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High resolution measurements of neutral density and ionization rate in the main chamber of the Alcator C-Mod tokamak

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Abstract

Recent theoretical and experimental work has focused on the importance of neutrals in the edge dynamics of Alcator C-Mod plasmas. Two new high resolution detectors have been installed on the Alcator C-Mod tokamak to measure the neutral density and ionization rate near the edge of the discharge in the main chamber. The detectors consist of a 20 channel photodiode array which views the plasma tangentially 12.5 cm below the outer midplane, and 10 cm above the inner midplane, with a nominal radial resolution of 2 and 3 mm, respectively. The spectral bandwidth is limited by a filter with a very narrow band around the neutral deuterium Lyman alpha wavelength (1215 Å). The local emissivity is then obtained via a standard Abel inversion of the absolutely calibrated brightness profile. Employing well-known branching ratios, and using measured local electron density and temperature, we therefore, infer the neutral density and ionization rate with similar radial resolution. We have observed that both Lyman alpha emissivity and ionization rate are usually peaked near the separatrix with a full width, half-maximum between 1 and 2 cm. The neutral density was found to drop rapidly with decreasing minor radius, from $2–3 \times 10^{17}/\mathrm{m}^3$ (5–10 mm outside the separatrix) to $1–2 \times 10^{16}/\mathrm{m}^3$ (5–10 mm inside the separatrix) for a line averaged density of $2.0 \times 10^{20}/\mathrm{m}^3$. Variations in ionization rate and neutral density from low to high confinement mode (L and H mode) are also discussed.

Keywords: Alcator C-Mod; Atomic density; Ionization; Neutral particle

1. Introduction

One of the difficult tasks remaining relative to optimized performance and steady-state conditions in a tokamak is to achieve particle control. However, before control can be achieved, it is important to obtain good understanding, and therefore good measurements of the neutral population and their effects. This is especially important as neutral transport modeling is usually hampered by a very complex geometry, the need for detailed measurements and time-consuming computer simulations. On Alcator C-Mod, preliminary observations indicate that neutrals may be influencing the particle, momentum and energy balance of the edge plasma [1]. The charge-exchange mechanism is a phenomenon which characterizes neutral deuterium particle dynamics at the edge of tokamak plasmas, which in turn can affect the ions particle and energy transport. The relative predominance of charge-exchange over ionization increases the penetration of neutral deuterium into the high temperature plasma, and increases momentum and heat transfer across field lines. In fact, since the charge-exchange cross-section is relatively large at conditions of interest, the effects of neutrals on the edge dynamics can be rather large, even in the presence of a relatively small number of neutrals.

The Alcator C-Mod tokamak [2] is based on a compact design, with high magnetic field, high particle and power densities. All plasma facing components are made of molybdenum, and wall conditioning consists

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primarily of electron cyclotron discharge cleaning (ECDC) and periodic boronization. Neutral pressures are usually relatively high, reaching $\lesssim 1$ mTorr in the main chamber, and ~100 mTorr in the divertor. Auxiliary heating consists of ion cyclotron heating (ICRF) only, and as a consequence, no central fueling source is present, and no direct momentum input is applied to the plasma. Standard measurements of escaping neutral flux and its energy dependence (using a neutral particle analyzer) are usually very arduous at low particle energies (~250 eV and below), and normally lack radial resolution. However, neutral deuterium can be excited and emit light in the Balmer and Lyman series, which lie in the visible and vacuum ultraviolet. We chose the Lyman alpha line over the usual H alpha line, for its larger brightness (factor of 50 or more), and to avoid problems related to reflections inside the vacuum vessel.

These neutral measurements were initiated for the study of H-mode physics, especially regarding the formation of the density pedestal, near the magnetic separatrix. High confinement regimes (H-modes) are readily obtained in Alcator C-Mod, both ohmically and with ICRF. These H-modes mainly fall into two categories. The first type, the edge-localized-mode (ELM)-free H-mode, [3] exhibits the best energy and particle confinement, but eventually reaches a radiative collapse. The second type, referred to as enhanced D_α H-mode (EDA), [4] exhibits a good energy confinement (near ELM-free levels) but is accompanied by a lower particle confinement. Its most prominent feature relates to an elevated level of H-alpha radiation, hence its name. In the case of ELM-free H-mode, edge pedestals are very narrow, with density pedestal widths as low as 3–4 mm, and the temperature pedestal being 8–10 mm or less. However, in the case of EDA H-mode these widths are found to increase.

2. Experimental technique

The information gathered on the neutral population is obtained through the electron-impact excitation of neutral deuterium (and hydrogen) in the Lyman series. A new type of photodiode (AXUV series [1]) is capable of measuring radiation in the VUV with high sensitivity and good time response. We installed one array comprised of 20 channels looking tangentially at the outer edge of the plasma, 12.5 cm below the midplane. In this experimental campaign, a second tangential system has been installed, viewing the inner edge of the plasma, approximately 10 cm above the midplane. A filter limits the spectral response to the neutral deuterium Lyman alpha line centered at 1216 Å, with a full width, half-maximum of 76 Å. This spectral region has been monitored by a high resolution McPherson spectrometer, and we found it to be dominated by the Lyman alpha line except when relatively large amounts of nitrogen are injected for divertor detachment studies. The photodiode has a sensitivity of 0.11 A/W at this wavelength. Since the individual channels are small (0.75×4 mm^2), and with a similarly sized aperture (1×3 mm^2), we achieved a spatial radial resolution of 2 and 3 mm for the outer and inner edge arrays, respectively. Since the neutral density is not too large (near the outer midplane), at least compared to the divertor area [5], no self-absorption or scattering is present. The local emissivity is obtained in both systems by using an Abel inversion technique. However, in the case of the inner edge view we need to take in account the emission viewed at the outer edge, which is actually measured. This contribution turns out to be small, first because the emission is much larger at the inner wall, and second because we are looking through the outer edge nearly perpendicularly, reducing its contribution compared to a tangent at the inner wall.

Subsequently, the local neutral density and ionization rate are derived from the Lyman alpha local emissivity using well established branching ratios [6]. The electron temperature and density are obtained with a Thomson scattering system which consists of 16 channels, with a nominal 2 mm resolution. In addition, fast scanning probes are used in the scrape-off layer to complement the information on electrons. Finally, the neutral pressure is measured away from the plasma near the outer midplane with a standard pressure gauge (ion gauge).

[1] AXUV-20EL model, International Radiation Detectors, CA.

3. Experimental results

The observed Ly_α emission profile, as shown in Fig. 1(a), is very peaked near the separatrix, with a radial extent of 1–1.5 cm. This is a L-mode discharge with $I_p = 0.8$ MA, $B_T = 5.4$ T, $P_{RF} = 1.2$ MW, $\bar{n}_e = 2.1 \times 10^{20}$ m^{-3} and $p_o = 1.0$ mTorr at the midplane. With the electron density and temperature profiles (shown in Fig. 1(d)), we infer the ionization rate and neutral density profiles (see Figs. 1(b) and (c)) by using the standard branching ratio and cross-sections [6]. In typical L-mode conditions, we observe that the ratio of the total ionization source inside versus outside the separatrix is nearly 1–1. This experimental result illustrates the influence of charge-exchange on neutral transport. It shows that neutrals can reach a region of much higher temperature than their ionization potential; without the charge-exchange process the neutrals would all be ionized in the scrape-off layer before reaching the separatrix. For the neutral density profile, we also observe the expected rapid radial decrease at the separatrix. Preliminary results from the second array, which views the near the inner wall, indicate a local emissivity larger by

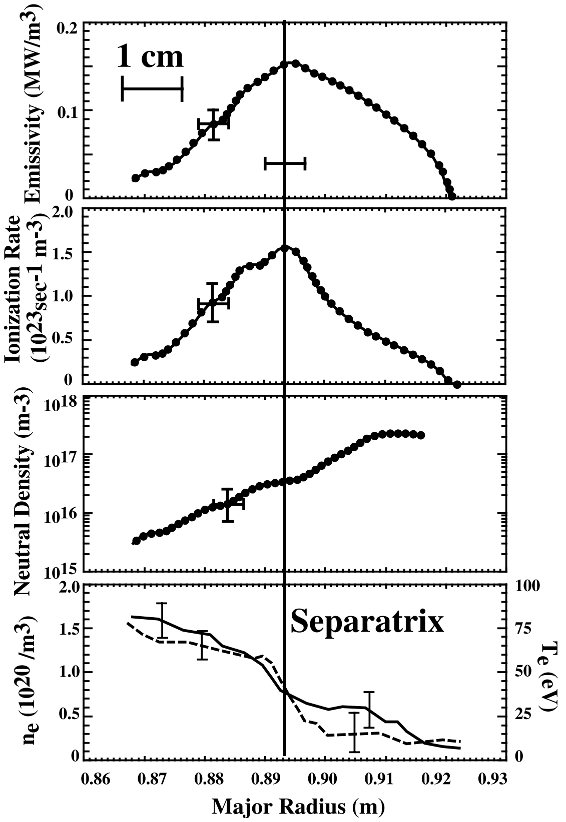

Fig. 1. Measured radial profiles (dotted lines) of the (a) deuterium Ly_α emission; (b) ionization rate; (c) neutral density near the separatrix; (d) electron density (line) and temperature (dash line) profiles for a L-mode discharge.

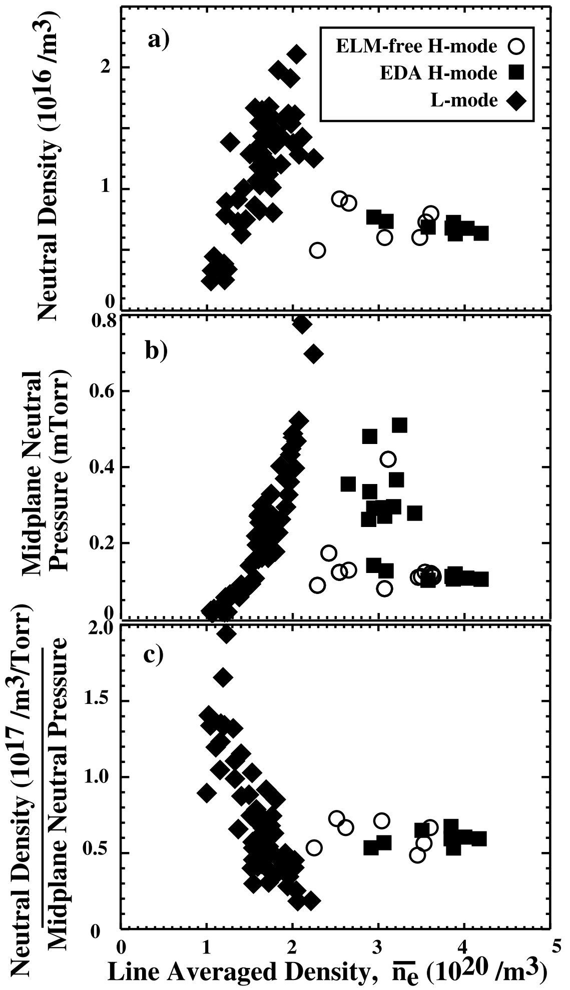

Fig. 2. (a) Measured neutral density (at 2 mm inside the separatrix); (b) midplane neutral pressure (measured at the wall); (c) ratio of neutral density to the wall neutral pressure as a function of the line averaged electron density.

an order of magnitude. This would indicate that the inner wall can be a strong source of neutrals through recycling. Overall, the uncertainties in the all measurements are dominated by the sensitivity calibration of the detector and uncertainty related to the input density and temperature measurements, with very little contribution from the Abel inversion process.

The neutral density measured inside the separatrix is revealed to be less sensitive to the line average density compared to the neutral pressure at the wall. Thus, in the study of the influence of neutrals on edge dynamics, the wall neutral pressure measurement can overstate the variation in neutral population, especially inside the separatrix. Shown in Fig. 2 are (a) the neutral density (measured at 2 mm inside the separatrix), (b) the neutral pressure (measured at the wall) as a function of the average electron density, and (c) the ratio of neutral density to wall neutral pressure. It is remarkable that for a range of $\sim$100 in neutral pressure, the neutral density varies at most by a factor of 5 or so. This behavior is more visible in the their ratio (Fig. 2(c)) which shows that, as we increase the density, the screening of neutrals increases, meaning that the fraction of neutrals penetrating inside the plasma from the vacuum region, decreases with plasma density. Also noticeable is that the neutral density inside the separatrix decreases only slightly while going into H-mode, and seems to be relatively independent of the density, at least in the small subset of data shown here.

Changes in Lyman alpha emission have been observed when the plasma makes a transition from L-mode to H-mode. Reminiscent to the standard drop in H alpha emission when moving to H mode, the Lyman alpha emission has been observed to drop across most of the profile. However, the ionization rate, as shown in Fig. 3, is increasing inside the separatrix. The combination of increasing neutral penetration, higher density and temperature contribute to a higher ionization rate in a small

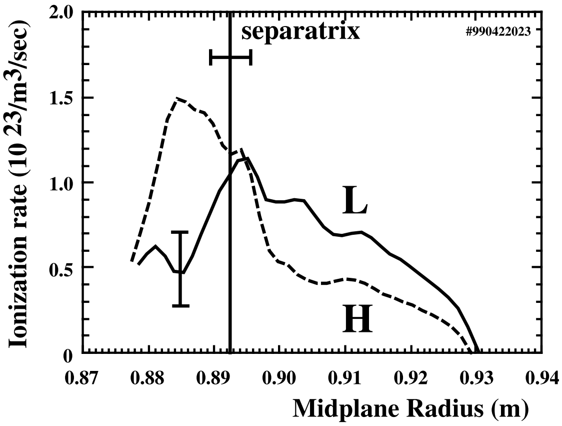

Fig. 3. Measured ionization rate profile for L-mode (line) and fully established ELM-free H-Mode (dash line) conditions.

region inside the separatrix. The neutral density remains the same within the error bars, but its gradient seems to increase near the separatrix in the presence of a pedestal.

While assuming that the ionization rate is poloidally and toroidally uniform, we calculated the total ionization rate as shown in Fig. 4. The first case shown corresponds to the total ionization rate for a discharge exhibiting many transitions from L-mode to ELM-free H-mode. Also shown is the particle inventory change rate (dN/dt), where N is the total number of particles. As the plasma makes a transition to H-mode, the ionization rate increases inside the separatrix, while dropping slightly on the outside. This increase in fueling rate (ionization) is similar to the change in particle inventory, indicating that it may contribute significantly to the H-mode edge density rise. In Alcator C-Mod, a different type of H-mode is also observed, the EDA H-mode, in which the density and radiation are approaching steady-state after an initial rise. So, by contrast, in the case of an EDA H-mode we observed, as shown in (Fig. 4(b)) that the ionization rate increases only during the brief ELM-free phase of the H-mode, while returning to the L-mode level during the EDA phase. However, the density remains at a higher level indicating that the particle confinement is still better than during the L-mode phase.

4. Summary and acknowledgements

First high resolution measurements of the neutral density and ionization rate profiles were obtained for Alcator C-Mod plasmas. The neutral density was found to decrease rapidly inside the separatrix, and to be a much weaker function of plasma density than the midplane neutral pressure. The ionization rate profile is usually peaked right at the separatrix. The profile has been observed to change significantly while making a transition

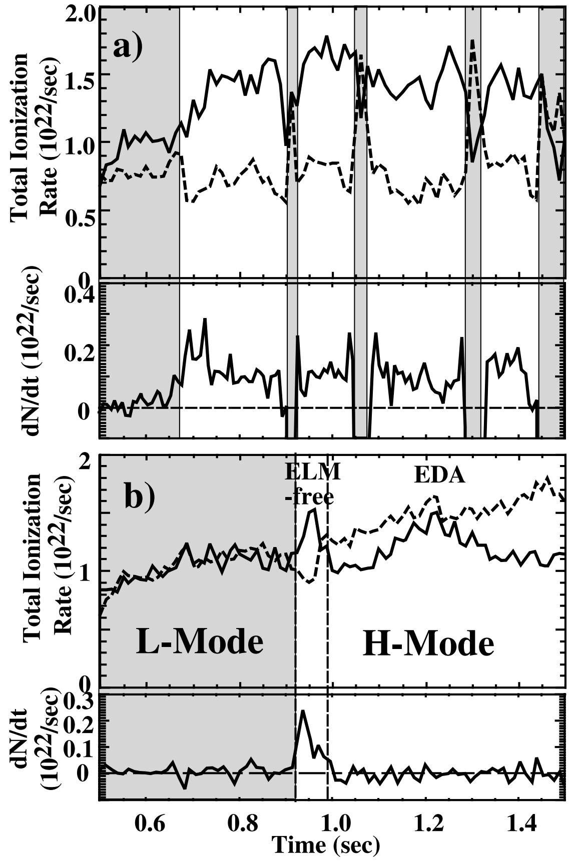

Fig. 4. Total ionization rate inside (line) and outside (dash) the separatrix as a function of time, and temporal variation of total number of particle in discharge for: (a) an ELM-free H-mode discharge; (b) a EDA H-mode discharge, preceded by a brief ELM-free phase.

from L- to H-mode, with higher ionization rates inside the separatrix, which could partly explain the usual rise in edge density during H-mode. We are now capable to assess the importance of the neutrals regarding the formation of the edge pedestal, and also to identify any effect on the local momentum and power balance.

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