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Electron cyclotron discharge cleaning (ECDC) experiments on Alcator C-Mod

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Abstract

Experiments were performed on Alcator C-Mod with electron cyclotron resonance (ECR) plasmas to help determine their applicabilty to a fusion reactor. Strong radial inhomogeneity of the plasma density was measured, decreasing by a factor of ten a few centimeters inside the resonance location, but remaining approximately constant ($n_e \approx 10^{16}$ m^{-3}) outside the resonance location. Electron temperature remained mostly constant outside the resonance location, $T_e \approx 10$ eV; ion temperature increased outside the resonance location from $T_i \approx 2$ eV to 10 eV. Toroidal asymmetries in ion saturation current density were observed, indicating local toroidal plasma flow. The ECR plasma was used to remove a diamond-like carbon coating from a stainless-steel sample. Removal rates peaked at 4.2 ± 0.4 nm/h with the sample a few centimeters outside the resonance location. Removal rates decreased inside and further outside the resonance location. The plasma did not remove the carbon from the sample uniformly, possibly due to plasma flow. Yields were calculated ($Y \approx 10^{-3}$) to be lower than other published results for chemical sputtering of deuterium ions on carbon, possibly due to toroidally asymmetric plasma conditions.

Keywords: Alcator C-Mod; Carbon erosion; ECR

1. Introduction

Experiments on magnetic fusion reactors have shown that conditioning of plasma-facing components affects performance. Electron cyclotron resonance heating of low density plasmas might be the only technique for conditioning the thick vessel walls of large fusion reactors with superconducting magnets. Electron cyclotron discharge cleaning (ECDC) plasmas operate in steady state, require no inductive currents, and require only small port access for waveguides. Alcator C-Mod has demonstrated effective first-wall conditioning using ECDC [1].

To help determine if ECDC could be made to work for a fusion reactor, measurements were performed on ECDC plasmas on Alcator C-Mod to answer the following questions: (1) How do the plasma conditions vary with neutral pressure? (2) What is the spatial structure of the plasma? (3) How effectively do different radial zones of the plasma clean a test sample? (4) Is the mechanism for surface cleaning simply understood in terms of ion-induced chemical and physical sputtering processes?

ECDC plasmas were produced with magnetic fields with $0.067 \leqslant B(\mathrm{T}) \leqslant 0.11$ using the toroidal field coils only. The location of cyclotron resonance was swept between 0.52 and 0.83 m torus major radius by varying the magnetic field. Electromagnetic waves were launched from a horn at one toroidal location, with a fixed frequency of 2.45 GHz and power of 3 kW. Here we report the results from experiments performed with deuterium fill gas with pressure between 0.04 and 0.08 Pa.

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2. Experiments

Fig. 1 shows a poloidal projection of Alcator C-Mod indicating the diagnostics used for these experiments. Langmuir probes at the top (Omegatron) and bottom (FSP) of the vessel were used to measure plasma density and electron temperature at the same toroidal location as the microwave horn. Bulk plasma ion temperature was measured at the top of the torus with a retarding field energy analyzer (Omegatron). A CCD camera view from the top of the torus was used to give a qualitative picture of visible light emission. The probe group at the bottom of the machine consists (FSP) of four Langmuir probes, arranged on the faces of a pyramidal structure; see Ref. [2] for details. Asymmetries in the ion saturation current density to the different probes indicate local toroidal flow.

Approximately 20 nm of carbon were deposited onto the end of a cylindrical stainless-steel sample, reported to be diamond-like carbon by the vendor who performed the deposition. A mask was used to expose two areas of the coated sample to plasma facing toroidally clockwise and counterclockwise (as seen from the top). Fig. 1 shows the coated sample mounted onto a scannable assembly, 180° toroidally from the microwave horn. For the carbon-removal experiments, the radial location of the cyclotron resonance was fixed at 0.72 m and the coated sample moved into the plasma.

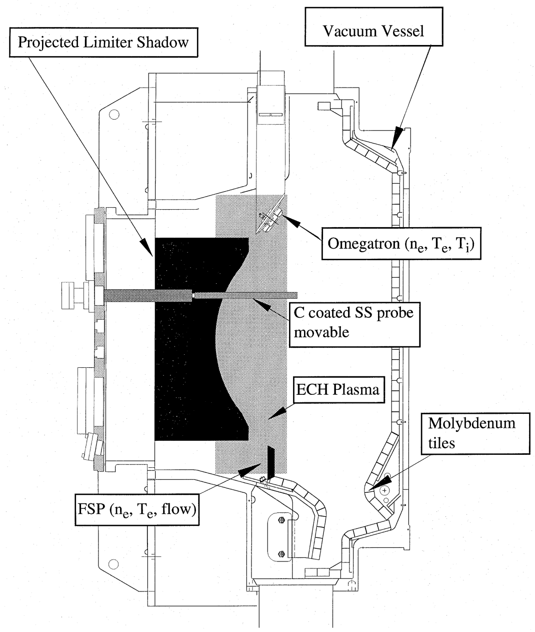

Fig. 1. Poloidal projection of Alcator C-Mod tokamak. ECH plasmas (gray region) are swept in major radius. The Omegatron and FSP probe systems record local plasma conditions at the same toroidal location. A sample, coated with diamond-like carbon, is mounted on an assembly near the midplane and is inserted radially into the plasma for erosion experiments. The sample assembly is located 180° toroidally away from the Omegatron and FSP.

The thickness of the remaining coating was measured using a technique involving Rutherford backscattering (RBS) of 1.7 MeV protons. The energy spectrum of scattered protons was measured at a fixed scattering angle. At a particular energy an increase in proton count over background was observed, which was attributed to the enhanced scattering cross section of the carbon coating. Measurements of the thickness of carbon performed twice at identical locations on the sample, but with proton beams of diameters 1.0 and 0.5 mm, gave results which agreed to within 2 nm. The coating uniformity was not verified before exposure to the plasma.

After exposure to the plasma the coating thickness was measured at 11 axial locations for each of eight azimuthal angles, corresponding to CW/CCW sides of the sample facing plasma for different durations. The standard deviation of the axial measurements gave the uncertainty in the carbon thickness at each azimuthal angle. In addition the coating thickness was measured at two axial locations (masked and exposed) at 36 azimuthal angles each. Comparison with adjacent uncoated regions of the sample gave the thickness of carbon removed from by the plasma.

3. Results

3.1. Plasma conditions, non-uniformities

Fig. 2 shows plasma density, electron temperature, and ion temperature measured as a function of deuterium neutral pressure, for resonance location held fixed at $R = 0.52$ m and microwave power of 3 kW. Results were obtained similar to Sakamoto et al. [3], but ion temperatures are reported as well. A camera view from the top of the machine showed visible light emitted in a toroidally symmetric region, with a sharp boundary on the smaller major radius side of the resonance location. Decreasing the neutral deuterium pressure contracted the extent of a broader light-emitting region on the larger major radius side of the resonance location.

Fig. 3 shows effective profiles of the plasma density and electron and ion temperatures, obtained by sweeping the location of the electron cyclotron resonance. The data presented in Fig. 3 do not represent actual plasma profiles since the probes were not moved relative to the plasma boundary, but the data demonstrate the lack of plasma source inside the resonance location and suggest outward plasma flux. Electron temperatures outside the resonance are approximately constant at $T_e = 10 \pm 3$ eV; 5 cm inside the resonance electron

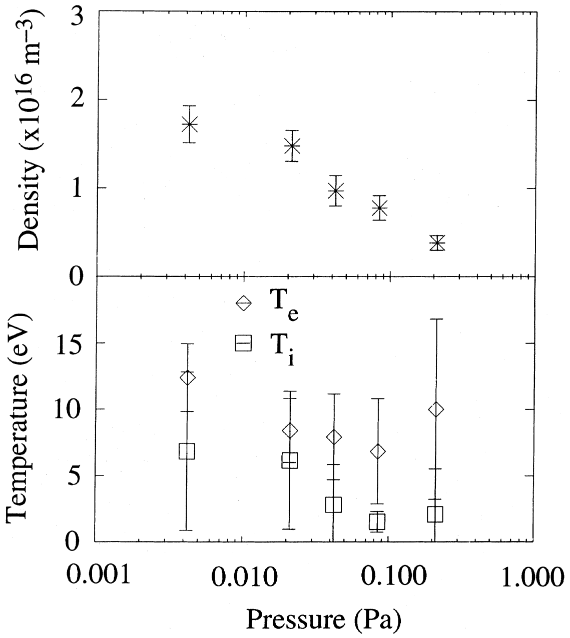

Fig. 2. ECDC plasma density, electron and ion temperatures measured by multiple sensors on the Omegatron probe head, as functions of neutral deuterium pressure; resonance location is held fixed at $R_{res} = 0.52$ m.

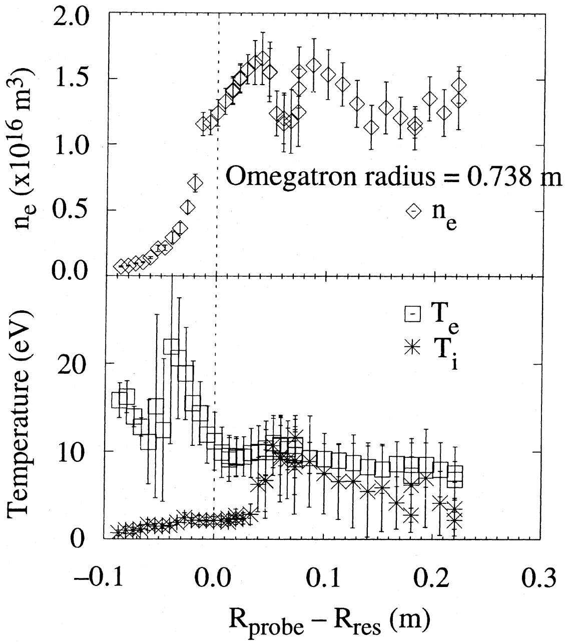

Fig. 3. Effective radial profiles of ECDC plasma density, electron temperature, and ion temperature, measured by sensors on the Omegatron probe head. Major radius of measuring probe is held fixed, plasma electron cyclotron resonance moved. Ion temperature obtained from retarding field energy analysis; electron density and temperatures obtained from Langmuir probes.

temperatures appear to increase to $T_e = 20 \pm 10$ eV, but this may be due to non-thermal electrons. Ion temperatures remain constant at $T_i = 2 \pm 1$ eV across the resonance location; 5 cm outside the resonance location the ion temperature increases to $T_i = 10 \pm 5$ eV and remains approximately constant further out. Ion temperatures shown in Fig. 3 are measured in a local scrape-off plasma defined by the Omegatron head; bulk plasma T_i is likely to be higher.

Fig. 4 shows effective radial profiles of saturation current density as measured by the Langmuir probes at the bottom of the machine. Note that the clockwise side of the probe receives higher ion saturation current density than the counterclockwise side by a factor of three, suggesting counterclockwise toroidal flow at the probe location. Fig. 4 also shows effective radial profiles of saturation current density as measured by the Langmuir probes at the top of the machine. The Omegatron head at the top faces couterclockwise and receives approximately the same plasma flux as the counterclockwise-facing probe at the bottom, confirming the vertical isotropy within a factor of two reported by Sharma et al. [4].

3.2. Surface erosion measurements

Fig. 5 shows the removal rates of diamond-like carbon by the ECDC plasma, revealing two significant trends: the plasma does not remove the coating evenly from each side of the sample, and the erosion rate depends on the location of the sample relative to the resonance.

Twice as much carbon is removed from the counterclockwise face of the sample as the clockwise face. Toroidal plasma flow at the bottom of the machine is inferred by the asymmetric ion saturation current densities to the Langmuir probe group there. If a toroidal plasma flow also exists at the location of the coated sample, albeit in the opposite direction, it could explain the asymmetry of the removal rates.

The plasma removed the most carbon coating when the sample was placed within 5 cm outside the resonant surface; the removal rate decreases both when the sample was placed further outside the resonance by 5 cm, and when the sample was placed inside the resonance. The effective yield of the plasma flux was calculated by $Y = n_c d/(\Gamma t)$, where $n_c = \rho_c/m_c$ represents the density of carbon deposited on the surface, d/t represents the linear removal rate of carbon, and $\Gamma = n_e C_s/2$ represents the ion flux to the surface. Using $n_e = 1 \times 10^{16}$ m^{-3}, $T_e = 10$ eV, $d/t = 4$ nm/h, $\rho_c = 4 \times 10^3$ kg/m^3 for diamond, and $m_c = 12$ kg/kmol gives an effective yield of $Y = 1 \times 10^{-3}$.

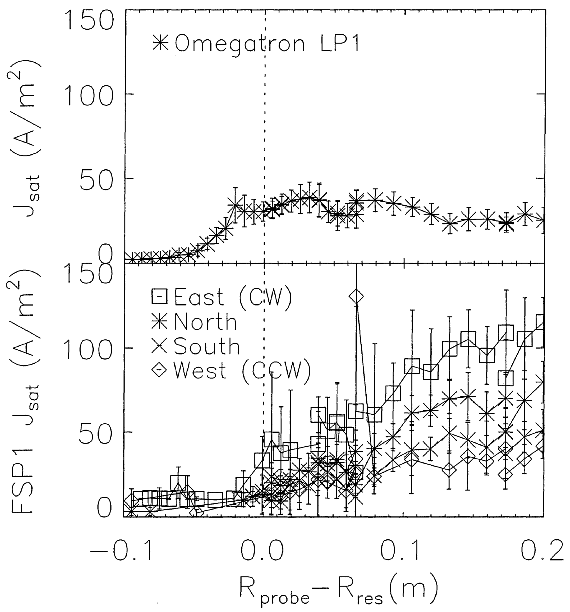

Fig. 4. Effective radial profiles of ion saturation current density, measured by a Langmuir probe on Omegatron probe head and the four Langmuir probes on the fast scanning probe. Note the plasma flow indicated by the toroidal asymmetry in saturation current density. ‘East’ points toroidally clockwise, viewed from top.

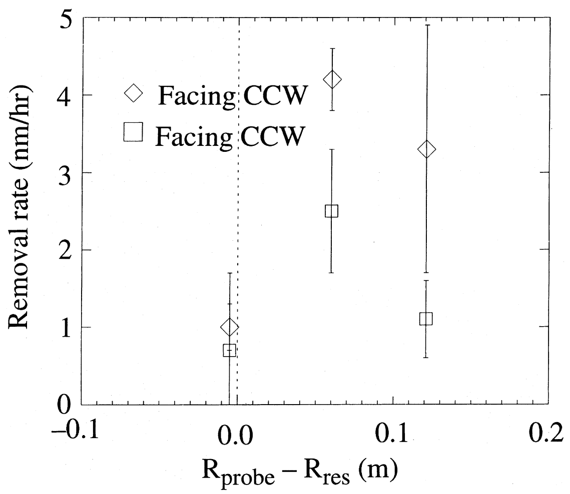

Fig. 5. Removal rate of diamond-like carbon coating stainless steel sample, as a function of the distance from cyclotron resonance location of the ECDC plasma.

This calculated yield is lower than yields given in recent literature for chemical sputtering of deuterium on carbon, but higher than yields for physical sputtering. Davis [5] reports $Y = 2 \times 10^{-2}$ for CD_4/D^+ yields of 50 eV deuterium incident energy on carbon at 500 K surface temperature. Here we assume 50 eV incident energy based on ions having $3kT_e$ sheath potential energy plus 10 eV thermal energy. Davis reports approximately 33 eV threshold energy for physical sputtering of deuterium on carbon. The plasma conditions reported here were not measured at the same toroidal location as the carbon-coated sample, yet toroidal symmetry was assumed in the calculation of the sputtering yield. The discrepancy of our calculated yields with published results might be due to toroidal asymmetry of plasma conditions. No significant deposit of carbon on the stainless-steel mask was observed, eliminating redeposition processes as a possible explanation for the discrepancy. Significant redeposition is not expected, as neutral mean free paths of carbon and hydrocarbons exceed one meter in the plasma conditions investigated here.

4. Conclusions

Experiments were performed on electron–cyclotron resonance plasmas on Alcator C-Mod. Camera views of the plasma showed toroidally symmetric visible light emission which decreased abruptly at a major radius near the cyclotron resonance, yet remained mostly uniform from the resonance location radially outward to the wall. Electron density measurements confirmed this radial structure: density decreased inside the resonant major radius by an order of magnitude over 10 cm while outside the resonance we recorded a uniform value of $n_e \approx 2 \times 10^{16}$ m^{-3}. Typical electron temperatures were $T_e \approx 10$ eV outside the resonance, increasing by a factor of two slightly inside the resonance; ion temperatures of $T_i \approx 2$ eV were measured inside and at the resonance, increasing to $T_i \approx 10$ eV, 5 cm outside the resonance. Toroidally asymmetric ion saturation current density measured at the bottom of the machine suggested toroidal plasma flow at that location.

The removal rate was measured of a diamond-like carbon coating on a stainless-steel sample which was inserted into the ECDC plasma. By moving the exposed part of the sample relative to the resonance location, a coarse radial profile of the carbon removal rate was obtained. Results indicated maximum carbon removal rates (4.2 ± 0.4 nm/h) a few centimeters outside the resonance location. Removal rates decreased inside the resonance location and further outside the resonance location, indicating localized effective cleaning. Twice as much carbon was removed from the side of the sample facing toroidally counterclockwise as the side facing clockwise. This asymmetry might have been due to toroidal plasma flow. Plasma conditions and carbon removal rates gave an effective sputtering yield of

$Y \leqslant 1 \times 10^{-3}$, less than yields reported in the literature for chemical sputtering of carbon by similar deuterium plasmas.

Acknowledgements

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