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Recent ICRF Results in Alcator C-Mod

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Ion cyclotron range of frequency (ICRF) power utilization poses several challenges regarding its compatibility with high performance plasmas. Relevant issues can be roughly divided into heating efficiency (wave propagation and absorption) and plasma surface interactions, in particular antenna – plasma interactions. In the Alcator C-Mod tokamak we have compared the plasma performance of a weak single pass absorption scenario (D (^{3}He)) with a strong absorption (D(H)) case and found that the former produces only "moderately" performing plasmas in H-Mode. We suspect that the underlying issue is increased high-Z core impurity radiation. The primary boronization erosion location and subsequent impurity source has been identified to be tiles on the top of the outer divertor that are magnetically connected to the ICRF antenna. Enhanced sputtering due to RF sheaths is believed to be the cause of the erosion. In a different set of experiments, "Faraday screen-less antenna" operation was limited by impurity influx and we have identified degradation of the antenna voltage standoff at high pressure to be the result of multipactor phenomena.

Comparison of D(^{3}He) and D(H) minority heating scenarios

Alcator C-Mod has 8 MW of ICRF source power to heat discharges in the D(H) or D(^{3}He) minority regimes. Realizing high heating efficiencies in D(^{3}He) discharges, where the single pass absorption is weak, is important for heating H-mode discharges at 8 T. As shown previously, we have observed that the heating efficiency is a sensitive function of the ^{3}He fraction.[1] Using the optimized concentration, the heating effectiveness for ^{3}He minority in L-mode, as defined by the stored energy per injected power, and the threshold power required to obtain H-mode appear to be similar to H minority heated discharges (see Figure 1). The H-mode plasma performance, however, for this series of ^{3}He minority heating experiments has been modest. Recent work has shown that H-mode performance is very sensitive to the radiated power fraction [2]; thus impurity generation must be minimized for good H-mode performance. This could explain the apparent discrepancy between L-mode and H-mode heating effectiveness where the H-mode performance is more negatively affected by increased impurity production. The impurity production rate for the D(^{3}He) case could be the consequence of increased sheath voltage due to far-field sheath enhancement[3]

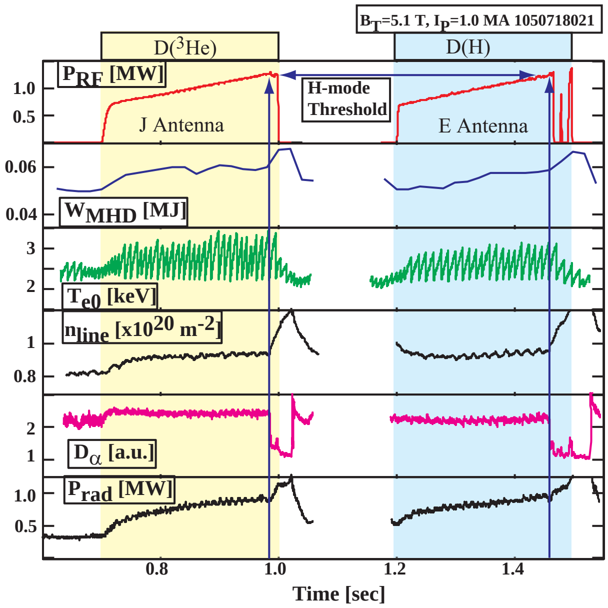

Figure 1: The plasma response in L-mode and the H-mode threshold are similar for D(3He) and D(H) minority heated discharges.

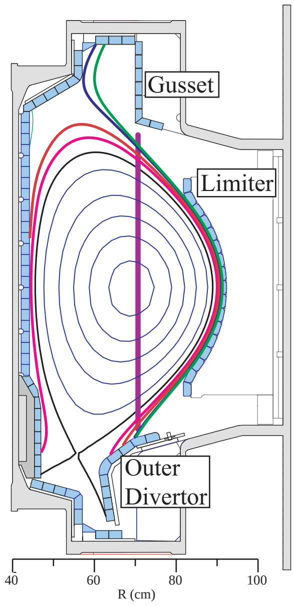

Figure 2: Schematic of flux surface reconstruction showing field line intersection with plasma facing surfaces.

resulting from lower single pass absorption or enhanced sputtering from energetic minority boron ions generated by the RF power. Future experiments are planned to examine the role of edge boron ion absorption on H-mode performance and boron layer erosion.

Localization of the RF Impurity Source and Boronization Erosion

Antenna compatibility with high plasma performance and all metal plasma facing components are critical issues for future devices such as ITER. In H minority heated discharges, time limited impurity control has been achieved through boronization and the lifetime appears to be limited to ~50 MJ of injected RF power in C-Mod.[2] Furthermore, RF heated H-mode performance degrades faster than Ohmic H-modes suggesting an RF related mechanism.[4] From post campaign inspections, the boron layer is still present everywhere except for a few regions indicating that specific locations are responsible for the resulting impurity sources and degraded H-mode performance. Furthermore, we found the largest reduction in radiated power in target L-mode plasmas when the boronization discharge resonance was centered on 0.7 m [2] (see Figure 2) indicating that a dominant impurity source contributing to the core radiated power is outside the divertor.

To identify the relative importance of the antenna and plasma limiters as core Mo sources, the protection tiles were replaced with insulating BN tiles.[5] This should have eliminated sheath effects on field lines connected to the antenna. Surprisingly, the H-mode plasma performance and core Mo content were not improved. This suggests that the antenna and limiter Mo sources are secondary compared with some other, yet unidentified source.

To identify potential Mo sources, we have mapped magnetic flux tubes from various parts of the antennas to PFC surfaces around the vessel. Since the previous experiments suggest that the RF and plasma limiters are secondary impurity sources,[6] the flux tubes that pass in front of the antenna between the separatrix and the main limiter radius are of greatest interest. As shown in Figure 2, these flux tubes terminate on the lower outer divertor with the other ends terminating on the upper gussets, inner wall, and inner divertor. These field lines, terminating on the top of the outer divertor, correlate with the radial location where the boronization was most effective at reducing impurity radiation and would have been unaffected by the installation of insulating limiters. Regarding the toroidal projection of these field lines, the D+E antennas map to the outer divertor modules at different locations than for the J antenna and this has significant consequences on RF sheaths and sputtering.

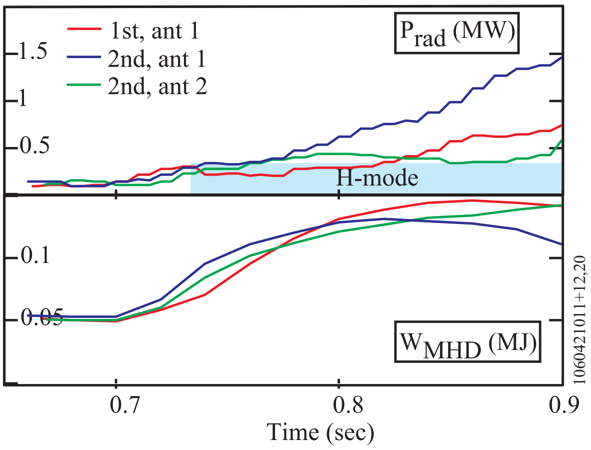

Figure 3: Second discharge following a boronization heated by second antenna has similar performance to the first discharge heated with antenna one following a boronization.

To test this hypothesis, the first discharge following a boronization was heated by antenna 1 (in this case D+E are utilized as one antenna) followed by a second discharge using antenna 2 (without additional boronization). Both discharges had good performance (see Fig. 3, red and green curves), indicating that impurity generation from RF sheaths that formed at different locations were controlled by the original boronization. For comparison following a new boronization, two successive discharges were heated with the same antenna (1 in this case) but without a second boronization (see blue curve in Figure 3). Importantly, the second discharge had increased radiated power and lower plasma performance, presumably due to the removal of boronization at the same location after the previous RF discharge. Thus the primary erosion surface and impurity source is the outer divertor tiles magnetically connected to the powered antenna. In addition, the heat flux and Mo influx rate are monitored at the top of the outer divertor at the toroidal locations that map to the D/E antennas. During the period when the D/E antennas are powered, regions on the top of the outer divertor increase by ~50

°C. This small temperature rise is insufficient to account for the observed increase in Mo influx suggesting that the RF enhanced erosion is a result of non-thermal ion sputtering.

Compatibility of Screen-less and High Neutral Pressure Antenna Operation

The Faraday screen was removed from the J antenna and simple Mo septa were installed between each of the 4 antenna straps to prevent direct interaction between the strap and the plasma.[6] The loading and voltage handling were very similar to previous operation with a screen, with no enhanced loading at low (10 kW) power levels.[3,7] The J antenna heating effectiveness, however, was ~10% (15-20%) less than D and E antennas in L-mode (H-mode) plasmas, respectively. The degradation of performance in both L- and H-mode plasmas can be largely attributed to the influx of Cu with RF power. Post mortem inspection indicates Cu loss from the strap near the midplane of the strap where one would expect a strong sheath effect. To improve screen-less operation in the future, strap modification could greatly reduce the local sheath effect and possibly lead to improved performance.

A long standing ICRF antenna operation issue has been decreased voltage breakdown limit in the presence of high neutral pressure. In the ST and PLT tokamaks, the antenna was shielded by ceramic sleeve to prevent gas build up in the antenna.[8] In C-Mod, the E and J antenna has a limit ~1.4 mTorr and ~0.4 mTorr, respectively, usually reached at high target densities. Using a small test-stand experiment, we observed that high neutral pressure reduced the pressure at which a discharge formed, typically ~100 times below the Paschen limit, however this limit could be raise by systematic discharge cleaning.[9] This tendency to rf breakdown appears to be related to multipactor effects. In experiments with the E and J antennas, the neutral pressure limit could be reproduced with operation into the torus with 0.1 T toroidal field and the pressure limit could be raised by RF discharge cleaning procedures.

Acknowledgements

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