ICRF-Enhanced Plasma Potentials in the SOL of Alcator C-Mod

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Abstract. We performed an extensive survey of the plasma potential in the scrape-off layer (SOL) of Ion Cyclotron Range-of Frequencies (ICRF)-heated discharges on Alcator C-Mod. Our results show that plasma potentials are enhanced in the presence of ICRF power and plasma potential values of >100 V are often observed. Such potentials are high enough to induce sputtering of high-Z molybdenum (Mo) plasma facing components by deuterium ions on C-Mod. For comparison, the plasma potential in Ohmic discharges is typically less than 10 V, well below the threshold needed to induce Mo sputtering by deuterium ions. ICRF-enhanced plasma potentials are observed in the SOL regions that both magnetically map and do not map to active ICRF antennas. Regions that magnetically map to active ICRF antennas are accessible to slow waves directly launched by the antennas and these regions experience plasma potential enhancement that is partially consistent with the slow wave rectification mechanism. One of the most defining features of the slow wave rectification is a threshold appearance of significant plasma potentials (>100 V) when the dimensionless rectification parameter $\lambda_o$ is above unity and this trend is observed experimentally. We also observe ICRF-enhanced plasma potentials >100 V in regions that do not magnetically map to the active antennas and, hence, are not accessible for slow waves launched directly by the active antennas. However, unabsorbed fast waves can reach these regions. The general trend that we observe in these “un-mapped” regions is that the plasma potential scales with the strength of the local RF wave fields with the fast wave polarization and the highest plasma potentials are observed in discharges with the highest levels of unabsorbed ICRF power. Similarly, we find that core Mo levels scale with the level of unabsorbed ICRF power suggesting a link between plasma potentials in the SOL and the strength of the impurity source.

Keywords: ICRF, plasma potential, SOL, sheath rectification, Alcator C-Mod.

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INTRODUCTION

An extensive assessment of ICRF-heated discharges on Alcator C-Mod reveals that plasma material interactions become enhanced by the presence of ICRF power. Specifically, sputtering of plasma facing surfaces and impurity levels in the plasma core increase with the application of ICRF power [1, 2]. The leading mechanism suspected of causing enhanced sputtering is the rectification of the plasma sheath on open magnetic field lines: oscillating electric fields aligned parallel to the magnetic field ($E_b$) becomes rectified at the plasma sheath and the net result of the rectification is the development of an electron repelling DC potential [3]. These DC potentials begin to accelerate incident ions toward the surface, which leads to enhanced sputtering. While enhanced plasma potentials ($\Phi_P$) of greater than 100 V (high enough to induce sputtering of high-Z molybdenum surfaces by deuterium ions on C-Mod) are observed in ICRF-heated discharges it is not clear what aspects of the ICRF power lead to the observed enhancement [2, 4]. The goal of the paper is to experimentally deduce what mechanisms are responsible for the observed enhancement of the plasma potential.

DIAGNOSTICS DESCRIPTION

In order to achieve our goal we installed multiple stationary and radially scanning probe stations in the SOL region of Alcator C-Mod to determine what role local plasma properties play in enhancing the plasma sheath. Emissive probes and ion sensitive probes were used to measure the plasma potential, Langmuir probes were used to measure the plasma density and the electron temperature, and B-dot probes were used to measure ICRF wave fields with fast and slow wave polarizations. Measurements were made on plasma flux tubes that directly magnetically map and do not map to active ICRF antennas. The ICRF antennas were operated at ~80 MHz in both dipole and monopole phasing and the heating scheme was minority (hydrogen) heating in deuterium plasmas.
EXPERIMENTAL RESULTS AND DISCUSSION

There are several proposed mechanisms that may generate $E_p$ in ICRF-heated discharges on open magnetic field lines. One mechanism involves the generation of slow waves (with a non-zero $E_{\parallel}$) directly by the active ICRF antennas: this process is expected to enhance the plasma potential only on plasma flux tubes that directly magnetically map to the active antennas [5, 6]. One of the most defining features of the slow wave enhancement is the threshold appearance of large plasma potentials when a characteristic plasma sheath parameter $\Lambda_o$ is above unity. An experimental scan of $\Lambda_o$ on plasma flux tubes that directly map to the active antennas reveals the existence of such a threshold, which, in part, confirms the slow wave theory (Fig. 1). $n_e$ is the plasma density. $\Delta_{\text{probe}}$ is the probe radial position (mapped to the midplane) with respect to the limiter plasma facing surface position: $\Delta_{\text{probe}} = R_{\text{probe}} - R_{\text{Limiter}}$, $R_{\text{Limiter}} = 0.910$ m at the midplane. The theoretical estimate is equal to the sum of the ICRF-enhanced plasma potential, as estimated in [5], and the thermal plasma potential ($\Phi_{\text{th}}$, $\Phi_{\text{th}} = 3*T_e$, where $T_e = 10$ eV is the electron temperature in the vicinity of the limiter on Alcator C-Mod.

However, we also measure significant plasma potential enhancement on plasma flux tubes that do not directly magnetically map to the active ICRF antennas (Fig. 2). Fig. 2 demonstrates a time history of a single discharge and shows the launched ICRF power ($P_{\text{RF}}$), the core electron temperature, the fast wave amplitude ($|E_{\text{RF, FW}}|$), the slow wave amplitude ($|E_{\text{RF, SW}}|$), and the plasma potential. The slow wave theory cannot account for this enhancement as the slow waves directly launched by the active antennas cannot reach these locations. $B$-dot measurements reveal a presence of fast ICRF wave fields in these “un-mapped” locations and the enhanced plasma potentials show a strong correlation to the strength of the local fast wave fields. While the fast wave does not have the necessary polarization to enhance the plasma potential on open magnetic field lines ($E_{\parallel} = 0$ for the fast wave), a proposed theory involves a fast-to-slow wave coupling at conducting surfaces [7-9].

![FIGURE 1](image_url)

**FIGURE 1.** Experimentally determined trend between $\Phi_p$ and $\Lambda_o$. The probes are mapped to the active antenna. The theoretical estimate is for realistic Alcator C-Mod parameters as in [5]. $\Delta_{\text{probe}}$ is the relative radial position of the probe with respect to the limiter surface: $\Delta_{\text{probe}} = R_{\text{probe}} - R_{\text{Limiter}}$. $R_{\text{Limiter}} = 0.910$ m at the midplane. $n_e$ is the plasma density.
A key prediction of the fast wave rectification theory is the appearance of plasma potential gradients ($\nabla r \Phi_P$) across surfaces with a changing geometry with respect to the background magnetic field. An example of such a surface is the plasma facing side of the limiter or the limiter tip. The component of the magnetic field that is normal to the surface ($b_x$, normalized to the total magnetic field) changes from nearly unity far from the tip to zero at the very tip. It is experimentally observed that large radial electric fields ($E_r \sim V_r \Phi_P$) appear in ICRF-heated discharges across the limiter tip region (Fig. 3). The edge safety factor ($q_{95}$) was scanned to determine the dependence of the plasma potential on the poloidal mapping along the limiter surface. The data in Fig. 3 is shown for two levels of ICRF power: open symbols are for $P_{RF} = 0.5$ MW and solid symbols are for $P_{RF} = 1$ MW. This result is in agreement with the fast wave rectification theory [7-10].

![Figure 2](image-url)

**FIGURE 2.** A time history of (a) the RF power, (b) the core electron temperature, (c) the fast wave amplitude, (d) the slow wave amplitude, and (e) the plasma potential during a single ICRF-heated discharge (dipole). The probes are unmapped to the active antennas.

We generally observe that ICRF-heated discharges heated with an ICRF antenna in monopole phasing generate higher plasma potentials than discharges heated with the same amount of ICRF power in dipole phasing (Fig. 4). The plasma potential values correspond to the peak $\Phi_P$ values across the limiter tip region. The monopole-heated discharges are characterized by poor ICRF wave absorption in the plasma core, thereby increasing the level of unabsorbed fast ICRF wave fields in the SOL region. Simultaneously, we observe an increase in the core impurity contents (molybdenum or Mo) that originate from plasma facing components (Fig. 4). These results suggest a link between the level of unabsorbed fast wave fields in the SOL, the strength of the plasma potential enhancement in the SOL, and the strength of the impurity source on Alcator C-Mod. However, it is currently not clear what surfaces...
dominate the impurity source as locations that are mapped and unmapped to the active ICRF antenna experience plasma potential enhancement. Our results suggest that it is crucial to operate ICRF heating in a strong single pass absorption regime to minimize the presence of fast ICRF wave fields in the SOL.

![Graph](image)

**FIGURE 4.** The core Mo signal normalized to the core plasma density as a function of the peak plasma potential values across the radial dimension of the limiter tip. The discharges are either Ohmic or ICRF-heated with the active antenna in either dipole or monopole phasing. The probes are unmapped to the active antenna. Vertical and horizontal bars are representative of the measurement errors.

**SUMMARY**

To summarize, our experimental assessment of the plasma potential enhancement in the SOL of ICRF-heated discharges on Alcator C-Mod reveals that the fast ICRF waves play a significant role in enhancing the plasma potential to values high enough to generate sputtering of plasma facing surfaces in regions that are non-local to the active antennas. Although we have yet to determine the regions that dominate impurity production in ICRF-heated discharges on C-Mod we observe a general trend that both the plasma potential and the core impurity contents increase with the level of unabsorbed ICRF power. Our results suggest that in order to minimize the effects of ICRF power on the core plasma performance it is crucial to operate in the high single pass absorption regime.

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**REFERENCES**