Impurity Densities from CXRS and Beam Emission Spectroscopy

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Experimental Validation of Ar CX Cross Sections

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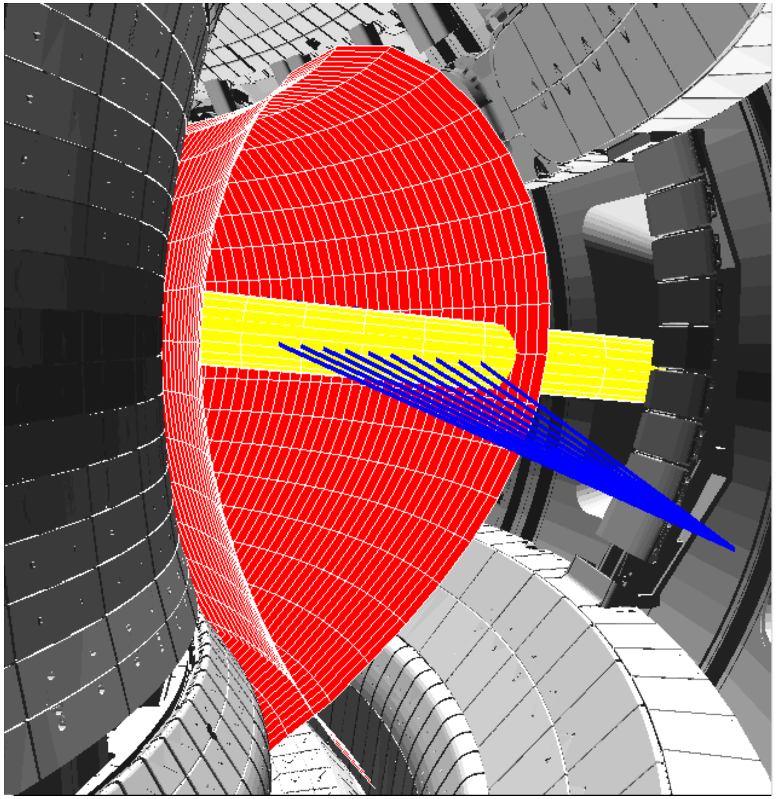
Impurity densities from CXRS

$$A^{+Z+1} + D(n=1,2..) \Rightarrow A^{+Z}(n,l) + D^{+}$$

$$A^{+z}(k) \Rightarrow A^{+z}(m) + h\nu$$

- CX cross sections σ
- effective CX emission rate coefficients q
- D-density distribution in n=1 and n=2
  - depends on beam geometry, attenuation, excitation, distribution of species with full, half and third energy



$$\langle n_{Z+1} \rangle = \frac{4\pi}{h\nu} \frac{L_{CX}}{\sum_{j,k} q_{j,k} \int n_{D,j,k}\, dl}$$

j=energy component, *k*=main quantum number

- Hα beam emission yields line-integrated densities in n=3
- thermal beam halo neutrals are produced by CX from beam neutrals onto thermal deuterons and produce a considerable fraction of the active impurity emission

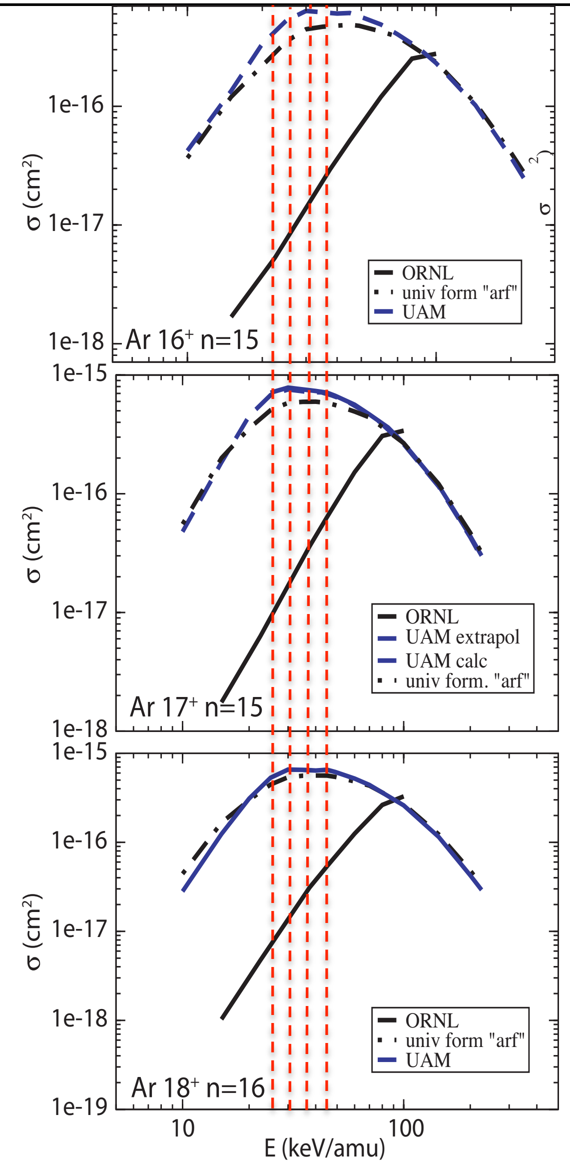
Experimental Validation of Ar CX cross sections

Motivation

- Ar used for radiation control and impurity transport experiments in fusion plasmas
- Ar charge exchange cross-sections from ORNL, ADAS scaling formula, and University Madrid differ by order of magnitude!
- Obtain experimental verification of correct calculation through comparison to X-ray data

Cross-sections differ by order of magnitude

- UAM (Madrid) data and ADAS universal formula cross-section order of magnitude larger than ORNL
- Differences are energy dependent
- AUG NBI can sample significant portion of energy spectrum

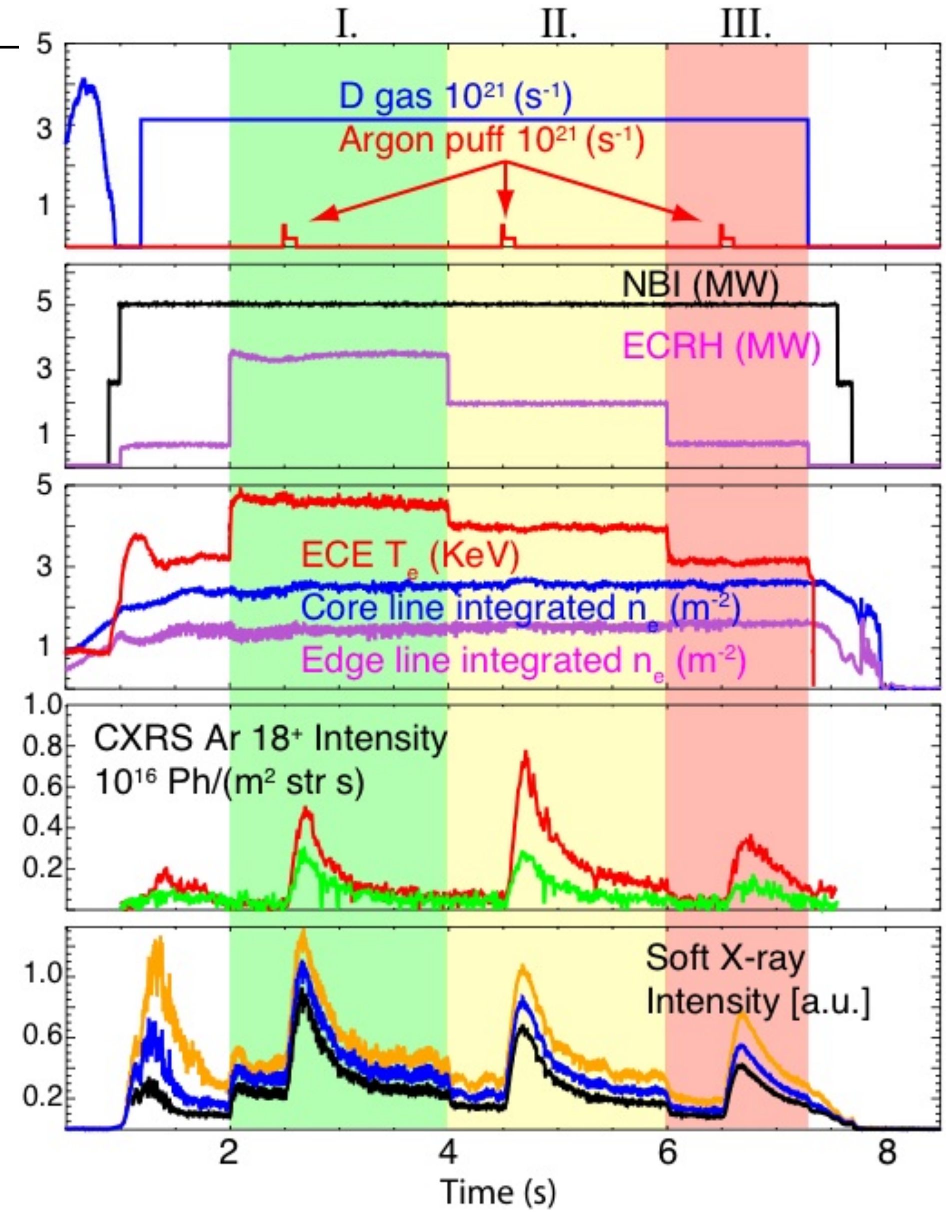


Experiment Setup

- 6 Discharges w/ 3 phases
  - ~5MW NBI ~3MW ECRH
  - ~5MW NBI ~2MW ECRH
  - ~5MW NBI ~1MW ECRH
- 1 Ar puff per phase
- 7 Ar CXRS lines
- Three optical heads:
  - ⇨CER – NBI I 60KeV (50KeV)
  - ⇨CFR – NBI I 60keV (50KeV)
  - ⇨CHR – NBI II 90KeV (75KeV)
- 2 Spectrometers:

Spec.1: CHR + CER (1 λ/discharge)

Spec. 2: CFR (1 λ/discharge)



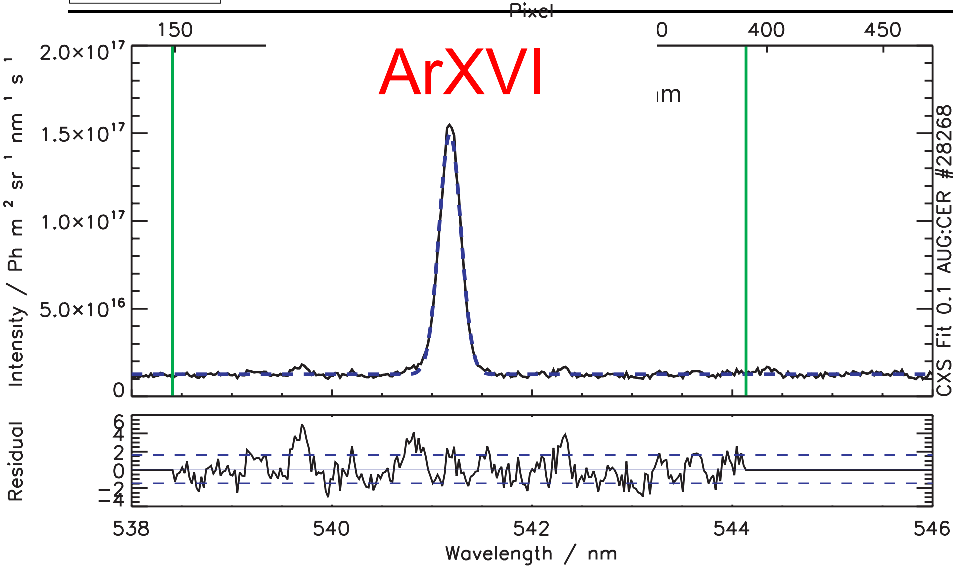
Summary of Shots

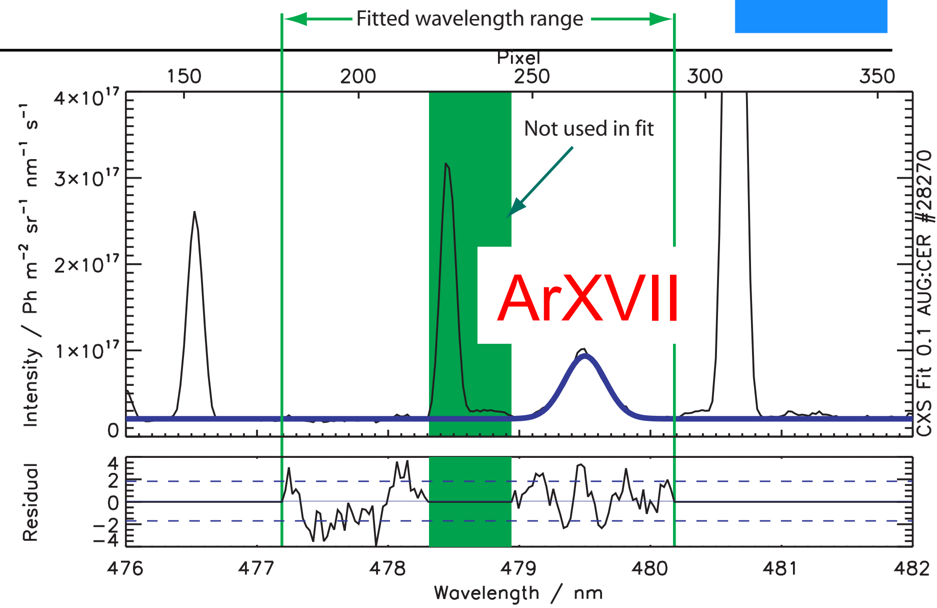
Discharge	Line CER (NBI 1)	Line CHR (NBI 2)	Line CFR (NBI 1)	NBI 1/NBI 2 (KeV)
28263	522.4nm (ArXVIII)	522.4nm (ArXVIII)	661.2nm (ArXVI)	90/60KeV
28265	585.7nm (ArXVII))	585.7nm (ArXVII))	479.4nm (ArXVII)	90/60KeV
28268	541.2nm (ArXVI)	541.2nm (ArXVI)	522.4nm (ArXVIII)	75/50KeV
28269	427.6nm (ArXVIII)	427.6nm (ArXVIII)	541.2nm (ArXVI)	75/50KeV
28270	479.4nm (ArXVII)	479.4nm (ArXVII)	630.3nm (ArXVIII)	75/50KeV
28271	541.2nm (ArXVI)	541.2nm (ArXVI)	522.4nm (ArXVIII)	90/60KeV

- Almost complete energy scans for best Ar line per charge state

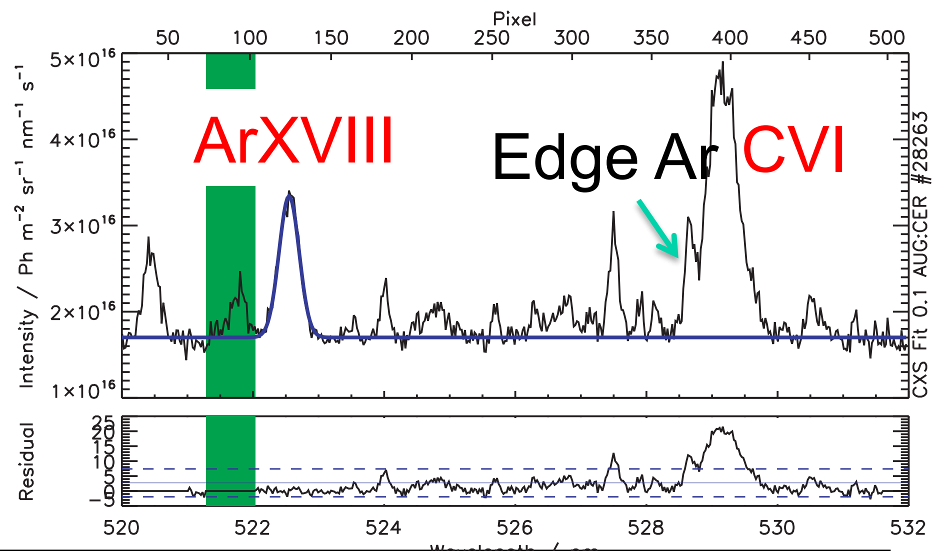
Ion	Line	90KeV	75KeV	60KeV	50KeV
Ar XVIII	630.3nm n=17-16	--------	--------	--------	Yes
Ar XVIII	522.4nm n=16-15	Yes	--------	Yes	Yes
Ar XVIII	427.6nm n=15-14	--------	No Sig	--------	No Sig
Ar XVII	585.7nm n=16-15	Un Rel	--------	Un Rel	--------
Ar XVII	479.4nm n=15-14	--------	Yes	Yes	Yes
Ar XVI	661.2nm n=16-15	--------	--------	Yes	--------
Ar XVI	541.2nm n=15-14	Yes	Yes	Yes	Yes

Best Ar CX Lines





- ArXVI 541.2nm: best Ar line. clean, isolated, easy to fit.
- ArXVII 479.4nm: reliable fit with sufficient signal, asymmetry to the blue when signal too low
- ArXVIII 522.4nm: can measure C and Ar simultaneously – note argon disturbs C measurement

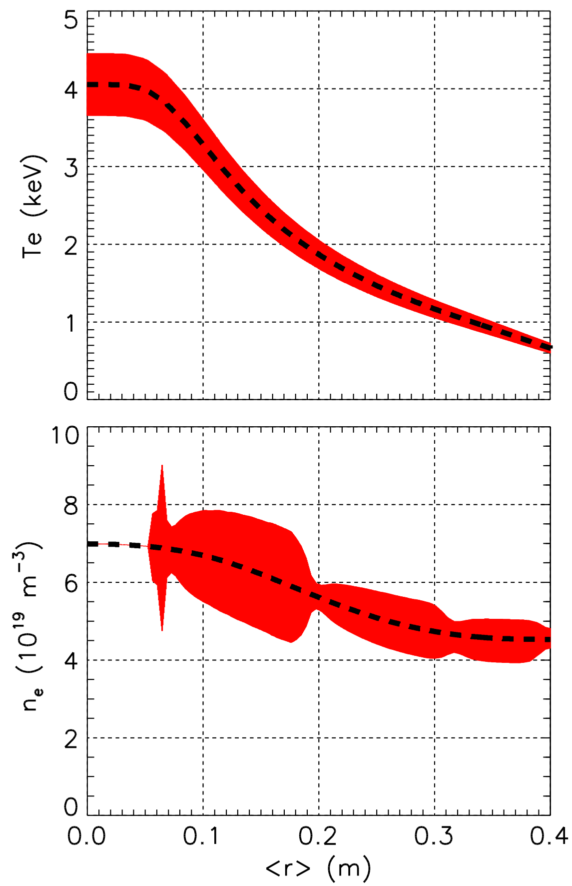


Ar Density from Soft X-Ray (SXR)

- SXR density measurement:
  - Local experimental SXR emissivity (background subtracted & Abel-inverted)
  - Electron density
  - Fractional abundance f_Z
  - SXR filtered photon emissivity rate coefficients k_z

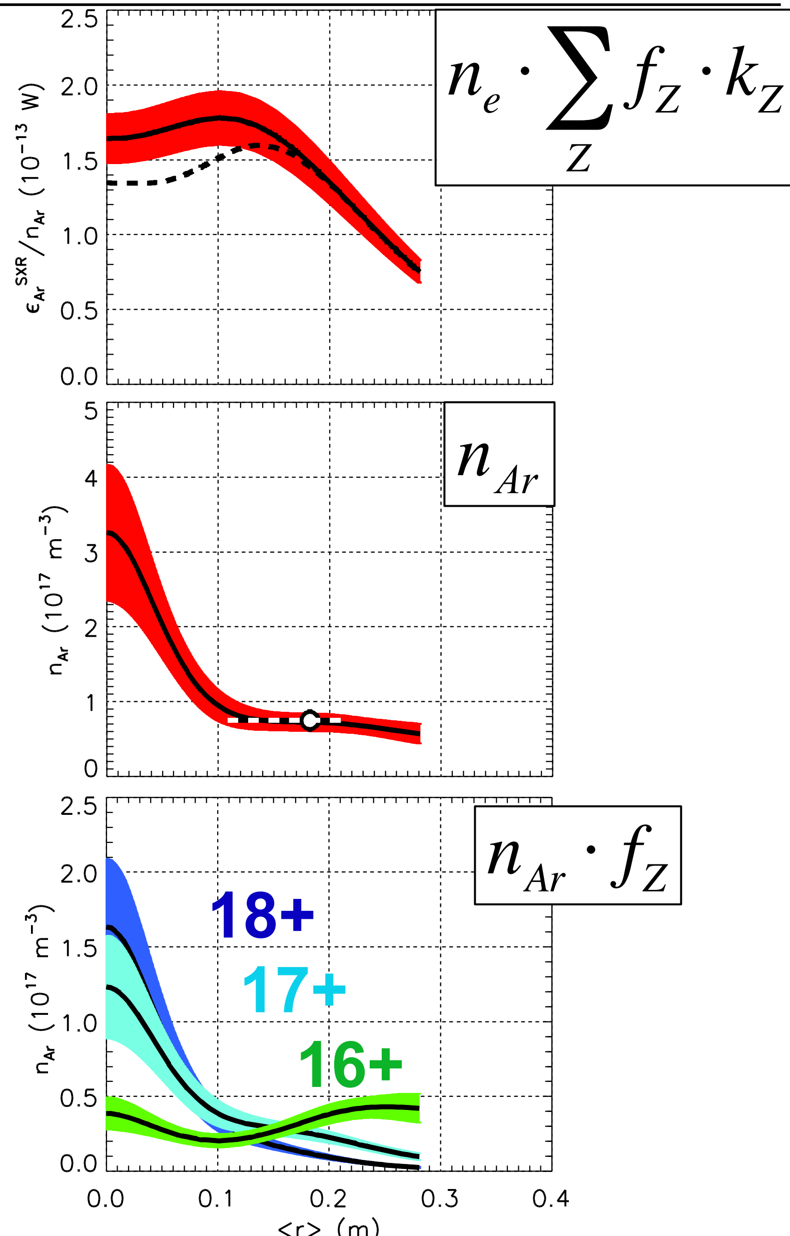
  → The denominator is evaluated using experimental n_e and T_e and calculating the ionization equilibrium assuming a standard set of transport coefficients

$$n_{imp} = \frac{4\pi}{h\nu} \frac{\varepsilon_{SXR}^{imp}}{n_e \cdot \sum_Z f_Z \cdot k_Z}$$

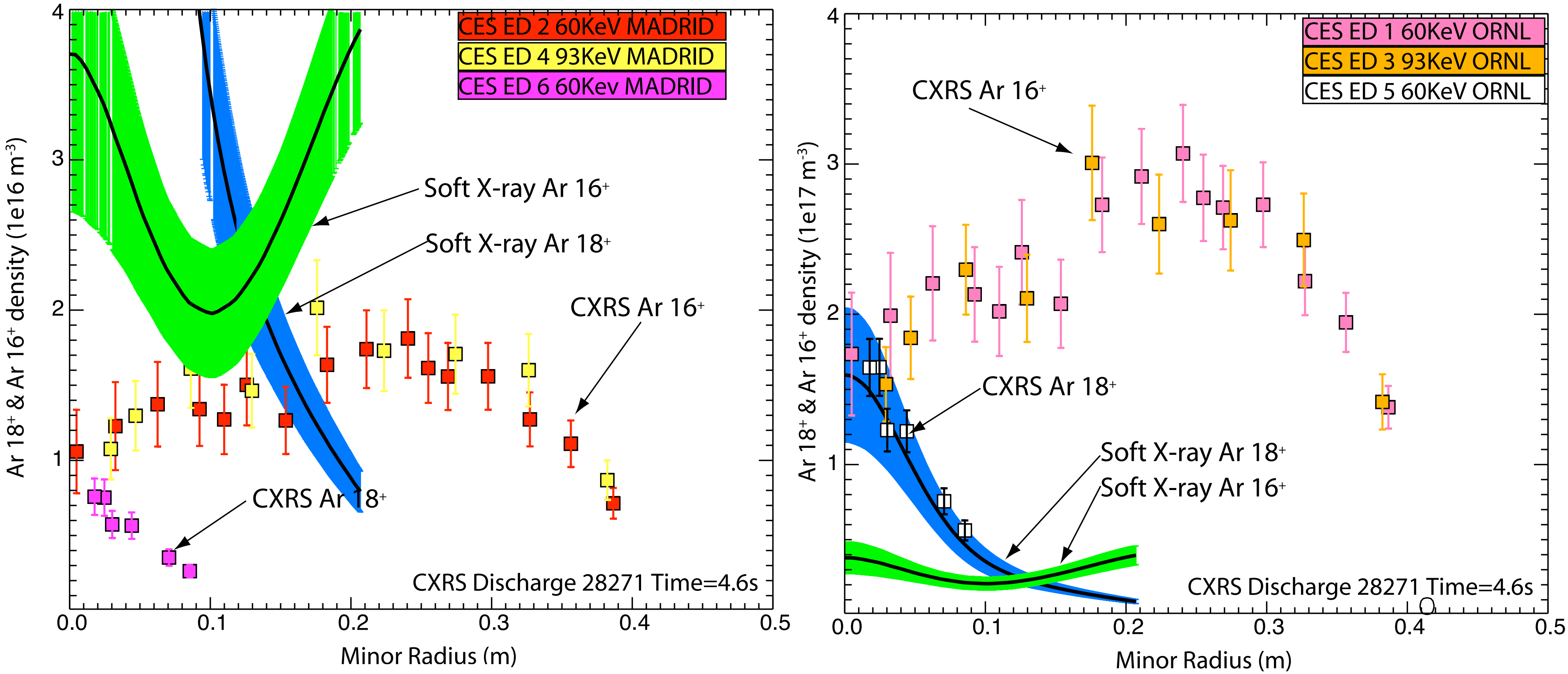


Ar Density from Soft X-Ray (SXR)

- SXR normalized emissivity (dashed = using local ionization eq.)
- Total Ar density (point with error bar = passive spectroscopic measurement of Ar^{16+} resonance lines)
- Ar density of 16+ → 18+ (fractional abundance includes transport)



Result



something is wrong with the ionisation balance … ➔ work in progress

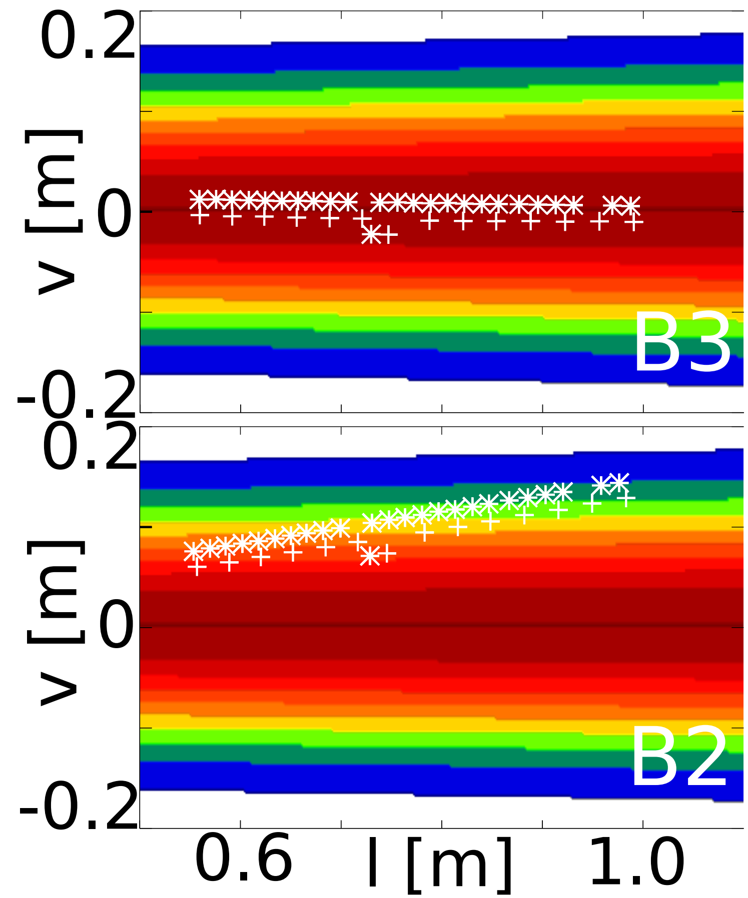
Impurity Densities from CXRS and Beam Emission Spectroscopy

Experiment Setup

- 60keV beams from NBI I
- 25 lines-of-sight (LOS) for CXRS and 14 LOS for BES
- LOS aligned to centre of beam 3
- vertical separation ≈1.6cm
- **Boron: n=7-6 transition at 494.7 nm**

- H-Mode discharge with P_{NBI}=5 MW, P_{ECRH}=0.7 MW, medium density $6 \times 10^{19} m^{-3}$
- beam blips (200ms) – active beam off for 100ms and replaced by beam of NBI II to have constant power

Cross-section of beam density and lines-of-sight (+ = BES, * = CXRS)



Beam Emission Spectrum

- Doppler effect

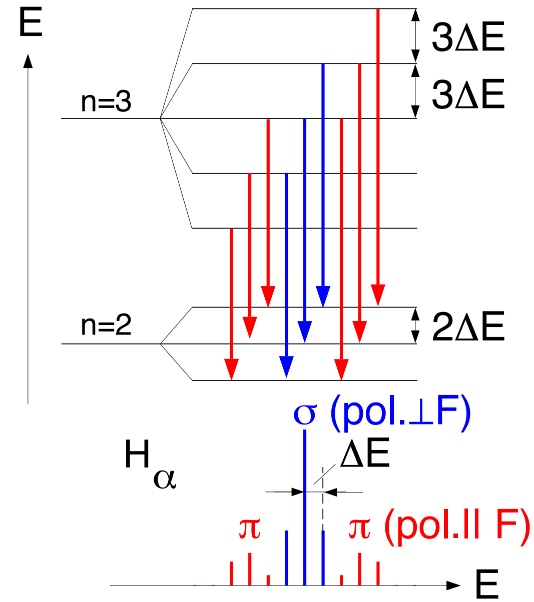
$$\Delta\lambda_{dop} = \lambda_0 \frac{v}{c}\cos\vartheta$$

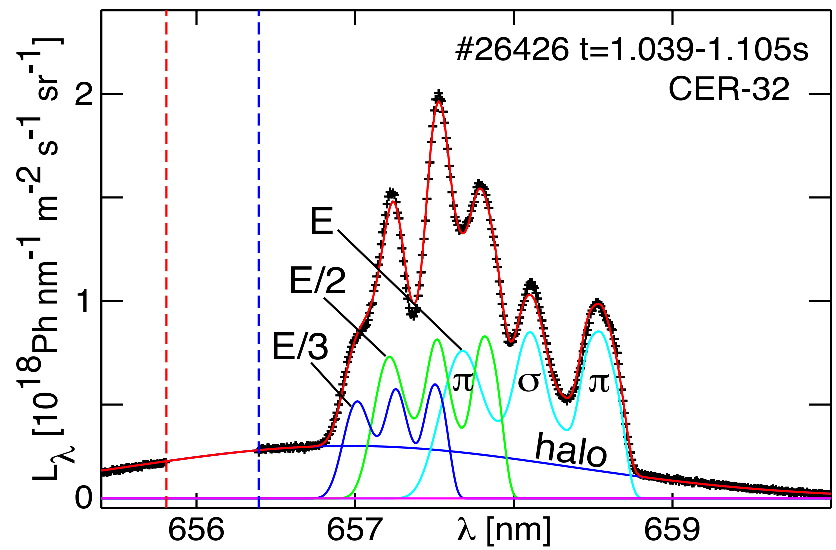
- motional Stark splitting due to electric field F in the rest frame of the beam atoms

$$\Delta\lambda_{\mathrm{MSE}} = 2.76\times10^{-2}\,k\left|\vec{v}\times\vec{B}\right|\left[\frac{\mathrm{MV}}{\mathrm{m}}\right]$$

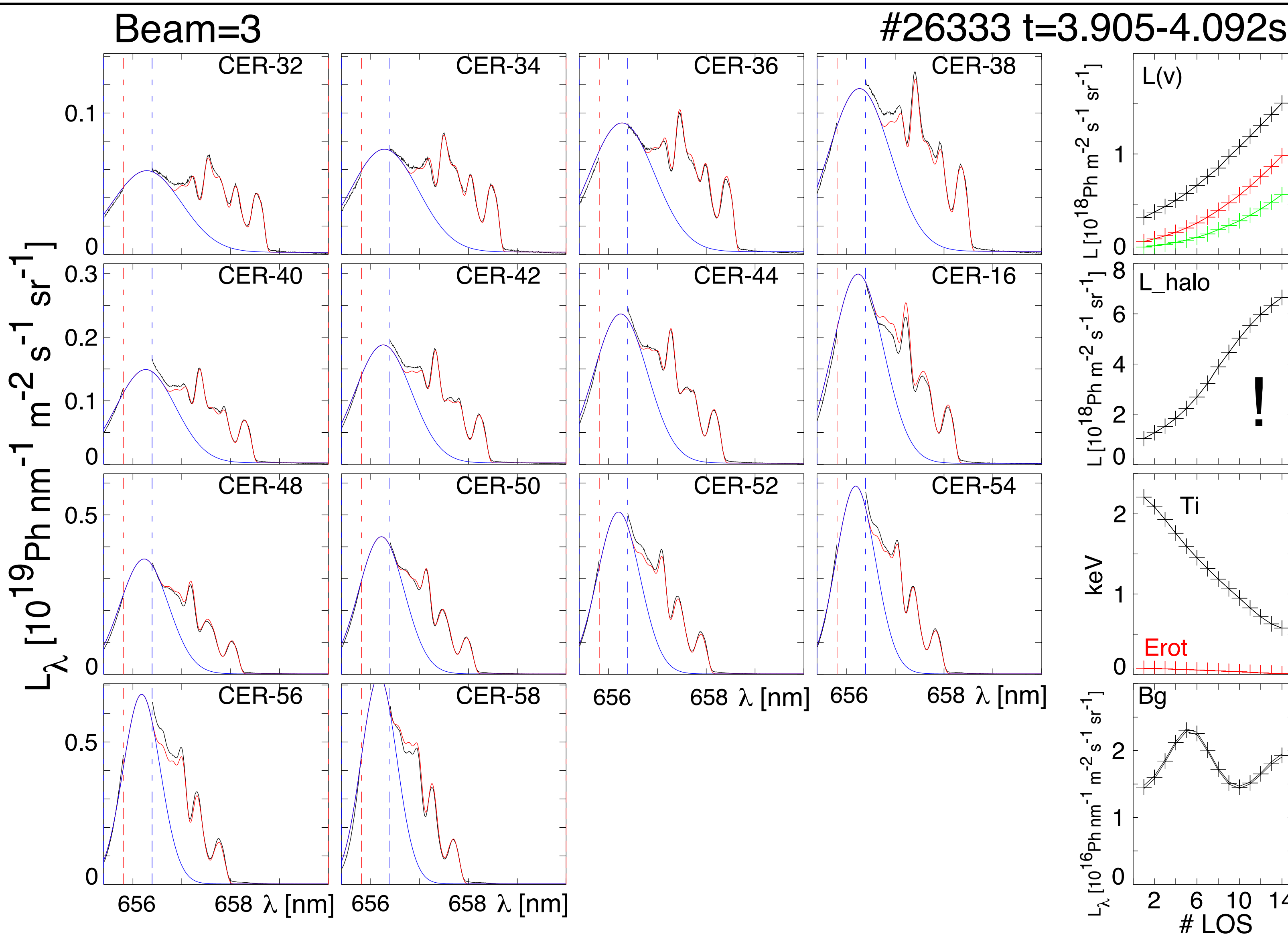
$$k = -4,-3,\ldots,4$$

- beam emission spectrum on top of halo emission (shifted Gaussian) – here for a case with high T_i





Combined Fit of Spectra on all LOS

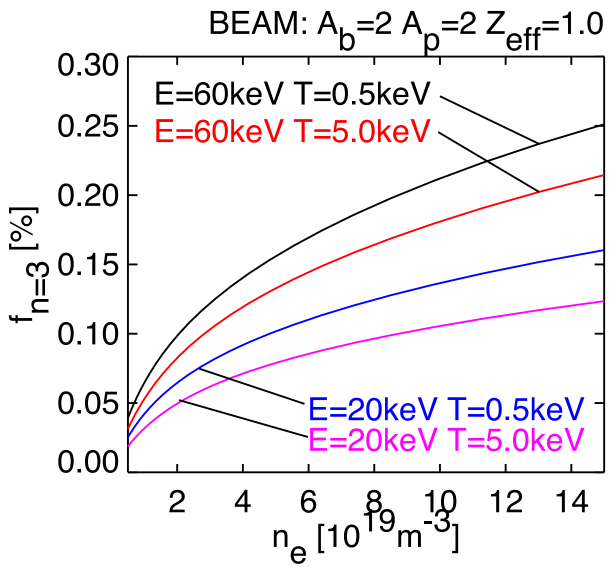


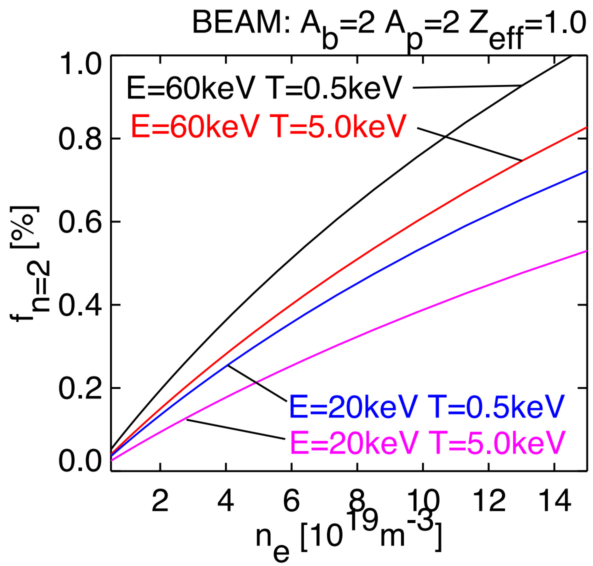
D-densities along CXRS LOS from Dα

setup CR models (cross-section data from Janev and ADAS) to calculate

- **excited state population of D in beam**
- beam stopping coefficients

- excited state population of D in halo
- halo production and stopping coefficients
- ratio of halo to beam particles





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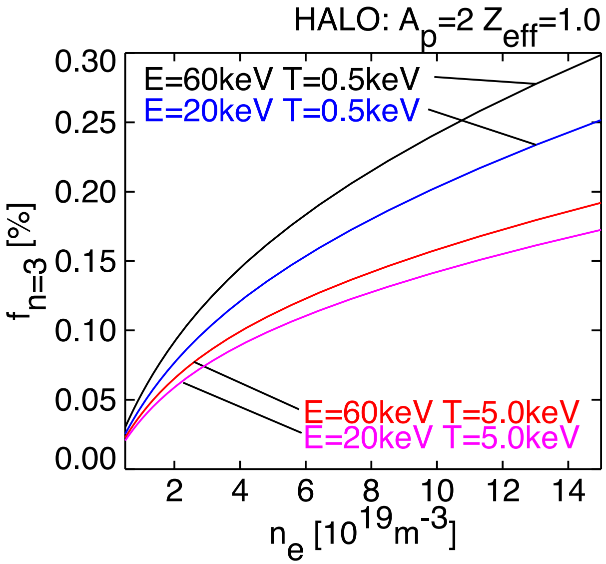

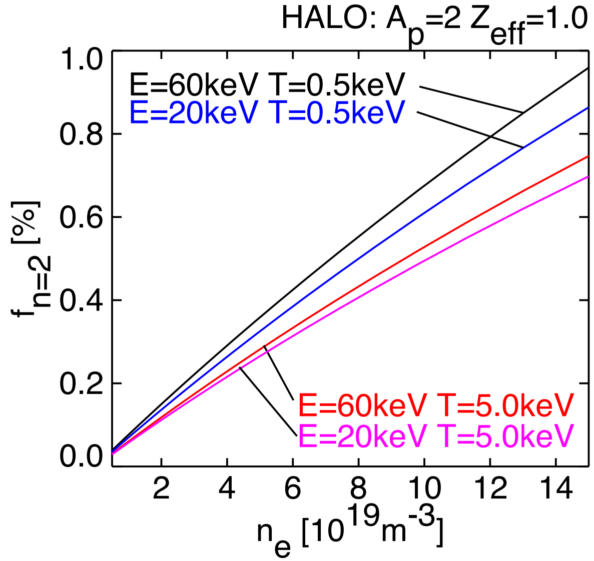

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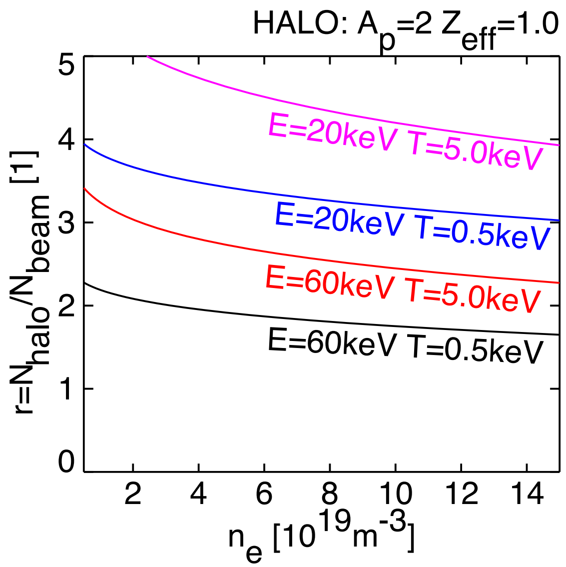
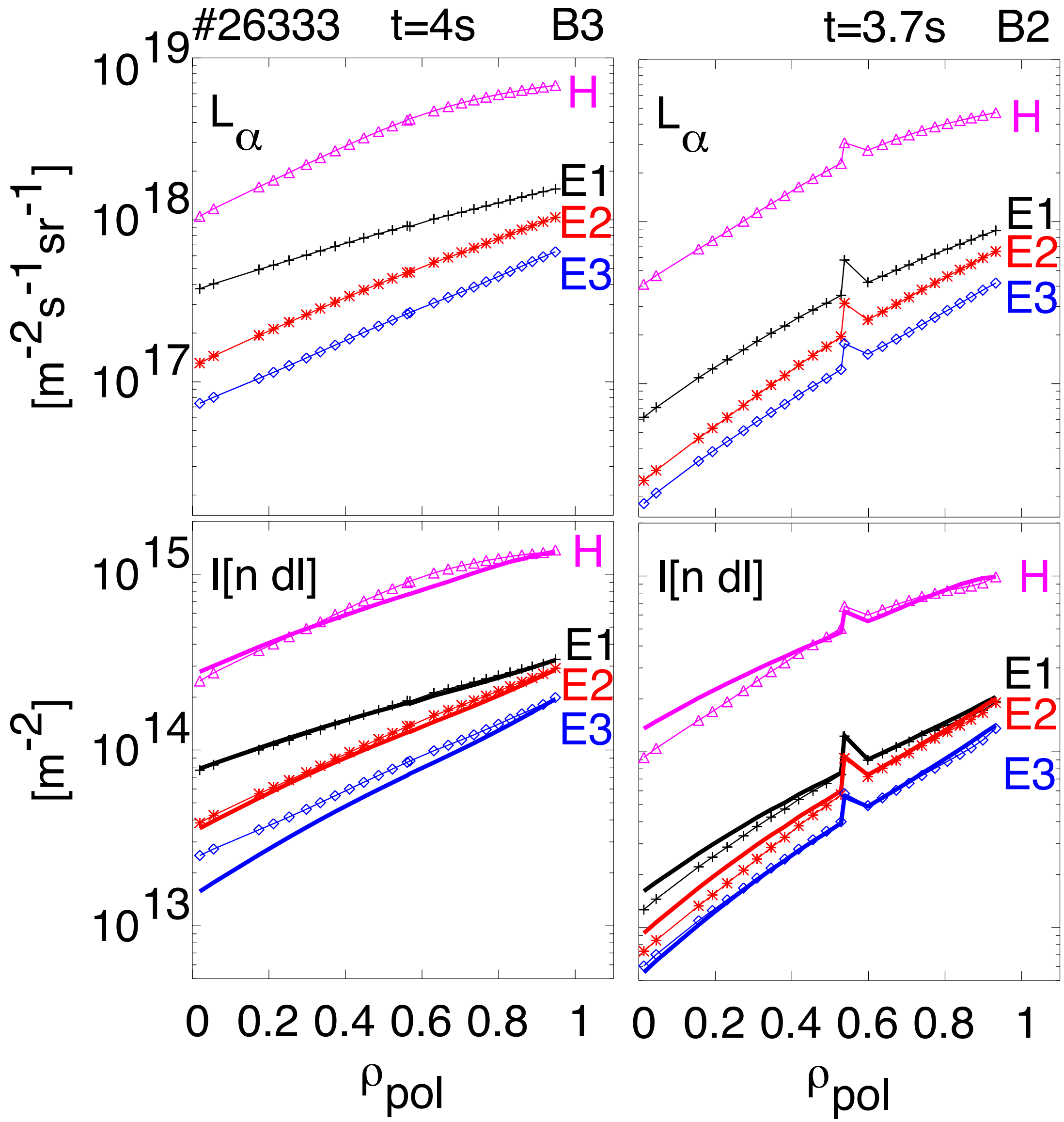


D-densities along CXRS LOS from Dα

- halo radiance and density dominant
- good agreement with calculated beam and halo density distribution

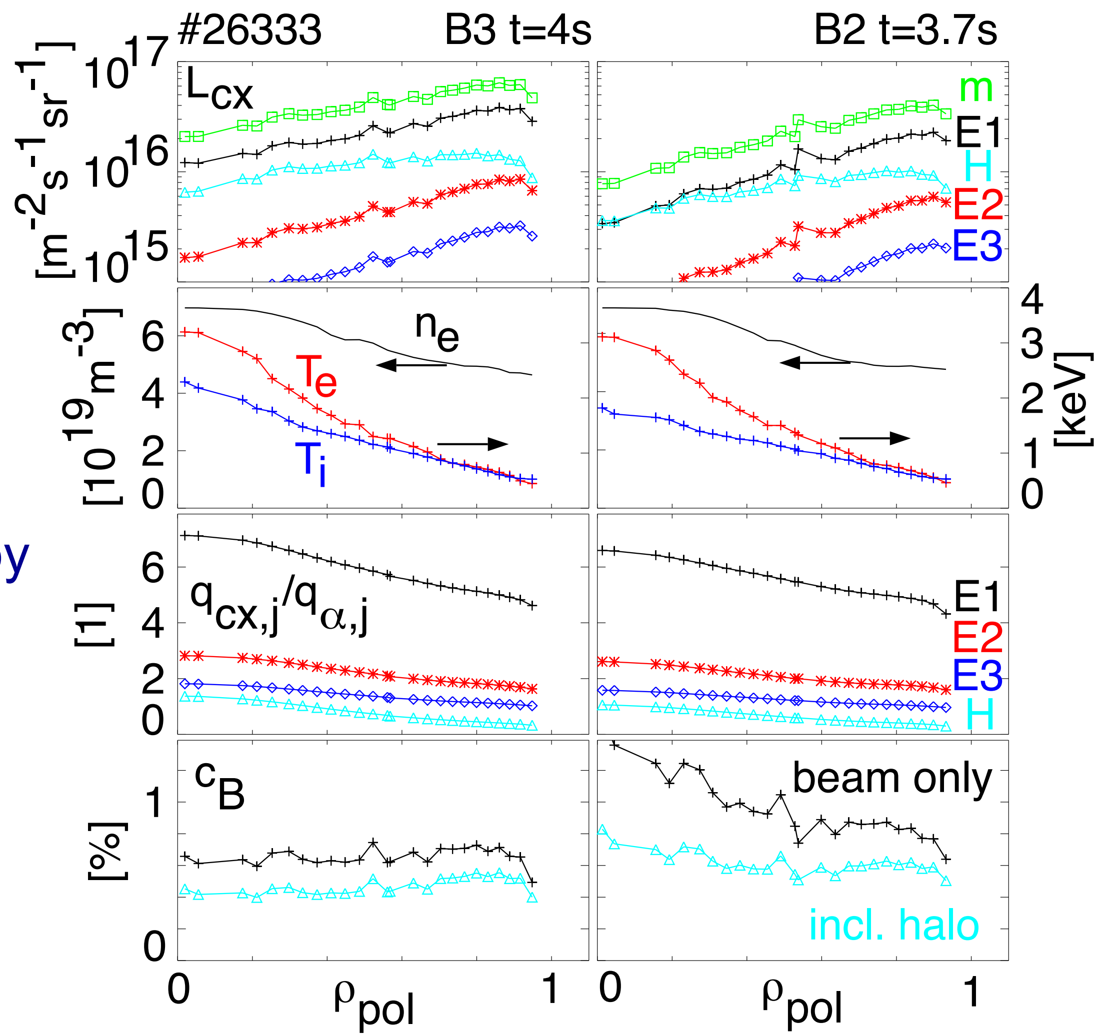


Boron Concentrations

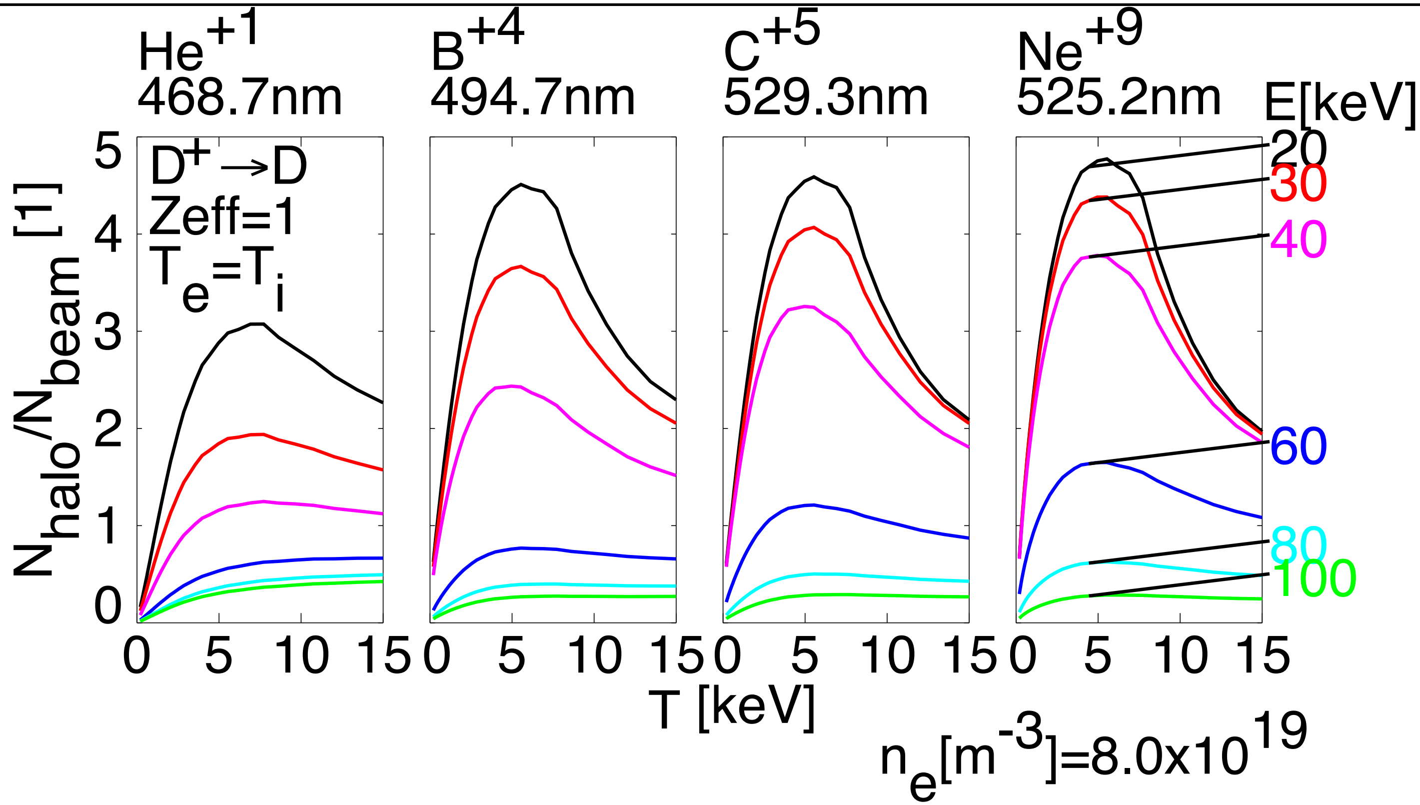
- radiance of impurity line

$$L_{cx} = c_{imp}\left[\sum_j L_{\alpha,j}\frac{q_{cx,j}}{q_{\alpha,j}} + L_\alpha^h \frac{\sum_j f_j q_{cx,j}^h}{\sum_j f_j q_{\alpha,j}^h}\right]$$

- boron signal mainly produced by beam species with full energy <u>and halo</u>
- contribution per halo neutral small but halo neutrals by far dominant species
- halo charge transfer only from excited atoms



Halo contribution for other popular lines



- ratio of photons induced by halo N_{halo} to photons induced by beam N_{beam}
- largest for low energy beams due to large halo production by CX
- at low T only excited halo neutrals contribute at large T also charge transfer from ground state (mainly for He, less for heavier elements)

Conclusion

- Atomic data for calculation of excited state population of D are sufficiently good to get extra information on the beam attenuation from beam emission spectroscopy.

- A combined treatment of BES data and beam attenuation calculations will be the optimum solution for future analysis tools.

- CX excited impurity radiation from halo neutrals is an important contribution to the *active* CXRS signal.