Study of the effects of neutrals in Alcator C-Mod plasmas

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Introduction

Recently, much effort has been dedicated to understanding the bifurcation involved in the transition from a low to high confinement regime. While several theories have been brought forward, many factors remain to be elucidated, one of which involves the role played by neutral particles in the evolution of a transport barrier near the edge of the plasma. Alcator C-Mod is especially well suited for the study of neutral particle effects, mainly because of its high plasma and neutral densities, and closed divertor geometry. Alcator C-Mod employs ICRF as auxiliary heating for obtaining a high confinement regime, although ohmic H-modes are routinely obtained as well.

The neutrals can enter the edge dynamics through the particle, momentum and energy balance. In the particle balance, the source of neutrals has to be evaluated vis-à-vis the formation of the edge density pedestal. It is widely believed that plasma rotation is an important factor in reducing transport. In this case, neutrals could act as a momentum sink, through the charge-exchange process. That same process can also modify the energy balance of the plasma near the edge by increasing the cross-field heat flux. These effects are quite difficult to measure experimentally, in large part because neutral particle diagnosis is not an easy task, and because of the inherent 3-dimensional aspect of the problem. Consequently, the neutral's spatial and energy distributions are usually not well known. In Alcator C-Mod, we recently implemented a series of diagnostics for the purpose of measuring these distributions. They include measurements of the neutral pressure at many locations around the tokamak, and spatially resolved measurements of Lyman-α and charge-exchange power emission. A high-resolution multichord (20 channels) tangential view of neutral deuterium emission (Lyman-α) has been recently installed near the midplane. The viewing area covers approximately 4 cm across the separatrix, with a nominal 2 mm radial resolution. Standard Abel inversion techniques give the local Lyman-α emission. In conjunction with electron density and temperature, we can infer the local ionization rate and neutral density profiles. Two types of bolometer arrays (16 channels each), one being sensitive and the other insensitive to power carried by neutrals, view the plasma cross-section, tangentially at the midplane of the tokamak. By Abel inverting the difference between the 2 measurements, we infer the local power emissivity carried by neutrals[1].

Experimental Results

One of the most recognized signatures of the presence of an H-mode is the dramatic drop in H-α light, usually seen across most of the plasma discharge. Such a phenomenon has also been observed in the Lyman-α emission. In Fig. 1, we show Lyman-α emissivity profiles for L and H-mode phases of the same discharge, in which 1 MW of ICRF heating was applied. In Fig. 2, the measured radial ionization profile is shown for the same times as in Fig. 1. Electron density and temperature profiles have been obtained from the edge Thomson scattering system, which has a minimum of 9 chords with a nominal 2 mm radial spacing. In this discharge, an ELM-free H-mode is obtained, with plasma and impurity densities increasing until the discharge reverts back to L-mode. Although the electron density is rising dramatically at the top of the pedestal (up to 3-4 x 10^{20} m^{-3}), the Lyman-α emissivity drops across the whole profile. At these densities, the ionization of neutrals from excited states prevents some de-excitation through a Lyman-α photon emission. We integrated the ionization rate inside the separatrix, with the assumption of poloidal and toroidal symmetry. In fact, simulations using the DEGAS code indicated a very broad poloidal distribution for the neutral density, due to large recycling on the inner wall, the outer limiters and RF antennas, in contrast to other larger tokamaks where the X-point is the region of highest neutral density [2]. This change in ionization rate inside the separatrix can explain in part the increase in density found during H-mode. However, the scaling of H-mode density rise with change in ionization rate requires more careful analysis as poloidal variation and separatrix location can potentially introduce large uncertainty in the fueling rate.

In addition to the ionization profile, the neutral density profile can be obtained from the Lyman-α emissivity profile, again using the electron density and temperature profiles. Shown in Fig. 3 is the neutral density profile for the same discharge (H-mode) shown in Fig. 1. As expected the neutral density falls dramatically when approaching the separatrix, with a scale-length as small as 3mm which is comparable to the measured electron density pedestal width. The neutral density right inside the separatrix is still surprisingly large, up to 0.1% of the local plasma density. This large fraction is simply the consequence of the dominance of multiple charge-exchange events over ionization, and by the large neutral pressure found in the main chamber. Fülöp[3] derived theoretically that when the neutrals are taken into account, they could modify the ion flows immediately inside the separatrix. In fact, measurements of edge rotation based on magnetic fluctuations have shown a decreasing velocity with increasing neutral pressure[4], an indication of that some damping mechanism may be at work near the edge of the plasma. We initiated a study of these viscosity effects by calculating the damping rates for the neo-classical and neutral components for a high density discharge, by using our 1-D neutral transport code. Shown in Fig. 4 are the calculated profiles for neo-classical and neutral damping near the edge of the plasma of a high density L-mode. We found, at least near the separatrix, that the neutral damping can be comparable to the neoclassical damping rate.

The relatively large neutral density also means that neutrals carry out a significant amount of power. It has been long recognized that bolometric measurements also include some neutral power flux. This neutral component has been recently measured by using a second type of bolometers (i.e. photodiodes), which are insensitive to neutrals but are normally sensitive to photon radiation. Since the two bolometric arrays have a similar tangential coverage (i.e. giving a radial profile after Abel inversion), the local power emissivity due to neutrals is obtained by comparing the two emissivity profiles. While technically the inversion is not strictly valid, the plasma being mostly opaque to neutrals, the results are approximately correct because the neutrals are largely coming from the extreme edge of the plasma. Shown in Figure 5 are the neutral power emissivity profiles shown for L and H-mode (ELM-free) phases within a same discharge. As expected, almost all the neutral power emissivity originates from the edge of the plasma. The edge neutral emissivity is mainly determined by the nominal 2cm radial resolution of the bolometers, although it is expected that the width of the edge neutral emissivity should peak dramatically with the presence of a sharp H-mode density pedestal. In addition, we performed some numerical simulations involving a 1-D Monte-Carlo neutral transport code which takes into account charge-exchange and ionization, and uses as inputs the neutral pressure at the wall, density and temperature profiles in the main plasma and scrape-off layer. We obtained very good agreement (within 25%) in local power emissivity versus the measured quantity[5]. The localization of these losses is also important. Simulations indicate that nearly 50% of the power carried by neutrals should originate from outside the top of the pedestal. However, since the pedestal width found in Alcator C-Mod is only a few millimeters wide, it is presently difficult to verify that directly with the bolometers.

Summary

New dedicated diagnostics and modeling have been implemented on Alcator C-Mod for the purpose of studying the effects of neutrals on the edge dynamics. We found that neutral particles are contributing in the onset and evolution of an H-mode in Alcator C-Mod. Analysis of particle, momentum and energy balance indicates that neutrals can modify the ion dynamics, because of their relatively large number in the edge (near 0.1%), and because of their strong coupling through charge-exchange. However, these effects are not all detrimental to the formation of an H-mode pedestal (e.g. increased ionization rate inside the separatrix), and consequently, they are not easily recognizable. We plan to extend this study on the so-called low and high-density limits, where neutral effects should be most visible. In contrast, these effects should be minimal in pure helium H-modes (ICRF heated).

Acknowledgement

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References

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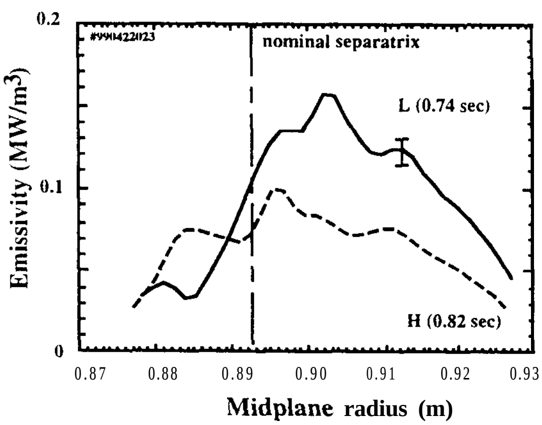

Figure 1: Measured Lyman-o: emissivity profile near the outer midplane. Shown are 2 phases of the discharge, L and H-mode. Also shown is the nominal location of the separatrix.

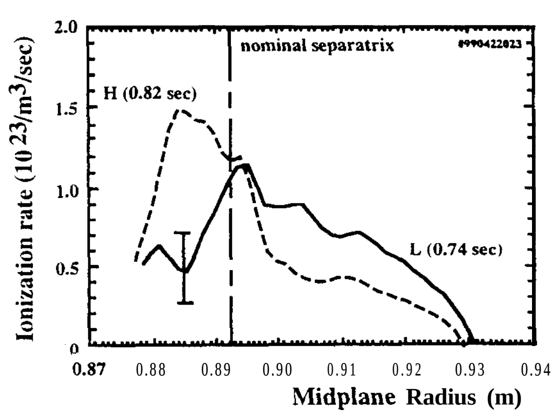

Figure 2: Measured ionization rate profile obtained from the Lyman- a measurement shown in Fig.1.

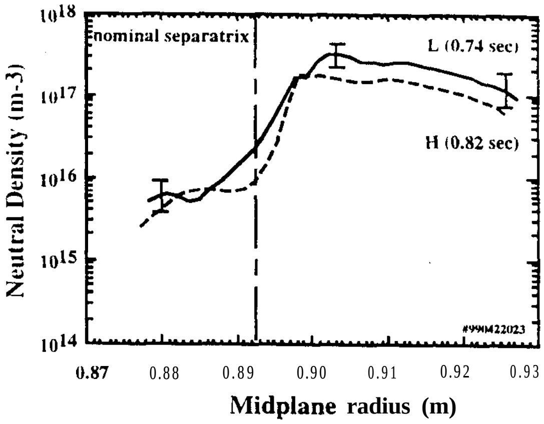

Figure 3: Measured neutral density profile obtained from the Lyman-α measurement shown in Fig. 1.

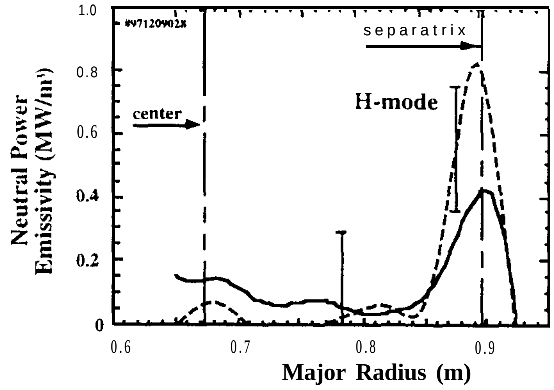

Figure 5: Measured power emissivity profiles for L and H-mode phases of a same discharge.

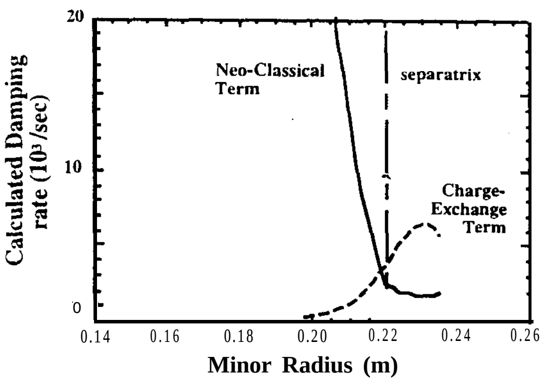

Figure 4: Calculated damping rate profiles for the neo-classical and neutral terms near the edge of a high density L-mode. In this case, the neutral density at the edge approaches $3x10^{17}/m^3$, and line average density is $4x10^{20}/m^3$.