

CXRS-based diagnostic for fast ion detection in the core of the Alcator C-Mod Tokamak*

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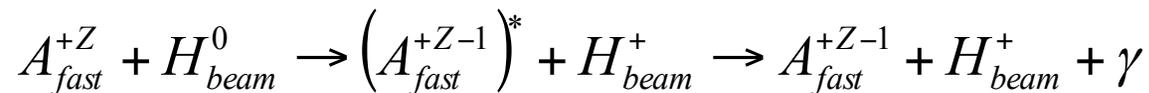
Abstract

Charge exchange recombination spectroscopy (CXRS) will be used to measure the spatial and temporal distribution of fast ions within the core plasma. Fast ions are generated in C-Mod by minority absorption of injected waves in the ion cyclotron range of frequencies. Typically, the minority is H in a D plasma or possibly ^3He in D. Emission from the fast ions is excited by charge exchange with the neutral atoms in a diagnostic neutral beam[†]. In the new diagnostic, the emission from approximately 30 poloidal and toroidal views with 1.2 cm spatial resolution are spectrally analyzed with a high throughput spectrograph that is modified to reduce scattered light from edge emission lines. The spectra are detected with a camera with 10 ms temporal resolution. The capabilities of the diagnostic are explored through simulation of the spectrum and measurements of the emission background. For C-Mod, the diagnostic is uniquely capable of detecting fast ions in the plasma core and thus contributing to RF physics as well as to fast ion transport. Expected fast ion signal-to-noise will be presented.

[†]W.W. Heidbrink, et al., Plasma Phys. Control. Fusion 47, 1855 (2004)

Introduction

- ◆ **Fast ions are high energy ions that are not in thermal equilibrium with bulk plasma ions**
- ◆ **They are formed by fusion, wave-particle interactions, or neutral beam injection**
- ◆ **If fast ions can be detected before they equilibrate or escape at the plasma edge, then they can contribute to our understanding of the physics of these processes**
- ◆ **The fast ions are fully stripped and do not have a line emission spectrum or a strong continuum emission spectrum**
- ◆ **A beam of neutral hydrogen is fired into the plasma to donate electrons to fast ions to produce fast neutrals which can emit line spectra (charge exchange recombination spectroscopy)**



- ◆ **Analysis of the fast neutral's spectrum provides information on the fast ion.**

Fast Ions in Alcator C-Mod

- ◆ **For C-Mod, the main interest is in wave-plasma interactions: fast wave heating of a two-component plasma (~5% hydrogen, 95% deuterium), i.e. absorption by hydrogen minority in deuterium plasma via Landau damping and transit time damping**
- ◆ **Fast hydrogen ions are generated with high perpendicular velocities near ion cyclotron resonances**
- ◆ **Fast ion generation comes into equilibrium with transport and collision processes, and gives rise to a velocity distribution function similar to Maxwellian but with higher density in the tails.**
- ◆ **The fast ion charge exchange emission is weak compared to edge emission, deuterium charge exchange emission, and neutral beam emission, but can be detected in favorable viewing geometries in the Doppler shifted emission of the high energy tail**
- ◆ **Fast ions detected in the plasma can be used to validate the physical models for RF deposition**
- ◆ **More ambitious experiments include study of Alfvén eigenmodes via the diffusive effect of these plasma waves on the fast ion population**

Physics of Fast Ion Spectrum

- ◆ Hydrogen ions gyrate about magnetic field lines
- ◆ The fast ions charge exchange with the neutral beam and also with the neutral halo to form a population of fast neutrals.
- ◆ The newly-formed fast neutrals follow a straight line trajectory.
- ◆ The initial charge exchange can sometimes leave the fast neutral in an excited state, or the fast neutral can be excited/de-excited by collisions.
- ◆ The excited neutral emits a Doppler-shifted Balmer H_α spectrum which stands out against the wing of the broad ambient background spectrum of plasma D_α .
- ◆ Since the fast neutral retains the velocity vector of the fast ion, the emission spectrum for the fast neutrals contains detailed information on the kinetics and the density of the fast ion population.
- ◆ Spectrum is computed from distribution function:

$$\varepsilon(\lambda) = \sum_i n_i \int f(\vec{v}) \sigma \left(\frac{1}{2} m \left| \vec{v} - \vec{v}_i \right|^2 \right) \delta \left[\lambda - \lambda_0 \left(1 + \frac{v \cos \alpha}{c} \right) \right] d^3 v$$

↑

sum over
beam
components

↑

combined CX
emission
cross section

↑

beam
velocity

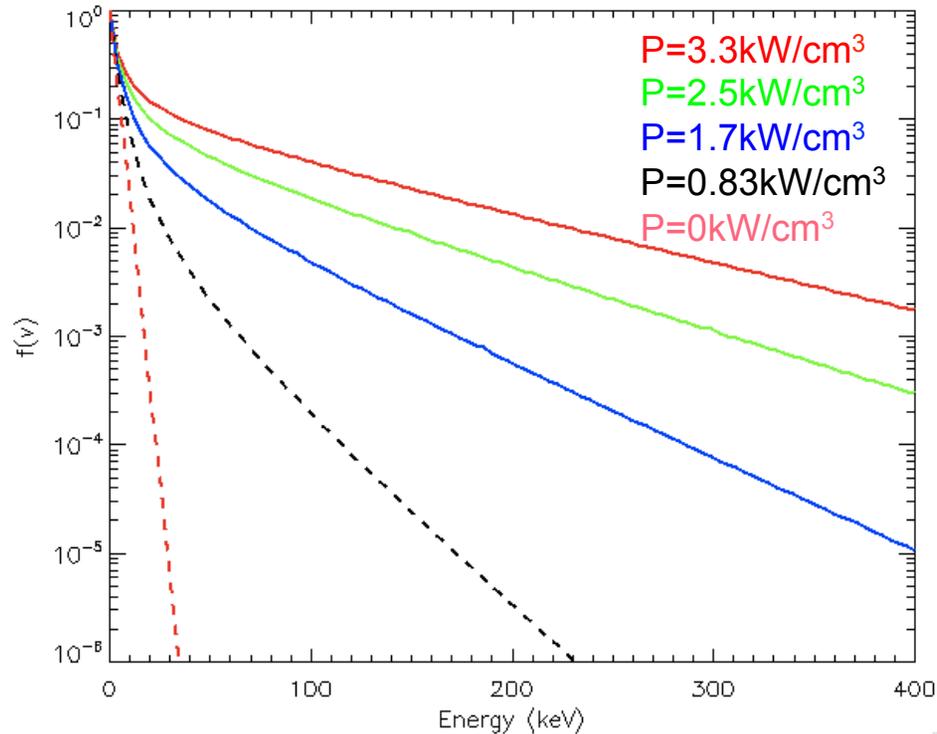
↑

angle between
beam and chord

Measurements and Calculations of Fast Ion Distributions

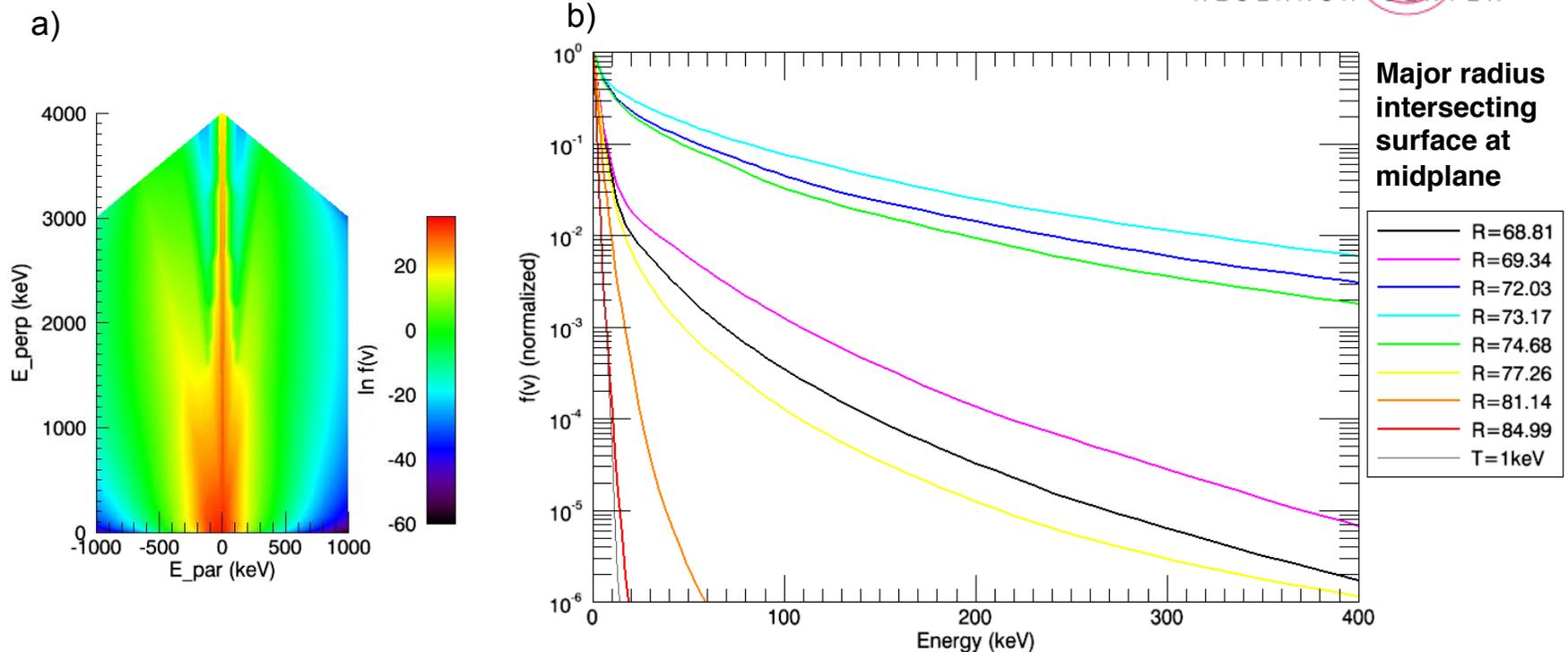
- ◆ **Fast ions that are lost (those that escape the plasma) are measured with the Compact Neutral Particle Analyzer (CNPA) diagnostic**
- ◆ **Fast ions that remain in the plasma are measured with the CXRS-Fast-Ion (CXRS-FI) (this work)**
- ◆ **Calculated in T. H. Stix, Nuclear Fusion 15, 735, 1975.**
- ◆ **Compared with simulations based on AORSA (E. F. Jaeger, L. A. Berry, E. D'Azevedo, D. B. Batchelor, and M. D. Carter, Physics of Plasmas 8 (5), 1573 (2001).) AORSA is used to predict mode conversion and high harmonic fast wave heating in tokamak plasmas.**
- ◆ **Compared with CQL3D (R. W. Harvey and M. G. McCoy, presented at the Proceedings of the IAEA Technical Committee Meeting on Advances in Simulation and Modeling in Thermonuclear Plasmas, Montreal, 1992 (unpublished)) . CQL3D is a quasilinear Fokker-Planck code used to model distribution functions.**

Fast Ion Isotropized Velocity Distribution Calculation



- ◆ Distribution as computed in T. H. Stix, Nuclear Fusion 15, 735, 1975.
- ◆ RF power varied between 0 red dashed curve (Maxwellian distribution) and 3.3 kW/cm^3 , solid red curve
- ◆ The emission spectrum is not unique. A distribution function must be used to analyze the spectrum.

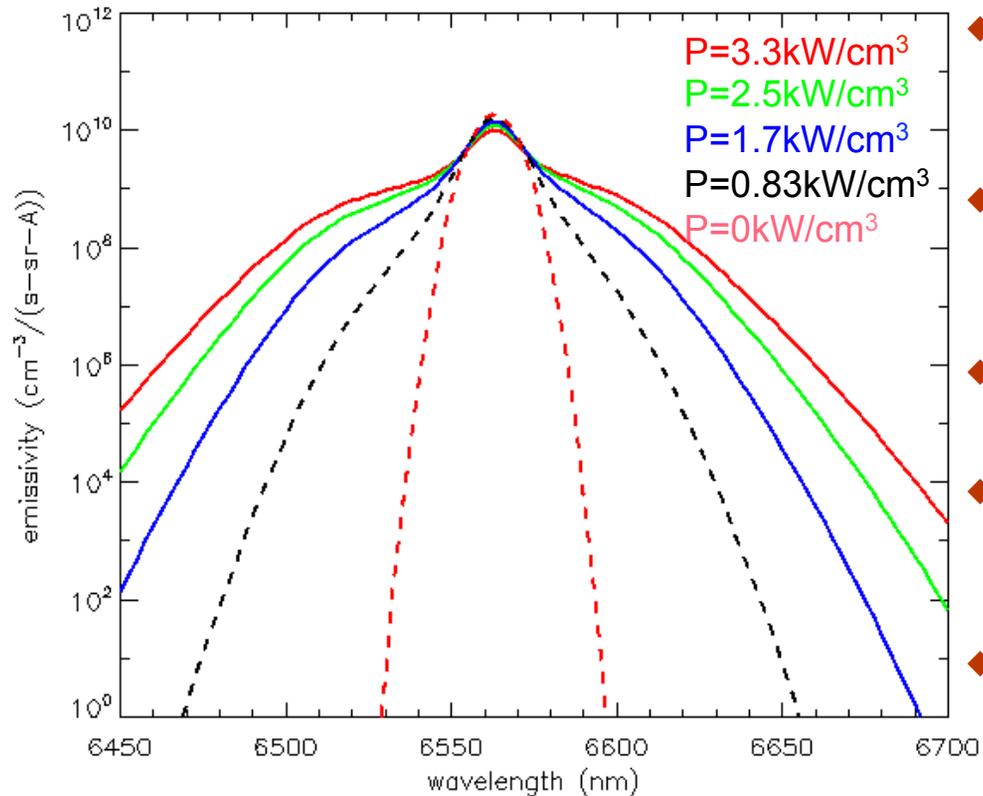
Fast Ion Velocity Distribution Function using CQL3D



Output from CQL3D (version: cql3d_cswim_100829_rza64_nraya1, shot 1100226028, J-port RF: 1.2MW)

- a) 2D distribution at $R=0.7317\text{m}$, near our poloidal channel 7 ($R=0.7326\text{m}$)
- b) normalized distributions averaged over 3D angles at chosen radii overplotted with a 1 keV M-B distribution

Simulation of the Fast Ion Spectrum

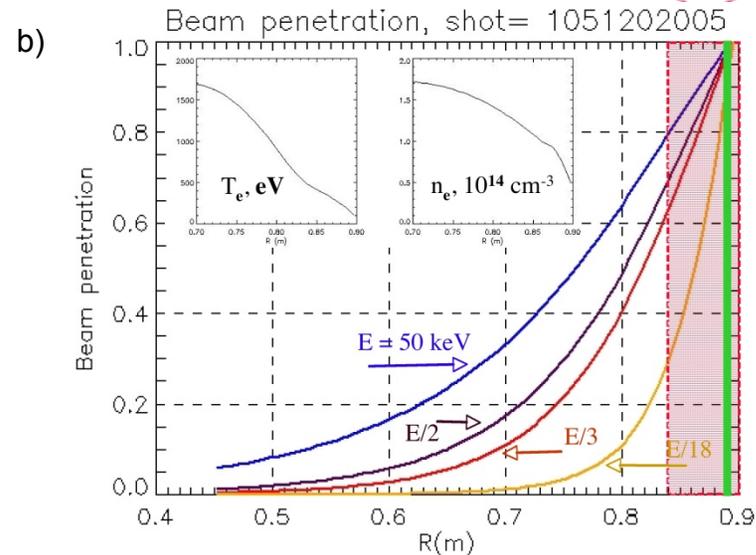
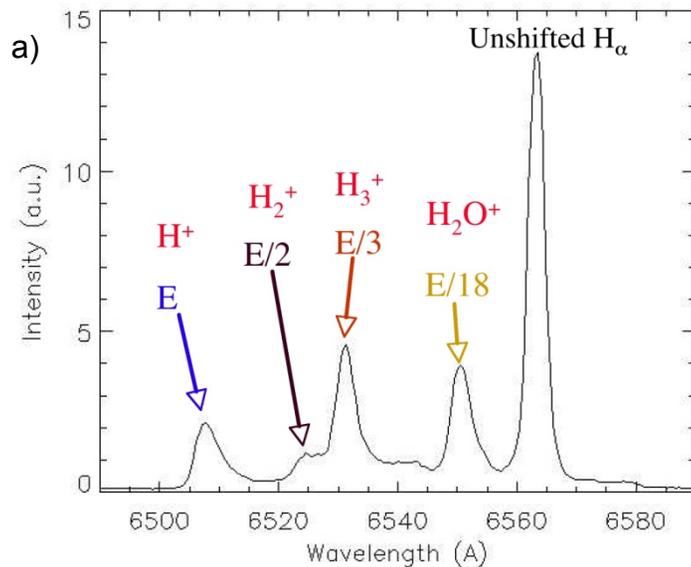


**Simulated spectrum for poloidal chord P16
(radius 0.8508m) for shot 1101015025**

- ◆ The hydrogen spectrum is simulated with various levels of wave power densities
- ◆ Spectrum shape is a Doppler pattern modified by cross section effects and Stark-Zeeman fine structure[†]
- ◆ Contributions from beam energy components are added together
- ◆ The wings clearly increase more than linearly as a function of the increase in RF power.
- ◆ Evidently, the region of primary interest is between the core and the far wing for sensitivity to the fast ion distribution function and to avoid competing spectral emission processes.

[†]R C Isler, PRA 14,3 (1976)

Diagnostic Neutral Beam



DNB: 50 kV H neutral beam. 6A accelerated current. 3.5 A neutrals into plasma

- Beam emission spectrum (measured in beam tank) showing 4 energy components separated by Doppler shift. The fast ion spectrum contains contributions from each component.**
- Simulated beam penetration for a typical tokamak discharge is shown. Signal to noise will decrease for locations nearer the plasma core.**

Halo Emission

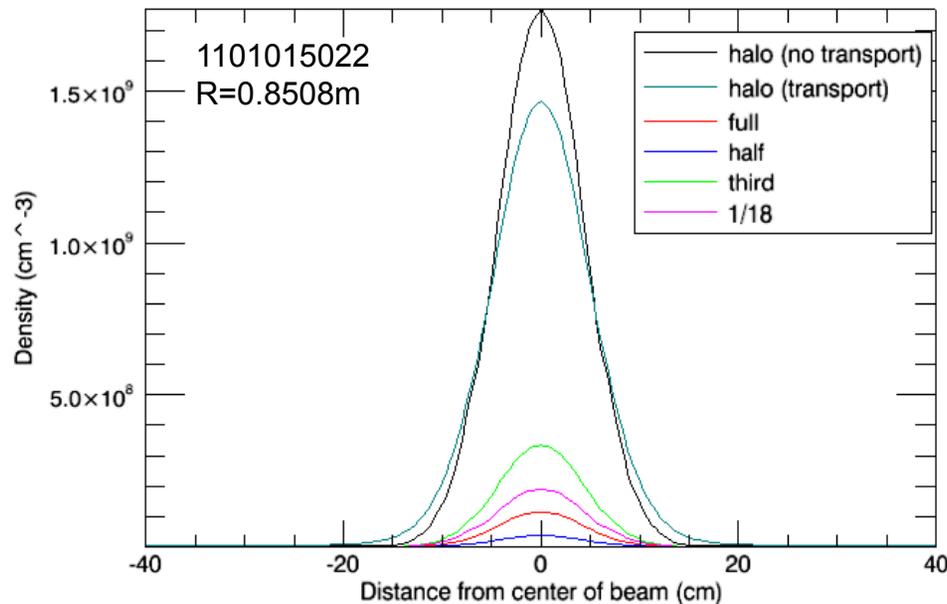
- ◆ The halo is a region of neutral D or H in the vicinity of the neutral beam.
- ◆ It acts as a secondary source of electrons to charge exchange with fast ions and deuterium, which increases total emission by about a factor of 2.
- ◆ The **source** is charge exchange between beam neutrals and plasma ions.
- ◆ The neutrals are **transported**.
- ◆ The neutrals are destroyed through **ionization**.
- ◆ In the mean time, halo neutrals **charge exchange** with ions, affecting the velocity distribution without changing the halo population.

$$\frac{\partial f_0(\mathbf{x}, \mathbf{v}, t)}{\partial t} + \nabla f_0 \cdot \mathbf{v} = - \int_{\mathbf{v}} S_i^e n_e f_0 - \int_{\mathbf{v}} S_i^i n_i f_0 + f_i \sum_{j=1}^{ncomp} n_B^j C_x^j + f_i \int_{\mathbf{v}} f_0 C_x^j - f_0 \int_{\mathbf{v}} f_i C_x^j$$

- ◆ A simple estimate of the steady state halo density can be obtained by neglecting the transport term:

$$n_0 = \frac{\sum_{j=1}^{ncomp} n_j C_x^j n_i}{S_i^e n_e + S_i^i n_i} \approx \frac{\sum_{j=1}^{ncomp} n_j C_x^j}{S_i^e + S_i^i}$$

Halo Density Simulation



Calculation for shot 1101015022

Radius: 0.8508m (chord P16)

Total beam density (peak): $6.8 \times 10^8 \text{ cm}^{-3}$

Halo density (peak): $1.5 \times 10^9 \text{ cm}^{-3}$

Ratio halo/beam density: 2.15

Beam FWHM: 10.07 cm

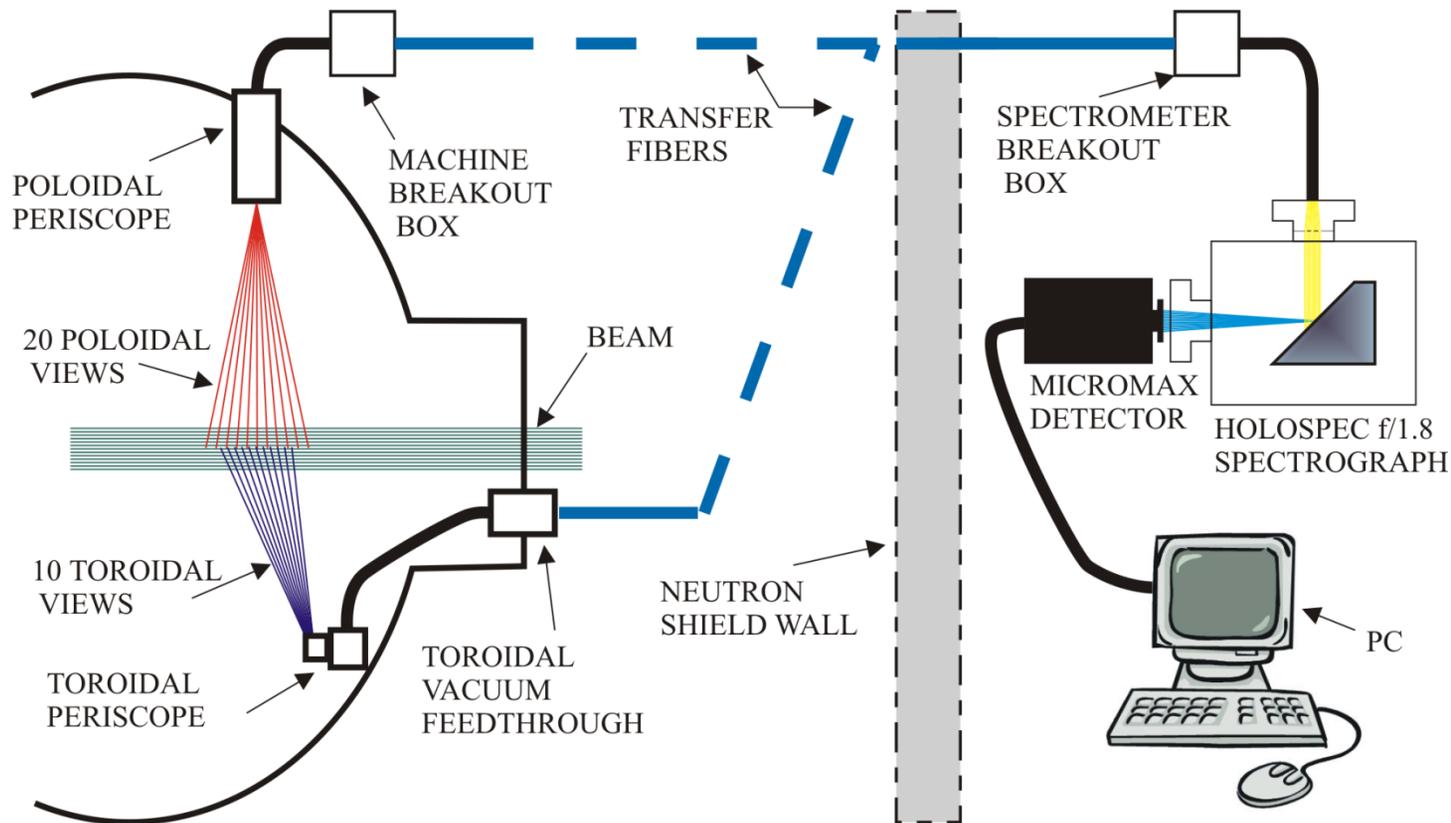
Halo FWHM: 11.49 cm

- ◆ **The beam components were calculated with Alcbeam, and the halo was simulated with a simple 1D Boltzmann code**
- ◆ **The halo increases the level of beam enhancement, as if it were a fifth beam component with thermal energy**
- ◆ **The full CXRS is a sum over beam components and halo contribution**

Measurement Summary

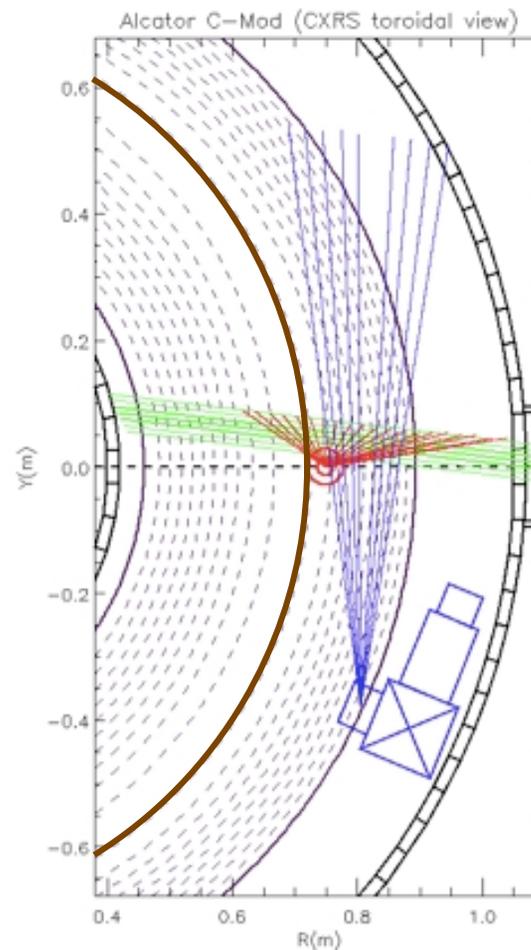
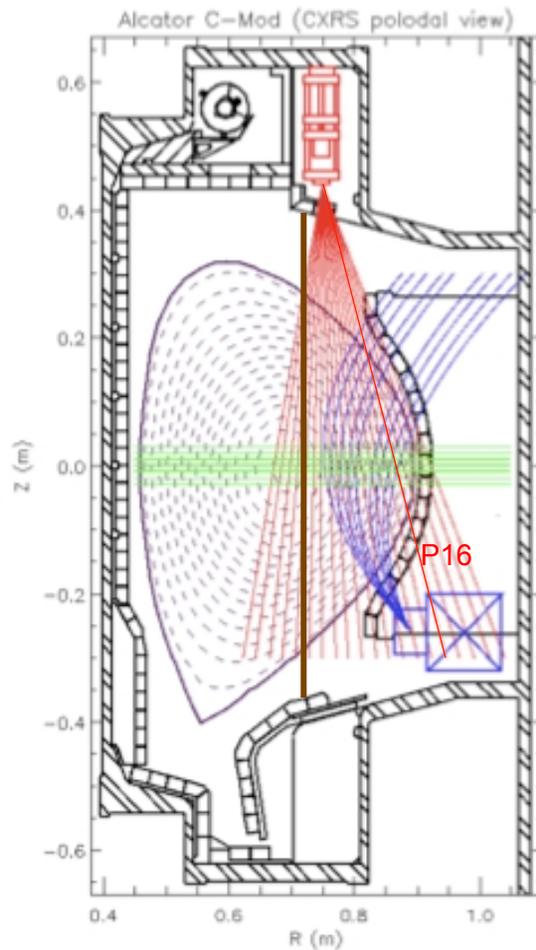
- ◆ **Instrument layout**
 - Plasma views
 - D-alpha blocking
- ◆ **Analysis of data**
 - Analyzed spectrum
 - Neutral beam modulation
 - Background subtraction
- ◆ **Measurement upgrade plan**
 - Poloidal optics upgrade
 - Blocking bar design

Wide-view CXRS system at C-Mod - current layout



- The light is collected by two optical periscopes (red and blue) 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.

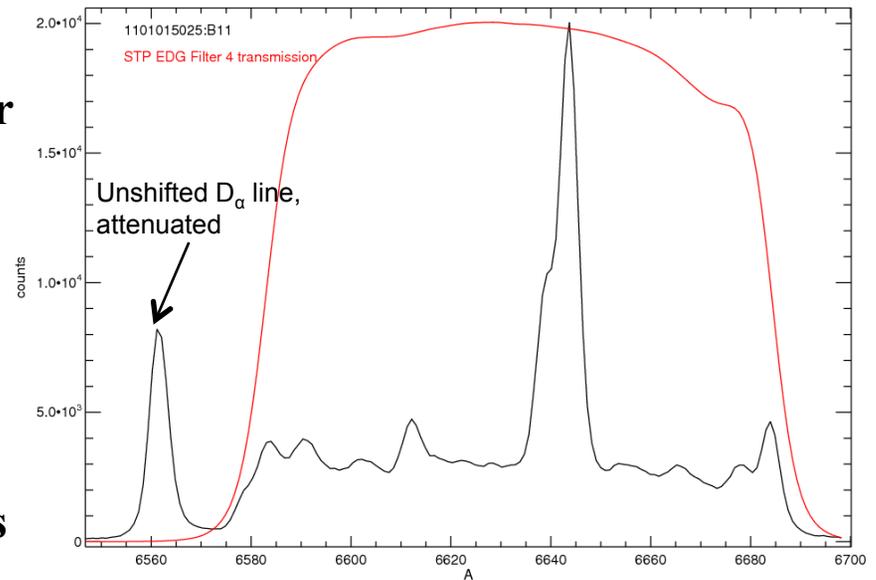
Plasma Views



- ◆ There are two viewing arrays for this diagnostic.
- ◆ The blue chords are the toroidal system, the red chords are the poloidal system. The beam is shown in green. The ICRF resonance is shown in brown.
- ◆ Poloidal and toroidal views will sense fast ion perpendicular and parallel distributions respectively

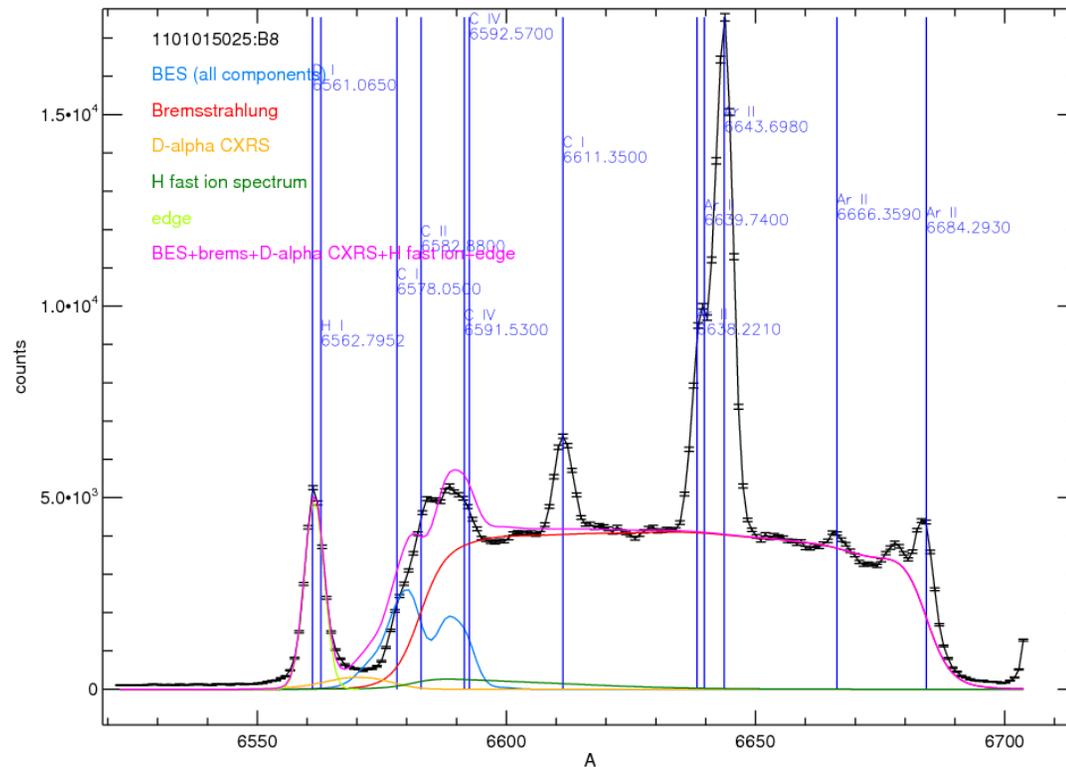
Blocking the D-alpha Emission

- ◆ Unshifted deuterium emission amplitude is at least 500 times as large as the fast ion emission in the region of interest. In order to not saturate the detector, and still maintain sufficient signal to noise in the region of interest, the D-alpha peak must be strongly attenuated or blocked.
- ◆ Three methods have been devised:
 - opaque or translucent blocking bar in between spectrometer and detector¹
 - moving the D-alpha peak outside the range of the spectrometer
 - use of a bandpass or edge filter
- ◆ We have done proof of principle tests with a bandpass filter which attenuates the D-alpha peak to the same intensity level as the region of interest



¹Luo and Heidbrink et al, *Review of Scientific Instruments* 78, 033505, 2007

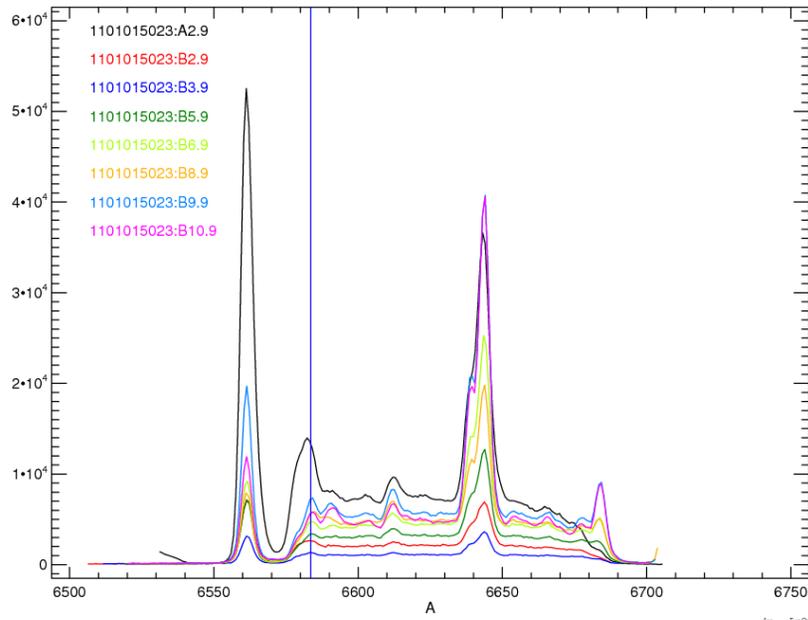
Analysis of Data



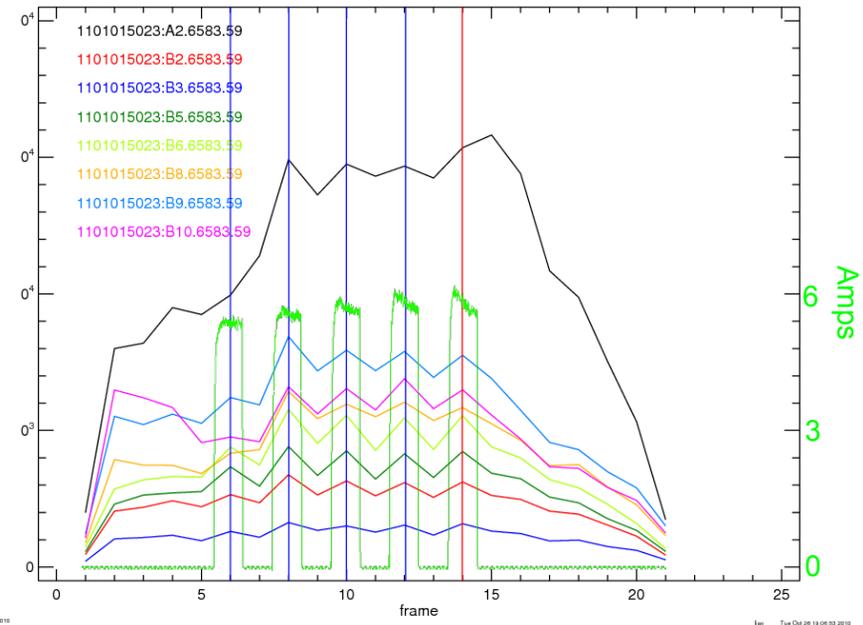
- ◆ Real spectra from H-alpha region contains many competing spectral features: beam emission, bremsstrahlung, D-alpha CXRS, D-alpha edge emission, and impurity lines.
- ◆ Partial background subtraction is achieved by modulating beam
- ◆ D-alpha lines are strongly suppressed by filter

Spectrum from shot 1101015025, toroidal channel with notable lines identified. Overplotted with BES, D-alpha CXRS, and fast ion spectra from calculation bremsstrahlung and edge D-alpha spectra from fitting

Neutral Beam Modulation and Spectral Enhancement



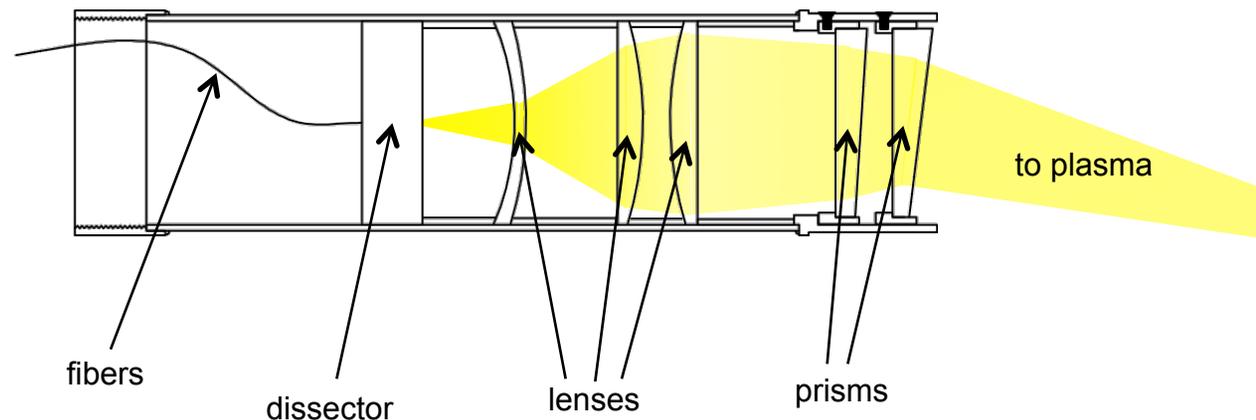
Spectra from several toroidal channels, with 6583A marked, for a single frame



Spectra value at 6583A, traced over time, with beam current indicated (bright green)

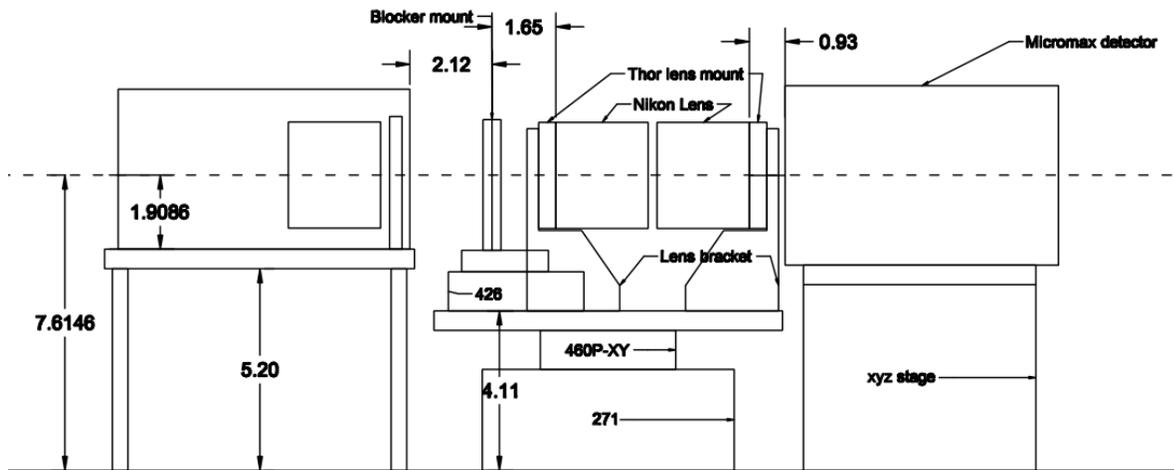
- ◆ Neutral beam is modulated in synchronization with detector frames
- ◆ Beam enhancement is observed at some regions of the spectrum
- ◆ Beam enhancement in 6580A-6590A region is observed in all channels
 - attributed to BES in some channels
 - possibly fast ion signature in other channels

Poloidal Optics Upgrade

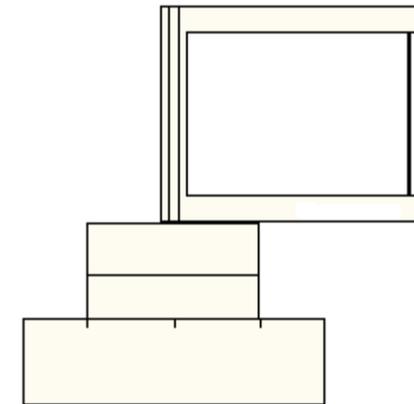


- ◆ The existing poloidal optics array uses a 25.4 mm diameter collecting lens to collect light
- ◆ A replacement poloidal periscope cartridge is being designed which will use a 50.8 mm acceptance lens to increase light flux by 4 times
- ◆ The entire assembly must fit within the periscope tube with inner radius 2.125"

Blocking Bar Design



Side view of setup



Blocker-Front

- ◆ The blocker is placed at the focal plane of the spectrometer, with micrometer x translation and tilt stage
- ◆ Two additional camera lenses (Nikkor 85mm f/1.8D) are used to focus the image that is formed at the plane of the blocker back on to the detector plane
- ◆ Assembly is enclosed in opaque shroud
- ◆ Combined transmission of lenses is measured: 85%

Role of the Diagnostic

- ◆ **This emission spectrum is the basis for just one of a complementary set of fast ion measurements.**
- ◆ **Its unique contribution is that it allows measurement of the fast ions inside the plasma.**
- ◆ **Escaping fast ions are measured independently by the CNPA diagnostic.**
- ◆ **Each measurement contributes a different view of the fast ion distribution which must be combined for a complete description of fast ions.**