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Modeling of 2-D Neutral Density Measurements in DIII-D

R. Maingi[a], L.W. Owen[a], R.J. Colchin[a], M.E. Fenstermacher[b], P.K. Mioduszewski[a], T.N. Carlstrom[c] and R.J. Groebner[c]
[a] *Oak Ridge National Laboratory, Oak Ridge TN*
[b] *Lawrence Livermore National Laboratory, Livermore CA*
[c] *General Atomics, San Diego CA*

The H-mode confinement scenario presents a method to achieve higher fusion power density and hence lower power cost for fusion power plant designs. Theoretical and experimental investigations of H-mode access have been ongoing since its discovery[1]. It is generally agreed that edge parameters are critical for H-mode access. It is clear that atomic processes, such as radiation and recycling, complicate the physics of the edge region. These processes are in addition to the normal plasma physics phenomena. The role of neutrals in damping plasma flow and increasing the L-H power threshold or suppressing the transition altogether has been predicted[2,3,4,5]. In particular a recent study[6] on DIII-D concluded that neutral density in the X-point region was high enough to affect the poloidal momentum balance in pumped discharges which showed 100% higher L-H power thresholds than observed for similar unpumped discharges. In those pumped discharges the analysis showed that the drag due to charge exchange damping was as large as the neoclassical viscous drag term averaged over the 95% flux surface. Locally near the X-point where neutral density was highest, the neutral damping term was dominant. This analysis relied on data-constrained 2-D edge plasma and neutral transport modeling with the B2.5[7,8] and DEGAS[9] codes. However, the neutral density itself near the X-point was not measured experimentally, which lead to a degree of uncertainty about the conclusions.

Recently a new method to measure neutral density in the X-point region was demonstrated[10] in DIII-D. A tangentially viewing Charge Injection Device (CID) video camera (TTV) measures the D_α light emission in the lower divertor; this image is inverted to produce a polodial D_α light distribution. The TTV is cross-calibrated against absolutely calibrated photomultipliers with D_α light filters. The neutral density at the divertor Thomson Scattering (DTS) measurement locations (Fig. 1) is determined by the relation $I_{D_\alpha} = n_e n_0 \langle \sigma(T_e, n_e) v_e \rangle_{exc}$, where I_{D_α} is the intensity from the TTV, n_e is the electron density determined by the DTS, and $\langle \sigma(T_e, n_e) v_e \rangle_{exc}$ is the electron excitation rate coefficient. Note that the molecular contribution to I_{D_α} is neglected. We have used this technique to measure X-point neutral density in L-mode discharges similar to the ones from Ref. 6. The remainder of this paper discusses modeling of these new data to corroborate our modeling technique and remove the uncertainty from our previous conclusions.

These discharges had I_p= 1.0 MA, P_{NBI}= 0.25 MW (just below the L-H transition threshold), B_t=2.1 T, $\bar{n}_e = 2.5\times10^{19}$ cm^{-3}, and the ion ∇B drift was towards the X-point. The X-point was adjusted to several different heights above the divertor floor, and each height was maintained for 0.5 s. The power crossing the separatrix was 0.6 MW and the divertor radiation was 0.28 MW, independent of X-point height. Figure 1 schematically shows flux surfaces in relation to the DTS data points and the areas from which TTV D_α intensity data were taken for a typical low X-point geometry. Fig. 2 shows that the measured neutral density at the DTS locations for 3 different X-point heights from a single discharge was between 10^{10} to 10^{11} cm^{-3}. In addition the e-folding length of the neutral density above the X-point into the core was about 5cm in all three cases.

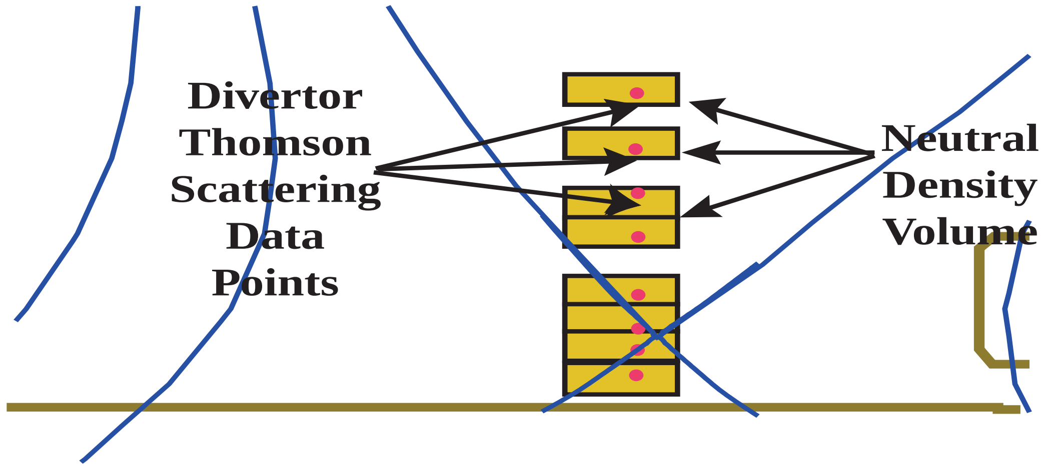

Fig. 1: X-point flux surfaces (lines), divertor thomson scattering data points (dots), and tangential TV intensity data sampling areas (rectangles), from ref. 10.

The modeling procedure[11] from ref. 6 was used to simulate these data. The main chamber Thomson scattering provided edge and scrape-off layer (SOL) n_e and T_e, which constrained the cross-field transport coefficients $\chi_\perp^e$ and $D_\perp$. The edge T_i was obtained by Charge-exchange Recombination Spectroscopy, which constrained $\chi_\perp^i$. The divertor heat flux was obtained from IRTV analysis, which provided guidance on the power flow into the SOL. The Divertor D_α emission, measured by calibrated, filtered photomultipliers, constrained the plate recycling coefficient. A deuterium plasma was modeled, and the divertor radiation was numerically increased to match bolometry data. The plasma solution from B2.5 was input into DEGAS to compute the neutral density profiles; solutions between the two codes were iterated to satisfy global particle balance at each time slice. Note that the X-point n_e and T_e from DTS provided an independent check on the modeling.

The best data quality and also quantity were available for the t = 2250 ms time slice. The transport and recycling coefficients from this time slice were then used for the later time slices to assure a systematic modeling effort; these coefficients provided excellent matches to the available data. It can be seen in Fig. 2 that computed atomic neutral densities are in excellent agreement with the measured neutral densities above the X-point in the core plasma. Fig. 3 shows the comparison between the X-point n_e and T_e measurements and the model calculations for the t = 4250 ms time slice: the agreement is quite reasonable in the core region, considering that these data were not used to constrain the free parameters of the edge plasma model. The agreement in the private flux region is worse: B2.5 needs an additional particle source (or possibly more detailed E×B drift physics) to increase the density and reduce the temperature to better match data. Since there is not a convincing physical justification for such a source term, it is not included in the simulations at present.

The agreement between model and data for neutral density gets worse below the X-point in the private flux region. This can be understood partly by the inaccurate representation of the plasma parameters in B2.5, as well as by the impact of molecules. The DEGAS calculations show a large molecular population in the private flux region, which can contribute as much as 40% of the total I_{D_α}. The equation used to infer neutral density from the data neglects molecular contribution to I_{D_α}, resulting in an overestimation of the atomic density. This discrepancy is not pertinent to the discussion of atomic neutral density above the X-point, where the molecular contribution to I_{D_α} is negligible. Note also that the model neutral density flattens out as the divertor floor is approached. This occurs because the plasma density in that region is too low for significant neutral ionization. Details of the modeling will be presented in an upcoming paper[12].

Based on these data and modeling, the main physics of neutral decay in the core above the X-point appears to be related simply to the atomic neutral ionization mean free path. The average n_e and T_e from the DTS system were in the range of 1.5-2 $\times$ 10^{19} m^{-3} and 30-50 eV respectively. The ionization mean free path for a 3 eV Franck-Condon neutral with these plasma parameters is 3-4cm, in reasonable agreement with the 5cm observed decay length from the data. If it can be proven that this simple physics dominates the neutral penetration into the core, then it can be inferred that X-point neutrals should not have an effect on the L-H power threshold in a reactor. Reactors will be unaffected because they will run at much higher electron density and significantly larger separation between the divertor and X-point region than present tokamaks. Indeed, gas fueling of reactor designs has been computed to be inefficient due to SOL plasma shielding and most designs rely on pellet or other deep fuel mechanism.

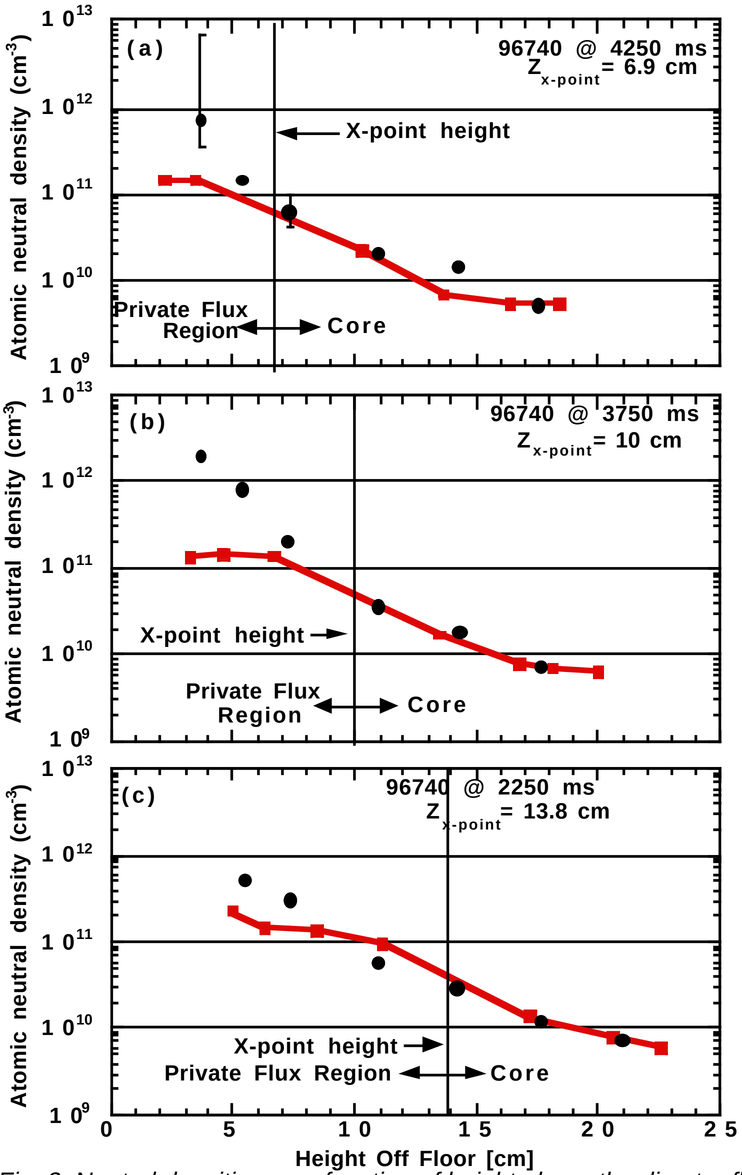

Fig. 2: Neutral densities as a function of height above the divertor floor. Typical error bars are shown in (a). The solid lines show model calculations.

Owing to flux expansion, our neutral density data above the X-point extend only to the 98% normalized flux surface, mapped to the outer midplane. The analysis of ref. 6 concluded that neutral density at the 95% flux surface was the critical parameter; extension of this technique[10] to measure neutral density at the outer midplane in to the 95% flux surface is underway.

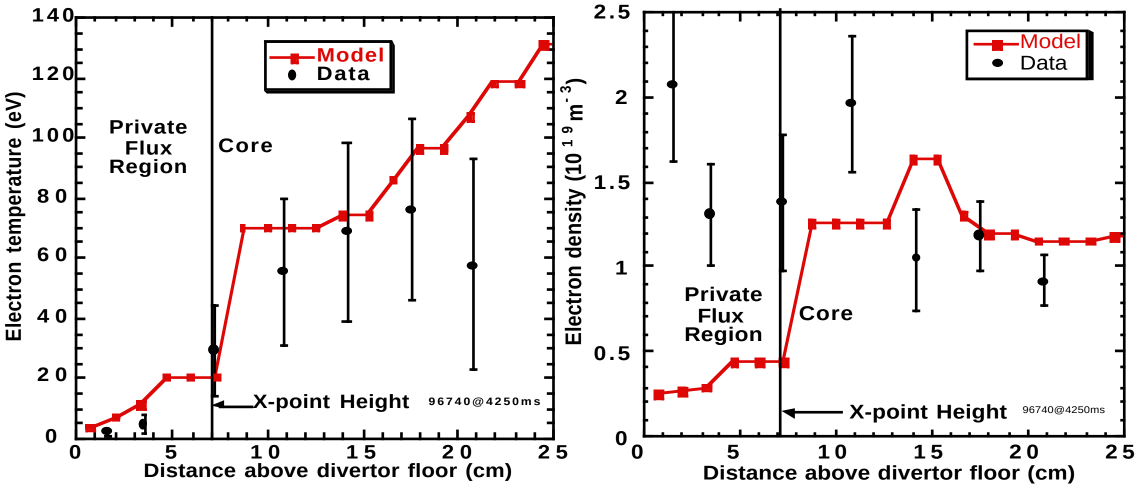

Fig. 3: Comparison between model and data for n_e and T_e near the X-point. Error bars are based on fluctuations in the quantities, not photon statistics.

In summary, we have obtained a good match between simulations and data of the neutral density just above the X-point in the core plasma, both in the range 10^{10} to 10^{11} cm^{-3}. Our previous conclusion[6] that neutrals can affect the poloidal momentum balance and the L-H power threshold at low line-average density was based on data-constrained analysis; however, the neutral density itself was not measured in that study. The good agreement between the modeling shown here and new data benchmarks our modeling technique and corroborates our previous[6] conclusion.

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