Characterization and Performance of a Field Aligned ICRF Antenna in Alcator C-Mod


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Abstract:

Ion cyclotron range of frequency (ICRF) heating is expected to provide auxiliary heating for ITER and future fusion reactors where high Z metallic plasma facing components (PFCs) are being considered. Impurity contamination linked to ICRF antenna operation remains a major challenge particularly for devices with high Z metallic PFCs. Here, we report on an experimental investigation to test whether a field aligned (FA) antenna can reduce impurity contamination and impurity sources. We compare the modification of the scrape of layer (SOL) plasma potential of the FA antenna to a conventional, toroidally aligned (TA) antenna, in order to explore the underlying physics governing impurity contamination linked to ICRF heating. The FA antenna is a 4-strap ICRF antenna where the current straps and antenna enclosure sides are perpendicular to the total magnetic field while the Faraday screen rods are parallel to the total magnetic field. In principle, alignment with respect to the total magnetic field minimizes integrated $E||$ (electric field along a magnetic field line) via symmetry. A finite element method RF antenna model coupled to a cold plasma model verifies that the integrated $E||$ should be reduced for all antenna phases. Monopole phasing in particular is expected to have the lowest integrated $E||$. Consistent with expectations, we observed that the impurity contamination and impurity source at the FA antenna are reduced compared to the TA antenna. In both L and H-mode discharges, the radiated power is 20-30% lower for a FA-antenna heated discharge than a discharge heated with the TA-antennas. However,
inconsistent with expectations, we observe RF induced plasma potentials (via gas-puff imaging and emissive probes to be nearly identical for FA and TA antennas when operated in dipole phasing. Moreover, the highest levels of rf-induced plasma potentials are observed using monopole phasing with the FA antenna. Thus, while impurity contamination and sources are indeed reduced with the FA antenna configuration, the mechanism determining the SOL plasma potential in the presence of ICRF and its impact on impurity contamination and sources remains to be understood.

I. Introduction

The primary role for ion cyclotron range of frequency (ICRF) power on ITER is to provide bulk plasma heating.[1] ICRF has been experimentally demonstrated to heat high performance plasmas on numerous experiments, including deuterium-tritium discharges on TFTR and JET, and has favorable scaling to burning plasmas.[2,3] Furthermore, the core wave physics can be accurately modeled with existing tools and the wave absorption can tailored to heat either ions or electrons. From a technological perspective, ICRF utilizes commercially available high power, steady state sources with high efficiency, ~65%. Coupling power to the plasma however is challenging because the waves are evanescent in vacuum; thus, the coupling structure needs to be situated near the plasma edge. RF-plasma interactions in this zone can be a challenge for antenna operation. In this work we will focus on ICRF impurity contamination which is of particular importance in devices with high Z plasma facing components (PFC).

A number of standard techniques have been employed in the past to ameliorate impurity contamination: operate the antenna in dipole phasing, align the Faraday screen with total magnetic field, utilize low Z coating of antenna surfaces, and employ absorption scenarios with high single pass.[4] Despite following this prescription, ICRF heated discharges in devices with metallic PFCs had impurity contamination that limited plasma
performance.[5, 6, 7, 8] Due to concerns regarding tritium retention and material erosion, high Z metallic, tungsten, PFCs for fusion devices are being considered despite obvious obstacles including maintaining core tungsten concentration to be $<10^{-5}$ to meet ITER’s performance goal.[9]

Possible explanations for impurity contamination with ICRF are: an increased source resulting from higher sputtering due to RF enhanced sheaths[10]; transport modification due to convective cells resulting from the evanescent RF fields near the antenna;[11] or a combination. A generally accepted model for an ICRF induced impurity source is enhanced sputtering caused by RF rectified sheaths (RF sheaths). Such sheaths have substantially higher voltages than expected for thermal sheaths ($\sim 3T_e$).[12] A simple electrical circuit model of RF sheaths is as follows. An open field line with its ends terminating on conducting surfaces has an RF electric field applied along it. Since the electrons are much more mobile in response to the RF field, they are preferentially lost to the conductor. To maintain ambipolarity, the sheath potential drop at the conducting surfaces increases, raising the plasma potential everywhere along the field line. RF sheaths based on this model are often referred to as near field sheaths; they can be localized to antenna elements and/or components linked by a magnetic field line such as plasma limiters and divertor tiles.[13] In the literature, another type of RF sheath has been identified: far-field sheath.[14,15] In plasmas that have weak single pass absorption, RF wave energy interacts directly with the sheath at the boundary object. Far field sheaths can be differentiated from near field sheaths in that they need not lie on a magnetic field line that connects to or passes near the RF antenna.

Impurity sources due to sputtering are proportional to the product of the effective sputtering yield ($Y_{\text{eff}}$) and ion flux to the material surface. As shown in Figure 1, $Y_{\text{eff}}$ is a sensitive function of sheath voltage. For a deuterium plasma with trace amounts of boron
(1%) and molybdenum (0.1%) and molybdenum PFCs, \( Y_{\text{eff}} \) is dominated by impurity sputtering below 100 V and increases rapidly for voltages above 100 V where the sputtering is dominated by deuterium. With molybdenum PFCs, limiting the sheath voltage to below 100 V would be advantageous; the corresponding value for tungsten is \( \sim 140 \) V.

In addition to increased impurity sputtering, RF sheaths are thought to modify SOL transport, particularly impurity transport perhaps increasing the penetration to the core.[11] As a result of a radial gradient in the RF fields, the open field lines nearest the antenna charge more positively than others. The resultant radial E-field creates an ExB drift convecting plasma, creating an asymmetry in the heat load to the antenna.[11,16]

Despite differences in geometric size between ITER and Alcator C-Mod, C-Mod has characteristics that are similar to that expected for ITER, which make these studies particularly relevant. The C-Mod ICRF antennas can achieve power densities in excess of that required for the ITER antennas and wave single pass absorption is expected to be similar. Since the RF fields in the plasma will be largely absorbed in a single pass, they will be localized toroidally. Thus, if non-linear effects are important in the antenna near field, experiments in C-Mod should be able to explore their impact. Furthermore, C-Mod utilizes high-Z (molybdenum) PFCs while most of the ICRF experience is with carbon machines with the notable exceptions of the recent ASDEX-U ICRF operation with tungsten coated PFCs [7] and the recent conversion of JET to tungsten-beryllium.[17] The C-Mod SOL is also opaque to neutrals, an important consideration for impurity transport, as it is expected in ITER.

To maximize high performance H-mode plasmas in C-Mod, we have found that boronization is required[6]; a similar response is observed in ASDEX-U boronization experiments[7] and in JET utilizing berylliumnization.[8] Boronization reduces the molybdenum influx keeping the radiated power inside the last closed flux surface (LCFS)
below 60% of the total injected power.[6] Since molybdenum radiation has been identified as the dominant contributor to the radiated power, control of the molybdenum influx is important, particularly during the formation stage of the H-mode. Through boronization, the impurity influx can be temporarily controlled and we find that after injecting a cumulative energy of ~50 MJ, the molybdenum levels rise and the confinement degrades.[6] Similar effects were observed on ASDEX-U.[7] Such limited wall-conditioning lifetime scales unfavorably to steady state devices.[18]

The primary goal of the experiments described below was to determine if a field aligned (FA) ICRF antenna can improve ICRF antenna operation, particularly reduce impurity contamination and impurity sources. A secondary goal was to characterize the plasma potential modifications associated with an FA antenna and conventional, toroidally aligned (TA) antenna with the aim of developing a better understanding of the underlying physics of ICRF impurity contamination. Ultimately we would like to operate an ICRF antenna without the need to resort to boronization and/or low Z films to control impurity contamination.

II. Experimental Setup

Alcator C-Mod is a compact (major radius $R = 0.67$ m, minor radius $a = 0.22$ m), high field ($B_T \leq 8.1$ T) diverted tokamak with molybdenum PFCs and auxiliary RF heating and current drive.[19] The discharges analyzed here are deuterium discharges using hydrogen minority heating with the hydrogen cyclotron resonance near the magnetic axis, 5.2-5.4 T where the hydrogen concentration is typically 3-5% corresponding to strong (>80%) single pass absorption. For these experiments, up to 3 MW of ICRF power is used to heat target discharges with central density $\leq 2 \times 10^{20}$ m$^{-3}$ and plasma current from 0.6-1.3 MA.
The ICRF heating power is coupled to the plasma via three fast wave antennas, see Figure 2. The two antennas are conventional, toroidally aligned antennas[20] and operated in dipole \((0,\pi)\) phasing, at 80 and 80.5 MHz, respectively and are referred to as toroidally aligned (TA) antenna. As can be seen in Figure 2, the FA antenna is a 4-strap, ICRF antenna where the current straps and antenna box structure are perpendicular to the total magnetic field. The Faraday screen (FS) rods are parallel to the total magnetic field. The TA antennas have their current straps and antenna structure perpendicular to the toroidal magnetic field, while their FS rods are parallel to the total magnetic field. A comparison of the antennas is shown in Figure 3. The FA-antenna is aligned to a 10° field pitch where the typical discharge range is 7-13° in C-Mod.

The FA-antenna has been analyzed using a full 3-D antenna model with a cold plasma using finite element method.[21] The FA-antenna had reduced integrated \(E||\) relative to the previous antenna geometry. The reduction in the integrated \(E||\) varies depending on phase, with a maximum reduction of a factor of 2-3 for dipole phasing occurring on field-lines sampling the top and bottom of the current straps. Somewhat surprisingly, the predicted integrated \(E||\) for monopole is lower than that for dipole the for the FA antenna as shown in Figure 4. This is due to symmetry along a field line that results in cancellation of fields. The FA antenna is operated at 78 MHz in dipole \((0,\pi,0,\pi)\) and monopole phase \((0,0,0,0)\) and is \(~180°\) from TA antenna and 90° from the plasma limiters. The local RF limiters’ leading edge is \(~0.3\) cm behind the plasma limiters and the limiters are fitted with molybdenum tiles.

In addition to standard diagnostics [22], impurity sources are monitored with a f/4, 0.25 m visible spectrometer with views covering the plasma limiter, divertor, and RF antennas to monitor Mo I. The antenna views monitor up to half an antenna with four views covering the FA antenna and two covering the TA antenna. Resistive bolometry is used to measure the total radiated power [23] and the core impurity content is monitored using VUV
spectrometers[24]: 10-30 nm (Mo XXXI (11.6 nm), Mo XXXII (12.8 nm)) for mid-Z elements and 1-10 nm for low Z materials. A reciprocating emissive probe[25] is used to monitor the plasma potential in the far SOL (1.5-11 cm outside the sepratrix) and maps along the field line through a limiter to the middle region of the FA antenna, see Figure 2, where the integrated $E_||$ is expected to be lower than at the ends of the current straps. The emissive probe utilizes a heated (~1800°C), thoriated tungsten filament where the emitted electron current is greater than the free streaming electron flux and the filament floating potential is the plasma potential within ~$T_e$ [26, 27]. A gas puff imaging diagnostic indirectly monitors the plasma potential in a radial region from the last closed flux surface (LCFS) to ~1 cm behind the antenna tile radius (88-92 cm). Since GPI measures the poloidal velocity of the SOL turbulence[28], the plasma potential profile is derived by first deducing the radial electric field profile, see reference 28 for more details. In the far SOL, the motion of the turbulence is dominated by cross-field convection via local $E \times B$ velocity, $v_\phi \sim E_r/B$. As shown in Figure 5, the potential profile can be obtained by integrating the $E_r$ profile. For reference, a potential profile derived from ~$3T_e$ is shown in Figure 5, which effectively assumes that the plasma potential is constant on a field line. The GPI maps to the corners of both the FA and TA antennas where the integrated $E_||$ is expected to be largest. GPI has a vertical coverage of ~4.4 cm and and resolution of ~0.4 cm in both the poloidal and radial dimensions. To estimate RF absorption efficiency, the H content is monitored through the ratio of $H_\alpha$ to $D_\alpha$ in the plasma edge.[29]

### III. Experimental Results

To assess the impurity response to the application of ICRF power, a series of discharges were performed prior to boronization where up to 2.5 MW of RF power was injected in L-mode. As shown in Figure 6, the plasma response in terms of stored energy is more favorable for the FA antenna compared to the conventional antenna largely because the
decay of the stored energy over time. The radiated power and core molybdenum contamination, as measured by the molybdenum line brightness, are also lower for the FA antenna relative to the TA antennas. The radiated power reduction is 0.4-0.6 MW per 2.5 MW injected RF power.

Following boronization, comparison discharges were performed in H-mode and an example discharge is shown in Figure 7. Here, the primary difference is the core molybdenum contamination which is significantly lower for the H-mode heated by the FA antenna. The difference in core molybdenum contamination is also reflected in the difference in the delay in H to L back transition following removal of the auxiliary heating. In addition the core radiated power increases more slowly for the FA-antenna compared to the TA antenna heated H-mode. The overall plasma response, however, is similar for the two antennas suggesting that they have similar heating effectiveness in H-mode and that the H-mode threshold is similar for both antenna configurations. In both L and H-mode discharges, the impurity contamination is about factor of 5 lower for discharges heated with the FA antenna than for the TA antenna suggesting the field alignment has reduced impurity contamination.

To investigate the local impurity sources, neutral molybdenum emission (Mo I) is monitored in similar L-mode discharges without boronization. In Figure 8, the first panel is a view covering the TA antenna and the second panel is of the FA antenna view where the RF power from a given antenna stepped from 1 MW (0.6-0.725 s) to 1.75 MW (0.725-0.875 s) to 2.5 MW (0.875-1 s). For the TA antenna view, the Mo I signal responds strongly when the conventional antenna is powered and is proportional to the injected power. When the TA antenna is off and the FA antenna is powered, the Mo I response in TA antenna view is weak. In contrast, the Mo I signal from the FA antenna view responds more strongly when the TA antenna is powered rather than when the FA antenna is powered. Although the results are
qualitative (signals from the different views are not cross calibrated), these measurements indicate the impurity source at the FA antenna is significantly lower when the FA antenna is powered than when the TA antenna is powered. Similarly, views of the plasma limiter show that the FA antenna results in lower Mo I signal response compared to the TA antenna despite the fact that field lines from the FA antenna map to the limiter.

To investigate whether the reduced $E_\parallel$ predicted by the antenna modeling resulted in lower RF enhanced sheaths, we compare the measured plasma potentials associated with the FA and TA antennas. First we confirm that both the emissive probe and the GPI diagnostic indicate a strong change in the radial electric field at the antenna limiter radius. This is shown in Figure 9. The consistency between the diagnostisc provides additional confidence that the GPI is correctly measuring a radial electric field brought about by the RF. Second we confirmed that the radial maxima of enhanced plasma potential profiles were on field lines that mapped to the front faces of the active antenna as previously observed.[28] Next we focus on that maximum in the plasma potential (radial) profile, occurring at the RF antenna radius: this plasma potential is the likely dominant contributor to enhanced Mo sputtering. We investigated whether the observed differences in molybdenum impurity source rates correlate with these potentials. As shown in Figure 10, the measured plasma potentials by GPI associated with the FA and TA are nearly identical in both magnitude and scaling with RF power. Thus, these observations suggest the reduction in the integrated $E_\parallel$ does not lead to a reduction in the RF enhanced plasma potentials.

A second test of the hypothesis that reduced integrated $E_\parallel$ should lead to lower enhanced plasma potentials is monopole phasing; recall that monopole phasing is predicted to have the lowest integrated $E_\parallel$ of all the antenna phases.[21] Our results do not support this prediction. As shown in Figure 11, comparisons of discharges heated using dipole phasing with those using monopole phasing indicate that the dipole phasing has better heating
efficiency than monopole. In addition, the local antenna impurity source is higher when the FA antenna is operated in monopole phasing than dipole phasing. As shown in Figure 12, the measured plasma potentials (from GPI) when the FA antenna is operated with monopole phasing is much higher than when the antenna is operated with dipole phasing. Again, these observations indicate the reduction of the integrated $E_{||}$ does not lead to a reduction in the RF enhanced plasma potentials.

**IV. Discussion**

The observation that the FA antenna has lower impurity contamination and impurity sources rates indicates that field line symmetry reduces ICRF impurity contamination and sources as expected. This observation however may be coincidence since we expected a reduction of integrated $E_{||}$ to result in lower impurity contamination and source rates. The plasma potentials enhanced by the ICRF indicate that the maxima of the enhanced plasma potentials are similar for both the FA and TA antennas. This suggests several possible explanations. First the potentials we have measured are unrelated to core impurity contamination and sources despite their correlation with RF power and field lines mapping (RF enhanced sheath only when mapped to an active antenna). Second, the integrated $E_{||}$ is not the proper metric and perhaps the local $E_{||}$ is more important. However, from the antenna simulations, both the integrated $E_{||}$ and the local $E_{||}$ were reduced for the FA antenna compared to the conventional antenna.[21] The emphasis on integrated $E_{||}$ is a consequence of the plasma potential being constant on a field line. Another possibility is that the plasma potential measurements are dominated by far field sheath while near field sheaths are reduced but not directly monitored. This hypothesis is consistent with the spectroscopic data: antenna source is reduced suggesting lower plasma potentials near the antenna but plasma potentials are similar for both the FA and TA antennas.

To explore these hypotheses, a more detailed investigation of the plasma potentials
with ICRF is required. Plasma potential measurements both near and far from the antenna with increased poloidal coverage are required. In addition to additional diagnostic measurements, a more complete investigation of the RF sheath parametric dependence on plasma density, current and majority species could provide some insight on the important plasma parameters. The influence of strength of wave absorption and light impurity Z seeding are likely to be important as well. Identification of important impurity source locations and assessment of the impact of ICRF on SOL impurity transport also are required for improved understanding of impurity contamination associated with ICRF antenna operation. The antenna-plasma model will also need to be improved particularly inclusion of sheath boundary conditions. Simultaneous operation of C-Mod with both FA and TA antennas gives us a powerful tool to study existing or emerging theories of RF-sheath induced impurity sources and impurity contamination, a primary limitation to extending ICRF to a reactor.

**Conclusions**

We have shown that a field aligned antenna can reduce the impurity contamination and antenna impurity sources. The impurity source measured at the FA antenna is lower when FA antenna is powered than when the TA antennas are powered. The impurity contamination associated with antenna operation is lower for the FA-antenna and the radiated power in L-mode is 400-600 kW lower for 2.5 MW injected ICRF power compared to our conventional ICRF antennas. While the FA antenna operational aspects have been encouraging, our understanding of the physics behind the improved performance is incomplete. The observed enhanced plasma potentials are similar for both the field aligned antenna and toriodally aligned antennas. Furthermore, simulation indicated that monopole phasing should have lower integrated E|| fields than dipole phasing yet experimentally monopole phasing resulted in higher plasma potentials and had poor heating effectiveness. These results challenge the
underlying hypothesis that field line symmetry would reduce integrated $E||$ resulting in lower RF enhanced plasma potentials, and further work is required to clarify the underlying physics.

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References


Figure 1: Effective sputtering yield for deuterium on molybdenum, deuterium with 1% boron+3 on molybdenum, and deuterium with 1% boron+3 and molybdenum+3 on molybdenum. Note that around 100 V the sputtering yield increases dramatically because deuterium is capable of sputtering molybdenum whereas below 100 V the sputtering is dominated by impurities.

Figure 2: Schematic of the outer tokamak wall showing the location of the antennas, limiters, and diagnostics. The field aligned antenna is aligned to the total field and the conventional, toroidally aligned antenna has only its Faraday screen bars aligned to the total field. Representative field lines show the mapping of the diagnostics to each antenna. The emissive probe maps to regions that are expected to have lower integrated $E||$ than the gas puff imaging. By fortuitous coincidence, the gas puff imaging maps to regions of both antennas that are expected to have maximum integrated $E||$.

Figure 3: Field aligned and conventional toroidally aligned ICRF antenna installed in C-Mod. The field aligned antenna is aligned to a 10° field pitch such that the current straps and antenna box structure are perpendicular to the total magnetic field and the FS rods are parallel to the total magnetic field. The toroidally aligned antennas have their current straps and antenna structure perpendicular to the toroidal magnetic field and the FS rods are parallel to the total magnetic field.

Figure 4: The integrated $E||$ field 1 cm in front of the Faraday screen along field lines that extend beyond the antenna sufficiently such that the $E||$ contribution is vanishing at the ends of the field line. The poloidal coordinate is perpendicular to the total field for the field aligned antenna and vertical for the toroidally aligned antenna. The bottom of the antenna box is at -0.25 m and the top of the antenna box is at 0.25 for the toroidally aligned antenna. The field aligned antenna monopole phase has the lowest integrated $E||$ and the field aligned dipole phase is 2-3 times lower at the antenna end compared to the toroidally aligned.
Figure 5: The scrape of layer plasma potential profile is estimated from GPI measurements of the poloidal phase velocity assuming the turbulence is ExB convected and integrating the radial electric field profile referencing to the typical 3Te potential. (a) The poloidal phase velocity profile in ohmic portion of discharge compared to the profile obtained with ICRF applied. (b) Plasma potential profile derived from integrating the radial electric field profile referenced to 3Te.

Figure 6: The plasma response to 2.5 MW of applied RF power from the field aligned antenna is superior to the response from the toroidally aligned antenna. The stored plasma energy is higher and the radiated power and molybdenum contamination is lower for the field aligned antenna than the toroidally aligned antenna.

Figure 7: In H-mode, the molybdenum contamination and the radiated power are lower for the field aligned antenna than the toroidally aligned antenna.

Figure 8: (a) Spectroscopic view (molybdenum I) of the toroidally aligned antenna shows strong correlation with RF power from the toroidally aligned antenna and a weak response with RF power from the field aligned antenna. (b) Spectroscopic view of the toroidally aligned antenna shows strong correlation with RF power from the toroidally aligned antenna and a weak response with RF power from the field aligned antenna.

Figure 9: Radial electric field profile derived from gas puff imaging (GPI – blue points) and the emissive probe (red line) shows a strong reversal at the RF limiter radius when the RF antenna is energized and the GPI and probe map to the energized antenna.

Figure 10: The measured plasma potential as a function of RF power for the toroidally aligned and field aligned are not significantly different.

Figure 11: Plasma response to dipole and monopole phasing indicates that dipole phasing heats more effectively than monopole phasing. In fact, the significant decrease in plasma temperature suggests a large influx of impurities cooling the plasma.
Figure 12: The maximum plasma potential for monopole and dipole phasing as a function of power shows that monopole phasing has significantly higher plasma potential than dipole phasing despite the model prediction that monopole phasing has the lowest integrated $E_\parallel$. 
Effectivie Sputter Yield, Y_{eff}

Sheath Voltage (V)

Figure 1
Figure 2
Figure 3

(a) Field aligned Antenna

(b) Toroidally aligned Antenna
Figure 4

Potential [kV] vs. Poloidal Coordinate [m] (Position along Antenna)

- Tor. Aligned Dipole
- Tor. Aligned Monopole
- Field Aligned Dipole
- Field Aligned Monopole
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9

Figure showing the variation of $E_r$ (KV/m) with $R_{nlb}$ (cm) for different points such as Separatrix, Main Limiter, GPI, and Emissive Probe.
Figure 10
Figure 11
Figure 12

The graph shows the relationship between $P_{ICRF}$ (MW) and $\phi_{\text{max}}$ (V) for both Dipole and Monopole modes.

- Dipole: The blue line represents the data for Dipole mode, with data points showing a clear upward trend as $P_{ICRF}$ increases.
- Monopole: The red line represents the data for Monopole mode, with data points also showing an upward trend but slightly above the Dipole line.

The graph includes error bars indicating the variability in the data points.