NSTX-U

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Comparison of neutral density profiles measured using D_α and C^{5+} in NSTXU

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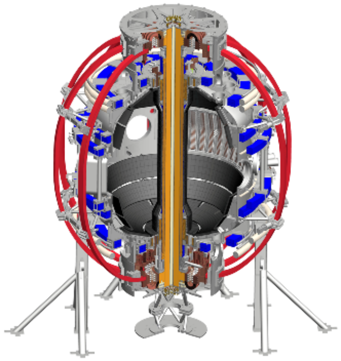
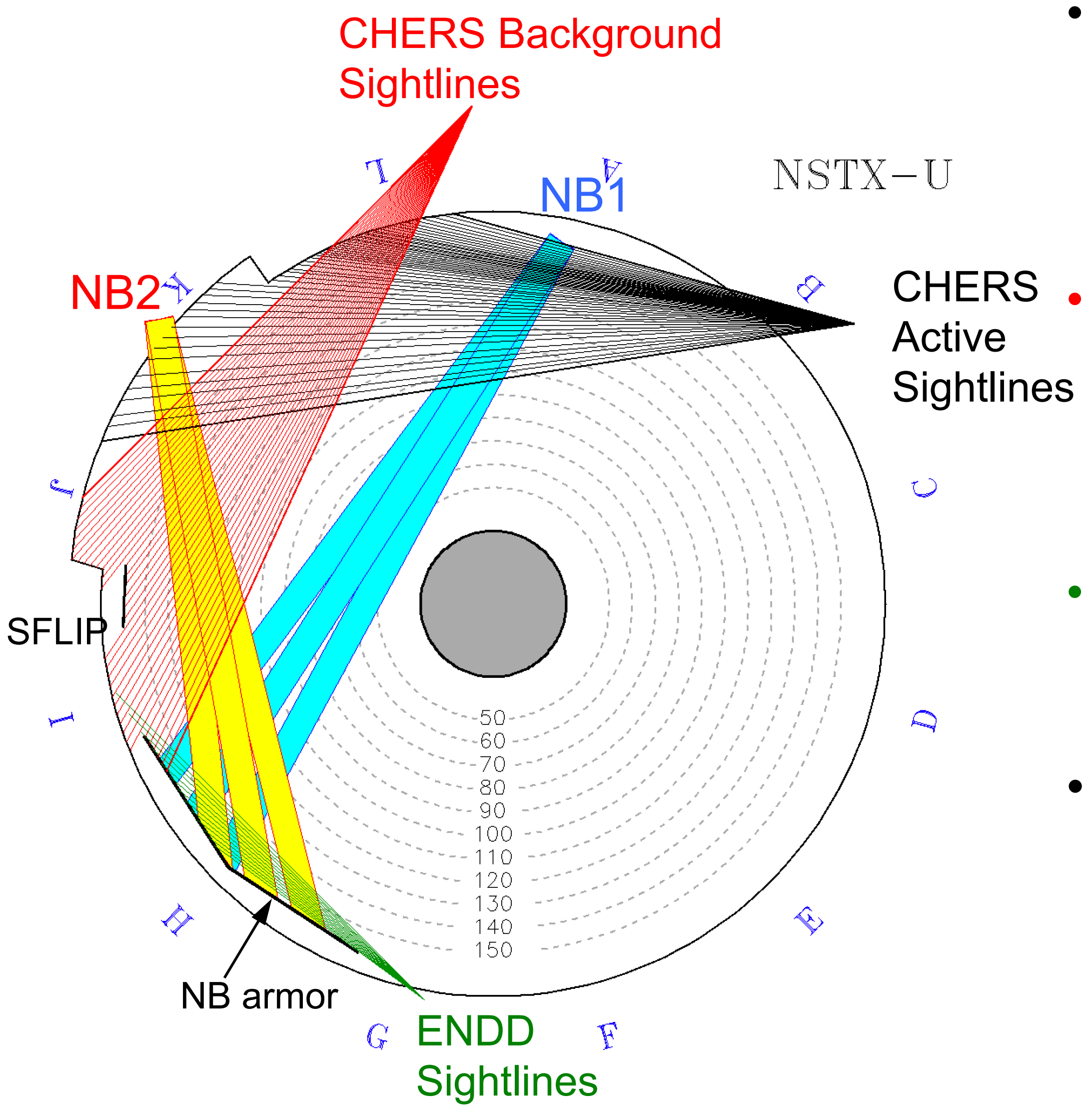


Abstract

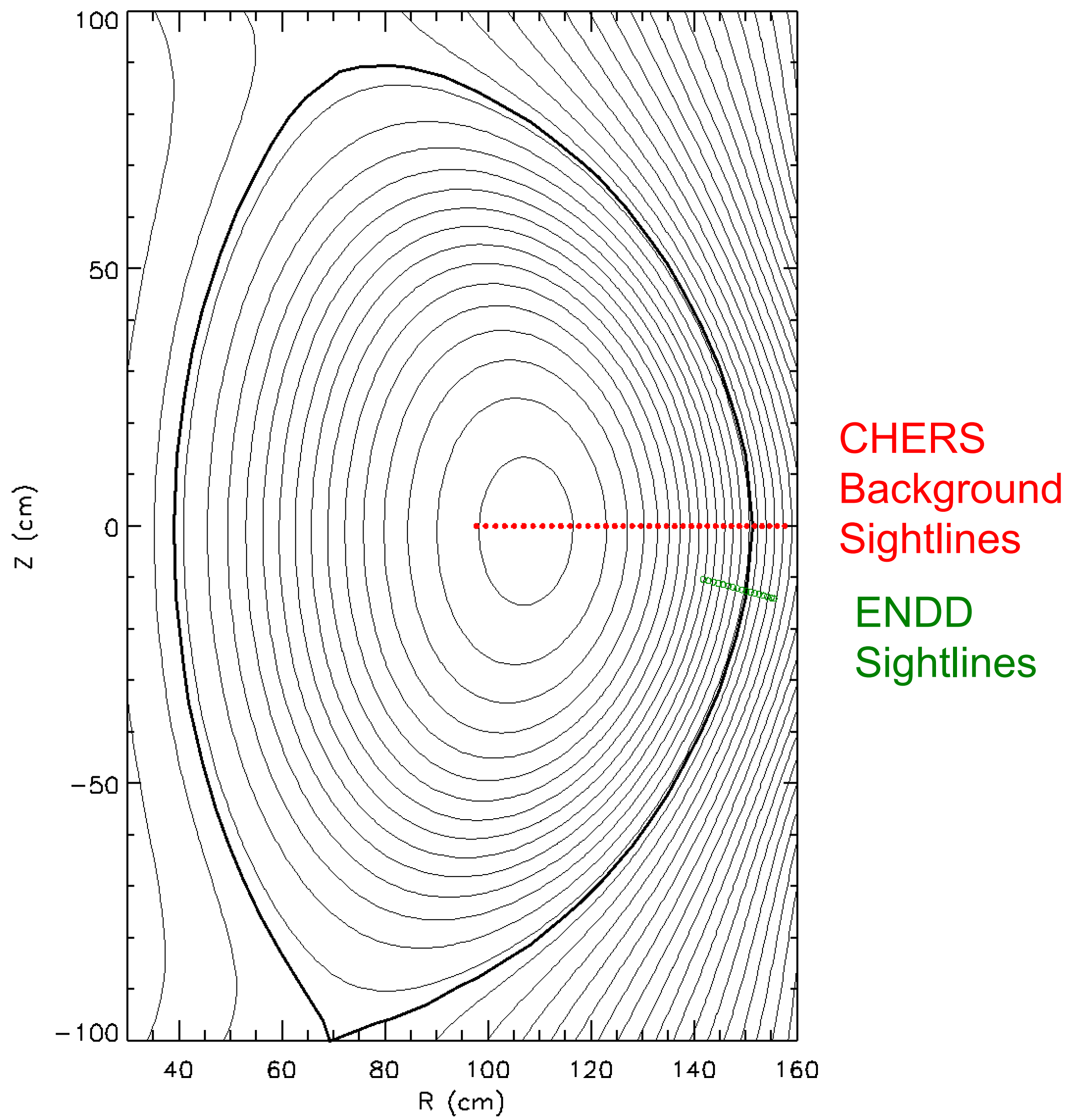
Edge neutral density profiles determined from two different measurements are compared on NSTXU plasmas. Neutral density measurements were not typical on NSTX plasmas. An array of fibers dedicated to the measurement of passive emission of C^{5+}, used to subtract background emission for charge exchange recombination spectroscopy (CHERS), can be used to infer deuterium neutral density near the plasma edge. The line emission from C^{5+} is dominated by charge exchange with neutral deuterium near the plasma edge. An edge neutral density diagnostic (ENDD) consisting of a camera with a D_{α} filter was installed on NSTXU. The line-integrated measurements from both diagnostics are inverted to obtain local emissivity profiles. Neutral density is then inferred using atomics rates from ADAS and profile measurements from Thomson scattering and CHERS. Comparing neutral density profiles from the two diagnostic measurements helps determine the utility of using the more routinely available C^{5+} measurements for neutral density profiles. Initial comparisons show good agreement between the two measurements inside the separatrix.

NSTXU Viewing Geometry



- CHERS Active views
  - Charge exchange recombination spectroscopy measuring T_i, N_C, V_ϕ
  - Optimized views across NB1
  - Views CX emission and background emission for C^{5+}
- CHERS Background views
  - View parallel to NB1
  - View *only* C^{5+}background emission
  - Background measurement *simultaneous* with active measurement
- ENDD
  - Edge Neutral Density Diagnostic sightlines below midplane viewing upward
- Second neutral beam (NB2) compromises CHERS Background views
  - Bright CX emission contaminates background views

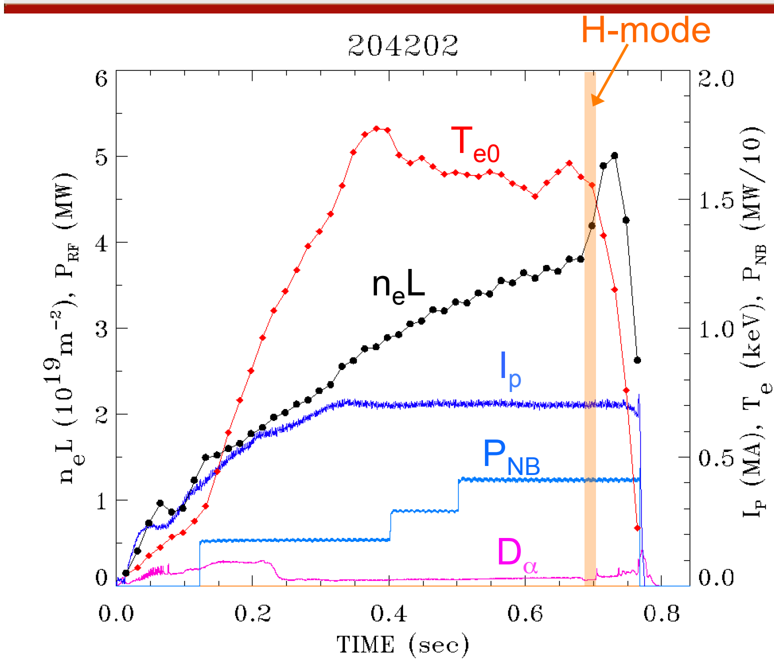
NSTXU Viewing Geometry



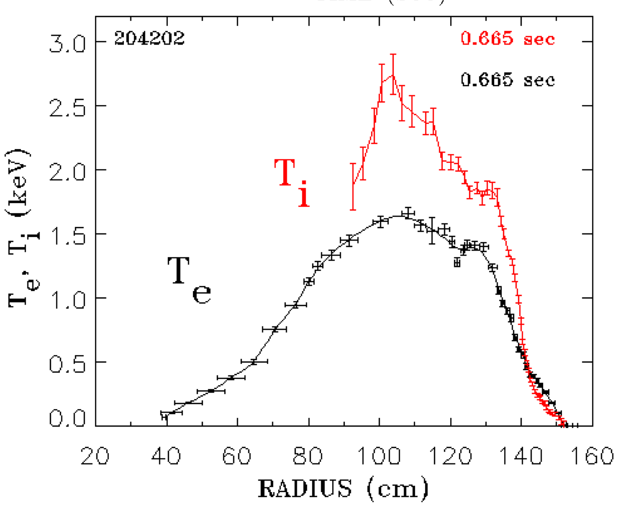
- CHERS Background views
  - On midplane
  - CHERS exposure 10 ms
  - 37 fibers in background view

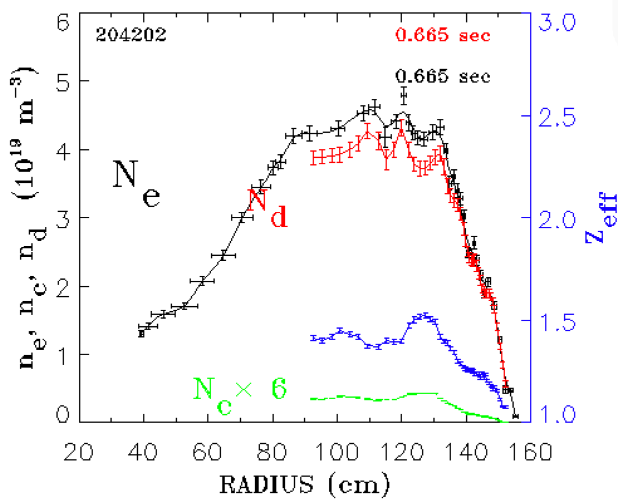
- ENDD
  - Edge Neutral Density Diagnostic sightlines below midplane viewing upward
  - ENDD exposure 3.7 ms
  - Camera with D_α filter
  - Subset of 127 x 128 pixels used

NSTX-U L-mode plasma

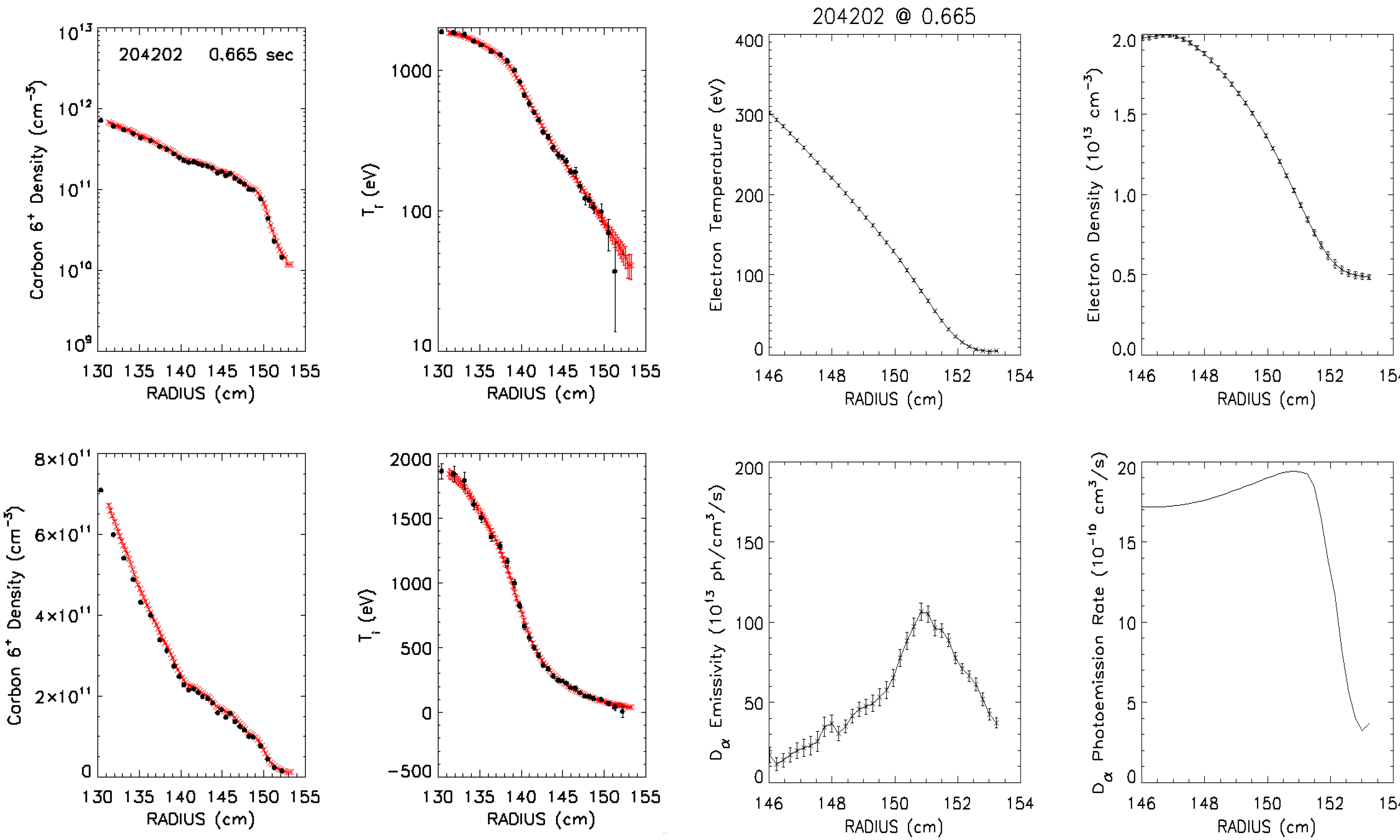


- L-mode plasma
- Brief H-mode 690-700 ms
- I_p= 700 kA





Measured profiles of temperature and density are interpolated or extrapolated onto common fine grid



Three Processes Contribute to C^{5+} passive emission

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

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+} $n = 87$
- 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 thermalthermal charge exchange $[T_e, n_e, Z_{eff}]$

Cannot independently determine both C^{5+} density and thermal neutral density

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

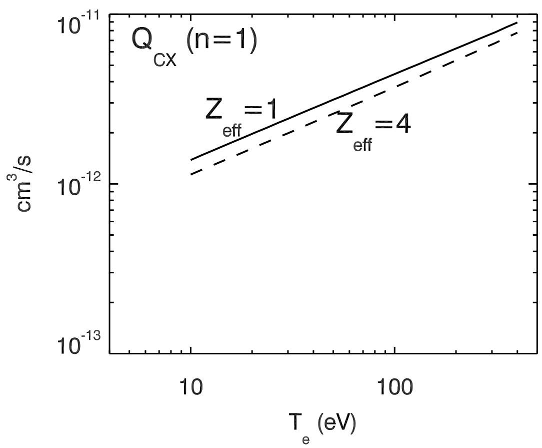
$$n_{C^{5+}} = \frac{E}{Q_{ex} n_e} - \left(\frac{Q_{rec}}{Q_{ex}} + \frac{Q_{cx}}{Q_{ex}} \frac{n_0}{n_e} \right) n_{C^{6+}}$$

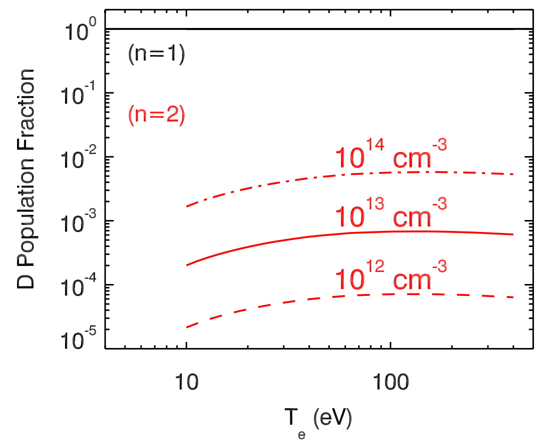
- Conversely, the thermal neutral density depends on the C^{5+} density or on the *ratio* of densities of C^{5+} to C^{6+}

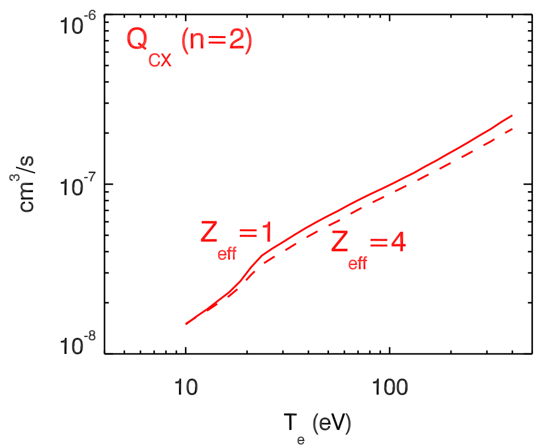
$$n_0 = \frac{E}{Q_{cx} n_{C^{6+}}} - n_e \left(\frac{Q_{ex}}{Q_{cx}} \frac{n_{C^{5+}}}{n_{C^{6+}}} + \frac{Q_{rec}}{Q_{cx}} \right)$$

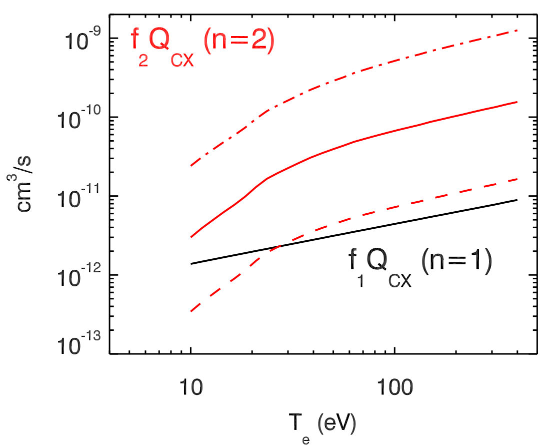
Effective thermal-thermal charge-exchange rate is dominated by n=2 excited population fraction

Effective CX rate: $Q_{cx}^{eff} \cong f_1 Q_{cx}^{n=1} + f_2 Q_{cx}^{n=2}$ $\quad n_0 = \sum f_i n_{0,n=i} \quad \sum f_i = 1$









- Thermalthermal charge exchange rates for C^{6+} and D computed using ADAS 308 data.
- Population fraction derived from ADAS photoemission coefficients,

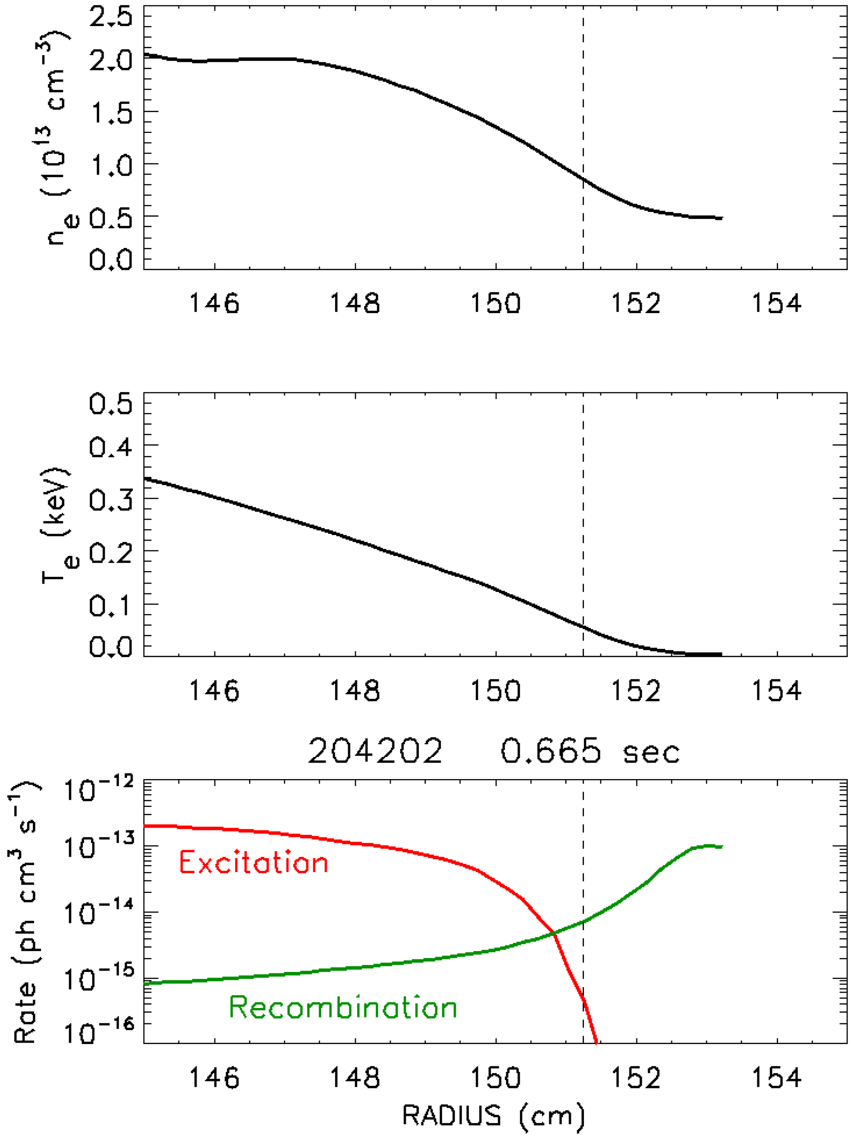
$$f_2 = \frac{n_D(n=2)}{n_D(n=1)} = \frac{PEC_{21}^{exc}}{A_{21}} n_e$$

or a from CollisionalRadiative model from DEGAS 2*

- 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 are only important at lower densities or low temperature

*http://w3.pppl.gov/degas2/ehr3.dat

At lower temperature (plasma edge), electron impact excitation can be neglected for carbon



- 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 to determine neutral density

Neutral density is determined from D_α emission

$$E_{D_\alpha} = Q_{ex}^{D_\alpha} n_e n_0$$

Excitation rate

$$n_0 = \frac{E_{D_\alpha}}{Q_{ex}^{D_\alpha} n_e}$$

UNKNOWN:

n_0 Density of thermal deuterium neutrals

MEASURED:

E Emissivity of passive emission from D_α (n = 3-2)

n_e Electron density

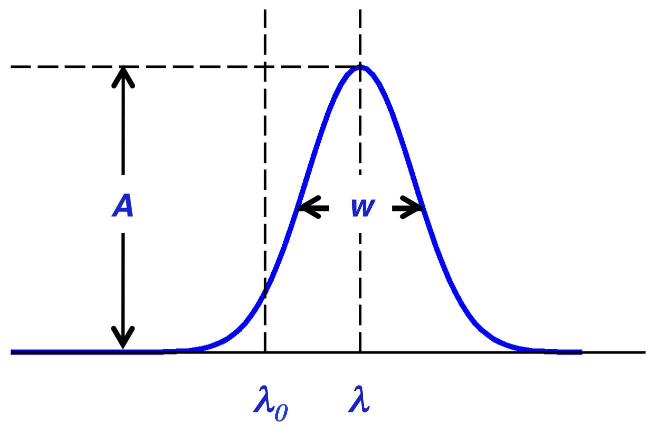
COMPUTED:

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

Local carbon 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

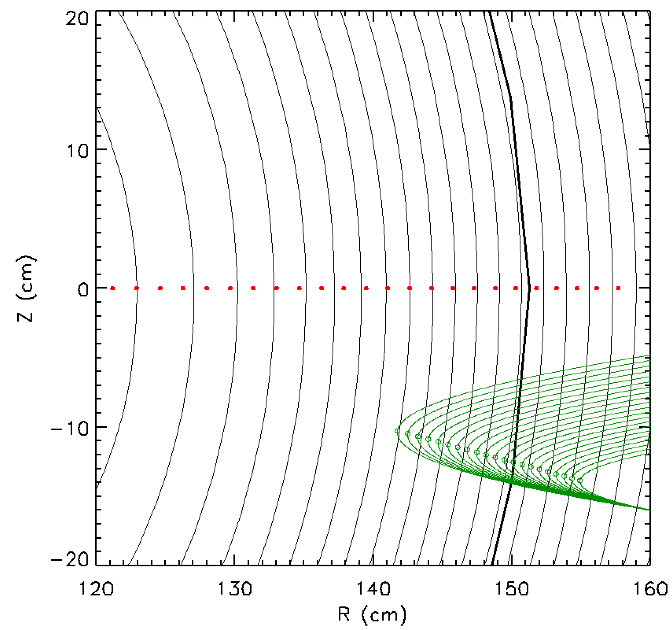
- Subscript i refers to a particular sightline (*line-integrated* measurement)
- Subscript j refers to a particular zone in the plasma (*local* value)
- L_{ij} is a matrix of path lengths
- Line-integrated brightness *(ph/s/cm^2/st)* can be related to local emissivity *(ph/s/cm^3)* by length matrix
- Local emissivity is obtained using inverted length matrix

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

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

Local D_α emissivity from line-integrated measurements with a matrix inversion approach

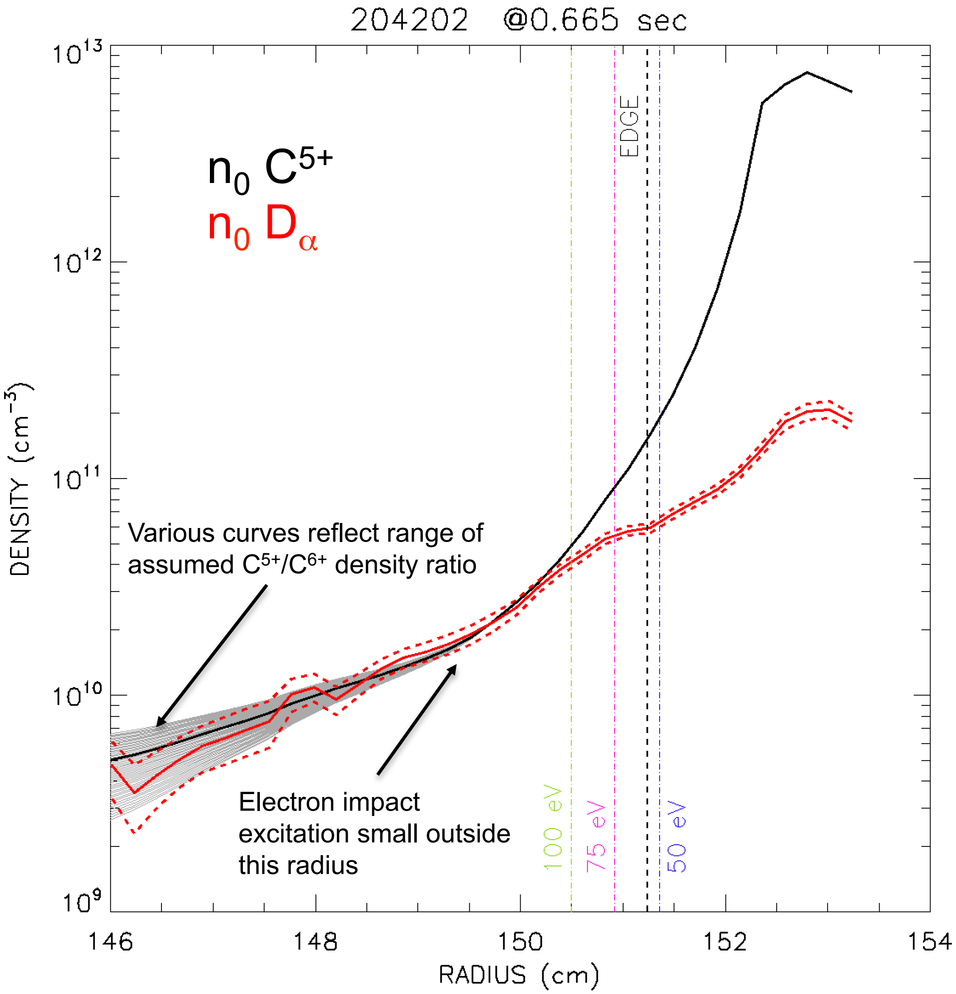
- Line-integrated measurements
  - Camera with 127 x 128 pixels
  - D_α filter
  - Absolutely calibrated
- Local tangency of sightline each pixel computed using EFIT equilibrium code
- Tangency mapped to R at Z=0
- Pixels binned to improve S/N
- Emissivity from Brightness using matrix inversion with length matrix calculated for 3D geometry



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

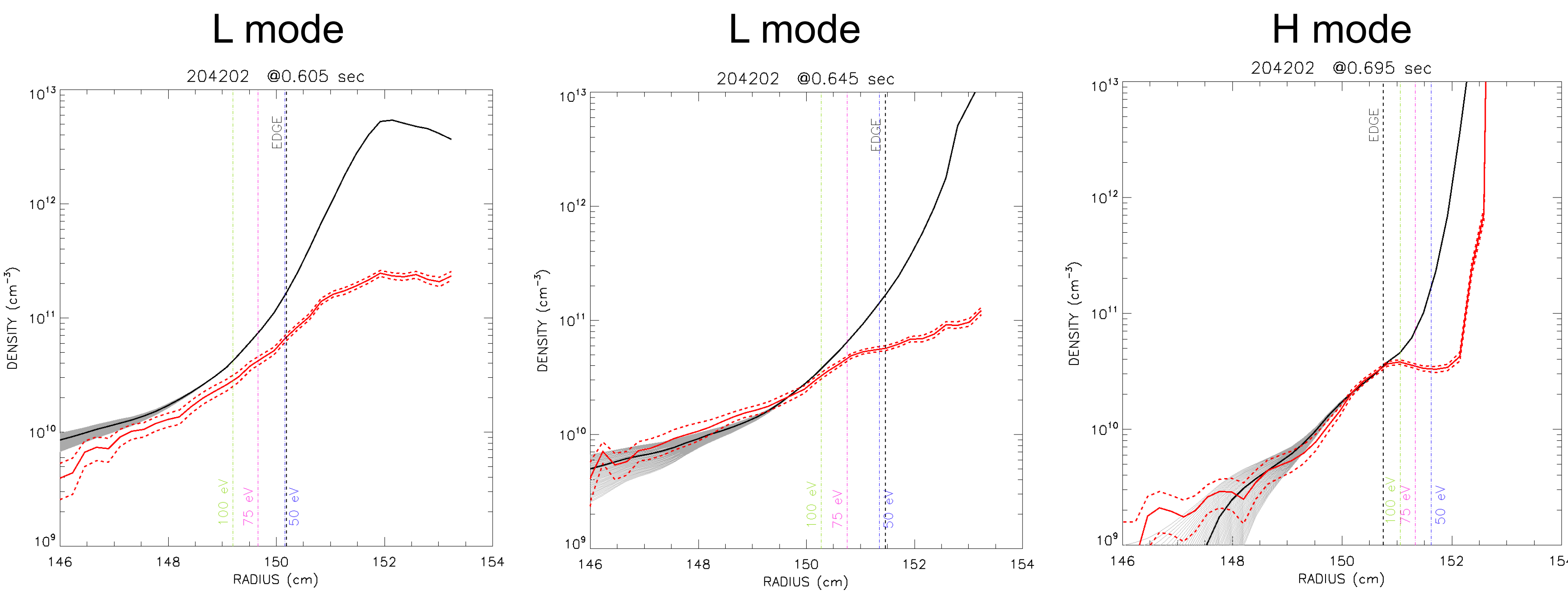
$$E_j = 4\pi \sum_i L_{ij}^{-1} B_i$$

Neutral density profiles from C^{5+} and D_α are comparable inside plasma edge

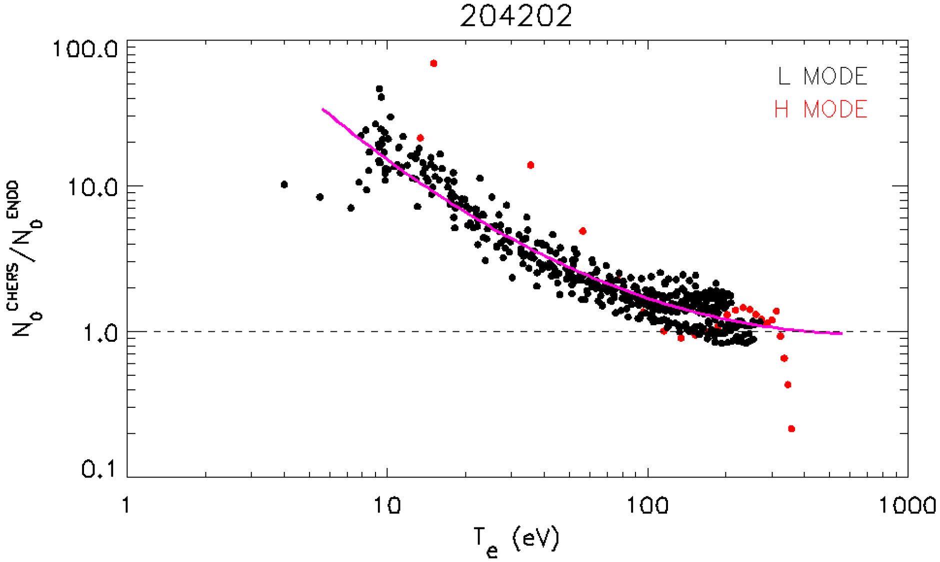


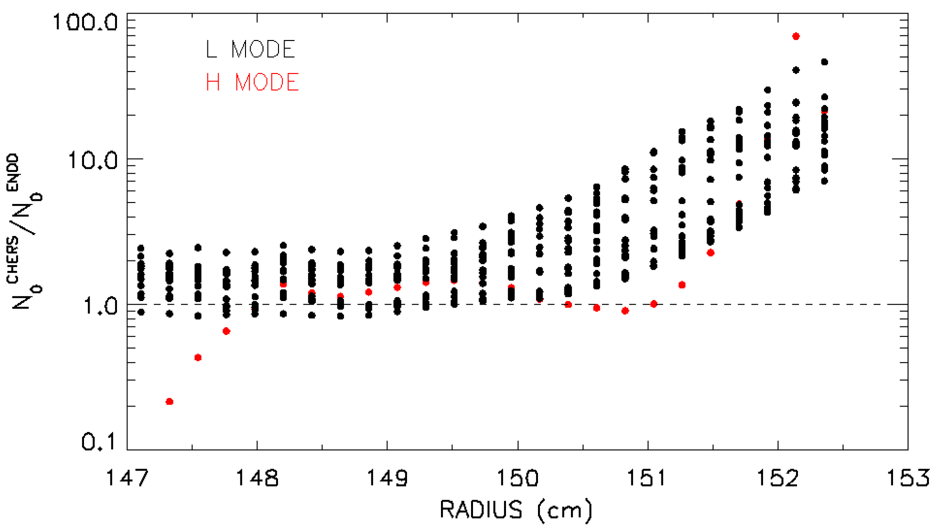
- L mode plasma edge
- Similar neutral density profiles over 45 cm inside LCFS
- Neutral densities strongly diverge outside LCFS
- n_0 from C^{5+} exceeds n_0 from D_α by an order of magnitude just a few cm away from edge

Some variation is observed in neutral density profiles inferred from C^{5+} and D_{α}



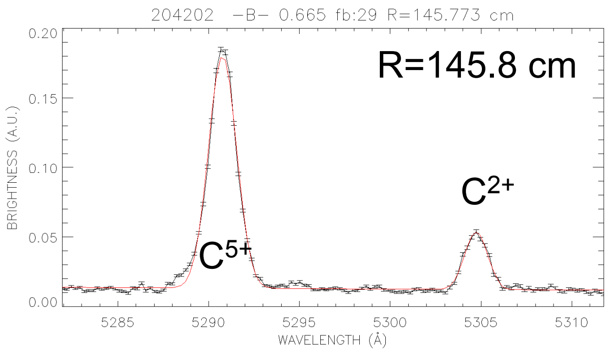
Better agreement between n_0 measurements at higher T_e

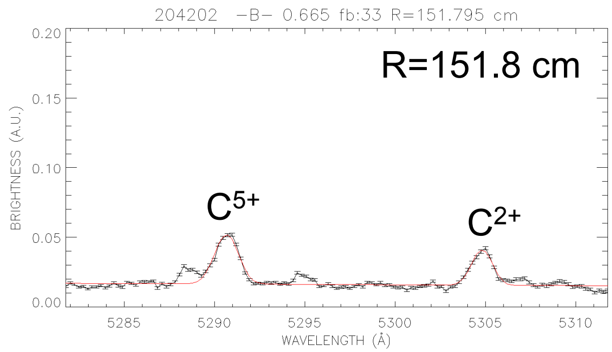


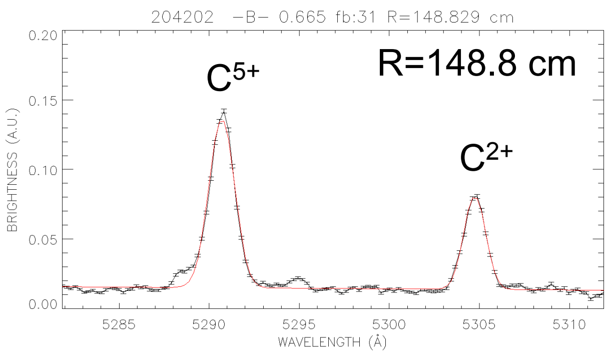


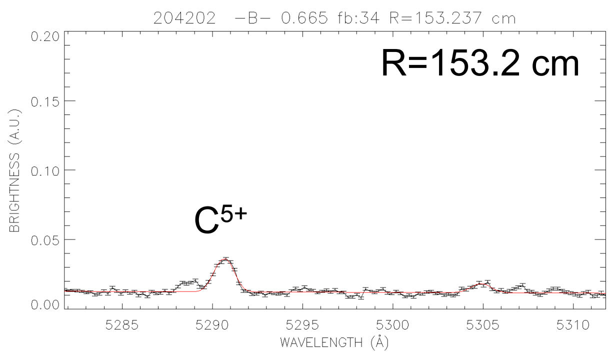
- Ratio of neutral densities plotted for multiple time
- Ratio trends toward 1 as T_e increases
- At higher T_e, agreement within a factor of 2
- At lower T_e, ratio of neutral densities ~10
- Plotting data vs. R shows strong deviation outside LCFS

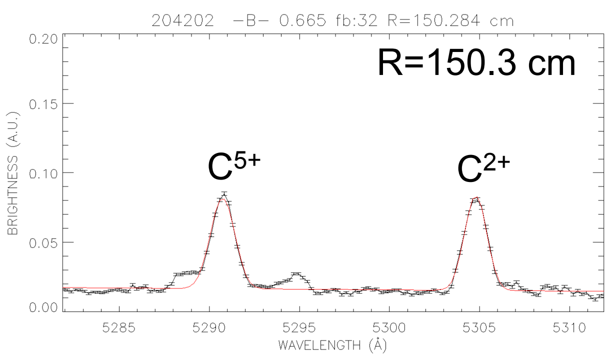
C^{5+} emission observed beyond the LCFS

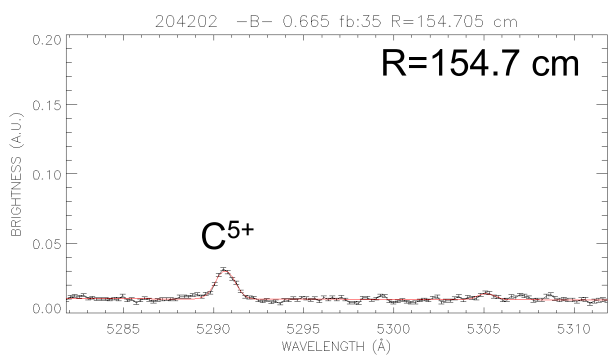


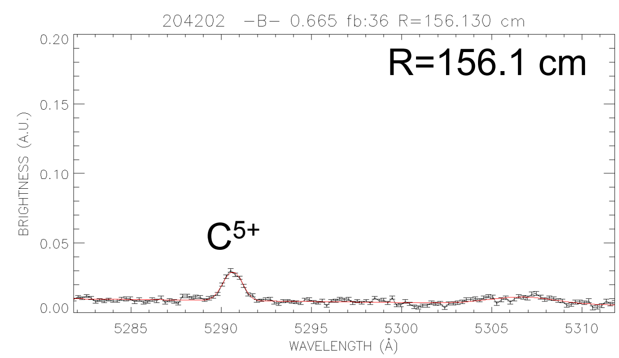












- C^{5+} emission in SOL is inconsistent with local T_e, N_e
- C^{5+} emission is observed outside of C^{2+} emission shell

Convective transport from "blobs" could explain "extra" C^{6+} beyond LCFS

- C^{6+} lifetime ~ 10^{-9} sec
- Distance into SOL ~ 5 cm
- Blob velocity ~ 10^{5} cm/s
- Edge T_e ~ 50 eV
- Edge n_e ~ 10^{13} cm^{-3}
- Edge n_0 ~ 10^{11} cm^{-3}

- Total recombination rate for Carbon Z=6

  $Q_{rec}(50\ \text{eV}, 10^{13}\ \text{cm}^{-3}) = 2.7 \times 10^{-13}\ \text{cm}^2/\text{s}$

- Total charge exchange rate for Carbon Z=6

  $Q_{cx}(50\ \text{eV}, 10^{13}\ \text{cm}^{-3}) = 6.9 \times 10^{-8}\ \text{cm}^2/\text{s}$

Characteristic Times:

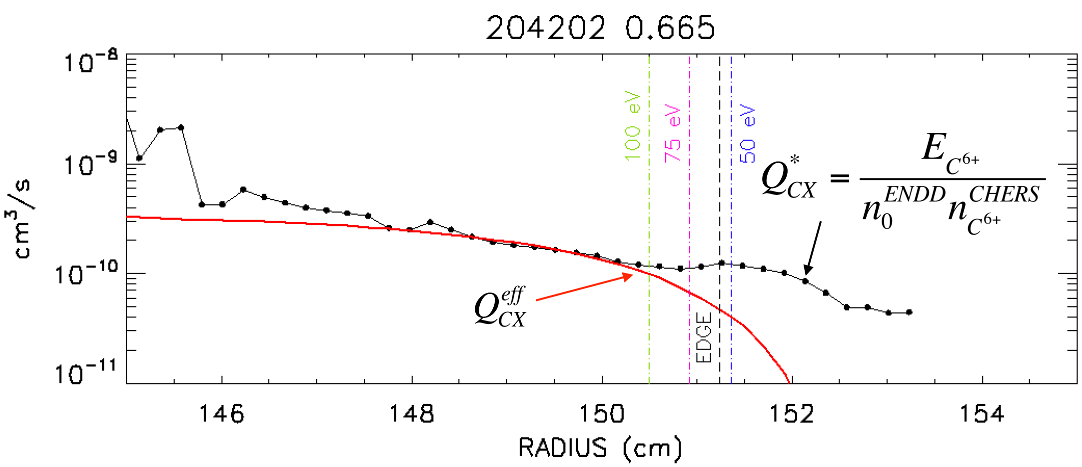
$$\tau_{blob} = \frac{5\ \text{cm}}{10^5\ \text{cm/s}} = 50\ \mu\text{sec}$$

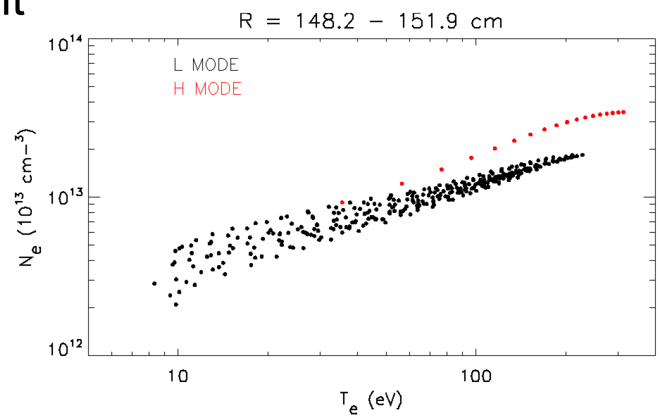
$$\tau_{CX} = \frac{1}{n_0\ \text{Q}_{CX}} = 145\ \mu\text{sec}$$

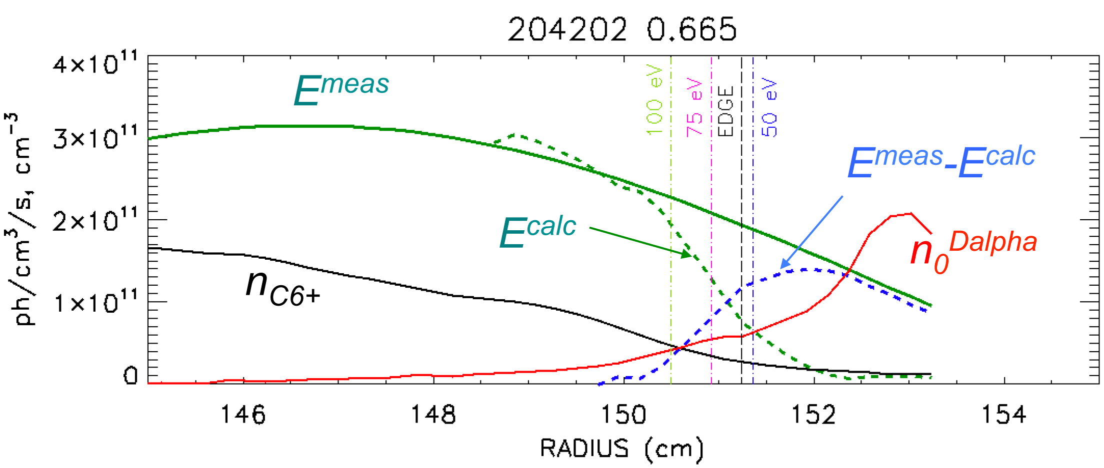
$$\tau_{REC} = \frac{1}{n_e\ \text{Q}_{REC}} = 365\ m\text{sec}$$

Neutral density from C^{5+} is overestimated outside LCFS due to “extra” C^{5+} emission

- Measured C^{5+} emissivity exceeds that expected with local T_e, n_e measurements and D_α neutral density measurement







- The required photoemission rate, $Q_{CX}^{*}=Q_{CX}(T_e^{*}, n_e^{*})$ corresponds to different values of electron temperature and density
- Subtracting the expected emission from the measured emission shows an excess signal, $(E^{meas}-E^{calc})$

Measured emissivity is a time average of steady emission and intermittent “blob” emission

- Introduce a simple model to describe the measurements
- Steady emission (E_0) is consistent with local measured T_e, n_e
- Intermittent “blob” (E_1) emission would correspond to different values (T_e*, n_e*)

$$Q_{CX}(T_e^*, n_e^*) > Q_{CX}^{eff}(T_e, n_e)$$

- The “duty cycle” of the blobs is given as f

$$E_{C^{6+}}^{meas} = E_0 + E_1$$

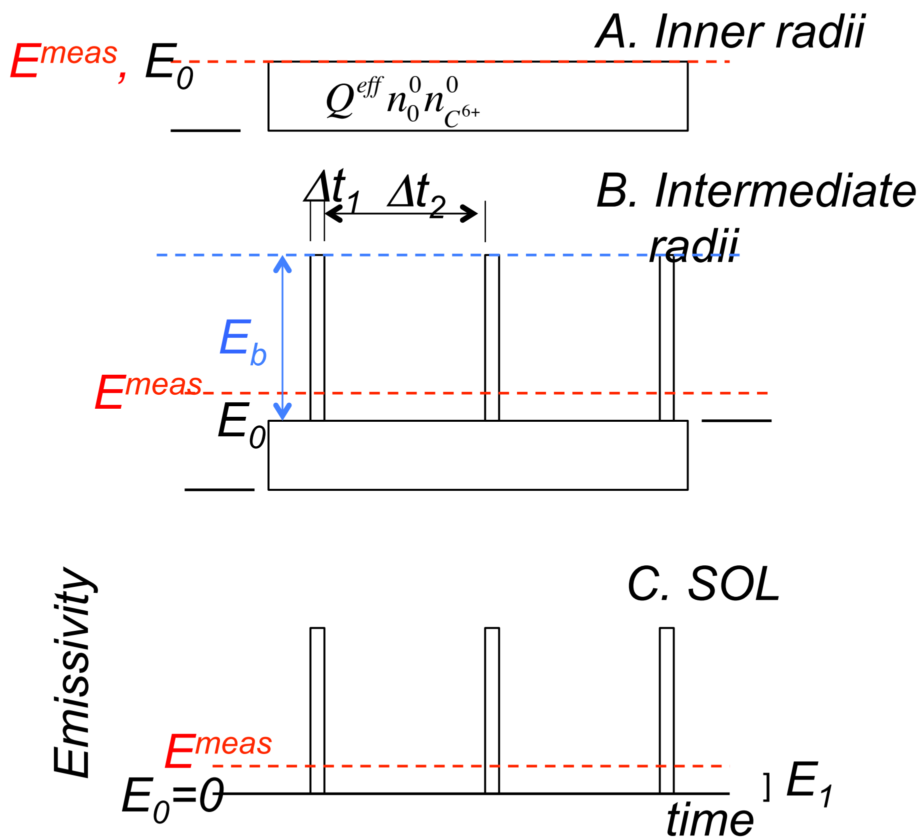
$$E_0 = Q^{eff} n_0^0 n_{C^{6+}}^0 (1 - f)$$

$$E_1 = Q_{CX}(T_e^*, n_e^*) n_0^B n_{C^{6+}}^B f$$

$$f = \Delta t_1 / (\Delta t_1 + \Delta t_2)$$

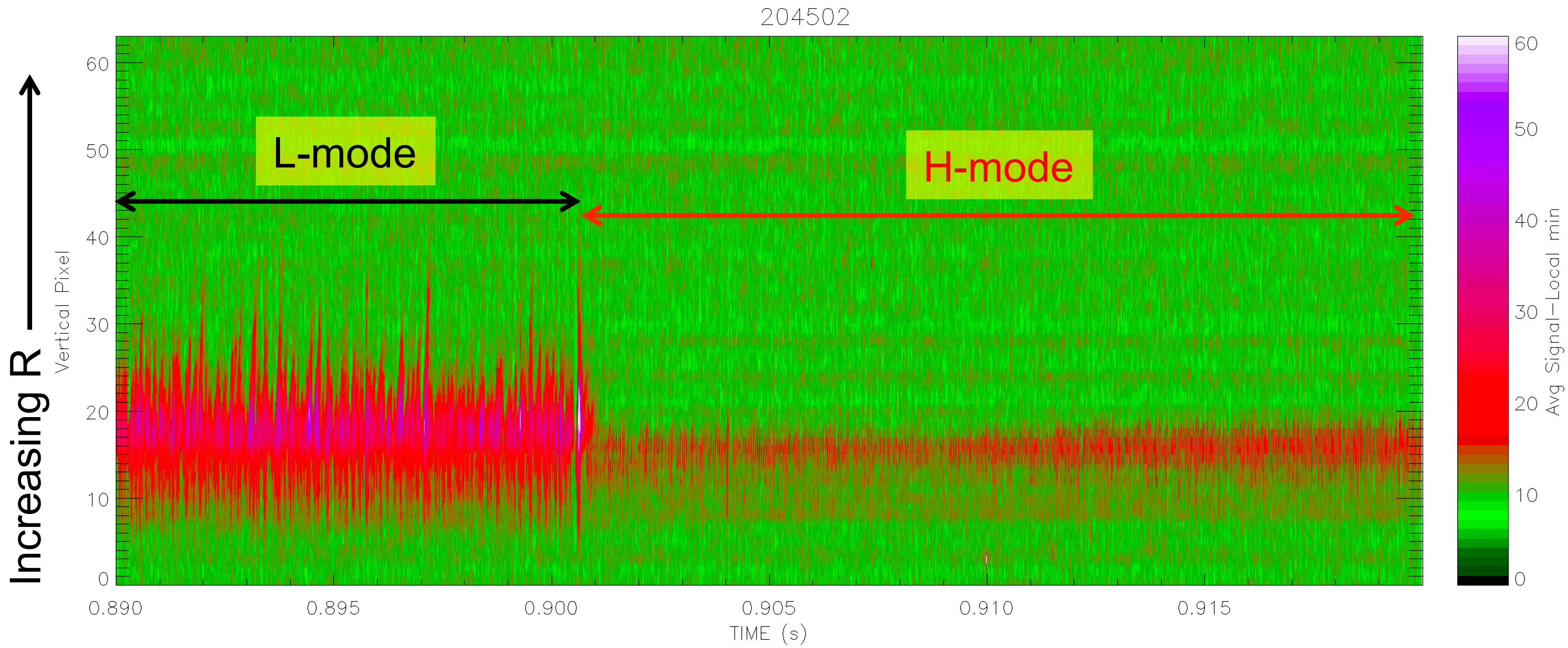
  - If the neutral density remains relatively constant, then in the SOL,

$$Q_{CX}^* = \frac{E_{C^{6+}}^{meas}}{n_0^{ENDD} n_{C^{6+}}^{CHERS}}$$



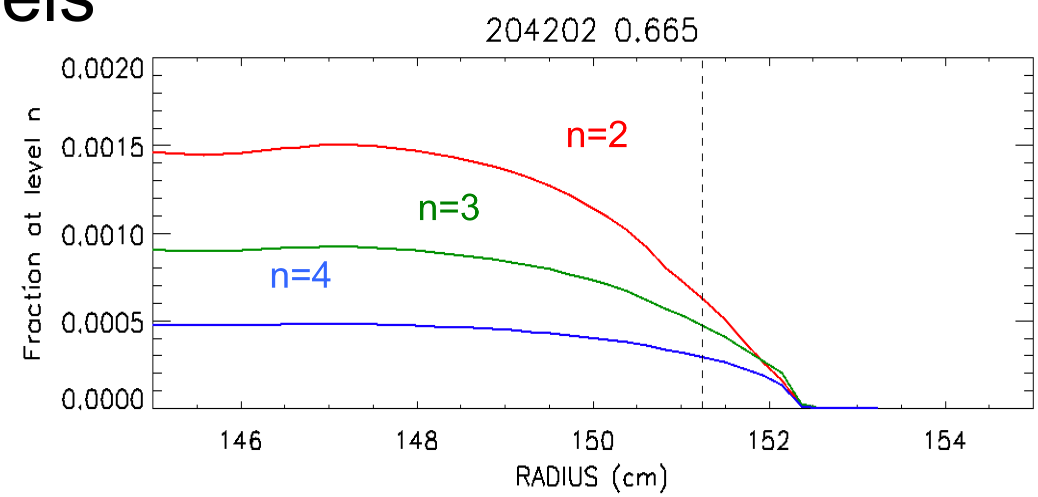
Intermittent signal from fast Gas Puff Imaging (GPI) system

- Signal from GPI across L-H transition
- Estimated "duty cycle" of blobs ~ 8% during L-mode
- ENDD and CHERS signals will be time-averaged over many milliseconds



Other Comments

- Reflections (ruled on for NSTX-U views) might cause unexplained emission in edge
- n_0 from D_α is an upper limit due to contributions to emission from molecular D_2
- The effective thermal-thermal charge exchange rate for carbon does not take into account contributions from n=3 and n=4 levels



Summary

- Neutral density measurements made with C^{5+} emission and D_{α} emission
- Neutral density profiles agree within a factor of 2 *inside the LCFS* for L-mode plasmas
- Neutral density profiles *outside the LCFS* deviate up to an order of magnitude
- C^{5+} emission is observed in SOL
- Estimate of necessary photoemission rate outside LCFS suggests higher T_e, N_e values than local measurements
- Convective transport (blobs) of C^{6+} could explain 'extra' C^{5+} emission in SOL