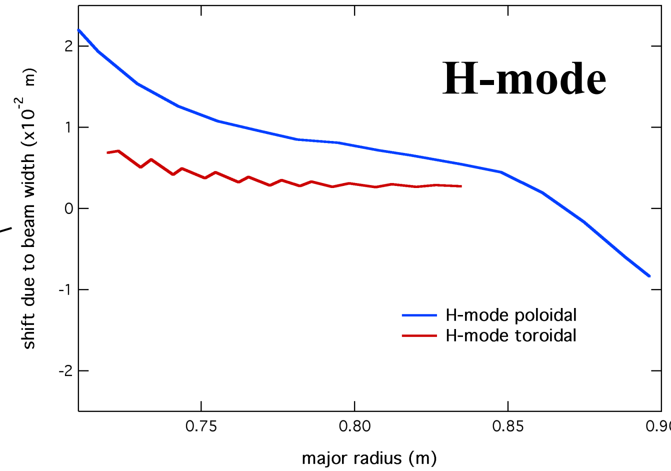
- The beam width alone causes a viewing chord to collect CXRS signal from -0.06 m < z < 0.06 m
- This can be accounted in ΔR
- For impurities constant on a flux surface, the radii sampled by the chord are marked.
- The signal weighting for each sampled radius is in the figure. One radius still dominates

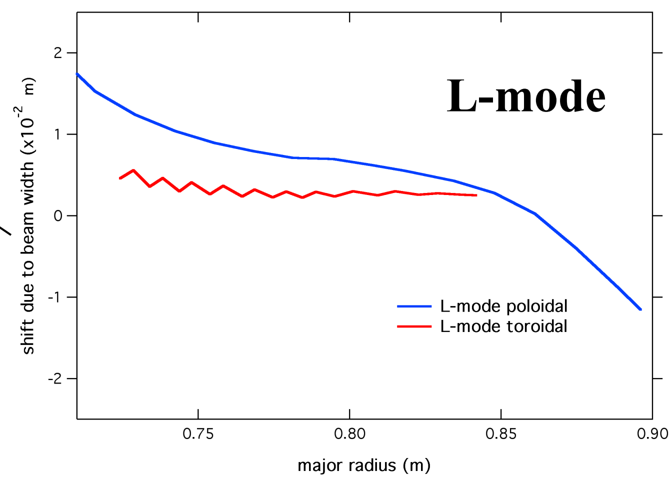




Accounting for the finite width of the beam with an uncertainty in radius







- **Examples for H-mode and L-mode.**
- **Effect is modest but for core.**

Fast Ion Measurement

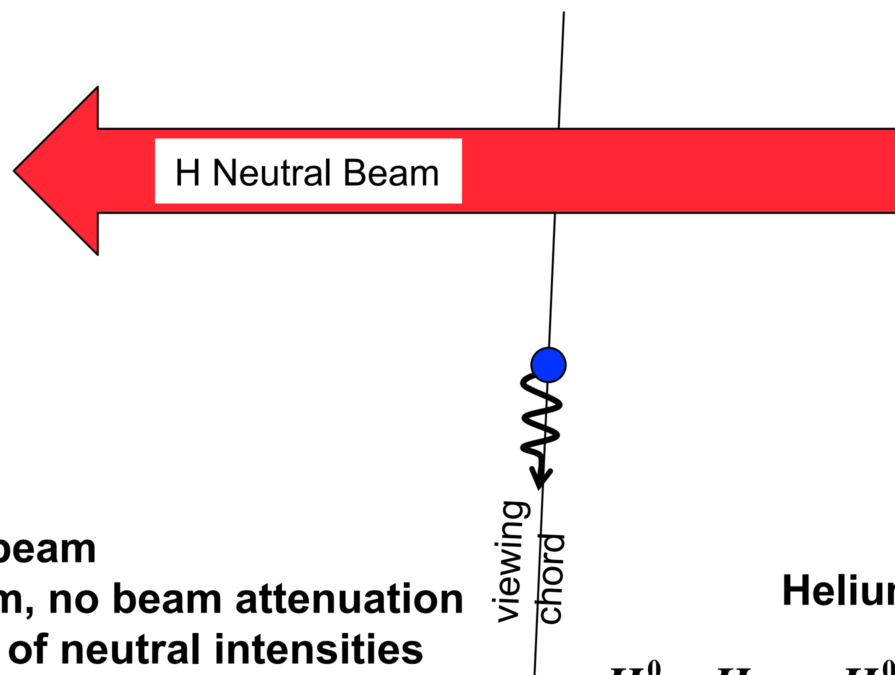
- Fast ion measurements are needed for ICRF deposition studies
- Signal to noise issues suggested that measurements were better for helium minority
- As a target of opportunity, it became clear that the addition of measurement capability for helium concentration would allow measurement dependence on minority concentration from minority heating through mode conversion.
- The minority concentration measurements require calibration of the diagnostic.
- Relevant spectra used for fast ion measurements in D(H) plasmas require isolation from a strong background. This was done with interference filters. For new measurements, a mechanical blocking bar will be used.

Measurement of the Helium Concentration Calibration

- Measurement of the absolute helium concentration is all about calibration
- Opportunities for radiometric calibrations are rare
- Additional techniques needed since transmission of the optical collection and/or sensitivity of the detection systems evolve on a time scale that is more rapid than the opportunities for radiometric calibrations
- Beam into gas: Fire beam into pure helium gas and measure emission to acquire relative channel-to-channel calibration
- Quasineutrality: Measure CXRS signal in pure helium discharge, infer helium density from Thompson scattering estimate of electron density
- Bremsstrahlung: Compare bremsstrahlung in measured spectra with Z_{eff} measurements

Measurement of Helium Concentration Beam into Gas

- Fire beam into pure helium gas and measure emission to acquire relative channel-to-channel calibration



Helium ionized by beam
Ion remains in beam, no beam attenuation
helium ions at 10% of neutral intensities

$$H_B^0 + He \rightarrow H_B^0 + \left(He^+\right)^*$$

$$He^+\left(4d\,^2D\right) \rightarrow He^+\left(3p\,^2P\right) + h\nu\left(\lambda_0 = 4686\right)$$

Helium excited by beam

$$H_B^0 + He \rightarrow H_B^0 + \left(He\right)^*$$

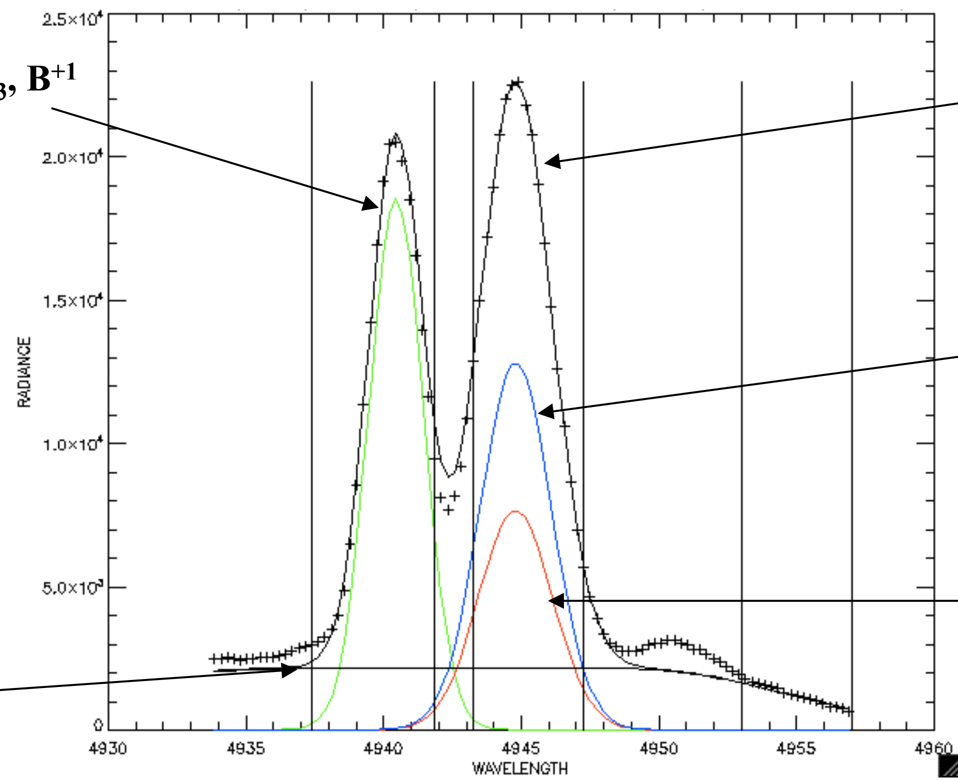
$$He^0\left(4s\,^3S\right) \rightarrow He^0\left(2p\,^3P\right) + h\nu\left(\lambda_0 = 4713\right)$$

Measurement of the Helium Concentration Bremsstrahlung Calibration

4940.376, 2s3d $^1D_2$ - 2s4f $^1F_3$, B^{+1}

total spectrum blended lines

line model used for analysis of boron spectrum



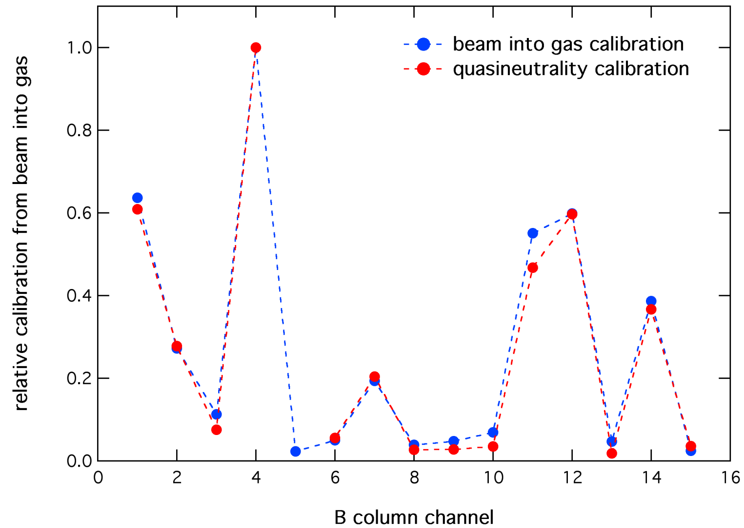
4944.67 (n=7→6) B^{+4} thermal charge exchange e →i collisions

4944.67 (n=7→6) B^{+4} Active charge exchange

continuum (bremsstrahlung)

- **Plasma's self-generated electron-ion bremsstrahlung emission is used to supplement standard radiometric calibration of visible plasma emission using lamps. B^{+5} profiles from CXRS**

Measurement of the Helium Concentration Comparison of Calibration



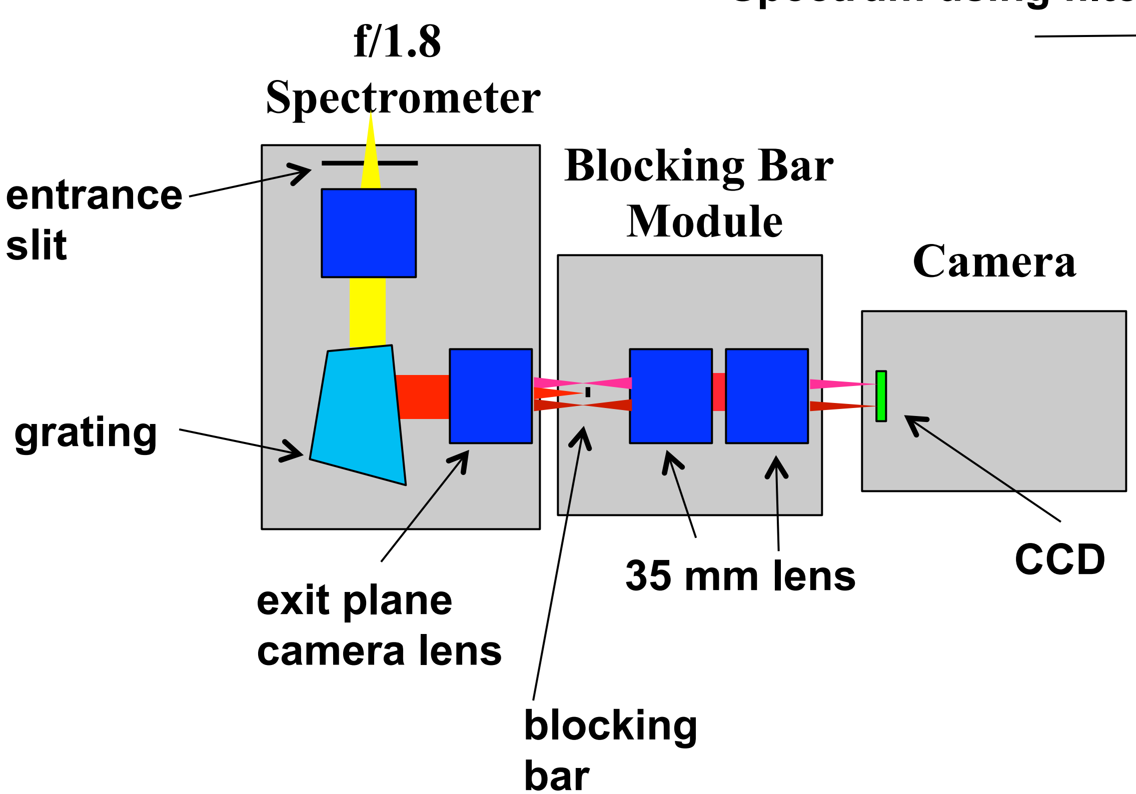
- The beam into gas and the quasineutrality calibrations agree.
- The calibration illustrates the strong channel to channel difference that must be calibrated after several months of tokamak operation
- Both can be done at need frequency

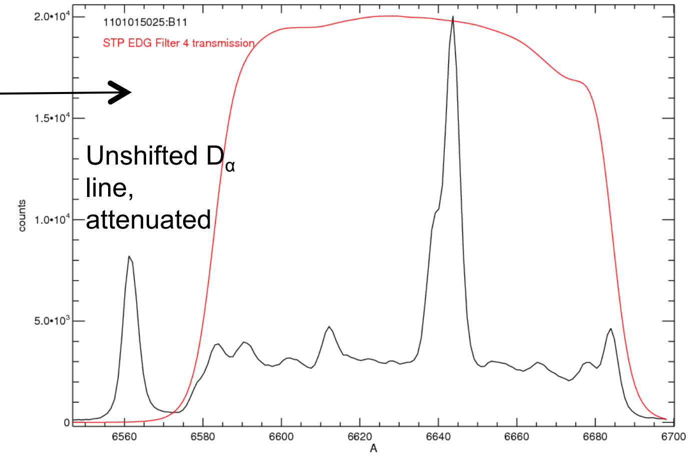
Isolation of the Fast Ion Spectrum for D(H)

- **The thermal D_α spectrum interferes with the fast ion spectrum.**
- **The closer to the core of the line that one gets more intense the spectrum becomes.**
- **Blocking bar is being developed as an alternative to the existing interference filter. Advantages include**
  - **Steeper cutoff**
  - **Flexible control of cutoff position to get closer to D_α peak**
  - **Measure wings on both sides of peak**
  - **Potentially better signal to noise**

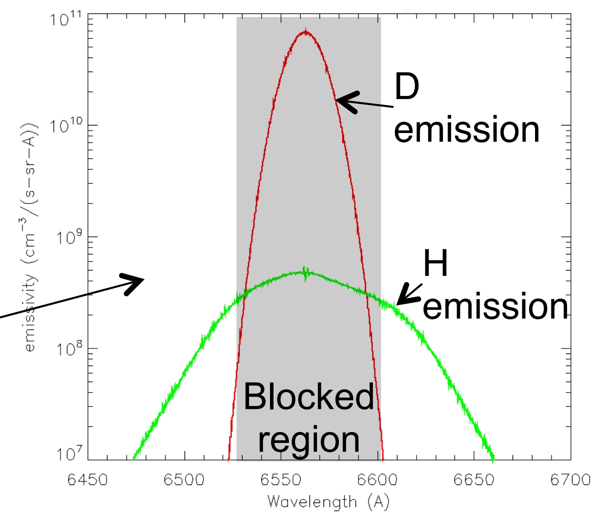
Isolation of the fast ion spectrum with a blocking bar

Spectrum using filter





Simulation of isolation with a blocking bar



Conclusion

- Summary of recent results
  - Identified impurity pinches
  - Measured thermal helium profiles and fast ions in ICRF minority heating
- For CXRS particle measurements require detailed DNB profiles
  - Developed improved simulation tools
  - Developed techniques to substitute beam emission measurements for beam density
  - Completed new beam profile diagnostics
- For fast ion measurements
  - Developed calibration techniques for thermal helium density
  - Developed techniques such as blocking bar to allow more flexible measurement