Utilization of passive emission contributing to charge exchange spectra in NSTX

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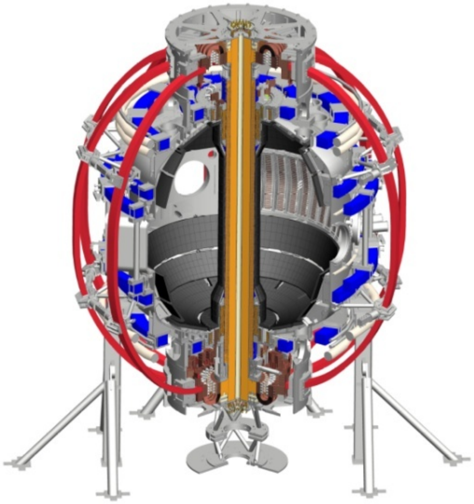

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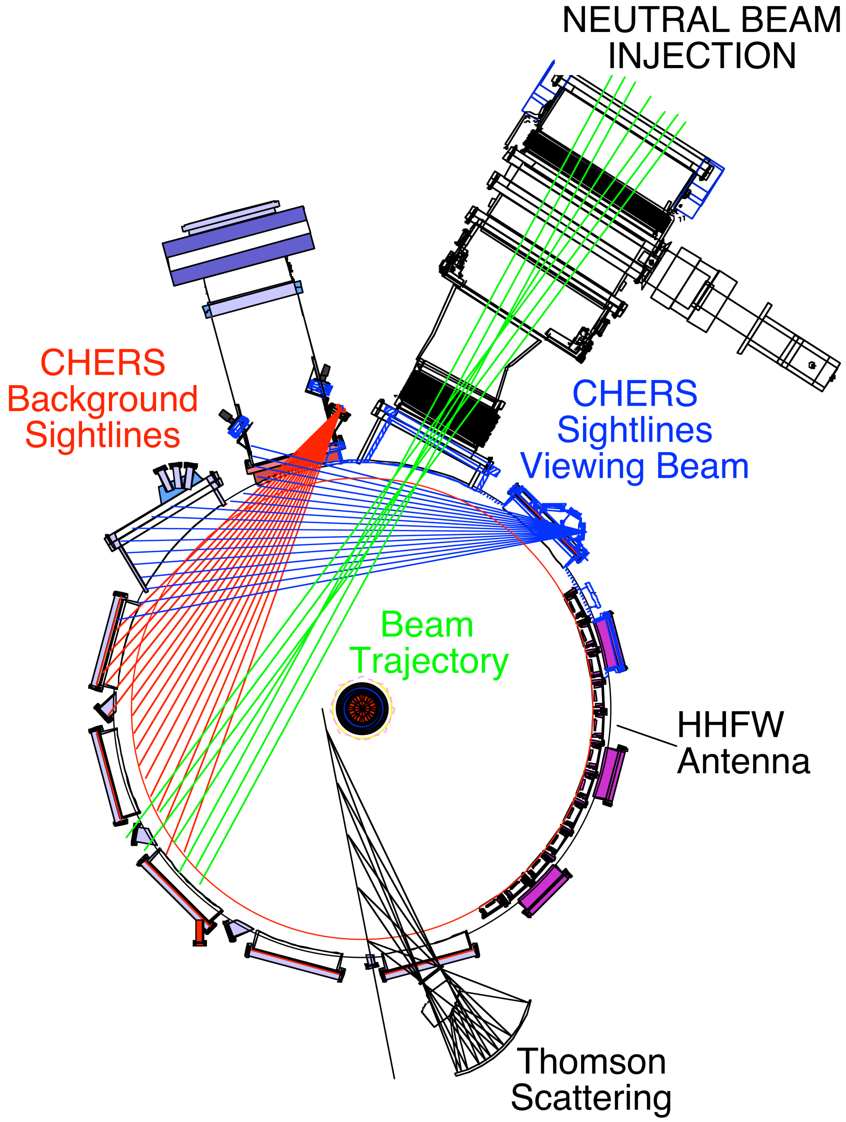
Abstract

The passive emission of C^{5+} ions from independent views is routinely measured on NSTX to subtract the passive contribution from active views across the neutrals beams used for charge exchange recombination spectroscopy. The passive emission can provide further useful information in the region of the C^{5+} emitting shell near the plasma edge. Inversion of the fitted spectrum of the line-integrated C^{5+} brightness from the passive views yields profiles of local ion temperature, velocity, and emissivity. Using rate coefficients for electron excitation, recombination, and thermal charge exchange, the relative contributions to the C^{5+} emission and the C^{5+} density profile could be uniquely determined if the local neutral deuterium density were known. Using the radial force balance equation and both active and passive measurements, the profile shape of the C^{5+} density can be determined. In turn, the amplitude of the C^{5+} density can be related to the neutral deuterium density profile, thereby establishing a range for the neutral deuterium density near the plasma edge. Independent information on the ratio of the C^{5+}/C^{6+} densities, from an impurity transport code or possibly from the C^{5+} emissivity profile shape, can improve the accuracy of the inferred neutral deuterium profile.

Scope of Presentation

- Measurements of T_e and n_e from Thomson Scattering
- Local measurements from active views of CHERS
- Line-integrated measurement from passive views
- Inversion of measurements from passive views
- Photoemission rates from ADAS
- Collisional-radiative model to obtain population of *n* levels of neutral deuterium
- Force balance equation to obtain C^{5+} profile shape
- MIST to get ratio of C^{5+} to C^{6+} density
- Upper limit of edge neutral density, profile estimate from edge emission
- Constraints on C^{5+} density
- Reconstruction of emission profiles

NSTX Diagnostics and Viewing Geometry

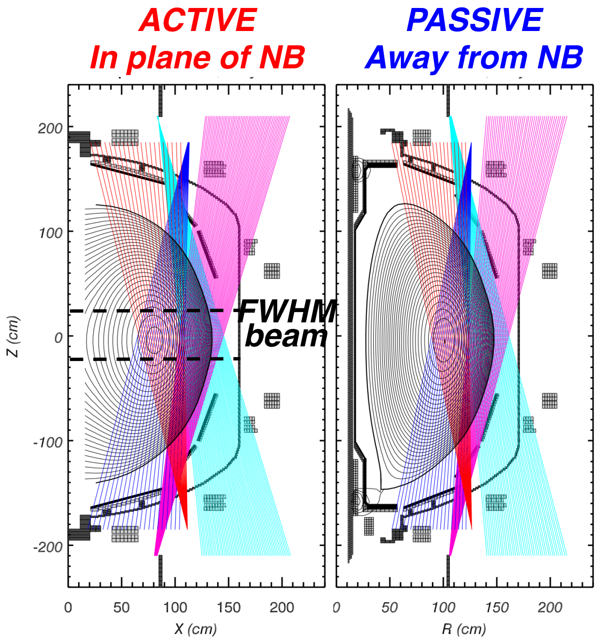


Midplane views

- CHERS – T_i, V_ϕ, N_c
- CHERS BKG – B_c, V_ϕ^{app}, T_i^{app}
- MPTS – T_e, N_e

Vertical views

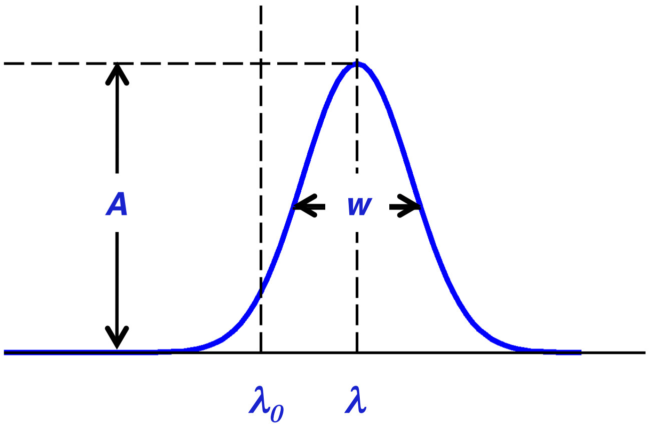
- Poloidal CHERS – V_θ
- Poloidal CHERS BKG – V_θ^{app}



Local values are extracted from line-integrated measurements with a matrix inversion approach

Line integrated measurements

- Spectral Brightness, B^λ
- Total Brightness, $B = \int B^\lambda d\lambda$



Fitted Parameters

- Amplitude, A $\quad A = \frac{B}{w}\sqrt{\frac{4\ln 2}{\pi}}$
- Line width, w
- Line shift, $(\delta\lambda)$

$$B^\lambda = \frac{B}{w}\sqrt{\frac{4\ln 2}{\pi}}\exp\left(-\frac{4\ln 2(\lambda - \lambda_0 - \delta\lambda)^2}{w^2}\right)$$

(Form for a Gaussian line shape)

Emissivity from Brightness

- Subscript i refers to a particular sightline (*line-integrated* measurement)
- Subscript j refers to a particular zone in the plasma (*local* value)
- L_{ij} is a matrix of path lengths
- Line-integrated brightness *(ph/s/cm²/st)* can be related to local emissivity *(ph/s/cm³)* by length matrix
- Local emissivity is obtained using inverted length matrix

$$4\pi B_i = \sum_j L_{ij} E_j$$

$$E_j = 4\pi \sum_i L_{ij}^{-1} B_i$$

Inversions of passive emission for local velocity and temperature

Velocity inversion

$\hat{s}_i$ is unit vector along sightline

$\vec{v}_j$ is local velocity vector

$$\hat{s}_i \cdot \vec{v}_j = v_j \cos\theta_{ij}$$

$$(\delta\lambda)_i = \frac{\int B_i^\lambda (\lambda - \lambda_0) d\lambda}{\int B_i^\lambda d\lambda} = \frac{\lambda_0}{c} u_i$$

$$M_{ij} = L_{ij} \cos\theta_{ij}$$

$$v_j = \frac{\sum_i M_{ij}^{-1} B_i u_i}{\sum_i L_{ij}^{-1} B_i}$$

Temperature inversion

$$q_i = \frac{\int B_i^\lambda (\lambda - \lambda_0)^2 d\lambda}{\int B_i^\lambda d\lambda} = \frac{w_i^2}{8\ln 2} + (\delta\lambda)_i^2$$

(See note below)

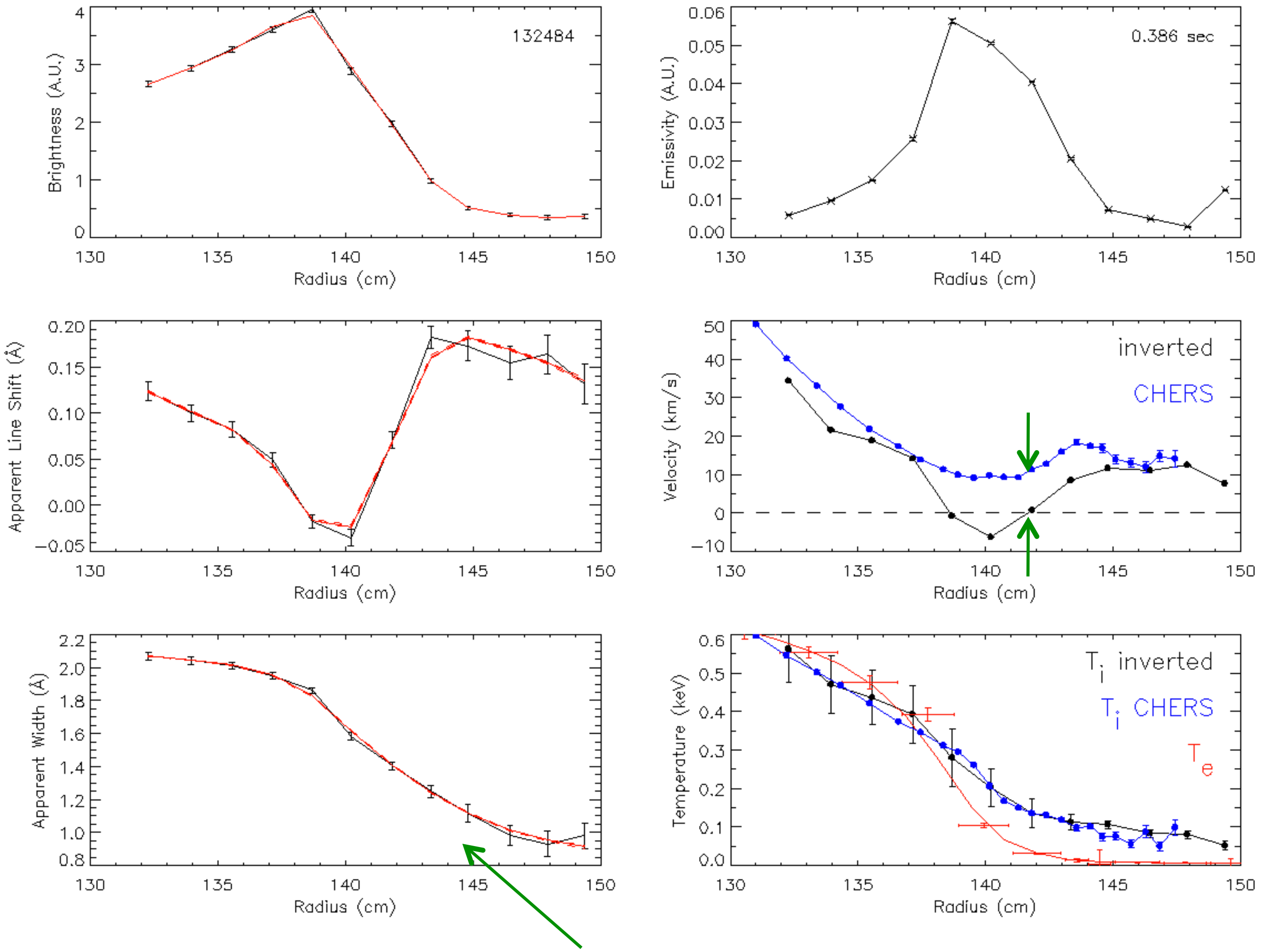
$$Q_i = 8\ln 2\left(B_i q_i - \sum_j L_{ij} E_j \left(\frac{\lambda_0}{c} v_j \cos\theta_{ij}\right)^2 \right) = \sum_j L_{ij} E_j w_j^2$$

$$w_j^2 = \frac{\sum_i L_{ij}^{-1} Q_i}{\sum_i L_{ij}^{-1} B_i}$$

$$T_i(keV) = 1.68 \times 10^5 M(amu) \frac{w^2}{\lambda_0^2}$$

Note: this form assumes a Gaussian line shape.
A multi-gaussian fit is necessary for high velocity shear.

Example of passive inversion profiles



Difference in toroidal velocity for C^{5+} and C^{6+} expected from radial force balance (same E_r but very different pressure gradients)

Inverted C^{5+} ion temperature matches C^{6+} ion temperature from CHERS

Fitted parameters fit with smoothing spline before inversion.

Three processes contribute to C^{5+} passive emission

$$E = Q_{ex} n_e n_{C^{5+}} + Q_{rec} n_e n_{C^{6+}} + Q_{cx} n_0 n_{C^{6+}}$$

Excitation *Recombination* *Thermal Charge Exchange*

UNKNOWN:

$n_{C^{5+}}$ - Density of C^{5+}

n_0 - Density of thermal deuterium neutrals

MEASURED:

E - Emissivity of passive emission from C^{5+} $n = 8\text{-}7$

n_e - Electron density

$n_{C^{6+}}$ - Density of C^{6+}

COMPUTED:

Q_{ex} - Photoemission rate for electron impact excitation, $[T_e, n_e]$

Q_{rec} - Photoemission rate for recombination from C^{6+} to C^{5+}, $[T_e, n_e]$

Q_{cx} - Photoemission rate for thermal charge exchange $[T_e]$

Cannot determine both C^{5+} density and thermal neutral density from available measurements

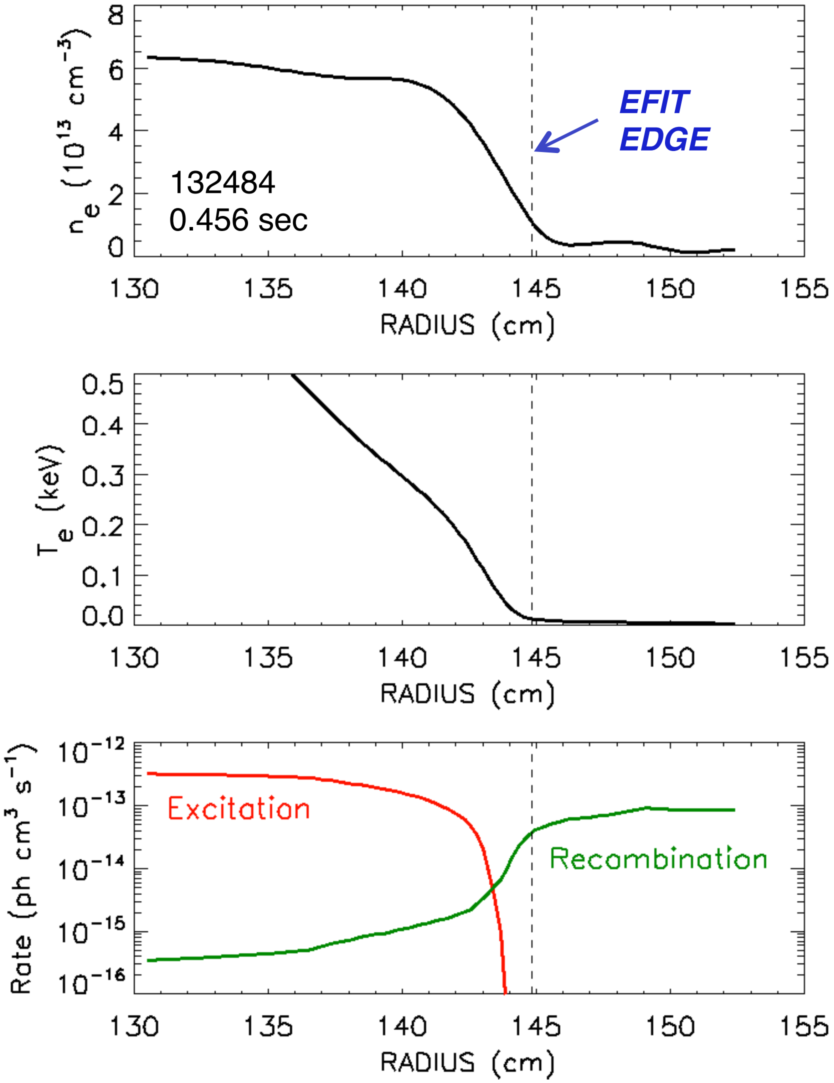
- Determination of density of C^{5+} requires thermal neutral deuterium *(n_0)* profile

$$n_{C^{5+}} = \frac{E}{Q_{ex} n_e} - \left(\frac{Q_{rec}}{Q_{ex}} + \frac{Q_{cx}}{Q_{ex}} \frac{n_0}{n_e} \right) n_{C^{6+}}$$

- Conversely, the thermal neutral density depends on the C^{5+} density or on the *ratio* of densities of C^{5+} to C^{6+}

$$n_0 = \frac{E}{Q_{cx} n_{C^{6+}}} - n_e \left(\frac{Q_{ex}}{Q_{cx}} \frac{n_{C^{5+}}}{n_{C^{6+}}} + \frac{Q_{rec}}{Q_{cx}} \right)$$

Profiles of excitation and recombination rates computed using T_e and N_e from Thomson scattering



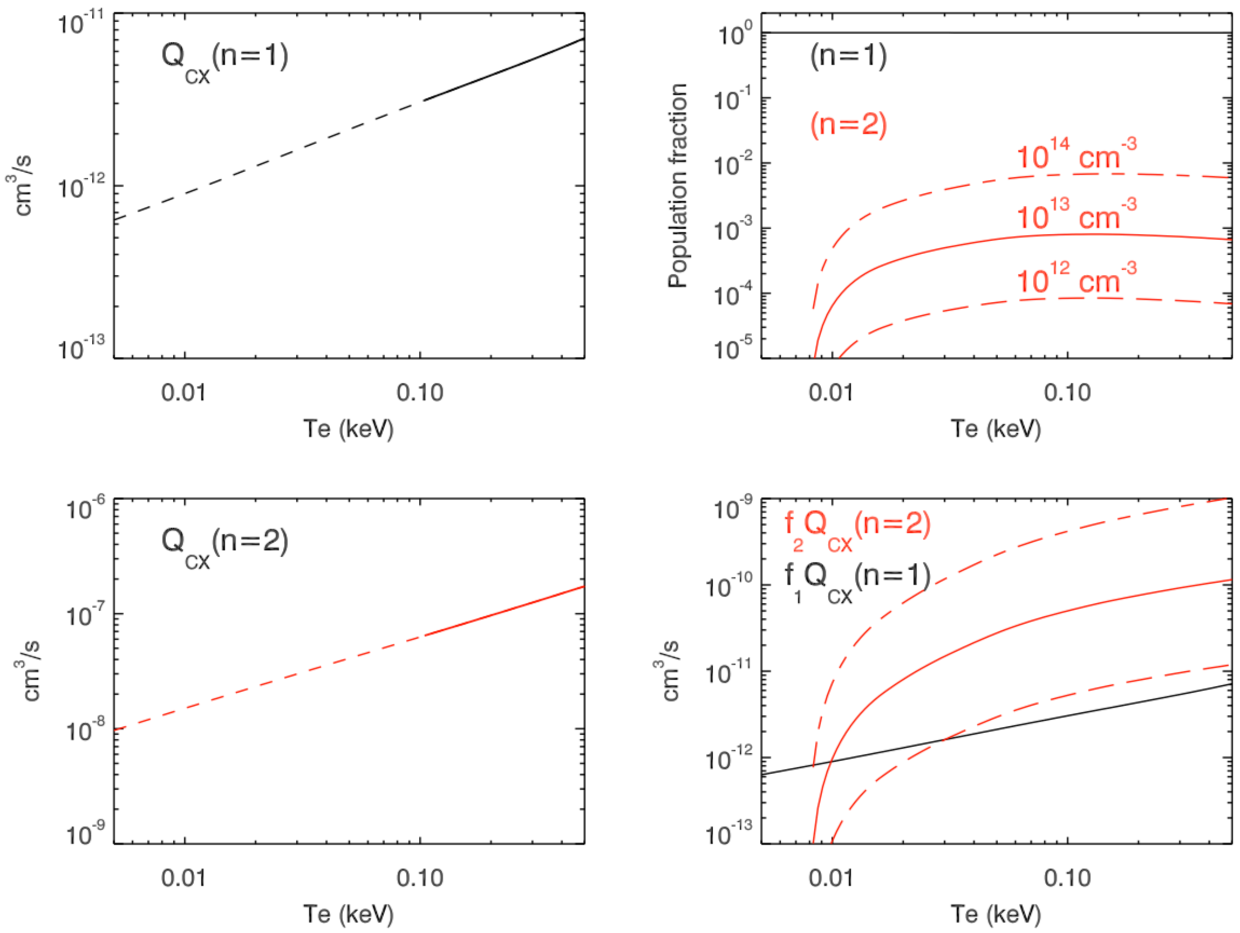
- **Photoemission rates from ADAS database**

- **Excitation rate plummets at low T_e**

Effective thermal charge-exchange rate is dominated by n=2 excited population fraction

Effective charge exchange: $Q_{cx} \cong f_1 Q_{cx}^{n=1} + f_2 Q_{cx}^{n=1}$

Neutral excited population fractions from Collisional-Radiative Model:



$$n_0 = \sum f_i n_{0,n=i}$$

$$\sum f_i = 1$$

- *n=2 neutral fraction varies with electron density*
- n=2 population is less than a percent of the thermal neutral density

Contribution from n=1 ground state neutrals only important at lower densities or low temperature

Thermal-Thermal CX rates from:
M. Tunklev, P. Breger, K. Günther, *et al.*, Plasma Phys. Control. Fusion 41 985 (1999)

Two strategies for estimating C^{5+} density and thermal neutral density

- Strategy I:
  1. Determine shape of C^{5+} density profile using radial force balance
  2. Use MIST to estimate ratio of C^{5+} density to C^{6+} density
  3. Compute thermal neutral density using estimate C^{5+} density profile
  4. Reconstruct contributions to C^{5+} emission profile

- Strategy II:
  1. Use low T_e region of C^{5+} emission, where electron impact excitation is negligible, to estimate thermal neutral density
  2. Assume exponential form for thermal neutral density profile
  3. With n_0 determined from exponential fit, compute C^{5+} density
  4. Reconstruct contributions to C^{5+} emission profile

I. The radial force balance equation provides additional information on C^{5+} density profile

- Using the radial force balance equation, $E_r = \frac{\nabla p}{Zen} + v_\phi B_\theta - v_\theta B_\phi$

- Equate the radial electric field from each species C^{5+} and C^{6+}:

$$E_r = \frac{\nabla p_{C^{5+}}}{Z_{C^{5+}} e n_{C^{5+}}} + v_{\phi_{C^{5+}}} B_\theta - v_{\theta_{C^{5+}}} B_\phi = \frac{\nabla p_{C^{6+}}}{Z_{C^{6+}} e n_{C^{6+}}} + v_{\phi_{C^{6+}}} B_\theta - v_{\theta_{C^{6+}}} B_\phi$$

- Solve for the pressure gradient term for C^{5+}:

$$\frac{\nabla p_{C^{5+}}}{Z_{C^{5+}} e n_{C^{5+}}} = \frac{\nabla p_{C^{6+}}}{Z_{C^{6+}} e n_{C^{6+}}} + \left(v_{\phi_{C^{6+}}} - v_{\phi_{C^{5+}}}\right) B_\theta - \left(v_{\theta_{C^{6+}}} - v_{\theta_{C^{5+}}}\right) B_\phi$$

- In practice, all terms on the right had side of the above equation are measured.
- The *difference* in velocity between C^{5+} and C^{6+} ions are needed (both toroidal and poloidal terms are important)

I. Shape of C⁵⁺ density profile from Radial Force Balance

Rearranging terms for $\dfrac{\nabla p_{C^{5+}}}{Z_{C^{5+}} e n_{C^{5+}}}$:

$$\frac{\partial \ln n_{C^{5+}}}{\partial r} = \frac{5}{6}\left(\frac{\partial \ln n_{C^{6+}}}{\partial r}\right) - \frac{1}{6}\frac{\partial \ln T}{\partial r} + \left(v_{\phi_{C^{6+}}} - v_{\phi_{C^{5+}}}\right)\frac{5B_\theta}{T} - \left(v_{\theta_{C^{6+}}} - v_{\theta_{C^{5+}}}\right)\frac{5B_\phi}{T}$$

Integrating the logarithmic derivative:

$$\int \frac{\partial \ln n_{C^{5+}}}{\partial r} dr = \ln n_{C^{5+}} + C \quad \Rightarrow \quad n_{C^{5+}} = A\exp\left(\int \frac{\partial \ln n_{C^{5+}}}{\partial r}\right)$$

where C and A = exp(C) are unknown constants.

★ *Shape* of the C^{5+} density profile is determined, but the magnitude is not.

II. At lower temperature, electron impact excitation can be neglected

- For $T_e < 50$ eV, the contributions to C^{5+} emission from electron impact excitation are negligible
- Neglecting electron impact excitation:

$$E \approx n_0 n_{C^{6+}} Q_{cx} + n_e n_{C^{6+}} Q_{rec}$$

$$n_0 \approx \frac{E}{n_{C^{6+}} Q_{cx}} - n_e \frac{Q_{rec}}{Q_{cx}}$$

- Most of the emission is from thermal charge exchange (second term above is small)
- This sets upper limit on thermal neutral density
- Without electron impact excitation, knowledge of C^{5+} density is not needed

Multi-Ion Species Transport (MIST) code used to get ratio of C^{5+} to C^{6+} density

- **Use particle diffusion equatio**

$$\Gamma_z = -D_z(r)\frac{\delta n_z}{\delta r} + v_z(r) n_z$$

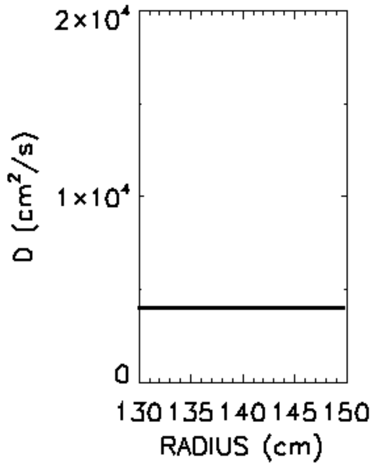
- **Assuming Steady State**

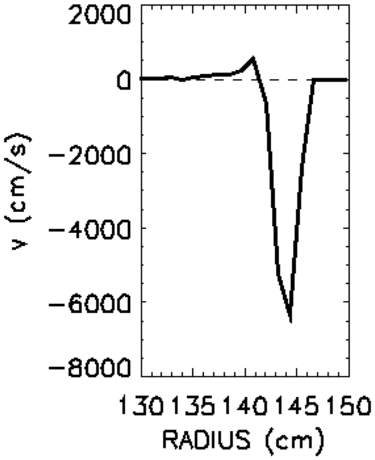
$$\Gamma_{C^{6+}} \approx 0$$

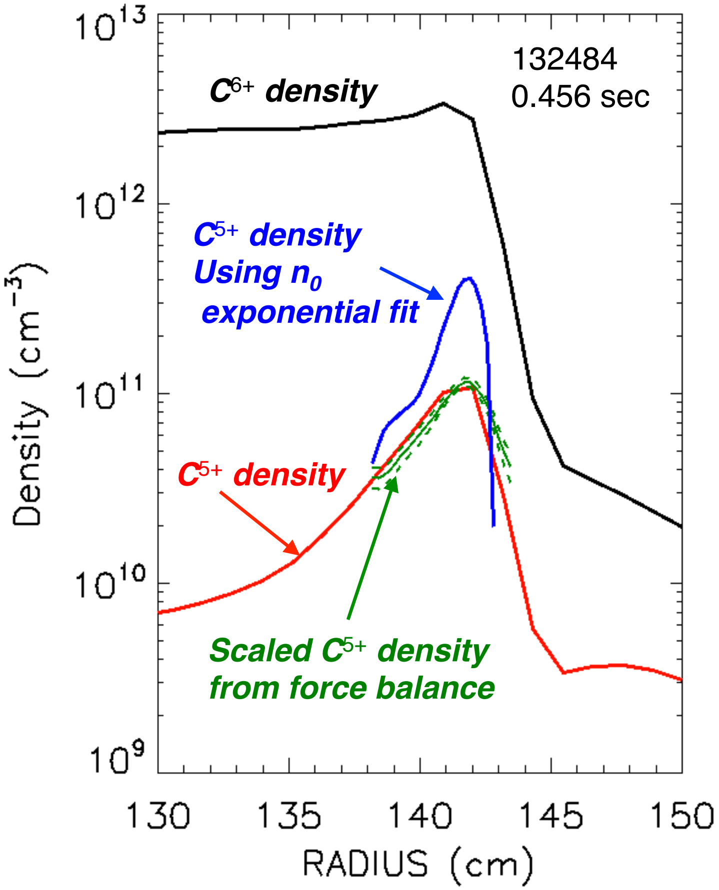
- **Use n_{C6+} to get v/D ratio**

$$\frac{v(r)}{D(r)} = \frac{1}{n_{C^{6+}}}\frac{\delta n_{C^{6+}}}{\delta r}$$

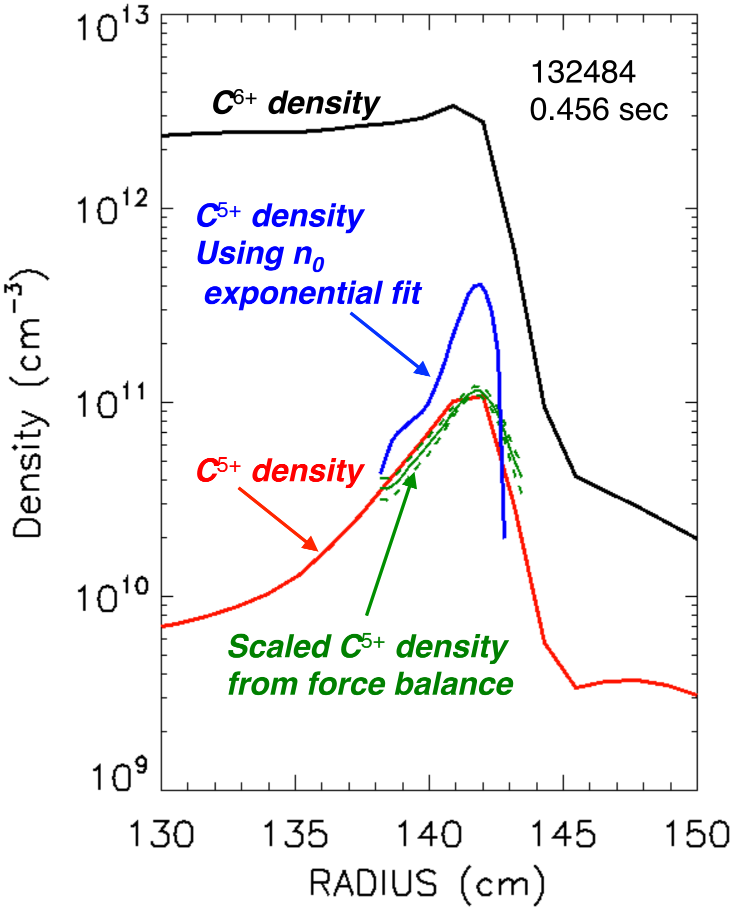
- **Vary D to match shape of C^{5+} profile**



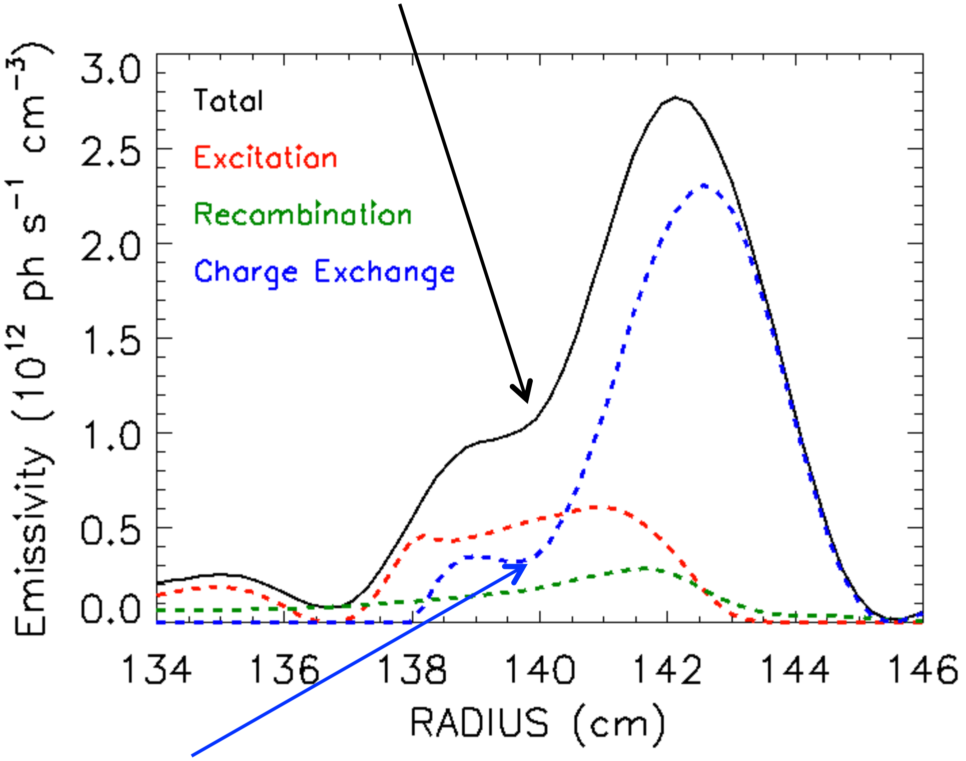




Reconstructed C^{5+} emission when C^{5+} density scaled to MIST value

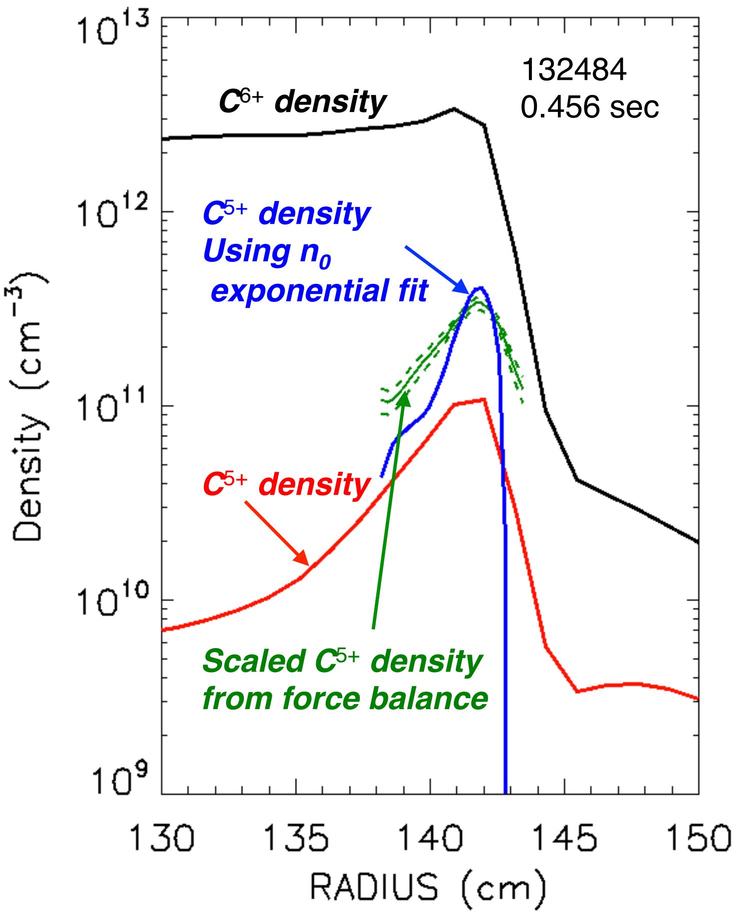


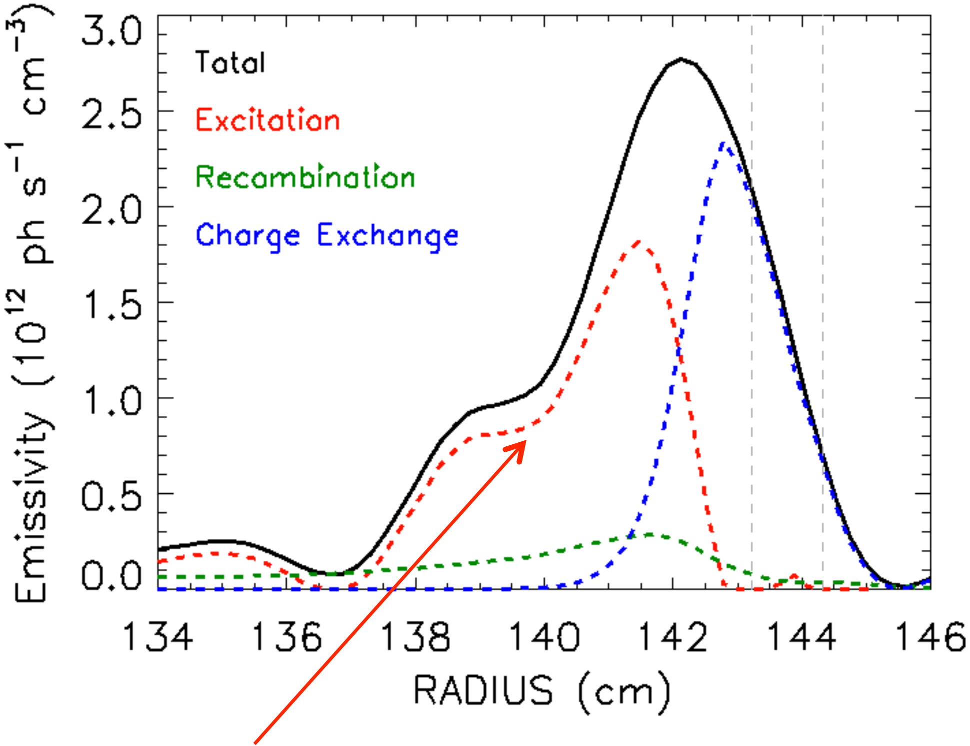
“Step” in C^{5+} emission profile suggests change in dominant emission process



“Corner” in charge exchange profile suggests MIST scaling may be too low

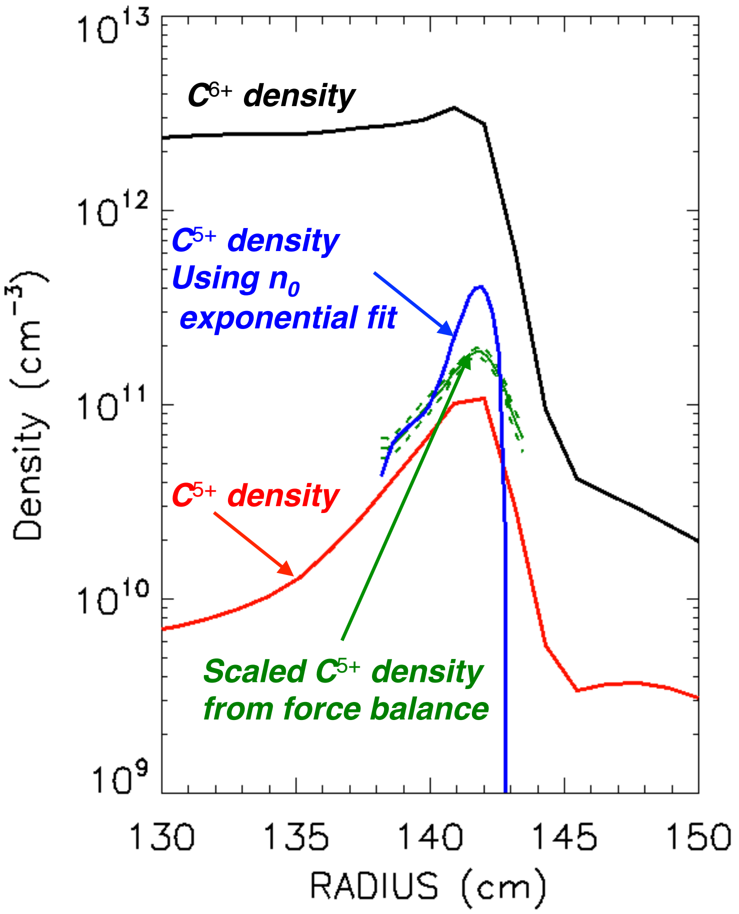
Reconstructed C^{5+} emission when C^{5+} density scaled to C^{5+} density using n_0 exponential fit



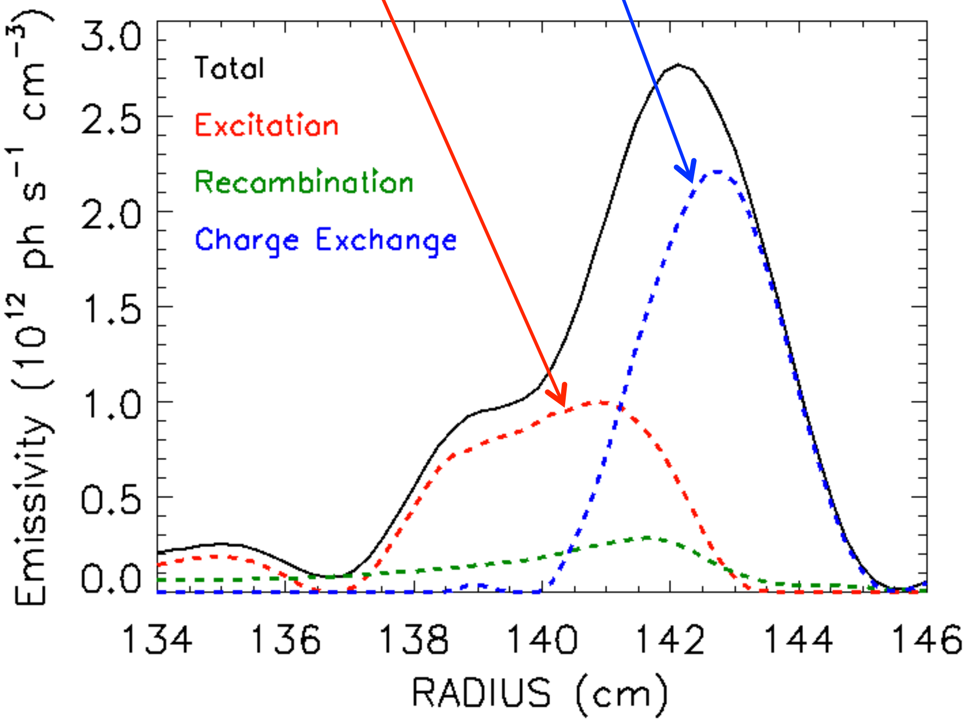


“Corner” in excitation profile suggests this scaling may be too high

Reconstructed C^{5+} emission when C^{5+} density scaled to intermediate value

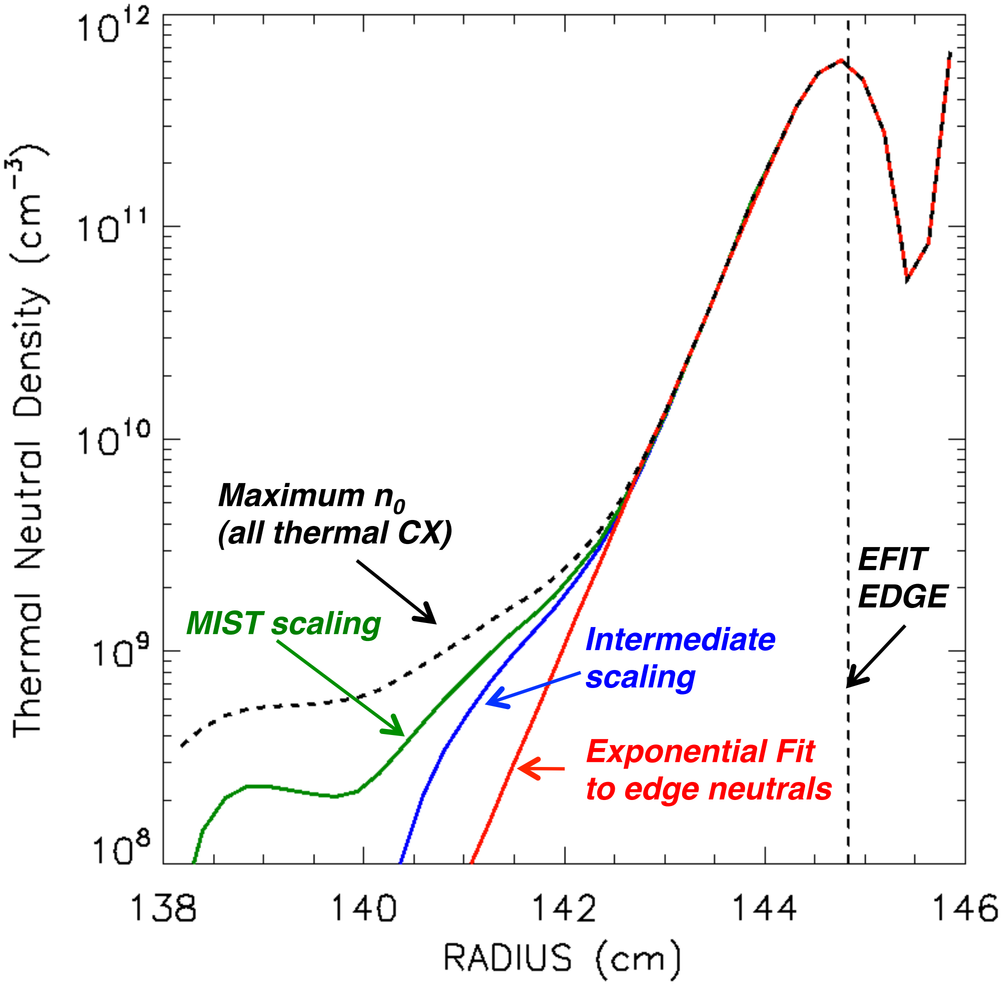


Intermediate scaling gives smoother transition from charge exchange to excitation profile!



Estimated Thermal Neutral Density Profiles

- **Edge emission is dominated by thermal charge exchange, shows exponential drop**
- **In low T_e region, inferred thermal neutral density varies little**
- **Changes in the thermal neutral profile away from the edge are seen with the different scalings**
- **Large changes in the inferred C^{5+} density profile result from difference in n_0 inside 142 cm**



SUMMARY

- Line-integrated measurements of passive C^{5+} emission are inverted to get local values of C^{5+} T_i, v_ϕ, v_θ, and emissivity
- Available measurements (active and passive) are insufficient to uniquely determine both C^{5+} density profile and thermal neutral density profile
- Charge exchange with thermal neutrals is a significant contributor the C^{5+} emission; *C^{5+} emission is sensitive to thermal neutral density*
- Shape of C^{5+} density profile can be estimated with active and passive CHERS measurements and radial force balance equation
- C^{5+} density profile estimated using C^{5+}/C^{6+} density ratio from MIST seems low, C^{5+} density from extrapolated edge thermal neutral density seems high
- Edge thermal neutral density (low T_e) can be well constrained without knowledge of C^{5+} density
- Two strategies show larger variation in estimated C^{5+} density (factor 3-5)