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Operation of Alcator C-Mod with High-Z Plasma Facing Components With and Without Boronization*

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Abstract: High-Z Plasma Facing Components (PFCs) are considered necessary for reactors due to their low tritium (T) retention, capability to handle high heat fluxes with low erosion, and robustness to nuclear damage and activation. Recent Alcator C-Mod experiments provide divertor tokamak operational experience utilizing all-metallic solid high-Z (molybdenum) PFCs, comparing boronized and unboronized surfaces. To assess the influence of boron coatings in plasma performance, previously deposited boron was removed from all PFC surfaces before the 2005 campaign. Subsequently, ICRF-heated H-modes were readily achieved, but energy confinement enhancements over L-mode were small. Molybdenum radiation is implicated. After boronization the Mo density was reduced by a factor of more than 10, and energy confinement doubled. The positive effects of boronization wear off, correlated with ICRF input energy. On the basis of experiments which included between-shot boronization, as well as from visual inspection, it appears that the Mo affecting the core comes from a small fraction of PFC surfaces, where the boron coating erodes rapidly. The evidence points to sputtering from RF sheath enhancement as the most important erosion mechanism.

Plasma Performance with all molybdenum plasma facing surfaces

Alcator C-Mod is unique among diverted tokamaks in its exclusive use of solid high-Z (molybdenum) plasma facing components.[1] It is likely that ITER will require the substantial use of high-Z PFCs (probably tungsten), and in fusion power plants (DEMO and commercial), low Z PFCs (particularly graphites) may be totally precluded because of tritium retention and material degradation due to radiation damage.[2] Other than on C-Mod, worldwide experience with high Z PFCs in diverted tokamaks is very sparse.[3] On C-Mod, prior to the 2005 campaign, all low Z secondary limiters (BN protection tiles on the ICRF antennas) were replaced with Mo, and boron buildup from years of operation with boronization was removed as thoroughly as possible. H-mode performance with high power

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ICRF auxiliary heating[4] was studied first with bare Mo PFCs, then with the standard overnight boronization used on C-Mod[5], and finally a between-shot boronization technique was developed.

Effects of Radiation on Confinement

It is known that strong radiation from the confined plasma can effect global energy confinement in tokamaks.[6] Figure 1 shows the effects of radiation on τ_E (as parameterized by the enhancement over the ITER-89 L-mode scaling[7]) for L-mode and H-mode discharges in C-Mod. Prior to the first boronization of the campaign, with bare Mo surfaces, P_{rad}/P_{input} is close to 100%, the pedestal pressure in H-mode is suppressed and the global energy confinement is barely enhanced over that in L-Mode. Following overnight boronization, which is applied using a low-temperature Electron Cyclotron Discharge (ECD) using 10% diborane (D_2B_6)/90% helium gas[8], Mo levels in the plasma are reduced by more than a factor of 5, and confinement nearly doubles.

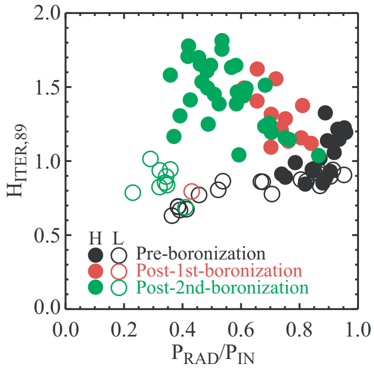

Fig. 1 Energy confinement enhancement vs. radiated power fraction for L- and H-Mode discharges, pre-and post boronization

Robustness of Boron Coatings

Overnight boronization on C-Mod is typically applied for about 10 hours. The average boron surface coverage (assuming uniform deposition) is about 200 nanometers. The coating is effective for approximately 20 to 40 high power discharges, or equivalently until about 50 MJ of total input energy from the ICRF heating system. Over this time, keeping nominal plasma parameters (field, density, topology, heating) constant, the core molybdenum level increases monotonically (figure 2a), and confinement also decreases gradually (figure 2b). Comparisons using ohmic heating alone to access H-modes show that the boron layer survives about 4 times as long (in terms of equivalent total input power) as is found with ICRF heating. This points to an RF specific effect as being primarily responsible for the observed boron erosion. Post-campaign surface analysis of sample tiles shows that the boron build-up is only removed

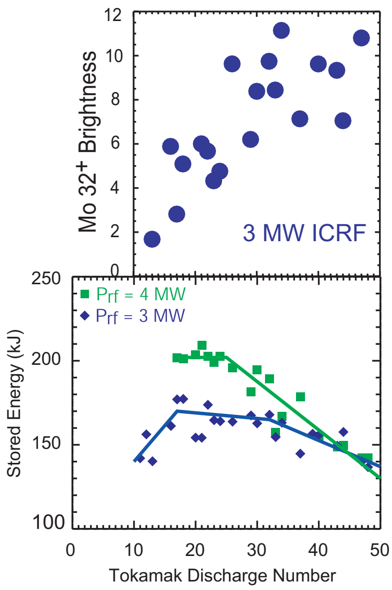

Fig. 2 a) Increase in Mo radiation from the core plasma for a sequence of tokamak discharges following an overnight boronization; b) Corresponding trends in stored energy for 2 levels of ICRF auxiliary power from a very small fraction of the PFC surfaces. Areas which are clear of boron are the highest heat flux region near the strike point in the divertor and leading edges of tiles outboard of the active divertor ("outboard shelf"). The probability that an impurity ion will reach the core plasma depends strongly on the source location. For typical diverted discharges in C-Mod, an ion generated from the outboard shelf is about 100 times more likely to reach the confined plasma than is one generated near the strike point.[9] Spectroscopic measurements of the relative source strengths show that, while the strike point Mo source is stronger than from other locations, divertor shielding prevents this region from being an important source for core impurities.

Between-shot boronization

To investigate the erosion question further, we developed an operational scheme for between-shot boronization, which after 10 to 30 minutes of ECD deposition, gives an estimated thickness of 30 to 100 nanometers. These coatings persist at most for a single high power RF pulse (~2 MJ input energy). The ECD is at least partially localized to the major radius of the electron cyclotron resonance which is controlled by varying the applied toroidal field. Because between-shot boronization wears off in one plasma discharge or less, we were able to search for an optimal location for the coating. Figure 3 shows the results of one such scan, where the impurity level during the ICRF pulse, just prior to the transition to H-mode, is monitored as a function of the ECD resonance location from the previous between-shot boronization. There is a clear minimum, indicating that the region near R=70 cm, coinciding with the top of the outboard shelf, is likely to be the most important location; this also corresponds to one of the few regions where post-campaign surface analysis showed reduced boron.

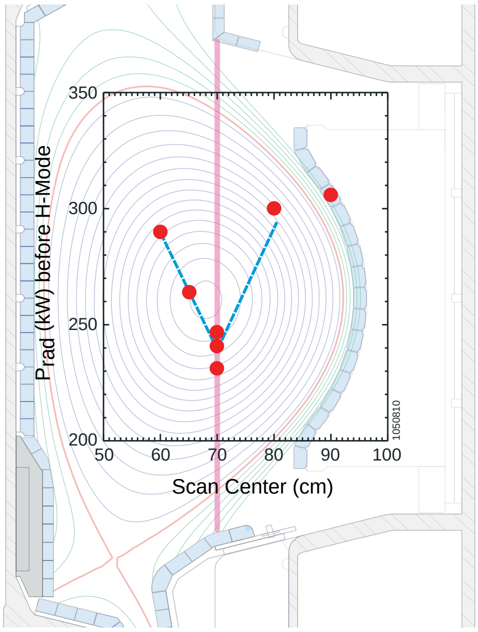

Fig. 3 Radiated power just before the H-mode transition as a function of boronization deposition location prior to each discharge. Superimposed is a typical equilibrium reconstruction for the tokamak plasma. The vertical line shows the EC resonance for the cases at R=70 cm.

ICRF induced sheaths

The accepted model for ICRF specific impurity production involves sputtering caused by enhancement of the sheath potential at the surfaces where field lines connect from the antenna(s) to the walls.[10] Figure 4 shows that, for the discharges studied with the between-shot boronization, the field lines from the ICRF antennas map to the top of the outer shelf, precisely the same location implicated by the previous evidence. As another test of this

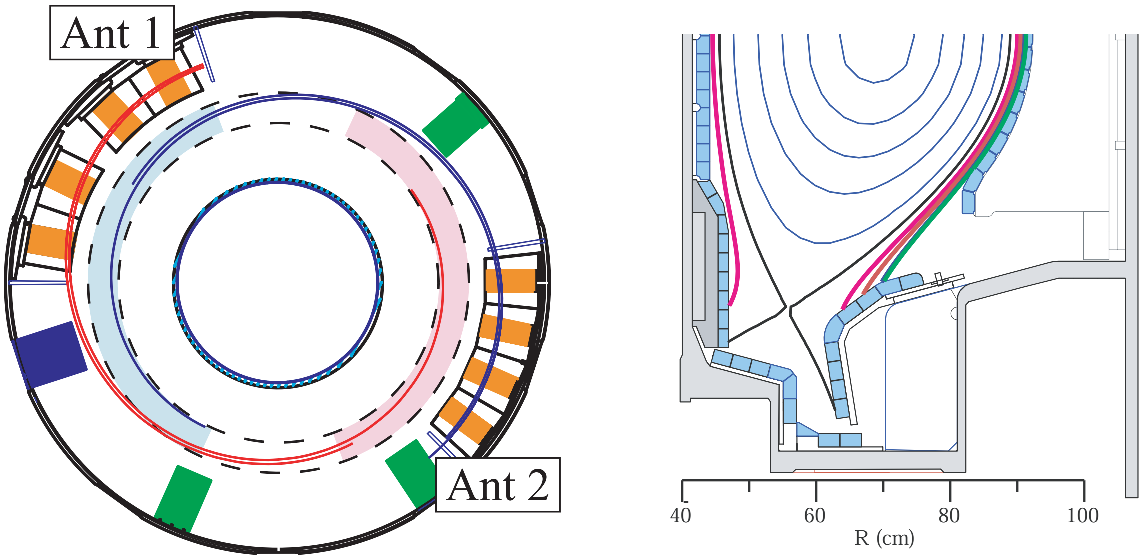

Fig. 4 Field line tracing indicates the locations of expected RF sheath enhancement from the 2 ICRF antenna systems which are toroidally displaced by 180 degrees. For the discharges in these experiments, both antennas connect to the shelf outboard of the divertor (shown on the right), but at toroidally distinct locations. For Antenna 1, the field lines (red) connect to the shelf along the pink shaded region, while for Antenna 2, the field lines (blue) connect to the shelf along the light blue shaded region.

picture, consecutive discharges were compared after a single thin boronization, utilizing first antenna 1 and then antenna 2. Since the two antennas should enhance the sheath potentials at different toroidal locations, we expected that the second discharge should be unaffected by erosion during the first, and this is precisely the result which was obtained.

Summary

Operation with bare metal (Mo) PFCs and high power ICRF heating on C-Mod leads to H-modes with high core radiation and modest confinement enhancement. Boronization ameliorates these effects. Thin boron layers are eroded locally, outside of the high heat-flux divertor region. Sputtering due to RF-enhanced sheaths on open field lines connected to the antennas is implicated. These results indicate that high-Z PFC operation, without boronization, carries the risk of degraded confinement; boronization, or other low-Z wall coating, might be required with high-Z PFCs.

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