In-Out B^{5+} Impurity Asymmetries in the Pedestal Region on Alcator C-Mod

R. M Churchill[1], B. Lipschultz[1], S. Lisgo[2], D. Stotler[3]

[1] MIT Plasma Science and Fusion Center
[2] ITER Organization
[3] Princeton Plasma Physics Laboratory (PPPL)

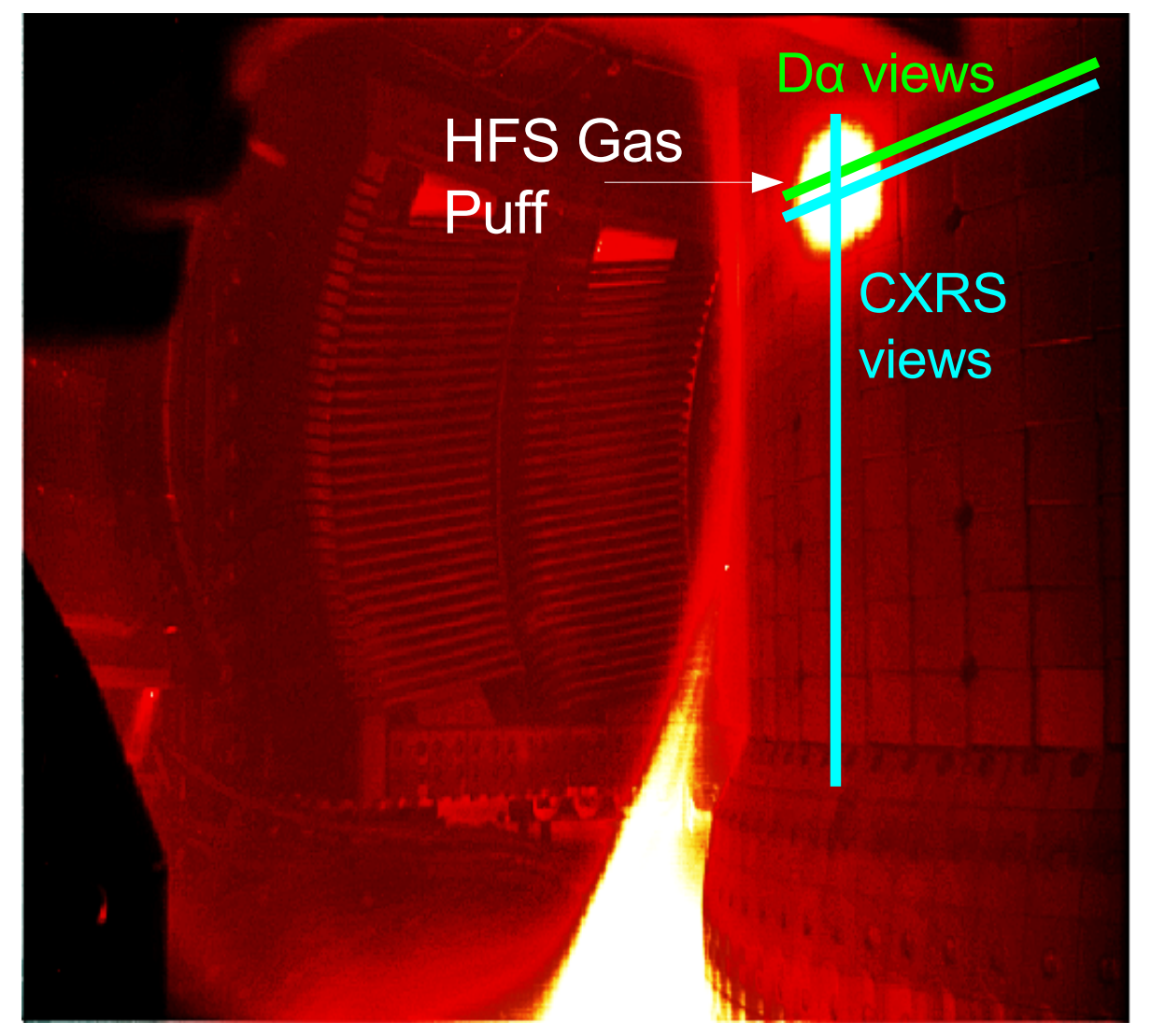
Introduction

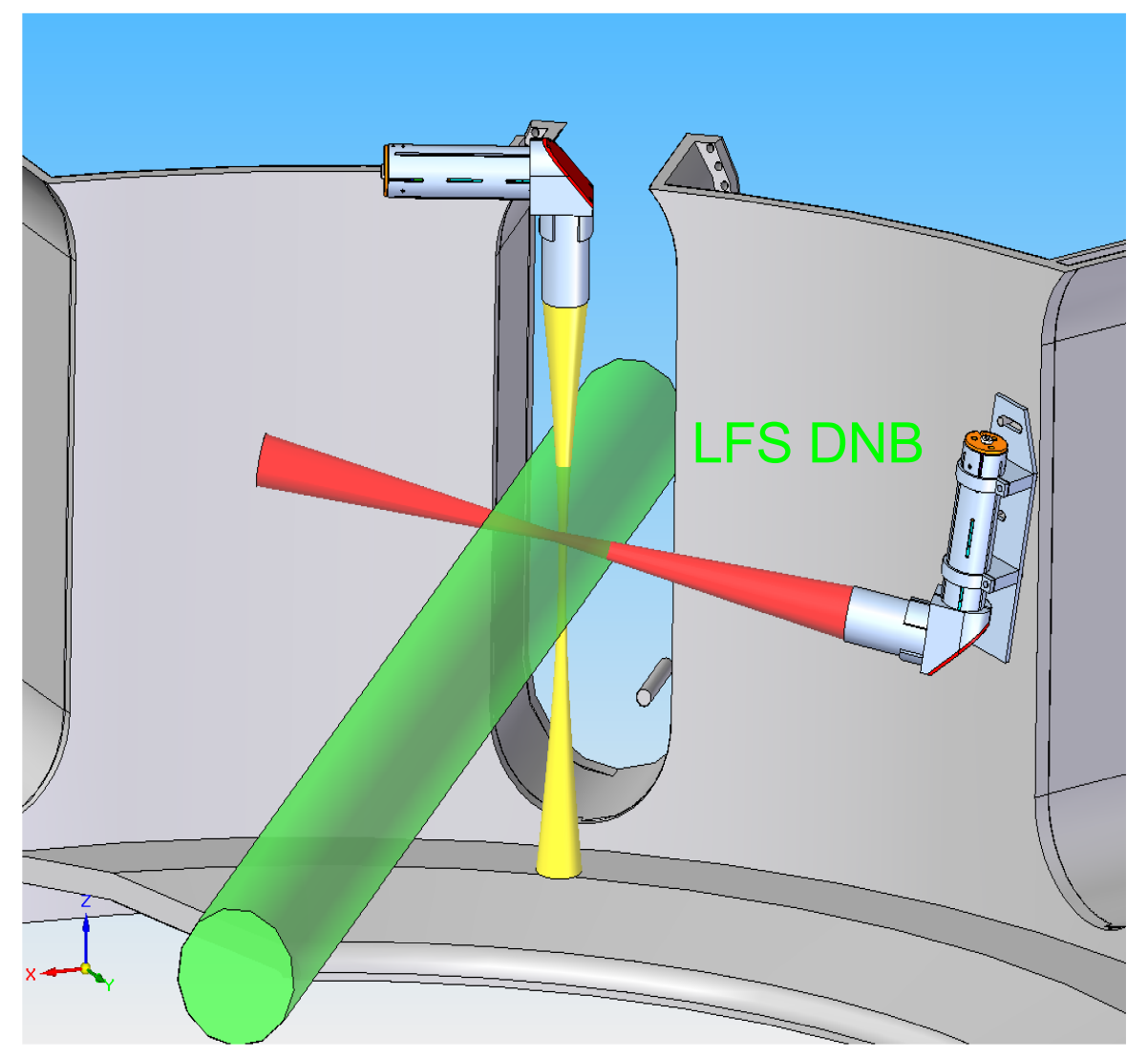
- Recent findings on Alcator C-Mod imply a poloidal impurity density asymmetry in the pedestal region [1], inferred from boron (B5+) velocity measurements at the inner- and outer-edge combined with neoclassical transport theory.
- To confirm these findings, the direct measurement of the boron density was made at the inner-wall and outer-wall pedestal using simultaneous spectroscopic views of boron charge exchange recombination spectroscopy (CXRS) and Balmer-α emission (Dα)
- Detailed neutral transport modeling is required to calculate the neutral density along the optical lines of sight.
- Boron density from inner-wall shows an increase over boron density from outer-wall

Diagnostics

- CXRS (BV n=7-6, λ=494.467 nm) toroidal and poloidal in-vessel optics focused at outer- and inner-wall mid-plane (LFS and HFS)
- Dα (n=3-2, λ=656.3 nm) optics focused at HFS mid-plane, directly next to CXRS views
- CXRS measured with Volume Phase Holograph (VPH) grating spectrometer (f/1.8) and Photonmax CCD cameras (5ms time resolution)
- Dα measured with fast diodes (1us time resolution)
- Localization provided by input neutral sources: at the LFS a 50kV, 6A hydrogen Diagnostic Neutral Beam (DNB), at the HFS a 4 torr-L, room temperature deuterium gas puff through a 1mm capillary

Views	Neutral Source	Average r/a	Line-of-sight angle w/ toroidal direction (deg)	Spot Size (mm)	Radial Resolution (mm)
LFS CXRS Poloidal	DNB & Gas Puff	0.76 - 1.03	-90	2.0	2.4
LFS CXRS Toroidal	DNB	0.77 - 1.03	+172.4	2.2	2.7
HFS CXRS Poloidal	Gas Puff	0.92 - 1.03	+90	3.8	4.0
HFS CXRS Toroidal	Gas Puff	0.92 - 1.03	-10	3.8	4.0
HFS Dα Toroidal	Gas Puff	0.92 - 1.03	-10	3.8	4.0





Previous Results

Marr et. al. [1] used the CXRS diagnostics (minus the inner-wall poloidal optics, which were installed FY2009) just described to measure velocities and apply them to the neoclassical velocity equation:

$$\vec{V}=\frac{k_z(\psi)}{n_z(r,\theta)}\vec{B}+\omega(\psi)R^2\nabla\phi$$

The ratio of inner- (low-field side "L") and outer- (high field side "H") wall boron impurity density can be then calculated using velocities and magnetic geometry:

$$\frac{n_{Z,H}}{n_{Z,L}}=\frac{V_{Z,\theta,L}\dfrac{B_{\parallel,H}}{B_{\theta,L}}}{V_{Z,\parallel,H}-\dfrac{R_H}{R_L}\cos(\zeta)\left[V_{Z,\theta,L}\dfrac{B_{\phi,L}}{B_{\theta,L}}-V_{Z,\phi,L}\right]}$$

Inferred **inner-wall densities were up to 2-3 times higher than outer-wall densities** in the narrow region where the outer-wall poloidal velocity peaks.

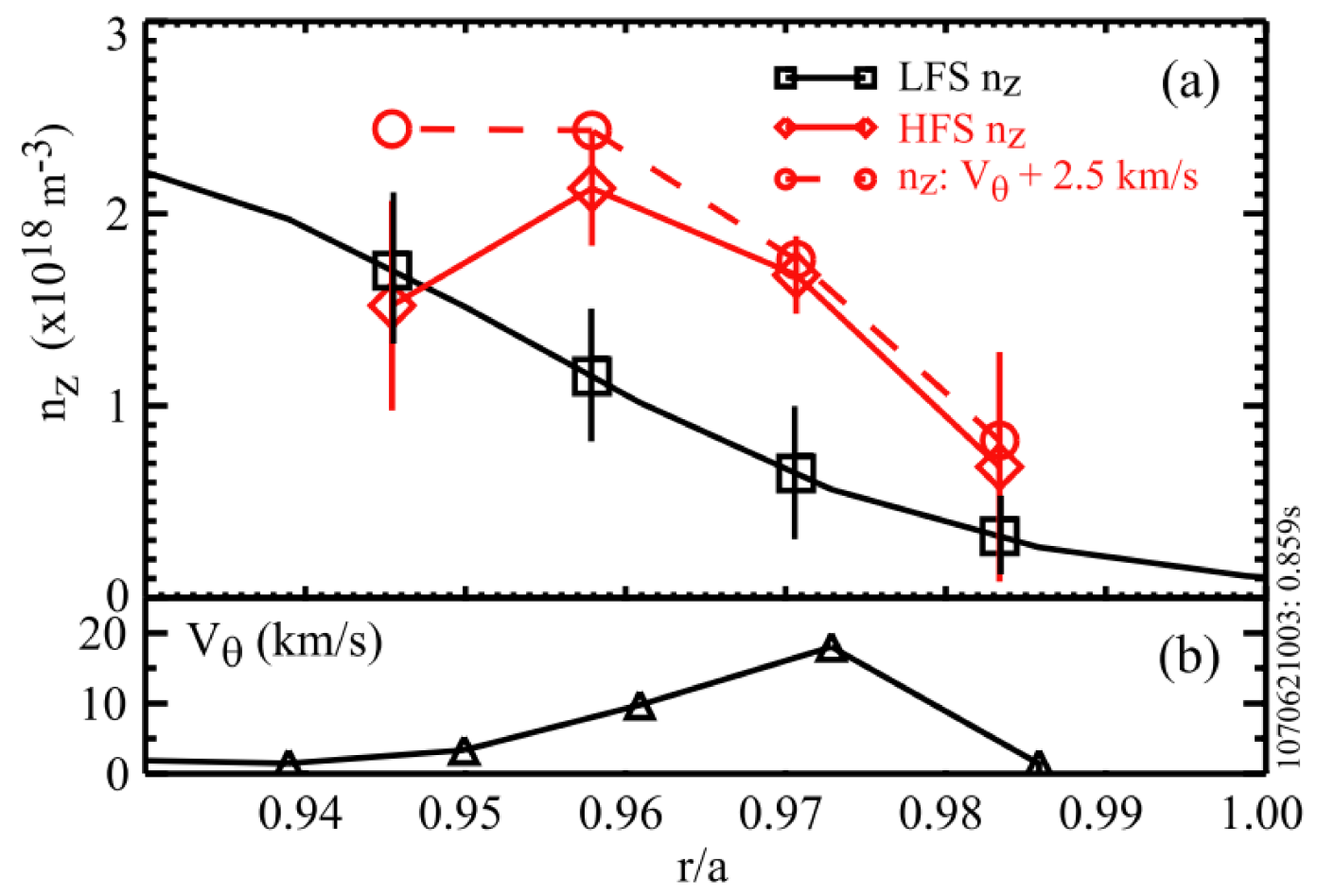


Figure 8 from [1]

Neutral Modeling

- Boron density equation
  - Requires
    - Measured boron line-integrated emissivity (brightness)
    - CX Rate coefficient for B^{5+}+D ("sigmav")
    - Neutral density
  - Assumes boron density is approximately constant over the line-of-sight (LOS) integral:

$$I_{CX}^{\lambda}=\frac{1}{4\pi}\sum_i\int_{LOS}\langle\sigma v\rangle_i^{\lambda}n_B n_{D,i}\,dl \quad\rightarrow\quad n_B=\frac{4\pi I_{CX}^{\lambda}}{\sum_i\int_{LOS}\langle\sigma v\rangle_i^{\lambda}n_{D,i}\,dl}$$

- Neutral density and rate coefficient from DNB calculated with beam-collisonal code [2]
- Neutral density and rate coefficient from gas puff require neutral transport codes to fully characterize.

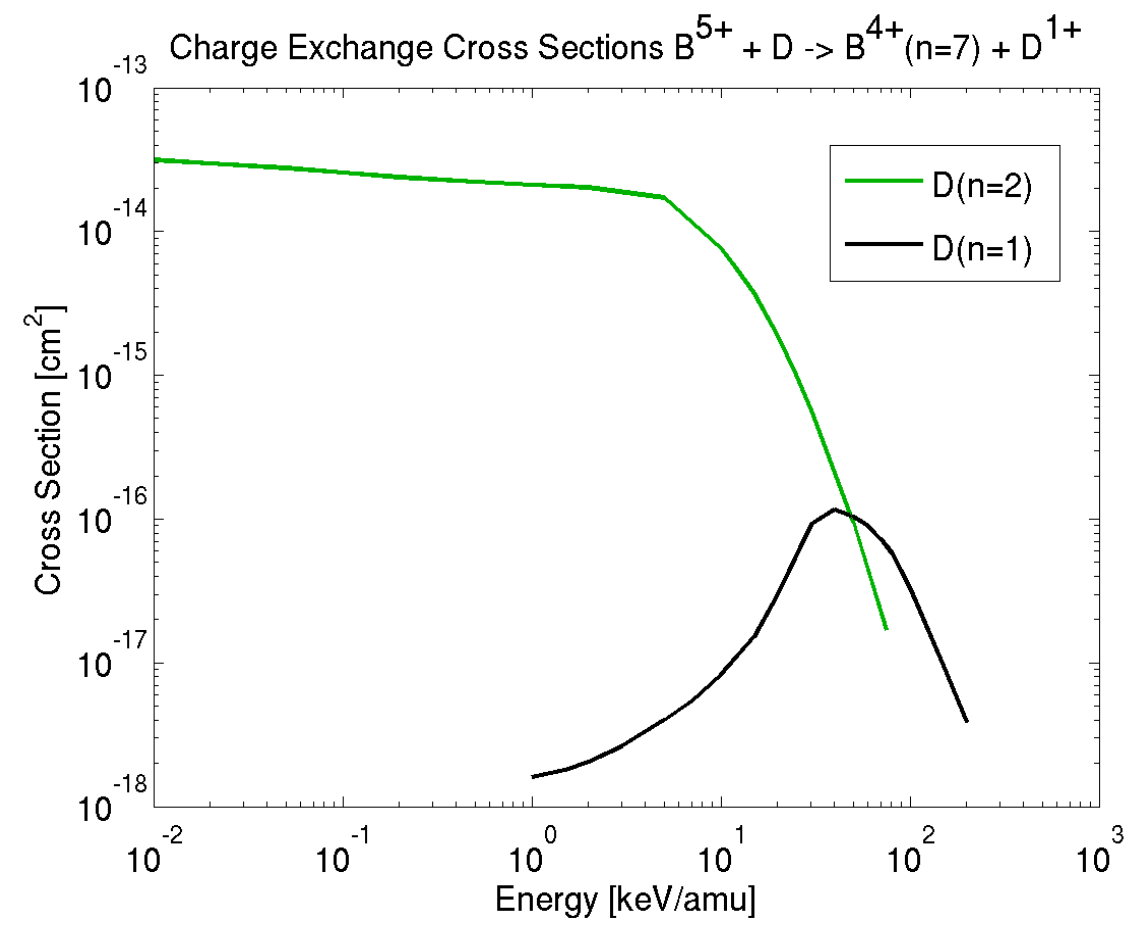
- Rate Coefficient equation
  - Gas puff neutrals penetrate into the plasma through multi-step processes of charge exchange and ionization. As a result, neutrals further into the plasma are thermalized.
  - Assuming neutrals are Maxwellian, but can have a different temperature from the plasma temperature, the thermal-thermal reaction rate is:

→ Requires thermal-thermal calculation

$$\langle\sigma v\rangle=\sqrt{\frac{8}{\pi m_{rel}}}\frac{1}{T_{eff}^{3/2}}\int_0^{\infty}\sigma(E)E\exp\left|\frac{-E}{T_{eff}}\right|dE$$

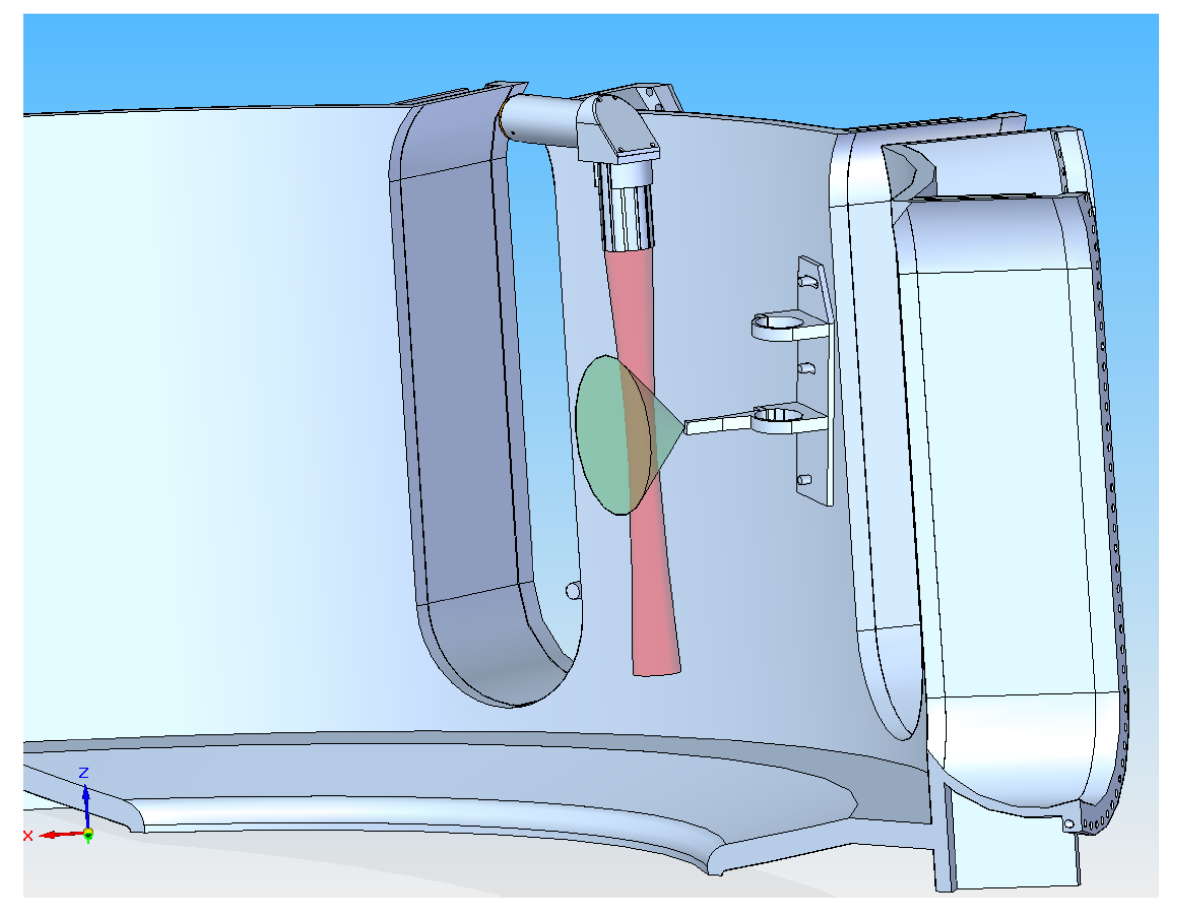
$$\text{where}\quad Teff=\frac{m_1T_2+m_2T_1}{m_1+m_2}\quad\text{and}\quad m_{rel}=\frac{m_1m_2}{m_1+m_2}$$

- CX Cross Section
  - For CX into the n=7 level of boron, at low energies the cross-section of CX with n=2 deuterium is ~10^6 larger than with ground state deuterium
  - n=2 deuterium density ~1/100 ground state neutral density
  - Only rate coefficient with D(n=2) important
  - Cross-section taken from ADAS [3]

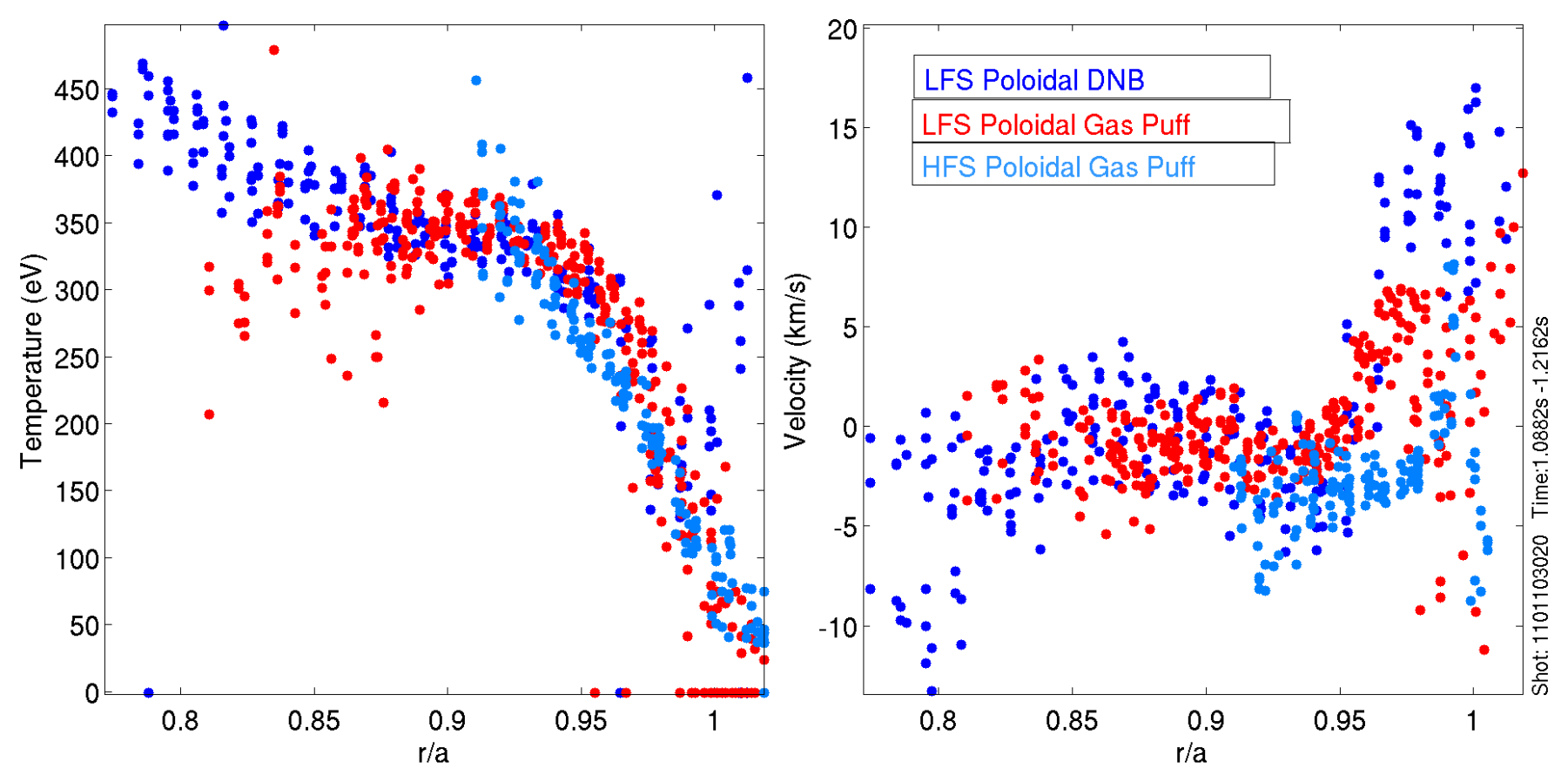


Outer-Wall Beam vs Gas Puff CXRS Comparison

- DNB and gas puff produces neutrals with very different energy distributions
  - Potential atomic physics effects on CXRS?
- Gas puff installed on OW to compare DNB vs gas puff CXRS



- Initial results promising, temperature and velocity measurements match closely
- Further neutral modeling needed to compare densities



- HFS poloidal velocity peak appears to be shifted out from that of the LFS, both the DNB based and gas puff based CXRS systems
- Combined with the toroidal viewing CXRS views, Er can be measured at the LFS and HFS

Neutral Transport Codes

KN1D

KN1D [3] is a kinetic neutral transport code, 2D in velocity space and 1D in space.

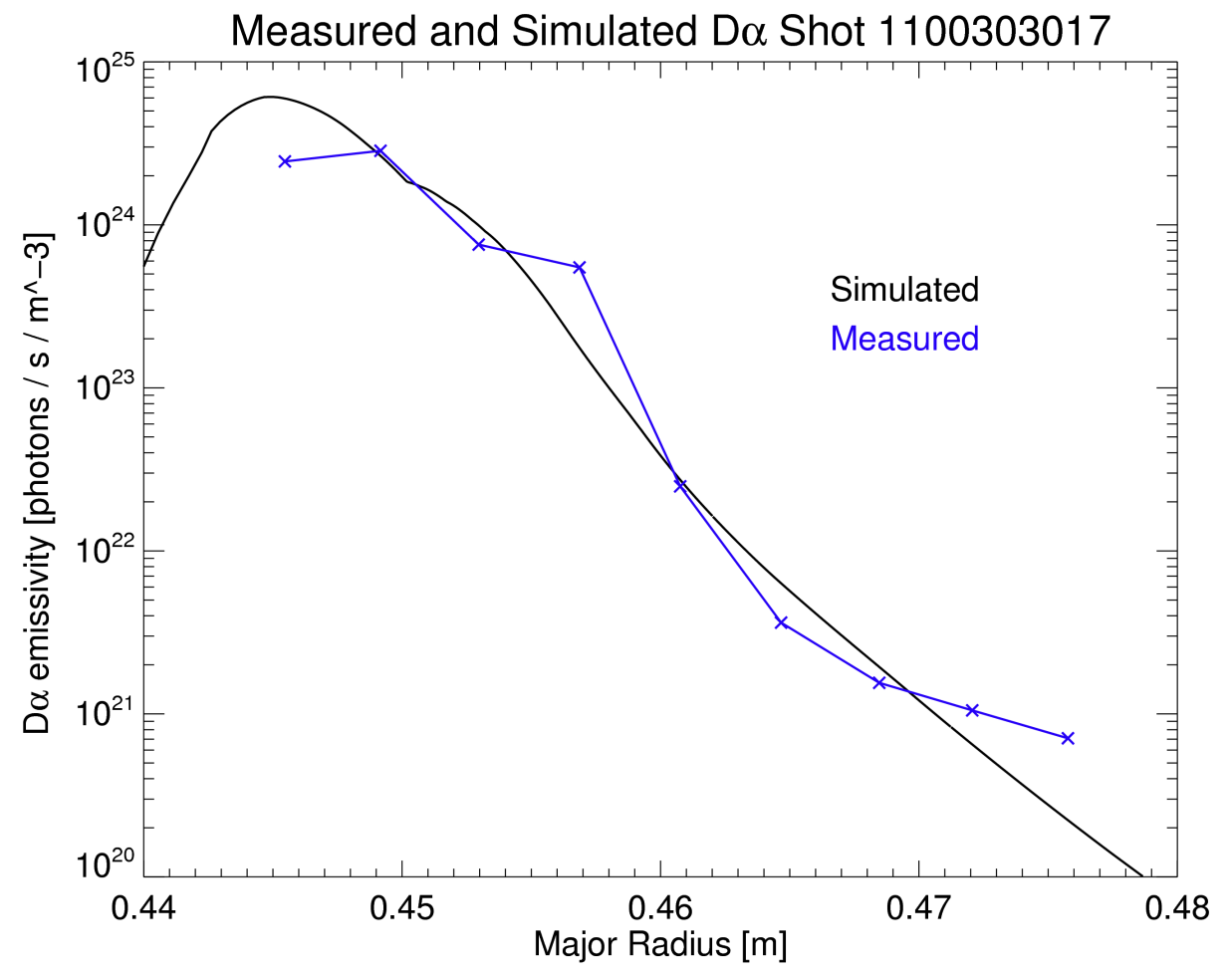
INPUTS

- Electron temperature Te (measured from Thomson)
- Electron density ne (measured from Thomson)
- Ion temperature Ti (measured from CXRS)
- Limiter geometry. For inner-wall, which doesn't have a limiter, assumed 1mm limiter region
- Neutral pressure at plasma edge

OUTPUTS

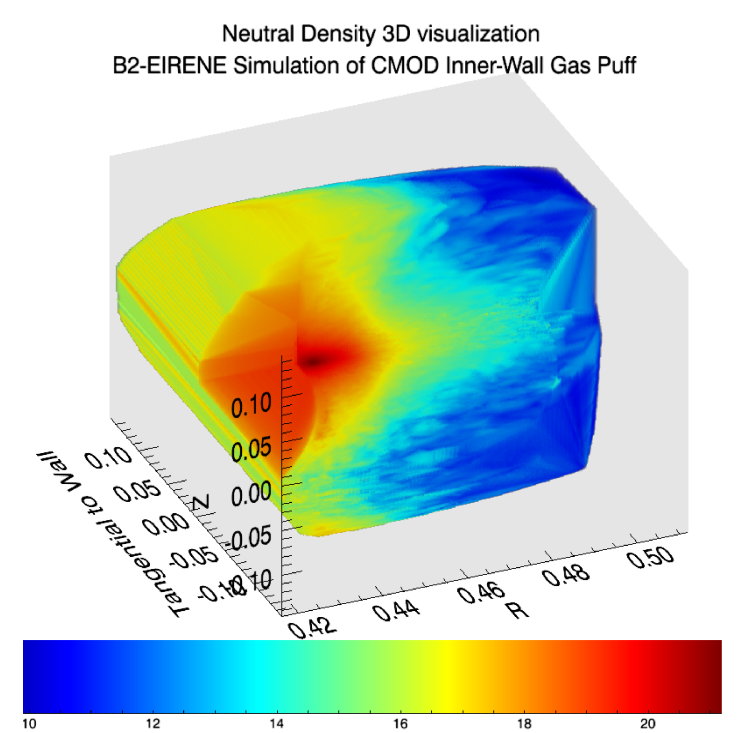
- 1D neutral density [m^-3]
- 1D neutral temperature [eV]
- 1D Balmer-alpha emissivity [photons/s/m^-3]

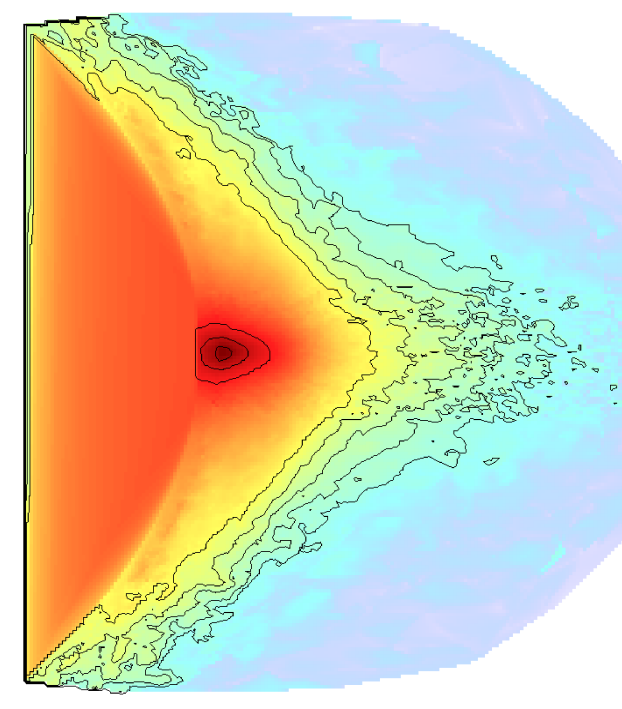
- KN1D input neutral edge pressure varied so to match KN1D output D-α emissivity with the measured line-integrated Dα emissivity
  - Required assumption about pathlength through the neutral gas cloud. Assumed the neutral cloud expanded with a cone half-angle of 45 degrees.



B2-EIRENE

B2-EIRENE[4] is a full 3D Monte Carlo neutral transport code. The same shot as the KN1D case was run in B2-EIRENE by Steve Lisgo at ITER.





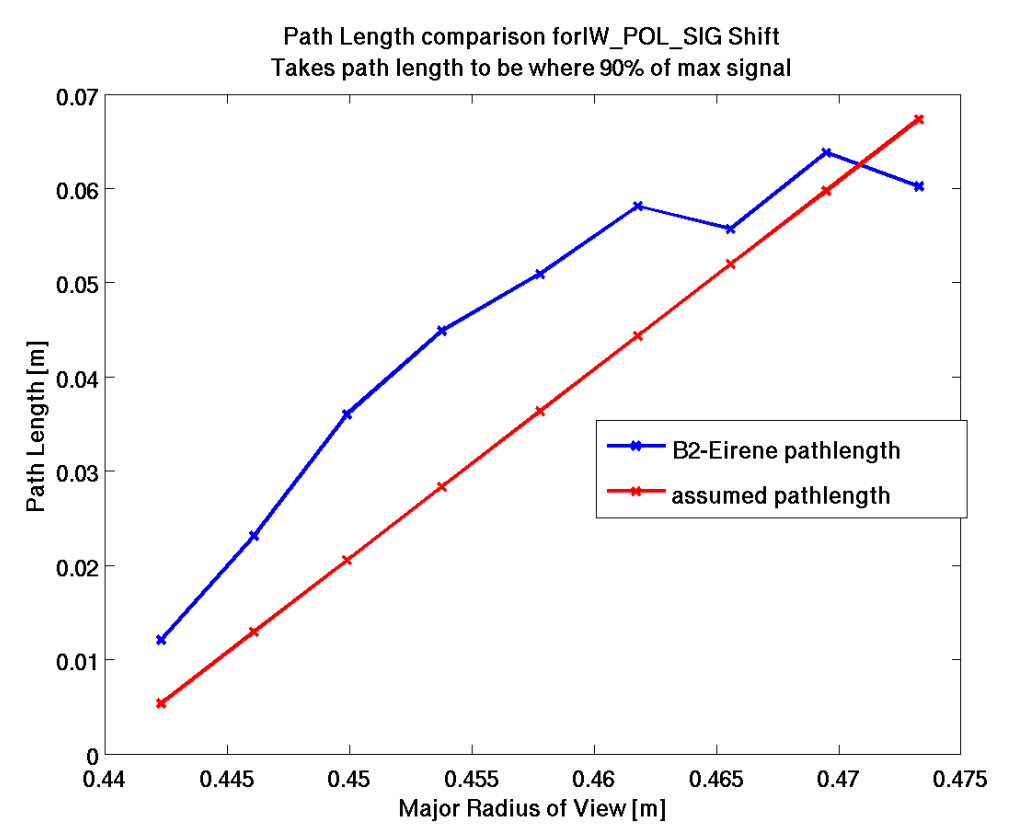
- 3D neutral density and average neutral energy was interpolated onto optical lines-of-sight using natural neighbor interpolation
- Statistics associated with Monte Carlo technique lead to noise on views further into the plasma

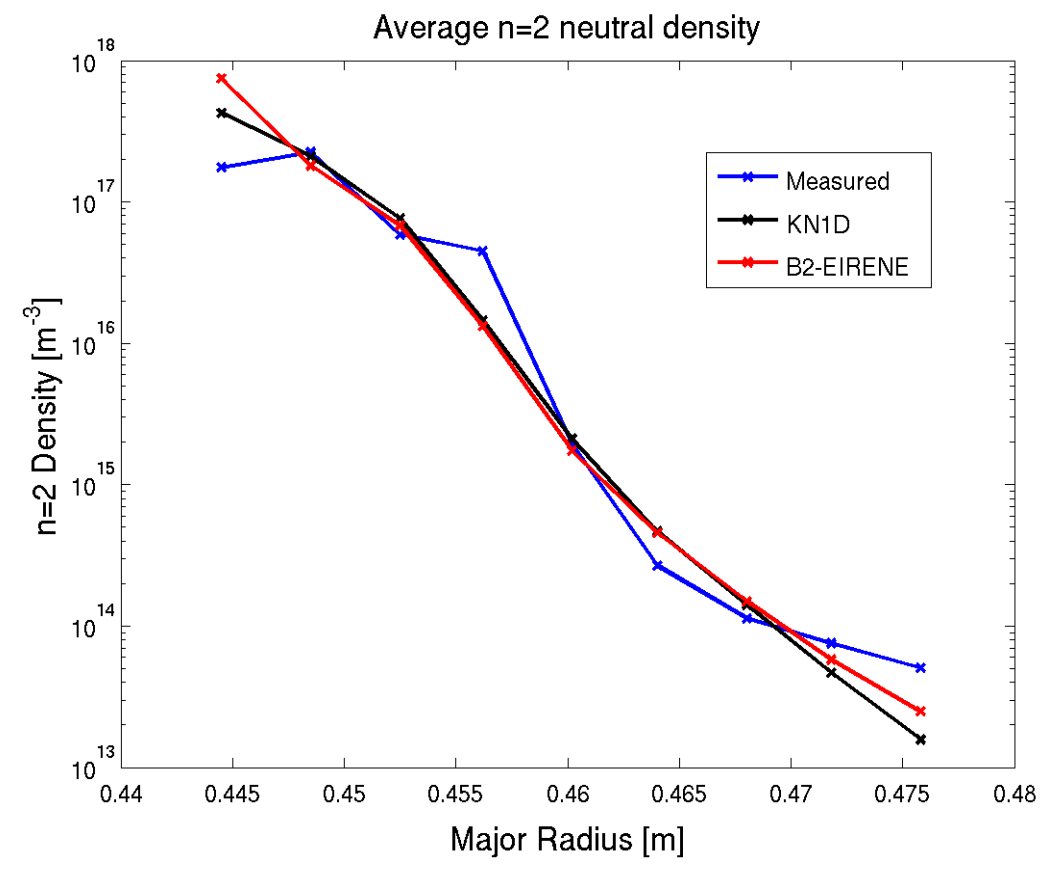
DEGAS 2

DEGAS 2 [5] is also a full 3D Monte Carlo neutral transport code, similar to B2-EIRENE. The same shot as the KN1D case was run in DEGAS 2 by Daren Stotler at PPPL.

RESULTS

- B2-EIRENE neutral density was averaged over a path length covering 90% of the signal. Comparison between this path length and the assumed path length show acceptable agreement.
- Good agreement was found between KN1D 1D neutral density profile, B2-EIRENE average neutral density profile over optical lines-of-sight, and neutral density using a Johnson-Hinnov collisional radiative model with measured Dα emissivity
- Initial DEGAS 2 showed good agreement between simulated and measured Dα brightness

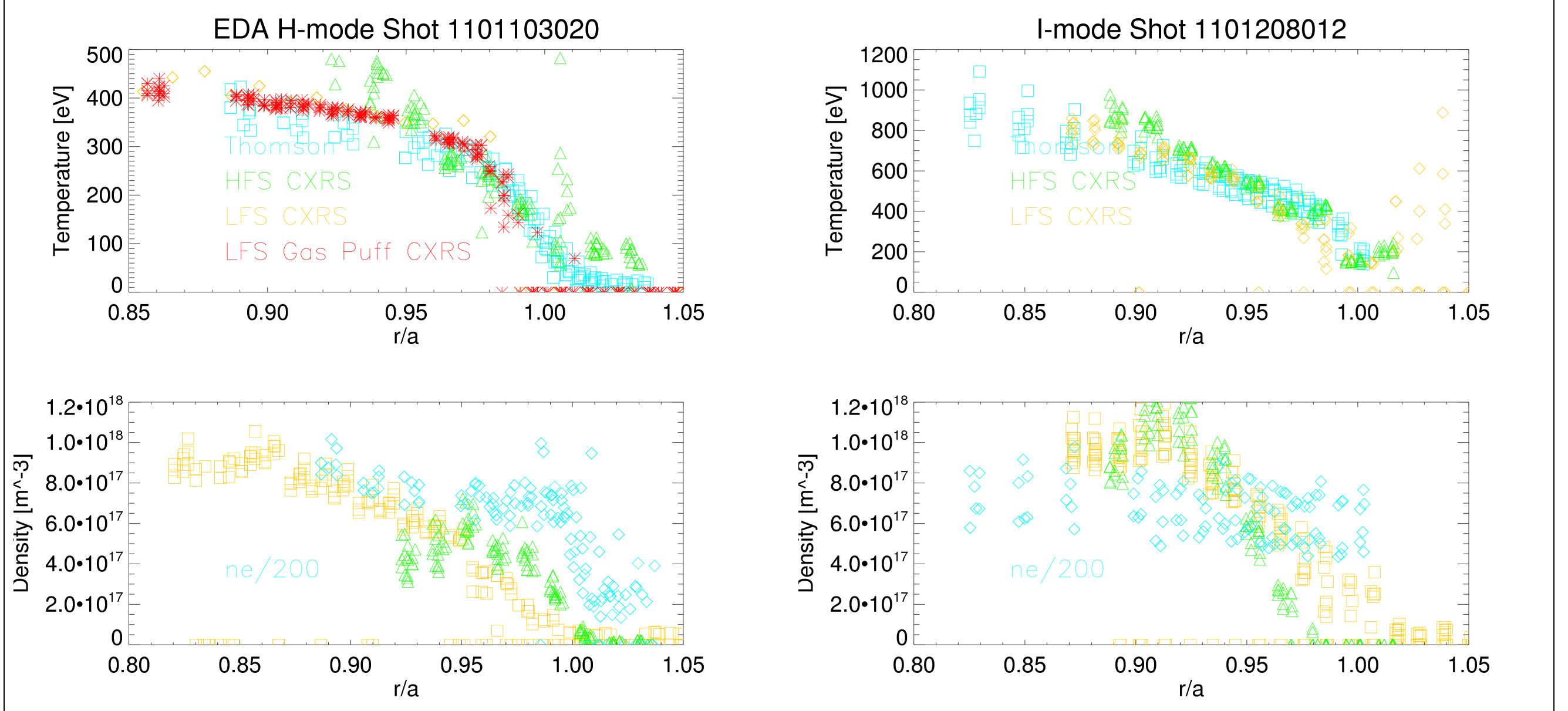




- These results from B2-EIRENE give some confidence that if KN1D matches the measured Dα, the simulated average neutral density from KN1D can be used to calculate the boron density.

Inner-Wall and Outer-Wall Boron Density Comparison

- EDA H-Mode shot and an I-mode shot analyzed
- I-mode is characterized by the presence of a temperature pedestal, but no **electron** density pedestal
- To reduce error associated with flux surface mapping (due to uncertainties from EFIT), electron temperature, HFS impurity temperature, and LFS temperature are shifted to match (Tz~Te in highly collisional CMOD edge, see Appendix A of [2])



EDA H-mode
In-out boron asymmetry as predicted

I-mode
In-out boron asymmetry weak, slightly reversed

- Temperature and density gradients responsible for the buildup of impurities on the HFS.
- I-mode

CONCLUSION

- Inner-wall boron density measured using a combination of CXRS and Dalpha views focused on a deuterium gas puff
- Neutral density (n=2) and neutral energy modeled in neutral transport codes.
  - KN1D simulated neutral density leads to Dα emissivity that matches the measured values.
  - B2-EIRENE full 3D neutral transport simulation showed average line integrated neutral densities match well with neutral densities from KN1D
- In-out boron density asymmetry seen in EDA H-mode, not present in I-mode

- Further studies:
  - Increase r/a coverage of the IW periscopes
  - Verify the applicability of the simplified KN1D neutral transport model with the full 3D Monte Carlo neutral transport models (B2-EIRENE and/or DEGAS 2) for shots with varying plasma parameters
  - Sensitivity tests to shifts in profiles

REFERENCES

[1] Marr KD, Lipschultz B, Catto PJ, et al. Plasma Physics and Controlled Fusion. 2010;52(5)
[2] R.M McDermott, PhD Thesis, MIT
[3] B. LaBombard, http://www.psfc.mit.edu/~labombard/KN1D_Source_Info.html
[4] http://www.eirene.de/
[5] D. Stotler, http://w3.pppl.gov/degas2/