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The Effect of ICRF on the Alcator C Scrape-Off Layer Plasma

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ABSTRACT

This paper presents a characterization of the Alcator C Scrape-Off Layer (SOL) plasma during ICRF hydrogen-minority fast wave heating experiments. The SOL plasma parameters were measured using a multifunctional probe, JANUS, which is capable of simultaneously measuring the ion and electron parameters both parallel and antiparallel with respect to the toroidal magnetic field. The probe data indicate, at low value of injected rf power, there is direct edge heating and density increases at radii greater than that of the antenna Faraday shield. Increasing the injected rf power spreads both the temperature and density increases throughout the edge region, flattening the radial profile. Varying the position of the resonance layer in the main plasma does not significantly change the effect of ICRF on the SOL parameters. Given this single spatial point characterization of the SOL, a crude estimate of power flow into and through the edge plasma indicate that $\approx 20\%$ of the ICRF power launched from the antenna is absorbed directly in the SOL plasma. Additional observation of the impurity source rates confirms the conclusions of an earlier paper, which attributed increasing central densities of high-Z impurities to the increase in physical sputtering rate at both the ICRF antenna's Faraday shield and the limiter surface.

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1. Introduction

Demonstration of successful bulk plasma heating in the ion cyclotron range of frequencies (ICRF) is important for future reactor applications. One of the major obstacles preventing significant bulk heating is the amount of input power directly lost through radiation resulting from generation of large quantities of high-Z impurities during both ICRF [1-7] and other rf heating schemes [8,9]. In order to understand the physics of wave coupling and impurity generation, it is important to measure the effect of the rf on the edge, or scrape-off layer (SOL) plasma and to understand the mechanisms of impurity generation.

The primary purpose of this paper is to examine the effect on the SOL plasma of waves launched from a fast wave antenna used on Alcator C. A previous paper [1] presented a study of impurity behavior during an earlier fast wave ICRF experiment conducted in 1984. This paper characterizes the SOL plasma parameters for recent (1985-86) ICRF experiments, and discusses the correlation of changes in the SOL with possible wave damping mechanisms in the SOL and impurity release mechanisms. Section 2 briefly describes the edge diagnostics used for this study along with description of the fast wave ICRF antenna. The experimental results will be presented in Section 3, with emphasis placed on the results of the fast wave experiment operating in second harmonic hydrogen regime of a plasma minor radius of 11.5 cm. Section 4 presents some possible explanations to the observed phenomena.

2. Experimental Setup

During the experiments, the plasma parameters in the SOL of Alcator C were monitored using a bidirectional, multifunctional edge probe, herein denoted by Janus [10]. Janus has two mirror-image sets of diagnostics; each set consists of a Langmuir probe, a retarding-field energy analyzer (RFEA), and a calorimeter. For convenience, the two sides of Janus, which are aligned in the toroidal direction, are denoted herein by the drift direction of electrons (the electron side) and ions (the ion side) relative to the plasma current, I_p . For the experimental setup of Janus, the electron side connection length to the nearest limiter is twice as long as

the ion side value. Typically the toroidal magnetic field (B_ϕ) is aligned antiparallel with respect to I_p and $\underline{B}_\phi \times \nabla B_\phi$ is directed upward.

Janus was inserted from the top of the machine, directly over the magnetic axis. In this configuration, large electron side/ion side parameter asymmetries were observed. Higher ion and electron temperatures and densities at the probe location occur on the electron side when B_ϕ is antiparallel to I_p . The direction of B_ϕ with respect to I_p , and variation of the plasma in-out position, change the magnitude of the asymmetry. Details of the effect of connection length and magnetic field direction on the edge plasma are discussed in Ref. [11].

The Langmuir probe is used to provide a measurement of the electron temperature, T_e , along with measurements of the plasma ion density, n_i , and the plasma floating potential, V_{float} . The RFEA is used to characterize the parallel energy distribution of the ions and electrons, which are well fit by Maxwellian with a characteristic temperature. The calorimeter provides data on the parallel heat flux incident onto an electrically isolated plate. The bulk of the T_e data presented in this paper consists of measurements with the Langmuir probes.

The measurement of the impurity behavior was made using a 2.2 meter grazing incidence time-resolving vacuum ultra-violet (VUV) spectrograph, which monitors impurity line radiation [1,12]. For the ICRF experiments described here, the VUV spectrograph monitored the spectral range from 30 – 600 Å, which includes an iron line (Fe^{+15}) at ~ 361 Å and a molybdenum line (Mo^{+12}) at ~ 341 Å. Impurity line brightnesses are measured from a horizontal central chord line of sight.

Figure 1a presents a view from the top of Alcator C, showing the locations of limiters, the grazing incidence VUV spectrograph, ICRF antenna, and Janus. The ICRF fast wave antenna is a half-wavelength resonant loop antenna located at the bottom half plane of Alcator C, at the same toroidal position as Janus. The radial locations of the antenna, limiter and wall components, and Janus are shown in Fig. 1b. The Faraday shields are made of stainless steel, with the outer shield coated with molybdenum. The innermost radial edge of the Faraday shield was located at 13.0 cm in minor radius.

During the ICRF experiments, the antenna is configured to study the heating in second harmonic hydrogen, typically operating at ~ 25 MHz. The magnitude

of the toroidal magnetic field varied from 7 to 8 tesla, allowing the position of the cyclotron resonance layer for second harmonic hydrogen to shift in in major radius. The line-averaged electron density ($\bar{n}_e$) is typically at $2.2 - 2.8 \times 10^{14} \text{ cm}^{-3}$, and I_p at 210-250 amps. The ohmic input power was typically of order 400 kW.

3. Experimental Results

3.1 Edge Parameter Variations

The Janus probe could scan radially across the fast wave antenna radius and measure plasma parameters between the antenna and the limiter edge (see Fig. 1b). The probe location is defined by the minor radial position of the RFEA entrance slit and Langmuir probe tip. For this paper, the region between the antenna and the limiter ($11.5 \leq r < 13.0 \text{ cm}$) is herein designated as the limiter zone, and the region extending beyond the Faraday shield ($r \geq 13.0 \text{ cm}$) is defined as the antenna zone.

Plotted in Fig. 2 are typical time histories of T_i and T_e on both the electron and ion sides with the probe located at 12.6 cm. The rf pulse (460 kW) lasts from $\sim 210 - 310 \text{ ms}$. During ICRF injection, the electron temperature on both the electron side (T_e^e) and ion side (T_e^i) rises sharply. Increases in electron temperatures were $\Delta T_e^e \sim 15 \text{ eV}$, and $\Delta T_e^i \sim 30 \text{ eV}$ (where superscript denotes side of probe). Due to limitations of the probe power supply, a value for T_e which exceeds 40-50 eV is difficult to resolve. The electron temperatures at this position, as determined by the RFEA, approximately agree with those measured by the Langmuir probe. The distribution function remains approximately Maxwellian. The RFEA also measures T_i during the rf pulse; $\Delta T_i^e \sim 0$ and $\Delta T_i^i \sim 30 \text{ eV}$. No significant density variations during ICRF were observed at this radius. In addition, the ion side V_{float} increased by $\sim 15 \text{ volts}$, although the electron side V_{float} exhibits no major variation during the rf pulse. The edge parameters return to approximately the pre-rf values immediately (within one Janus sweep period: $\sim 5 \text{ ms}$) after the termination of the rf pulse.

Over a series of similar discharges with ICRF injection, radial profiles of edge parameters and their changes during the rf pulse were measured. Figure 3 is a plot

of such profiles for a low value of injected rf power (95 kW). Electron and ion side parameters are designated by circles and triangles respectively. The solid and open symbols correspond to parameters averaged during and without ICRF injection. For this set of discharges, $\bar{n}_e = 2.7 \times 10^{14} \text{ cm}^{-3}$, $I_p = 250 \text{ kA}$, the fuel gas is hydrogen, and the toroidal field ($= 7.3 \text{ tesla}$) is such that the cyclotron resonance layer for second harmonic hydrogen is $\sim 5.5 \text{ cm}$ outward in major radius from the plasma axis.

Radial scans without ICRF have typically shown the radial profiles of edge parameters to monotonically decay as a function of minor radius; thus the source of edge energy without rf is inferred to be predominantly due to perpendicular transport from the bulk plasma [13-15]. However, when the rf is turned on, figures 3a and 3b show large increases of T_i^e and $T_e^{e,i}$ in the antenna zone. It is difficult to measure T_i^i in the antenna zone due to low signal to noise. In the limiter zone, the temperature profiles still resemble the pre-rf profiles, although the magnitudes of both T_i and T_e increase slightly when the rf is turned on. One logical explanation for these temperature increases is that there is a local energy source (e.g. rf heating) in the antenna zone during the rf pulse.

When the ICRF is turned on, the densities on both the electron and ion sides in the limiter zone drop while the scrapeoff length remains approximately constant. No noticeable plasma position shifts were observed to explain these density reductions. However, in the antenna zone, differing effects are found. During the rf pulse, the electron density is observed to increase on the ion side with accompanying decreases occurring on the electron side. There appears to be a localized particle source in the antenna zone which increases the flux of particles to the ion side of the probe, and/or a bulk plasma flow in the direction of the plasma current.

Figure 4 shows the effect of increasing the total rf power to 460 kW. The central parameters averaged over the rf pulse period are changed slightly from those quoted for the low power rf shot data shown in Fig. 3; $\bar{n}_e = 2.3 \times 10^{14} \text{ cm}^{-3}$ and $I_p = 217 \text{ kA}$, but the initial edge parameters (before rf) stay approximately constant. The radial profiles of edge parameters for these high power discharges are significantly different than the case shown in Fig. 3. The electron temperatures measured on both the electron and ion sides of the probe in the antenna zone still are (Fig. 4c,d)

elevated over the pre-rf values. Now, however, T_e also increases in the limiter zone. Similar changes in the ion side ion temperature (T_i) (Fig 4b) is also found.

The increase in rf power also causes changes in the edge density profiles (Fig. 4e,f). A flattening of the density profile in the SOL on both the electron and ion sides is now observed. The density still drops slightly near the limiter radius. However, from $r = 12.6$ cm and outward, the electron and ion side plasma densities during rf both exceed the pre-rf values.

Keeping the operating parameters at roughly the same values, a toroidal magnetic field scan was performed. When the toroidal field strength is increased, the cyclotron resonance layer is shifted from the high field side toward the low field side. In this field scan the resonance layer positions for the second harmonic resonance positions were 2.6 cm, 5.5 cm, and 8.4 cm outward in major radius from the magnetic axis, toward the low field side. For a total injected power of $\sim 400 - 460$ kW, no clear differences in the edge or central plasma parameters were observed. The radial profiles of all SOL parameters resemble the data presented in figure 4.

Figure 5 shows the change in T_i , T_e , and n (normalized to its pre-rf value) during the ICRF pulse as a function of the input ICRF power. Janus was located in the limiter zone at $r = 12.8$ cm for this set of data. In general, the increases of temperatures (ion and electron) measured by the ion side detectors were greater than that measured on the electron side. There does not appear to be any trend in the ΔT_i data (Fig. 5a) with increasing amounts of injected rf power. There may be a slightly increasing trend with rf power for ΔT_e (Fig. 5b).

At low values of input power, there is a trend toward decreasing $(\Delta n)/n$ as a function of rf power (Fig. 5c). However, this trend starts to reverse near 350 kW. At high power levels of injected rf power, $(\Delta n)/n$ becomes positive. The relative change of density is more pronounced on the ion side. The reversal of $(\Delta n)/n$ may be due to the effect of increasing amounts of injected rf power on the profile shape (figures 3 and 4). The flattening of the density profile extends closer to the limiter, and thus to a probe located in the limiter zone, at higher values of injected rf power.

3.2 Effects of the ICRF Fast Wave Injection upon Impurities

For a high rf power ($P_{rf} \sim 450$ kW) fast wave heating discharge using the second harmonic hydrogen mode, Fig. 6 displays the time histories of the central chord brightnesses of the lines from ionization states of molybdenum (Fig. 6a) and iron (Fig. 6b) located in the plasma periphery ($r \geq a$). During the ICRF (417 kW) pulse, the brightnesses of the Fe and Mo lines increased by factors of ~ 5 and 7 respectively. In particular, the Mo brightness shown is proportional to the Mo source rate at the plasma edge. The possible sources of iron are the inner Faraday shield, the wall, or Fe deposited on the limiters.

In reference 1 it was hypothesized that the most likely process by which iron is removed from the material surfaces surrounding the plasma is physical sputtering. Preliminary probe results presented in that paper were consistent with that conjecture. In this paper, a much more detailed probe survey of the edge plasma during ICRF heating is made which reinforces this conclusion. T_e , T_i , λ_{T_e} , and λ_{T_i} all increase during the rf pulse. The nonlinear relationship between T_e ($\propto$ sheath potential), T_i , and sputtering rate [16], imply a much greater increase in the sputtered Mo source rate at the Faraday shield. A further confirmation that sputtering is the dominant impurity release mechanism is the time correlation between the behaviors of the edge ion temperature (ion side, $r = 12.8$ cm) and impurity brightness during the rf pulse (figures 6a-c). The impurity brightness shown can be interpreted as approximately proportional to their corresponding edge source rate [1]. The time behavior of the injected rf power correlates strongly with ion temperature and impurity brightness time histories. When the rf power is constant, the edge ion temperature and the impurity source rate are constant. When arcing shuts down the rf operation in the middle of the pulse, both the edge T_i and impurity emissions drop abruptly, and all resume to pre-arcing levels when rf injection resumes. This behavior is to be compared with the process of evaporation, which for the same P_{rf} and $T_{i,edge}$ behavior, would cause a nonlinearly increasing evaporation source rate.

4 Discussion

It is clear that ICRF heating causes localized effects in the edge plasma. These effects spread radially through the edge region as the amount of injected rf power is increased. One implication of this result is that some fraction of the injected rf power is coupled directly to the edge plasma. From the data of Fig. 4, and assuming a poloidal symmetry and a standard model for the power flow through the sheath at the limiter surfaces [17], a very crude estimate for the increased power flow to the limiter surfaces is found to be approximately $P_{lim} = 45$ kW (at $P_{rf} = 460$ kW). The increased power flow to the limiter surface, ΔP_{lim} , is related to rf power directly coupled to the edge plasma ($P_{edge,rf}$) and the change in power flowing to the edge plasma from the main plasma ($\Delta P_{edge,main}$) through the following equation:

$$\Delta P_{lim} = \Delta P_{edge,main} + P_{edge,rf}. \quad (1)$$

$\Delta P_{edge,main}$ is estimated on the basis of extrapolating the measured density and temperature profiles to the limiter radius. Then the convective and conductive heat flow into the edge plasma can be calculated. From this estimate, $\Delta P_{edge,main} \approx -50$ kW during the rf pulse. The implication, from equation 1, is that $P_{edge,rf} \approx 100$ kW. The uncertainty of this result is quite large given the assumptions of poloidal symmetry, constant electron thermal conductivity ($\chi \approx 4 \times D_{\perp}$) and extrapolation of probe data to the limiter radius. Nevertheless, it is quite possible that a large amount ($\sim 20\%$) of the rf power is directly coupled into the edge plasma. Furthermore, the temperature increases observed in the antenna region for the low rf heating regime (Fig. 3) also support the possibility of direct rf heating in the scrape-off layer.

Just what could cause such strong coupling of rf waves to the edge plasma is not well understood although several mechanisms have been suggested [1-7]. For example, components of the antenna's spectral power density that are not well matched to propagating waves in the main plasma can couple to surface modes at the plasma periphery. From the observed changes in the electron temperature profile in the SOL plasma (figures 3 and 4), such surface, or cavity modes, clearly have a sharp radial dependence. The stored energy in these modes can be coupled to the

SOL particles by processes such as collisional damping, Landau damping, turbulent heating, or nonlinear coupling to evanescent, short-wavelength waves, and therefore result in direct heating of the edge plasma by the rf.

5 Conclusions

For fast wave experiments with 11.5 cm (radius) molybdenum limiters, radial profile measurements at low rf power indicate direct edge heating at the radial location of the antenna. Increases in measured values of electron density on the ion and electron sides of the probe are found which are indicative of either a localized particle source and/or bulk plasma flow. Near the limiter radius the edge density decreases during rf and the temperature increases are smaller than in the antenna region. The strong edge heating and density increases extend beyond the antenna region, toward the wall, and into the limiter region (between the antenna and the bulk plasma), when the input rf power is increased. Varying the position of the ICRF resonance layer had no significant effect on either the edge or central plasma conditions.

A crude power accounting model for the edge region shows that for large amounts of injected rf power ($P_{rf} > 350 \text{ kW} \approx P_{ohmic}$), approximately 20% of the total ICRF power may be absorbed directly in the edge region. This result has quite large uncertainties because of the number of assumptions used in interpreting the probe data. At lower values of injected power the calculation becomes even more difficult.

Large increases in the concentration of high-Z impurities from both the limiters and ICRF antenna were observed during ICRF experiments. The impurity increases are most likely caused by increasing physical sputtering due to the correlation of the observed T_e , T_i , and impurity emission increases in the scrape-off layer plasma.

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Figure Captions

- [Figure 1.] Figure 1a shows a top view of the Alcator C including the relative toroidal positions of the limiters, Janus, the VUV spectrograph, and the ICRF antennas. Figure 1b shows the relative radial positions of the fast wave antenna, limiters, wall, and Janus.
- [Figure 2.] Time histories of edge temperatures measured during an ICRF wave heating experiment: a) T_i (electron side), b) T_i (ion side), c) T_e (electron side), and d) T_e (ion side).
- [Figure 3.] Radial profiles of edge parameters for a series of fast wave heating discharges ($P_{rf} = 95$ kW): a) T_i (electron side), b) T_i (ion side), c) T_e (electron side), d) T_e (ion side), e) n_e (electron side), and f) n_e (ion side).
- [Figure 4.] Radial profiles of edge parameters for a series of fast wave heating discharges ($P_{rf} = 460$ kW): a) T_i (electron side), b) T_i (ion side), c) T_e (electron side), d) T_e (ion side), e) n_e (electron side), and f) n_e (ion side).
- [Figure 5.] Scaling of edge parameter changes with amount of injected rf power: a) T_i , b) T_e , and c) $(\Delta n)/n$.
- [Figure 6.] Correlation of impurity brightness time histories with edge ion temperature: a) Mo^{+12} , b) Fe^{+15} , and c) T_i . The rf power stops and starts midway through the pulse.

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(a)

(b)