Carbon ion plume emission in NSTX

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NSTX Results Review
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WHAT IS A PLUME ION?

1) Charge exchange interaction with beam neutral produces a excited impurity ion

$$D^0(n_D) + C^{6+} \rightarrow D^+ + C^{5+}(n).$$

2) The impurity ion will emit and decay to n=1

$$C^{5+}(n) + \lambda \rightarrow C^{5+}(n\text{-}1) + \lambda\text{'s} \rightarrow C^{5+}(n=1)$$

3) Parallel transport carries the ion away from the beam volume

4) The ionization time is long enough so there is a chance the ion will be re-exited by electron impact and reemit at

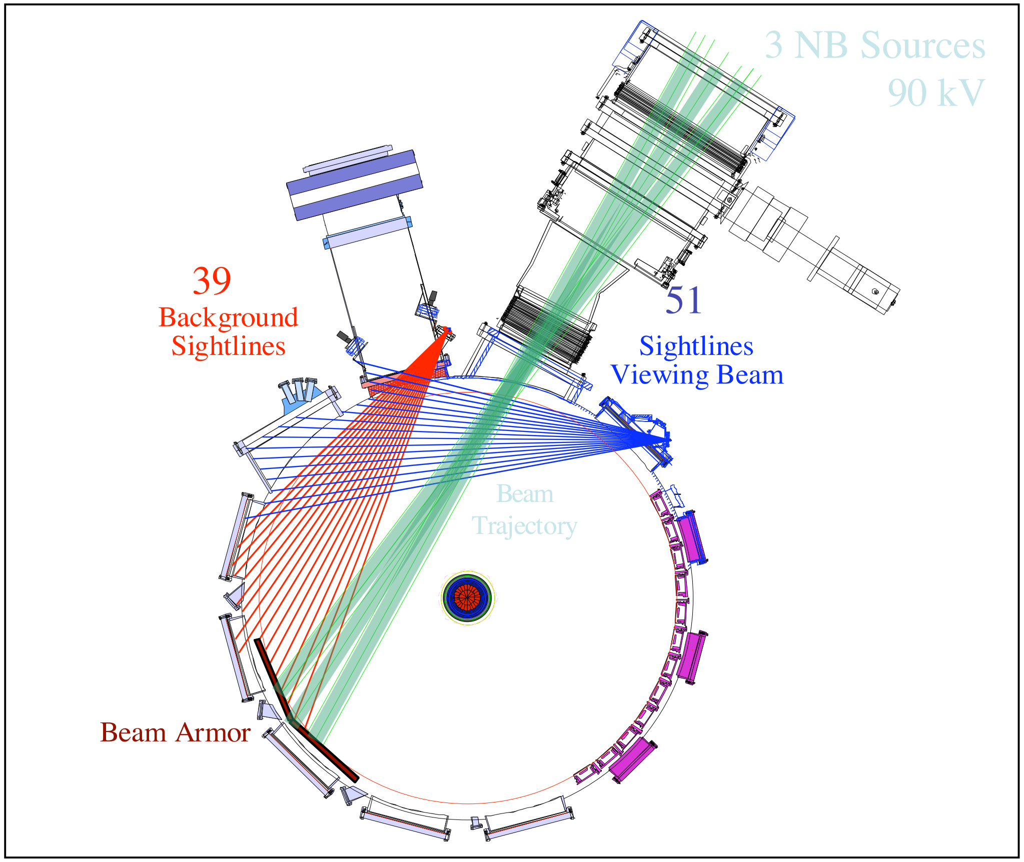
$$C^{5+}(n=1) + e\text{-} \rightarrow C^{5+}(n) + e\text{-} \rightarrow C^{5+}(n\text{-}1) + \lambda$$

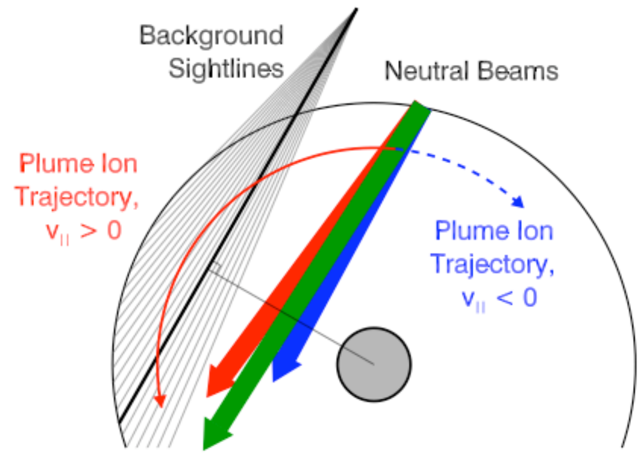
5) Non-local emission contaminates views at other locations

6) Important for low Z impurity ions (He, Li) for visible transitions (lower n levels are easier to excite)

7) Often considered negligible for higher Z (C, O) impurities

CHERS Viewing Geometry

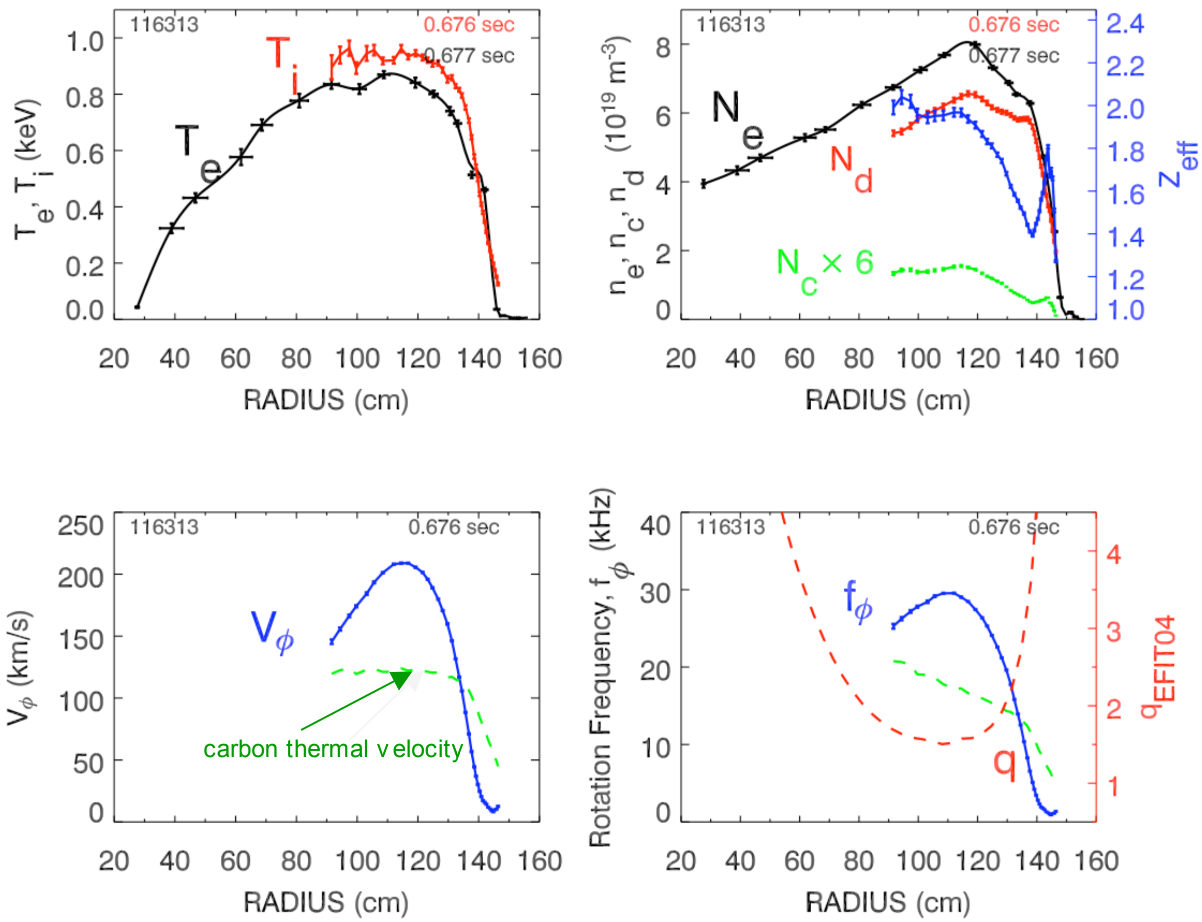


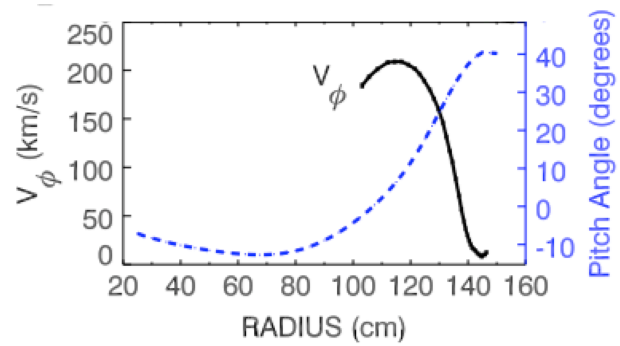


- Active sightlines for CX emission
- Background sightlines for dynamic subtraction of edge emission

- Non-local emission from plume ions can contaminate measurements

CHERS / MPTS Profiles





High rotation and large pitch angle help identification of plume spectrum

- T_e, n_e for beam attenuation, excitation and ionization rate coefficients
- High rotation plasma, carbon ions exceed thermal velocity

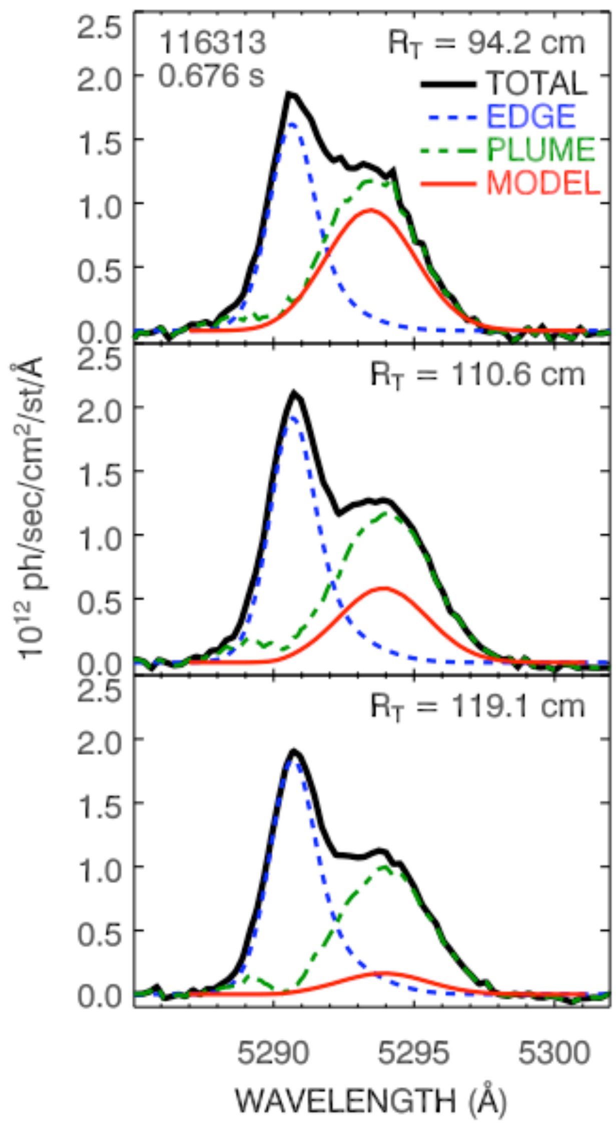
Background Spectra With Plume

- Spectra at different tangency radii
- Wide (hot) and shifted (fast rotation) spectral component observed in some plasmas
- Spectrum due to edge emission reconstructed from inverted edge brightness and local T_i, V_ϕ

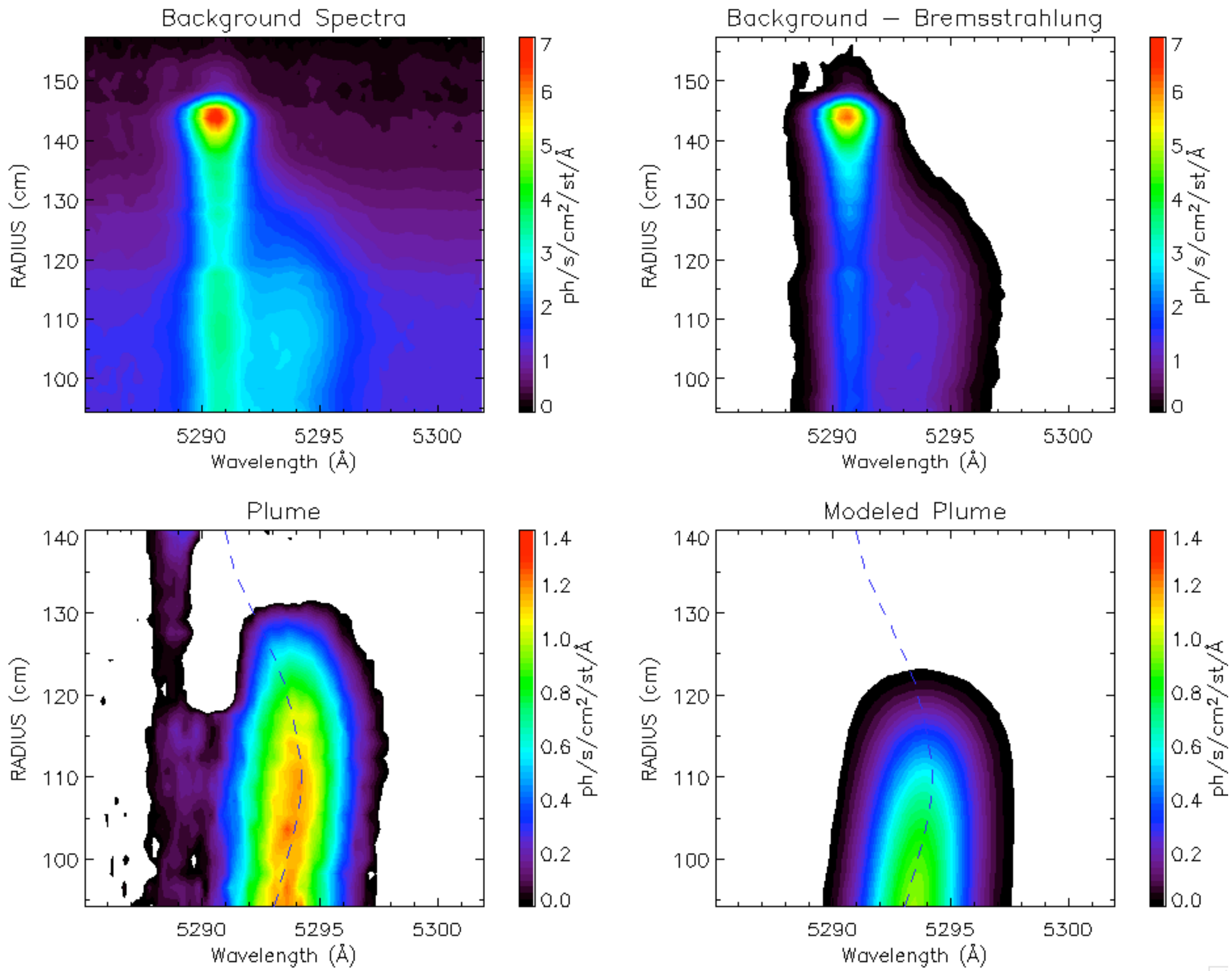
$$E_{ij}^{\lambda} = \frac{E_j}{w_j}\sqrt{\frac{4\ln 2}{\pi}}\exp\left[\frac{-4\ln 2\left(\lambda - \lambda_0\left(1 + \frac{v_j}{c}\frac{R_i}{R_j}\right)\right)^2}{w_j^2}\right]$$

$$B_i^{\lambda} = \sum_j E_{ij}^{\lambda}$$

- Plume spectrum from subtracted edge, near Gaussian shape
- Modeled spectrum reproduces line shift and width, amplitude difference increases with radius
- Scaled CX emission (not shown) is similar to plume brightness



Extracting Plume Spectra



- Plume spectral brightness profile is emphasized by subtracting VB emission and reconstructed edge spectra from background

- Dotted line indicates shift associated with measured V_ϕ profile

Modeling Steps

1) Map midplane T_e, n_e, T_i, n_c profiles to 2D using equilibrium reconstruction
2) Compute power density of profile of NB
3) Compute neutral beam density in beam volume with 3D beam attenuation code
4) Compute total CX rate by integrating over 3D velocity space using only positive $v_{//}$
5) Map magnetic field line from points along background sightline to NB volume
6) Integrate path through beam to get product ion density
7) Attenuate product ion density to sightline position
8) Integrate brightness along viewing sightline
9) Spectral profiles obtained by limiting integral over velocity space to 2 dimensions perpendicular to viewing direction

Modeling Equations

- Plume brightness
  - $n_e Q^{ex}$ = electron impact excitation rate
  - n_{C5+} = plume ion density
  - b_λ = branching ratio
  - dl = line element along line of sight

$$B_\lambda^{\text{plume}} = \frac{1}{4\pi} \int n_e Q^{ex} n_{C5+}^{cx} b_\lambda d\ell$$

- Plume ion density along field line
  - $n_e Q_{C5+}{}^{ion}$ = ionization rate
  - $\Sigma n_j{}^b \langle \sigma v \rangle_j{}^{tot}$ = total CX rate
  - ds = line element in beam volume
  - w = beam width
  - $\xi(S)$ = attenuation coefficient from continuity around torus

$$n_{C5+}^{cx}(S) = \frac{\xi(S)}{w} \int n_{C6+} \frac{\sum_J n_j^b \langle \sigma v \rangle_j^{tot}}{n_e Q_{C5+}^{ion}} ds$$

$$\xi_+(S) = \frac{2\sinh(d/\lambda_i)}{1 - e^{-2L/\lambda_i}} e^{-S/\lambda_i}$$

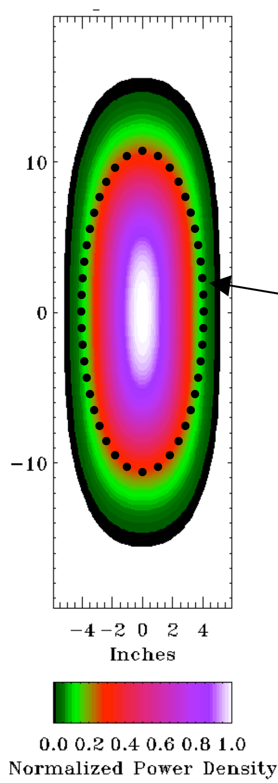
- Carbon density from CHERS
  - B^{cx} = CX brightness
  - $\Sigma n_j{}^b \langle \sigma v \rangle_j{}^{tot}$ = CX rate for n=8-7

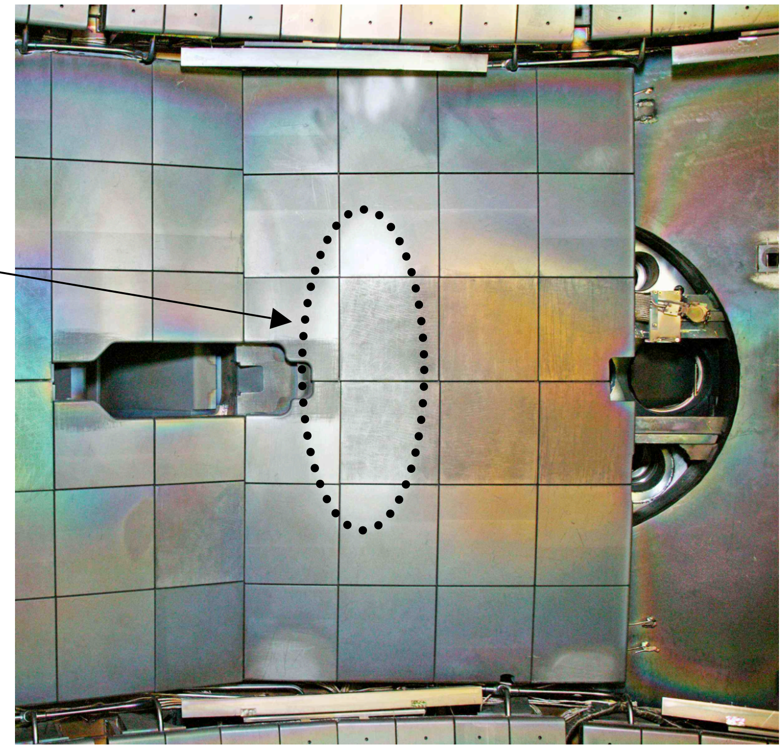
$$n_{C6+} = \frac{B^{cx}}{\frac{1}{4\pi} \int \sum_J n_j^b \langle \sigma v \rangle_j^\lambda d\ell}$$

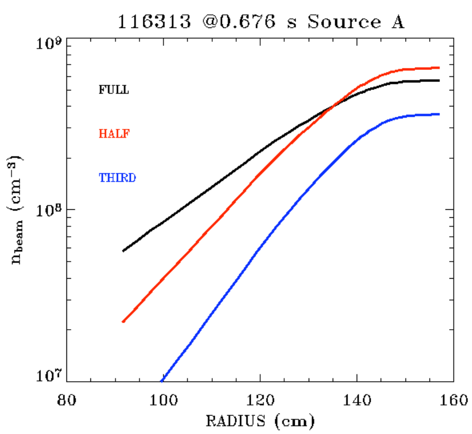
Neutral Beams

NSTX National Spherical Torus Experiment

Power density profile is computed taking into account horizontal and vertical beam divergence



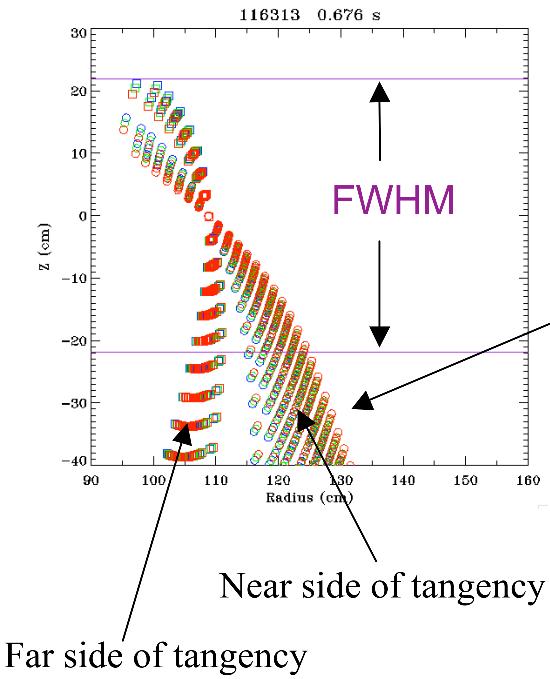




Beam attenuation code computes beam density for each component

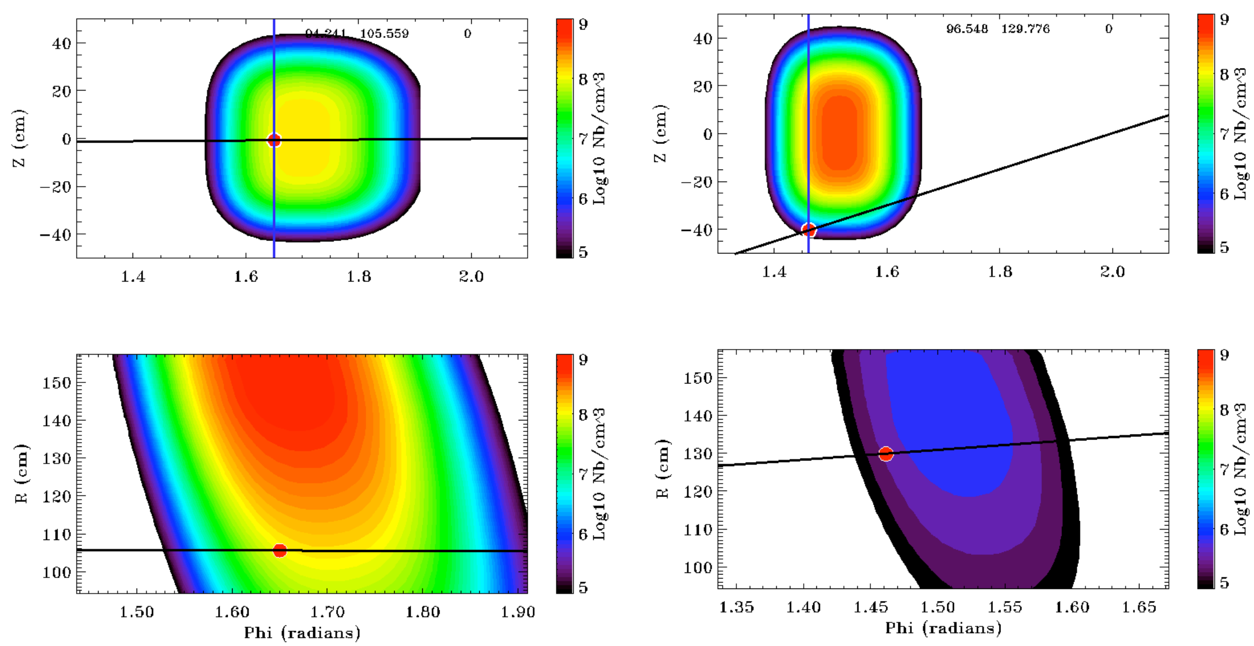
- NB footprint in plasma: 12 cm x 44 cm
- Size of neutral beam power appears on NB armor (tile = 7x7 in)

Following the Magnetic Field Lines

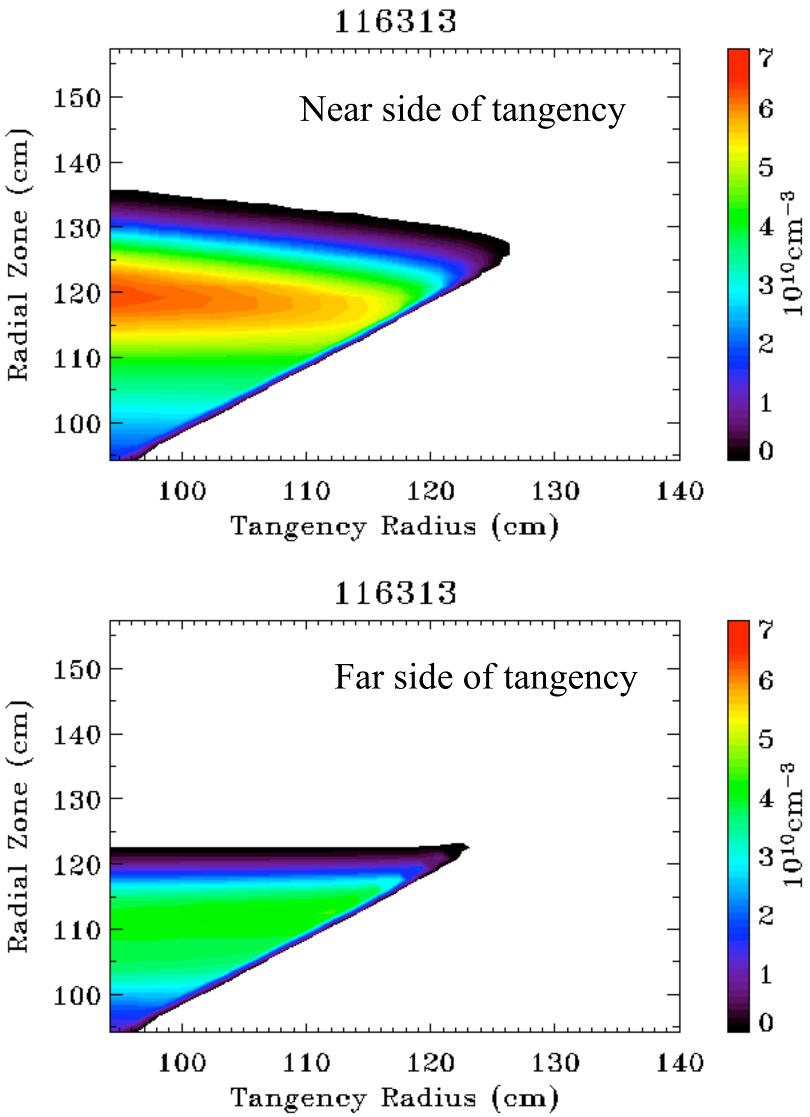


Each point along the background sightlines
Is mapped to a position in the NB volume

- A path is defined through the NB volume
- Average carbon density in flux tube determined by path integral

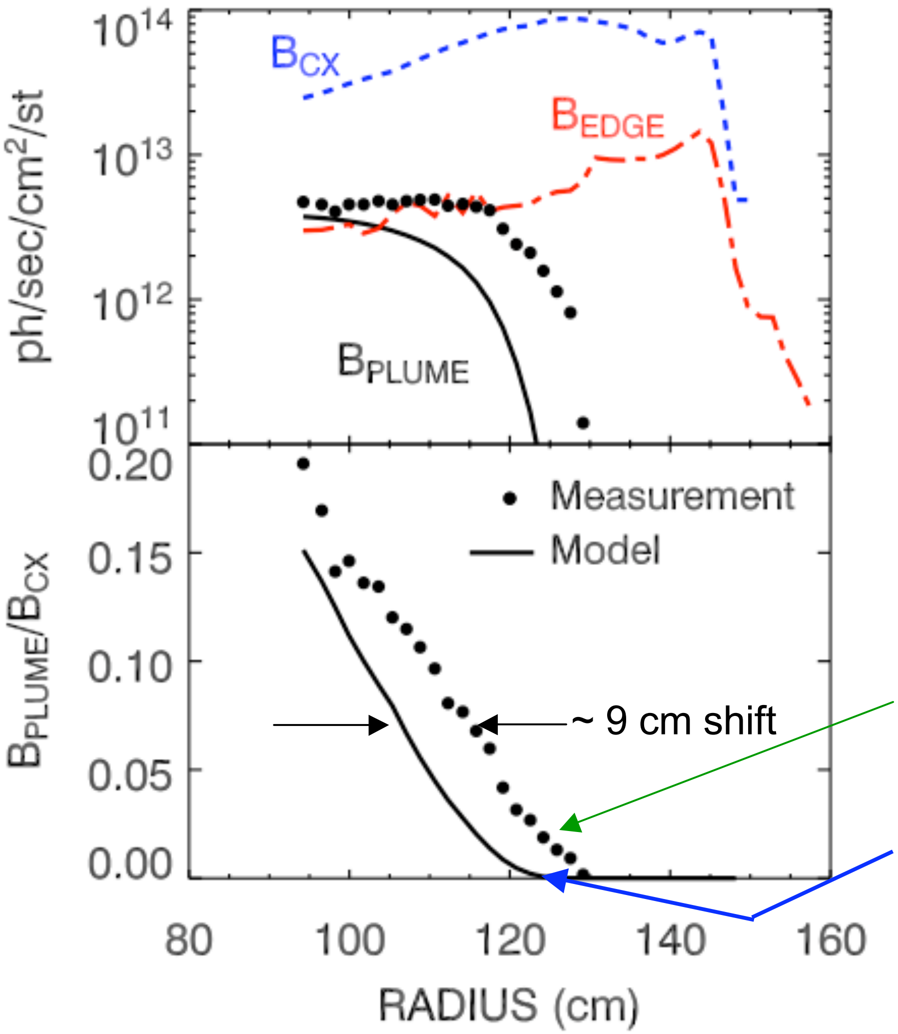


Modeled plume ion density at sightlines



- Beam attenuation yields highest C^{5+} density at large radii due to beam attenuation
- Falls off when magnetic field line do not cross neutral beam volume
- Maximum tangency radius observing plume near 125 cm

Modeled Plume Brightness



Modeled plume brightness comparable to measured brightness

Plume brightness exceed edge brightness at inner radii

Shift in measured and model brightness ratio point to problems with pitch angles used

Measured emission indicates magnetic field line connects sightline to beam

Model uses equilibrium which has magnetic field line missing beam

Observations

- Carbon ion plume emission observed on NSTX in high rotation discharges
- Modeled brightness consistent with measured using standard atomic rates
- Agreement in line shape and line width shows promise for modeling other plasmas, e.g. low-rotation
- Shift between measured and modeled plume brightness:
  - Beam footprint taller than used? Checked with NB armor damage
  - Cross field transport? Have to be many cm/meter arc length
  - Pitch angle wrong? MSE, V_ϕ used as midplane constraints
  - Halo neutrals producing plume ions outside of NB volume?

    Need additional calculations to assess
  - possible new constraint for equilibrium reconstruction