ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 609–613

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Neutral particle fueling at the midplane of DIII-D

R.J. Colchin *, L.W. Owen

Oak Ridge National Laboratory, Fusion Energy Division, P.O. Box 2009, Oak Ridge, TN 37831-8072 USA

Abstract

Data from an array of eight tangential D_α viewchords, located at the outer midplane of DIII-D, are inverted to obtain atomic neutral density profiles across the separatrix and are compared to results of B2.5 and DEGAS simulations. In H-mode and (low density) L-mode plasma conditions, charge-exchange neutrals reflected and desorbed from the outer midplane region of the vacuum vessel wall can account for the midplane neutral density that is deduced from the D_α data, making it unnecessary to invoke main chamber ion recycling. The midplane measurements and DEGAS calculations are used to validate a slab-model of neutrals in the edge. In this model, cold neutrals from the wall fuel the edge and are attenuated by charge-exchange and ionization, and the results are in agreement with measured neutral profiles.

Keywords: Plasma fueling; Plasma edge, DIII-D; B2.5-DEGAS

1. Introduction

An array of eight tangential D_α viewchords has been installed in DIII-D in order to view plasmas near the outer midplane. These chords can view both the core and SOL, with the number of points in each region determined by the position of the separatrix. Data from these viewchords are inverted using an onion peeling model [1]. By mapping the upstream Thomson scattering electron temperatures and densities to the midplane and applying appropriate cross sections, the neutral densities are determined.

Recent work [2,3] to simulate the DIII-D edge and scrape-off layer (SOL) plasmas with an analytic model based on the Engelhardt–Fenenberg model [4] used radially invariant transport coefficients and neglected the charge-exchange scattering process. Measurements of DIII-D midplane neutral density profiles and detailed Monte Carlo neutral transport simulations permit the validation of a somewhat more detailed slab-model of edge neutrals transport near the midplane of DIII-D. Results of the model calculations agree with measured neutrals profiles when detailed charge-exchange processes are included. The inclusion of these effects, in addition to ionization, means that the model, although much simpler than the full Monte Carlo simulation, cannot be expressed by a closed set of equations.

Strong main chamber recycling in the C-Mod tokamak [5] and large radial particle fluxes far from the separatrix in DIII-D [6] have been observed in high density discharges. In both devices the fluxes are largest for L-mode operation. Although the present study focuses on low density L-mode plasma where main chamber recycling is less important, these observations motivate an objective of this work, which is to determine the origin of the neutrals that give rise to measured midplane D_α profiles in DIII-D.

Data-constrained B2.5 [7] and DEGAS [8] transport simulations, have been used to reconstruct the plasma and neutrals distributions. In the discharges studied, neutrals incident on the plasma near the midplane D_α array originate at the divertor and reach the region of the outboard midplane by multiple charge-exchange scattering and wall reflection events. These transport simulations serve to validate the assumptions and boundary conditions of the semi-analytic model. These include the assumption that the neutrals that give rise to the

---

[*] Corresponding author. Tel.: +1-865 574 0982; fax: +1-865 574 1191.

E-mail address: colchinrj@ornl.gov (R.J. Colchin).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01436-8

measured midplane D_α intensity can be introduced into the plasma at the vacuum vessel wall near the outboard midplane and are primarily wall temperature molecules that dissociate into Franck–Condon neutrals before reaching the separatrix.

2. B2.5–DEGAS transport modeling

Diagnostic data from a lower single-null DIII-D discharge are analyzed with the 2-D plasma fluid transport code B2.5 and the resulting plasma parameters are used in the Monte Carlo neutrals transport code DEGAS to calculate the core fueling rates and 2-D neutrals distributions. The data that are used to constrain the transport model include electron densities and temperatures from the main chamber and divertor Thomson scattering systems, ion temperatures from charge-exchange recombination spectroscopy, divertor density, temperature and ion flux profiles from an array of Langmuir probes embedded in the lower divertor tiles, core and divertor radiation from bolometry, and D_α emissivities from the midplane and lower divertor filterscope arrays. In the transport analysis the plasma and neutrals codes are not linked but core particle balance is imposed as a constraint to ensure consistency of the core fueling rate calculated with DEGAS and the core ion efflux calculated with B2.5. Typically this requires iteration of the plasma and neutrals calculations.

From DIII-D discharge 103417, an L-mode time slice at 2000 ms and a time slice in the H-mode phase at 2900 ms have been selected for analysis. The average density and total input power at these times are 2.4×10^{19} m^{-3} (1.5 MW) and 5.2×10^{19} m^{-3} (2.0 MW), respectively. The corresponding energy confinement times are 0.11 and 0.24 s. The transition to H-mode occurs at approximately 2500 ms, and the H-mode time slice is chosen to be in the quiescent phase just before the first ELM. This discharge has a lower divertor X-point.

L-mode ionization rates, just inside the separatrix, are shown in Fig. 1 as a function of poloidal angle. The poloidal angle is taken as rotating in the counterclockwise direction, starting at the outer midplane. At that point, (angle 0) ionization rates are relatively low. Most of the ionization, and hence the plasma fueling, takes place in the region of the X-point in the lower divertor. As such the core fueling distribution has strong poloidal asymmetries.

Good fits to the diagnostic data are obtained from the transport analyses. Only the fits to the D_α emissivities from the midplane filterscope arrays are shown (see

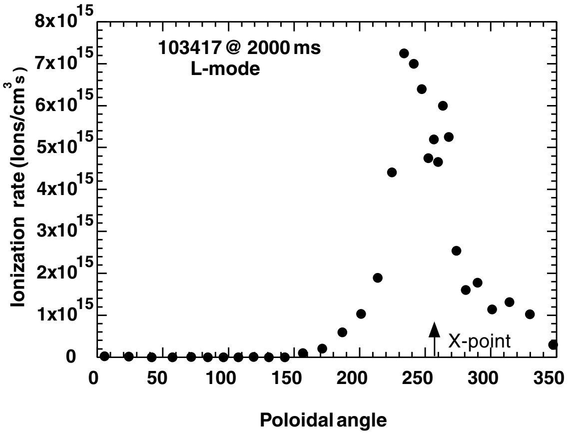

Fig. 1. Poloidal distribution of the ionization rate (calculated by DEGAS) in DIII-D just inside the separatrix in the L-mode. The origin of the poloidal angle is taken at the outer midplane, and the angle is rotated in the counter-clockwise direction.

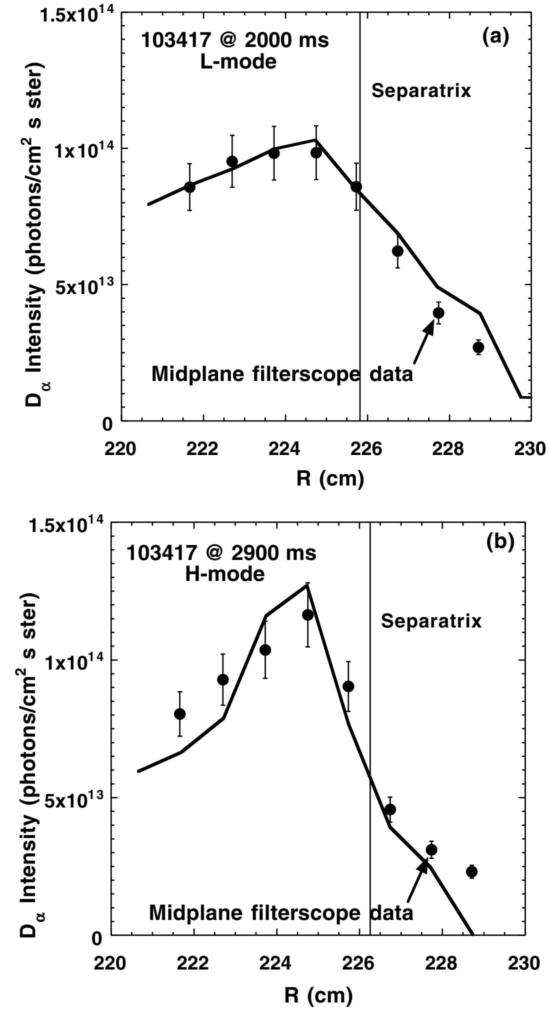

Fig. 2. Comparison of D_α midplane data and DEGAS calculations for (a) L-mode and (b) H-mode plasmas.

Fig. 2). In both the L- and H-modes the calculated global core plasma particle confinement times are approximately equal to the corresponding energy confinement times. A good fit to the midplane D_α emissivities requires that the vacuum vessel wall pump approximately 20% of the neutral flux that impinges on the wall. Divertor tiles are assumed to be saturated and not pumping.

An objective of the 2-D transport simulations presented here is to determine the origin of the neutrals that give rise to the measured midplane D_α emissivities. As indicated in Fig. 1, the analysis results indicate that the core ion efflux recycles from the divertor rather than the midplane for the discharge studied. Neutrals can reach the midplane from the divertor by charge-exchange reactions through the intervening plasma or through multiple charge-exchange and wall reflection events. The assumption of the 1-D model discussed in Section 3 is that the midplane neutrals can be introduced into the model plasma from the region of the outboard midplane wall. In order to test the validity of this assumption we calculate the effects on the midplane D_α intensity of absorbing all of the charge-exchange neutrals that strike the vacuum vessel wall at locations between $\pm Z$ from the position of the midplane filterscope array. As seen in Fig. 3 the H-mode midplane D_α is strongly dominated by neutral flux from the region of the wall nearest the midplane array. The results for L-mode (not shown) show a similar behavior.

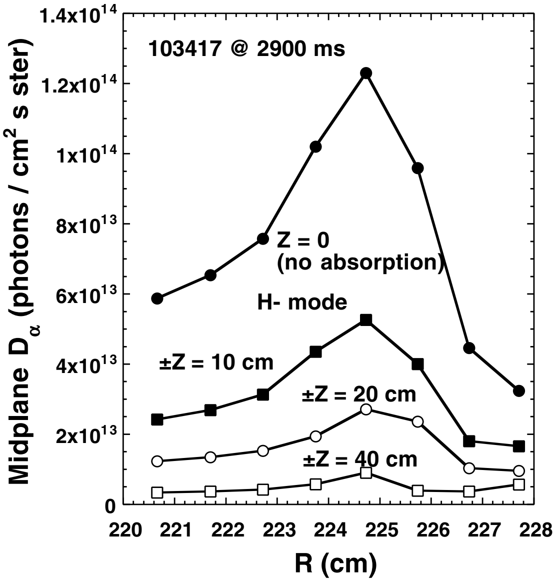

Fig. 3. DEGAS calculations of D_α light intensity on midplane filterscope chords assuming perfect wall absorption in a range of $\pm Z$ of the midplane.

3. Midplane neutrals

The shape of the flux surfaces and the uniformity of the wall charge-exchange flux near the outer midplane makes the transport problem particularly well suited to a 1-D model treatment. Based on the 2-D calculations of Section 2, a slab-model neutrals code was devised to model neutral fluxes at the midplane of DIII-D. Neutral molecules from the wall are assumed to be dissociated by the SOL plasma [9,10], so that only 3 eV Franck–Condon neutrals [11] enter the main plasma through the separatrix. Measured values of T_e, T_i, and n_e (see Fig. 4) are used in the code. The measured density of these neutrals at the plasma edge (outer radial data points in Fig. 5) is used as the starting point for the calculation. Neutrals are ionized and charge-exchanged in radial increments, and followed as they penetrate into the plasma. The result of multiple charge-exchange events is a longer decay length of the neutral density distribution in the core plasma, i.e., the fueling is much deeper than that obtained in the absence of charge-exchange.

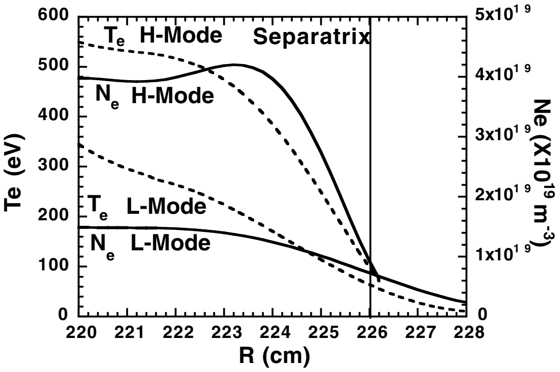

Fig. 4. Fits to T_e (dashed lines) and N_e (solid lines) measured by Thomson Scattering.

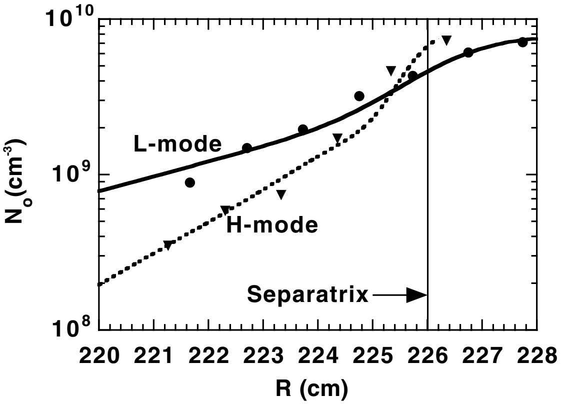

Fig. 5. Comparison of L-mode (solid line) and H-mode (dotted line) neutral density profiles. Curves calculated from a slab-model are shown as lines and data as discreet points.

A comparison of measured and modeled L- and H-mode neutral density profiles is shown in Fig. 5. The H-mode neutral densities are slightly higher than L-mode values near the separatrix, due to less attenuation of wall neutrals by the SOL plasma. Farther into the plasma, the opposite is true, and the higher-temperature-and-density H-mode plasma causes a faster attenuation of the neutrals.

Fig. 6 shows the contributions of the slow 3 eV Franck–Condon neutrals and the hot charge-exchanged neutrals to the total neutral density in the L-mode. The Franck–Condon neutrals dominate the neutral density profile in the SOL and near the separatrix but are attenuated within a short distance into the plasma. These cold neutrals also charge-exchange with hot edge ions and penetrate into the core plasma. The measured neutral densities cannot be matched without a correct accounting of these fast charge-exchanged neutrals.

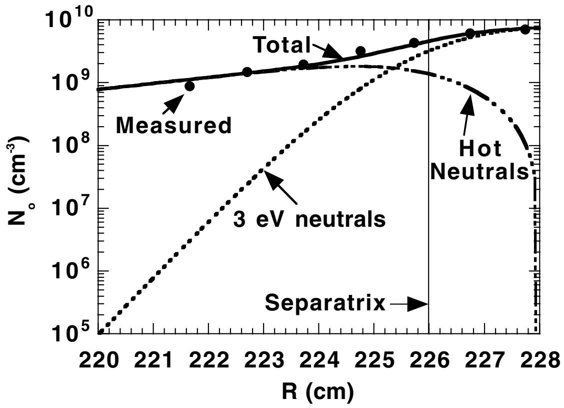

Fig. 6. Comparison of slab-model and measured neutral densities in an L-mode plasma. Measured points are shown as dots, and the total calculated neutral density by the solid curve. Calculated hot and cold neutral components are plotted as dot-dashed and dotted lines, respectively.

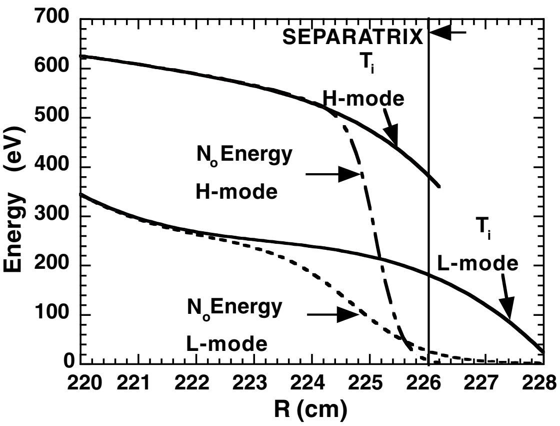

Fig. 7. Average neutral particle energy for H-mode (dot-dashed line) and L-mode (dashed line) plasmas, calculated with the slab-model. Corresponding fits to measured ion temperatures are shown as solid lines.

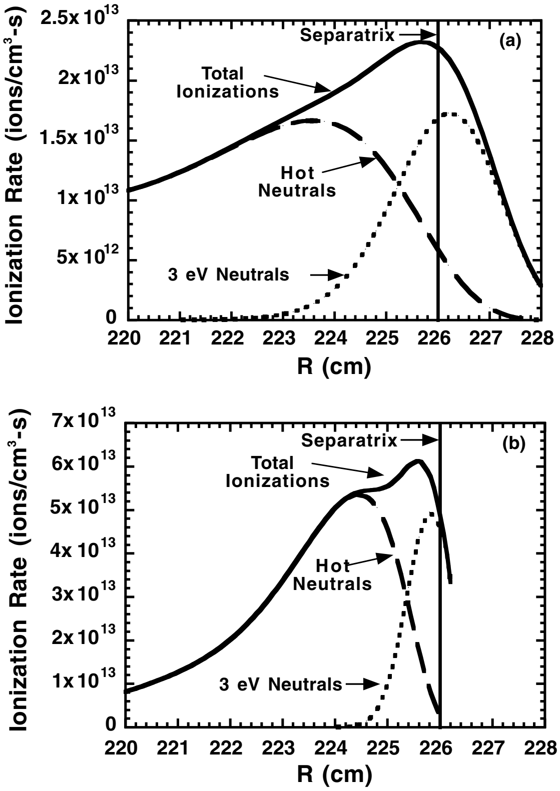

Fig. 8. Slab-model-calculated ionization rates of hot charge-exchanged neutrals (long-dashed curves), cold 3 eV neutrals (short-dashed curves), and total ionization (solid curves) in (a) L-mode and (b) H-mode plasmas.

As the result of multiple charge-exchanges, the slow Franck–Condon edge neutrals take on the energy of the ions within a few centimeters after passing through the separatrix. The average energy of the charge-exchange neutrals is shown in Fig. 7 for L- and H-mode plasmas.

Plasma fueling arises from ionization of the Franck-Condon (cold) neutrals and fast charge-exchanged (hot) neutrals. The ionization rates of each component (as well as the total) are shown in Fig. 8 for the L- and H-modes. Cold neutrals provide the fuel for the plasma for a few centimeters inside the separatrix, particularly in the L-mode plasma. However, as shown in Fig. 8 it is the hot neutrals that provide fueling deeper into the plasma edge. Ionization rates are higher in the H-mode.

4. Summary

L-mode and H-mode plasmas have been analyzed with the B2.5–DEGAS transport codes with the objective of determining the origin of the neutrals that give rise to the measured midplane D_α emissivities in DIII-D. It is found that these neutrals reach the midplane predominantly from the diverter through multiple ion charge-exchanges in the plasma edge and wall collisions rather than as a result of migration through the plasma. This finding validates a key assumption of the slab-model presented here. This model reproduces the observed midplane neutral density profiles and should be a valuable tool in the analysis of higher density discharges in which the occurrence of intermittent plasma objects leads to strong main chamber recycling.

Acknowledgements

This work was Supported by US DOE under contract nos. DE-AC05-00OR22725 to ORNL, and DE-AC03-99ER54463 to GA.

References

[1] R.J. Colchin et al., Measurement of neutral densities at the outer midplane in DIII-D, 27th European Conference on Controlled Fusion and Plasma Physics, Budapest, Hungary, 12–16 June 2000, vol. 24B, p. 760.
[2] R.J. Groebner et al., Phys. Plasmas 9 (2002) 2134.
[3] M.A. Mahdavi et al., Nucl. Fusion 42 (2002) 52.
[4] W. Engelhardt, W. Fenenberg, J. Nucl. Mater. 76&77 (1978) 518.
[5] B. La Bombard et al., Nucl. Fusion 40 (2000) 2041.
[6] J.A. Boedo et al., paper I-17, these Proceedings.
[7] B.J. Braams, Contributions to Plasma Phys. 36 (1996) 276.
[8] D.B. Heifetz, D. Post, M. Petravic, J. Weisheit, G. Bateman, J. Comp. Phys. 46 (1982) 309.
[9] D. Reiter et al., J. Nucl. Mater. 196–198 (1992) 1059.
[10] H. Kubo et al., Plasma Phys. Control. Fusion 40 (1998) 1115.
[11] S.J. Fielding et al., J. Nucl. Mater. 162–164 (1989) 482.