ICRF-induced Radial Electric Fields in the Far Scrape-Off-Layer of Alcator C-Mod

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Abstract: By observing, with 2D Gas-Puff-Imaging, the radial structure in the poloidal dynamics of the SOL turbulence during the application of ICRF power (0.15 MW < P_{ICRF} < 3 MW), we find that the ICRF application results in a fine-scale radial structure of the poloidal phase velocities (V_{pol}) of the broadband turbulence. The radial profiles are very different from typical profiles in Ohmic plasmas. Attributing the V_{pol}(r) to ~6MW of cyclotron waves and the plasma that are not understood. The radial extent is found to be significantly larger than the basic theoretical expectation; radial penetration distance, \lambda_v, is \approx 5x\delta_e, where \delta_e is the skin depth for RF waves in the C-Mod far SOL. The fields induced by different active antennas are superposed depending upon the magnetic mapping between the observation region and the antennas. The ICRF-induced fields of two antenna geometries are compared, and changes in impurity penetration due to the presence of the fields are examined.

1. Introduction

Heating using the Ion-Cyclotron-Range-of-Frequencies (ICRF) is one of few viable auxiliary heating methods for achieving thermonuclear fusion-grade magnetically-confined plasmas. Indeed, a significant portion of the auxiliary heating planned for ITER is from ICRF. Alcator C-Mod relies on ICRF heating for most of its heating power, employing three antennas for up to ~6MW of coupled power. While ICRF-heating has been an efficient and reliable heating method on C-Mod, there are many areas in the complex interaction between the launched waves and the plasma that are not understood. While increases in DC plasma potential induced via sheath rectification of the radiated RF waves has been observed for many years and while 2D patterns of electric fields generated by this mechanism have been confirmed to exist in the vicinity of energized RF antennas [1-8], there is still no verified predictive capability for these fields, and their effects on the edge plasma are not well understood.

Additionally, plasmas with strong ICRF heating and high-Z PFCs have often suffered from increased core impurity concentrations that result from the ICRF[9-11]. Enhanced sputtering due to the ICRF enhancement of plasma potentials have long been thought of as the primary cause for the increased concentrations. However, the observations of 2D ICRF-induced electric fields and theoretical considerations of convective cells connected with such fields
[12-15] have raised the possibility that transport modifications that increase the penetration of impurities may also be playing an important, or even dominant, role. Thus the experimental investigation of the properties of the ICRF-induced fields is of both scientific and practical interest, since ITER (as well as DEMO) will have some high-Z PFCs and optimized antenna designs are desirable. The work presented here concerns our observations of the 2D RF-induced fields in C-Mod. It is motivated by the desire to understand the role these fields play in the impurity issues associated with ICRF-heating.

The paper is organized with an initial explanation of the measurements as well as a description of the geometry of the C-Mod RF antennas and measurement location (Section 2). Section 3 describes the scaling of the induced potentials with launched power and their dependence on antenna geometry. Finally, in Section 4 we discuss the results of experiments testing the penetration of impurities at various RF power levels and induced-field strengths.

2. Experimental details of the measurements

The determinations of ICRF-induced radial electric fields come from analysis of the poloidal dynamics of the SOL turbulence as measured using Gas-Puff-Imaging. For the results presented here we utilize two imaging diagnostics, both viewing a local gas puff from a nozzle just below the outboard midplane. The primary imaging diagnostic, GPI-APD [16], measures puffed He I (587 nm) emission utilizing a 9x10 2D array of views that is coupled to fast APD detectors. Also used is a fast-camera-based system (“GPI-camera”) with higher spatial resolution (~ 2 mm vs ~4 mm for GPI-APD), but with slower temporal resolution (190 kHz vs 1 MHz for GPI-APD). The GPI-camera is used in this application to measure the source emission (N II –

Figure 1: (a) Poloidal X-section of C-Mod at the GPI toroidal location. GPI views are oversize for clarity. (b) Top view of C-Mod showing the GPI view in relation to the ICRF antennas. (c) Rollout of the toroidal locations of the antennas and GPI view along with the field-line that maps from the GPI view to its “just piercing” location on the FA-J antenna. The “J antenna” (in gray behind the “FA-J ant”) was replaced by the “FA-J ant” in early 2012. Note that the straps of the “J antenna” were vertical, while those of the “FA-J ant” are perpendicular to the local field-line for $q_{95}=3.8.$
567 nm) from N seeded in the puffed He. This is used for evaluations of impurity penetration efficiency (Section 4). Fig. 1 shows the poloidal cross-section of the GPI view and nozzle in the plane of GPI-viewed area. The GPI view is toroidally removed from the three ICRF antennas, as illustrated schematically in Figs. 1b and 1c. In 2012 the “J antenna” was replaced by a “field-aligned” antenna, the “FA-J ant”, whose four current straps and antenna box structure are perpendicular to the total magnetic field (for q95~3.8)[17]. C-Mod’s pre-2007 ICRF system is described in [18]. One of the primary motivations for installing the field-aligned antenna was to reduce unwanted parallel RF electric fields (E), the very field whose sheath rectification gives rise to the RF-induced plasma potentials that are examined in this work. This was intended to thereby reduce the impurity concentrations associated with high-power heating. Indeed reduced impurity concentrations associated with the activation of the field-aligned antenna are observed [17].

The GPI-APD 2D array of views yields radial profiles of frequency- and poloidal wavenumber-resolved spectra of emission fluctuations [16, 19]. The emission fluctuations result from density (primarily) and temperature fluctuations in the local background plasma. In the far SOL, turbulence that leads to these fluctuations is convected at the local ExB velocity, which is \( \approx 3\delta r T_e/(eB\phi) \) if there are no externally imposed potentials, since the electrostatic potential is \( \phi \approx 3T_e/e \). At the outboard midplane, this ExB flow is directed downward for C-Mod’s normal B_\phi direction, and upward in a reversed-B_\phi configuration. In Ref [16] it was shown that the turbulent structures in the far SOL of C-Mod do indeed move at the ExB velocity associated with the T_e gradient. In the absence of independent measurements of the local plasma potential during ICRF heating, it is assumed that the turbulent structures still move at the E \times B velocity. The time- and space-resolved spectra resolve features propagating poloidally upward (k, > 0) or downward (k, < 0). Since we are interested in measuring the phase velocities of the turbulence as manifested in the GPI signals, we give equal weight to each frequency in the (10-250 kHz) band of interest by normalizing at each frequency by the sum over k, at that frequency, creating “conditional” spectra, such that \( S^\text{cond}(k,f)=S(k,f)/\Sigma_k S(k,f) \).

Examples of \( S^\text{cond}(k,f) \) spectra are shown in Fig. 2 for three adjacent

![Figure 2: (a) S^\text{cond}(f,k) spectra from three adjacent R_maj or columns of GPI views of the far SOL during ICRF heating. (b) The profile of V_e(r) derived from such spectra (V_e - diamonds, V_r - squares). The E_r values are referenced to the ordinate axis on the right. The red line is the location of the innermost field-line in the GPI view that pierces the active antenna. The blue band is the typical range for V_e and E_r Ohmic plasmas. IDD (EDD) are the ion (electron) diamagnetic drift directions, respectively.](image-url)
radial locations in the far SOL within the GPI-APD field-of-view. Straight lines passing through \( f=0, k_z=0 \) are lines of constant phase velocity for all frequencies, and contours of \( \mathcal{S}^{\text{cond}}(k, l, f) \) that align with such straight lines are lines indicative turbulence propagating at that phase velocity. As seen in Fig. 2a the measured spectra from the far SOL show that such constant phase velocities typically obtain, although as shown in panel 2(b), there can be both upward-propagating and downward-propagating features within each radial column of views. By integrating the conditional spectrum along all possible lines of constant phase velocity, we can determine the dominant constant phase velocity, \( V_{\theta(\cdot)}^{\text{dom}} \), for each propagation direction in the spectrum, shown as the black dashed lines in Fig. 2(a). As shown in Fig. 2b, the \( V_{\theta(\cdot)}^{\text{dom}} \) and \( E_r (=V_{\theta(\cdot)}^{\text{dom}} B_{\phi}) \) profiles are then constructed and the profile of the plasma potential can be estimated by \( \phi = \lambda E_r \), where \( \lambda \) is the penetration depth of the rectified potential into the magnetic field as mapped to the location of the active antenna, and is a quantity determined from the GPI-APD \( V_{\theta(\cdot)}^{\text{dom}} r \) measurements.

3. Observations of the ICRF-induced radial electric fields

Using the GPI-APD measurements and analysis methods described above (and in more detail in Ref [19]), the propagation of turbulence in the far SOL is profoundly altered when ICRF heating is applied. This is illustrated in Fig. 2b where a profile of \( V_{\theta} \) with RF is plotted and compared to typical values from Ohmic plasmas (blue band). The main results of our initial study of this phenomena [19] are summarized here:

- The plasma potentials are strongly affected by the ICRF in regions far removed from the active antenna. The observations are made > 1 m and > 60° toroidally from the nearest antenna, see Fig. 1.

- The RF-induced potential has a radial maximum on those fieldlines that just pierce the front face of the active antenna.

- The radial maximum in the potential varies in the poloidal coordinate, depending on what regions of the antenna the just-piercing field-line samples. This is observed by changing the pitch of the field-lines linking the GPI observation region and the active antenna (by changing the \( q \)).

- The radial maximum in the potential for a fixed GPI-antenna mapping is proportional to the square root of the antenna power, as shown in Fig. 3 for a power scan with the D antenna. This scan and all others reported here are accomplished by increasing the power in steps during a single discharge.

- The potentials are found to extend into the SOL a quite significant distance, i.e. the penetration depth, \( \lambda_c \), is as much a 0.95 cm for high power cases, as seen in the inset of Fig. 3. This is roughly \( 5 \delta_c \), where \( \delta_c \) is the skin depth for RF waves in the C-Mod SOL and is the 0th-order expectation. This fact can have very important consequences for impurity physics in the presence of ICRF heating, since it provides a possible mechanism for modifying the transport of impurities through the

![Figure 3](image-url): The maxima in the RF-induced potential (radial) profile vs. power from the D antenna (points) with a \( P^{1/2} \) fit (line). In the inset is plotted the penetration depth of the induced potential, \( \lambda_c \), vs. power.
SOL and increasing the penetration efficiency for impurities during ICRF application. This aspect of the phenomenon is addressed in Section 4.

- Large ICRF-induced potentials are also observed (using emissive probes) in the shadows of the antennas and limiters, well outside of the region accessed by the GPI view [8]. They can exist in regions not even magnetically connected to an active antenna, and their role in this phenomenon and their relationship to the potentials in the region observed by the GPI are also under investigation. However, discussion of these observations is outside the scope of this report.

The first four observations listed above are all fully consistent with the explanation (also found in other investigations of ICRF effects in the edge, e.g. in [5]) that the potential arises from the rectification of the RF parallel electric field component, and is therefore proportional to the potential drop along the field line, so that

\[ \phi_{\text{rect}} = C_{\text{rect}} \int E_\parallel |dz| \propto P_{\text{ICRF}}^{1/2} \]

where the integral \( E_\parallel \) depends on the geometry of the antenna and \( C_{\text{rect}} \) depends on plasma and sheath physics. Since primary reason for installing the “FA-J ant” was to reduce the residual RF integral \( E_\parallel \), we have compared the power scaling potentials induced by “FA-J ant” with those of the “J-antenna”, which it replaced. The comparison is made using plasmas of the same \( q_{95} \) and is shown in Fig. 4. As seen the potentials are significantly larger with the field-aligned antenna. This is an unexpected result since the finite element simulations using the realistic antenna geometries [20] (but without inclusion of a plasma response) show that the integral \( E_\parallel \)'s at the top and bottom regions of the antennas (i.e. including that part of the antennas magnetically connected to the GPI field-of-view) are roughly a factor of 2 smaller in the field-aligned case. We have no verified explanation of this observation as yet. However, as noted above, the impurity production with the FA-J ant is reduced compared to the non-field-aligned antenna it replaced [17].

![Figure 4: The maxima in the RF-induced potential (radial) profile vs. power from the J antenna (red diamonds) compared to those from the field-aligned antenna (blue squares). The solid lines are proportional to \( P^{1/2} \).](image)

4. We have also compared the dependence of the induced potentials on antenna phasing, using the 4-strap field-aligned antenna, FA-J ant. The power scans shown in Fig. 4 were done employing so-called heating-phasing with the 4 straps having \((0,\pi,0,\pi)\) relative phases. Monopole phasing \((0,0,0,0)\) has poor heating efficiency and typically results in very strong impurity production/concentration[17]. The comparison of the induced potentials using heating- and monopole phasing is shown in Fig. 5.
As expected the induced potentials are higher in the monopole-phasing, where values up to 700V are inferred, corresponding to peak \(E_r\)'s > 60 kV/m. This observation does nothing to separate the relative roles of increased source (through increased sputtering) and more efficient impurity penetration (presumably through the SOL modified by the RF) in addressing the reasons for higher impurity concentrations with ICRF. Thus we address this question in the next section.

4. Impurity penetration during ICRF heating

The effect of ICRF heating on the confinement and/or penetration of a controlled source of non-recycling N was investigated with the goal of untangling the relative roles of changed transport and increased impurity source in the ICRF-impurity issue. In particular, we investigated any correlation between the magnitudes of the SOL potentials induced by the RF and changes in transport of the puffed N. This was accomplished by mixing the He puffed at GPI nozzle (and used for the local \(E_r(r)\) determination by the GPI-APD) with a small amount of \(N_2\). As described in Section 2, the GPI-camera was used to measure the N II emission within its field-of-view in front of the nozzle, i.e. essentially the entire extent of the puff. We then assume that view-integrated emission is proportional to the integral of the total N flux, i.e. we assume the number of ionizations per measured photon (=\(S/XB\)) is not changing during the puff. Thus we take the view-integrated N II emission to be proportional to the integrated flux term in the continuity equation

\[
dN_{nit}/dt = \iint \Gamma \cdot dA - N_{nit}/\tau
\]  

(Eq. 1), where \(\tau\) represents changes in confinement or penetration and \(N_{nit}\) is the volume-integrated density of N in the main plasma. Radial profiles of this N II “source” emission are plotted in Fig. 6 at two times, one when 1.5 MW of ICRF power from the FA-J is being applied and the other after the RF has turned off. Examination of the typical “RF on” profiles shows more source in the far SOL just in front of the nozzle. We also use an XUV spectrometer to measure the H-like nitrogen (I.P.=666 eV) Ly\_α line emission along a radial chord, presumably emitted from the region inside the LCFS where the temperature is a roughly 200 eV. The intensity of this line, normalized by the electron density, is taken to be proportional to \(N_{nit}\) in Eq. 1. In steady state \(\tau\) is proportional to the ratio of these quantities. We plot this ratio, called \(\tau_{eff}\), for a typical case in Fig. 7d, along with the RF power time history and the magnitude of the RF-induced potential measured locally at the N source location. Also plotted are (a) the line-integral \(n_e\), (b) the H-like N intensity, (c) the field-of-view integrated N II emission. The determination of \(\tau\) is complicated by the fact that there are two \(N_2\) puffs, initiated at the times indicated by the two vertical purple lines, and a true steady state is not realized. There is a clear factor of two enhancement in \(\tau_{eff}\) during the time periods when ICRF power is applied and when ICRF-induced \(E_r\)’s are present. However in the ~0.1 s after each puff onset, the
\[ \frac{dN_{\text{nii}}}{dt} \] term is large and positive, resulting in the rapid increases in \( \tau_{\text{eff}} \) at 0.5 s and just after the RF has turned off for the first time at 0.85 s. \( \tau_{\text{eff}} \) is obviously not equal to \( \tau \) during those time intervals. On the other hand after each of these \( \sim 0.1 \) s intervals, \( \frac{dN_{\text{nii}}}{dt} \) is \( < 0 \) and smaller in magnitude, so that \( \tau_{\text{eff}} \) is a better approximation of \( \tau \) during those intervals. Thus in the time period beyond \( \sim 0.9 \) s the N confinement/penetration appears to be \( \sim 2x \) greater with the presence of the ICRF. However, in the absence of a true steady state, we conclude only that these are intriguing indications that the transport is changing in response to the RF so as to increase the confinement/penetration efficiency of the impurity.

5. Summary

We find that there are strong radial electric fields induced by the application of ICRF power in Alcator C-Mod. The potentials associated with them are maximal (radially) on field-lines that just pierce the antenna Faraday shield structure and exist in regions well separated from the active antenna(s). While we infer that these fields convect plasma poloidally at speeds greater than 10km/s, we are primarily interested in whether these fields also influence the penetration of impurities into the main plasma. We do not have a clear answer to that important question. We find that the fields induced by the field-aligned antenna are greater than those from the vertical-strap antenna that it replaced, even though the impurity concentrations measured when using the field-aligned antenna are reduced compared to those observed when using the old antenna. On the other hand, use of monopole phasing, which engenders large impurity concentrations, does exhibit very large induced fields, the largest so far observed. In addition, the controlled puffing of non-recycling N, combined with measurements of the N integral source, the main plasma N content, and measurements of the induced fields at the location of the N source, revealed imperfect evidence of an increase in the impurity confinement/penetration with the existence and magnitude of these fields.

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