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ABSTRACT

Plasma parameters and impurity fluxes in the scrape-off layer of the TCA tokamak have been measured during Alfvén wave heating. Langmuir probes are used to measure electron density, electron temperature and plasma potential. Collection probes, in conjunction with XPS surface analysis, are used to determine impurity fluxes and ion impact energies. During RF heating, the electron edge temperature rises, the plasma potential drops and impurity fluxes are enhanced. Probe erosion due to impurity sputtering is clearly observed. The measurements are correlated with other diagnostics on TCA.

1. Introduction

Accumulation of heavy impurities during RF heating has been observed in several tokamaks. The effect has been seen both for ion cyclotron [1, 2, 3] and lower hybrid heating [4]. The heavy impurities lead to a progressive increase in the radiated power loss and eventual decrease in electron temperature during the later phases of the RF heating pulse.

Similar phenomena have been observed in TCA [5], using Alfvén wave heating at frequencies $\omega < \omega_{ci}$. Bolometric measurements [5] show that the radiated power loss increases drastically during the RF pulse (Fig. 1). A spectroscopic survey [6] indicates that this radiation is mostly due to iron impurities, and that the average iron concentration in the plasma can reach 1% during RF heating.

In the present paper, we report on detailed measurements of plasma parameters and impurity fluxes in the scrape-off layer of TCA. Electron density, electron temperature and plasma potential are measured by means of Langmuir probes. Impurity fluxes and ion impact energies are obtained from collection probe measurements of the edge plasma, in the shadow of the limiter. The probes are subsequently analyzed by x-ray photoelectron spectroscopy.

The TCA tokamak [7] has been built with the specific aim of studying Alfvén wave heating. Its main parameters are $R = 0.61$ m, $a = 0.18$ m, $B \leqslant 1.5$T, $I \leqslant 140$ kA. The machine has been in operation since 1980. RF experiments were begun in 1981, and the first heating results were obtained in 1982 [5].

2. Langmuir probe measurements

Fixed and movable Langmuir probes were installed in the equatorial plane of the TCA torus. The fixed probe was placed at a distance of 50 mm outside the limiter radius, whereas the movable probe allowed a scan of the entire space between the limiter surface and the vacuum vessel wall (52 mm). The active section of the probe had a radial extent of 5 mm. The probe voltage was swept typically between -50 and + 50 volts, at frequencies between 0.5 and 1 kHz, thus giving time resolution in the millisecond range.

Fig. 2 shows the electron density, electron temperature and plasma potential in the scrape-off layer, as measured by the fixed Langmuir probe, for two typical discharges with and without RF heating (100 kW). Plasma current, loop voltage and line average electron density are also shown in the Figure. The electron temperature in the scrape-off layer shows a large increase at the beginning of the RF pulse. This may be due to RF energy deposition in the edge plasma, or to enhanced transport from the hot core.

The plasma potential (Fig. 2) changes sign when the RF power is switched on, dropping typically from +20 to -20 volts. In this context, it should be noted that the RF antennae in TCA are electrically floating. They are placed in the immediate vicinity of the plasma (2 cm behind the limiter) and they cover a considerable fraction (16%) of the total plasma surface. During an RF pulse, the antenna potential drops by about 50 volts [6], which may be related to the well-known phenomenon of DC-bias build-up in RF discharges. It is conceivable [8] that the antenna potential in TCA has an influence on the plasma potential.

The electron density in the scrape-off layer can either decrease or increase during RF heating, depending on the type of discharge. When the MHD mode activity is low in the outer regions (shot 10912, Fig. 2) the density generally decreases, but when the mode activity is high it can easily increase by a factor 5 during RF.

The movable Langmuir probe has been used to measure radial profiles of n_e and T_e at specific times during the discharge. Fig. 3. shows the results obtained before and during the RF pulse. We observe a significant increase in the density decay length during RF heating. Similar measurements have been performed in other tokamaks [9 -12].

3. Collection probe measurements

Collection probes have been used on several tokamaks for measuring impurity fluxes in the scrape-off layer, e.g. [13, 14]. On TCA, carbon and gold foil probes were inserted into the edge plasma, in the shadow of the limiter. The foils were wrapped around a circular rod-shaped probe of 30 mm diameter and 70 mm length. The surface analysis port on the TCA vacuum vessel was equipped with a tubular shield which had a slit facing the electron drift side, and in some cases tow slits facing the electron and ion drift sides. Several selected areas of the probe could be exposed to the desired shot sequences during an experimental run. A custom-built vacuum suitcase, equipped with a self-contained pumping system, enabled in-vacuo exposure, transport an analysis of the probes, under UHV conditions. A detailed description of the experimental hardware and techniques is given elsewhere [15].

Areal concentrations of impurities retained on the carbon and gold foils were determined using x-ray photoelectron spectroscopy (XPS) [15]. Fig. 4 shows the dependence of the areal concentration of iron retained on a gold probe as a function of the number of shots fired. We observe a nonlinear dependence typical of simultaneous deposition and erosion of the probe. This behaviour has also been observed in other tokamaks, e.g. [16]. If one assumes that the erosion of the impurities is proportional to the areal concentration of impurities retained, n, one finds that [15]

$$n = \frac{D}{E} \left[1-e^{-EN} \right] \qquad (1)$$

where D is the impurity flux to the probe per shot, E is a first order rate constant for erosion and N is the number of shots fired. The parameters D and E can be obtained by performing a least-squares fit of Eq. (1) to the measured data (Fig. 4).

Deposition rates are plotted as a function of radial distance from the limiter surface in Fig. 5, for the two cases, with and without RF heating. It should be noted that the results are integrated over the entire duration of the shot. If we take into account that the RF pulse lasts for 30 ms and that the shot duration is approximately 90 ms (Fig. 2) we find that the iron impurity flux during Alfvén wave heating must be about twice the flux without heating (at a distance d = 20 mm from the edge of the plasma). When we plot the erosion constant, E, as a function of the deposition rate, D, (Fig. 6) we find that the two quantities show a linear dependence, $E = \alpha D + E_0$, where $\alpha = 7 \times 10^{-16}$ cm^2. These data indicate that sputtering by impurities is significant. Furthermore, sputtering by deuterium seems to be significant in clean discharges and it might not be negligible even in the case of high impurity fluxes. Further data are required to clarify this point.

Experiments with carbon probes show that, in addition to the iron impurities, there is also a significant concentration of oxygen trapped in the probe. The oxygen concentration is very nearly proportional to the iron concentration, the O:Fe atomic ratio being of order unity. This leads us to conclude that oxygen impurity fluxes are at least as large as iron fluxes in our experiments. We must note, however, that due to CO formation at the surface [17], the true oxygen flux may be considerably larger than the flux trapped in the carbon probe.

Ion impact energies can be estimated from the measured implantation depths [18]. We find typical implantation depths between 3 and 5 Å, corresponding to ion energies between 100 and 150 eV. Using this information, we can estimate the true oxygen flux in the scrape-off layer. Let us consider the gold foil experiment, where the implantation depth is less than the interatomic distance, so that we can assume monolayer sputtering. The total number of iron atoms lost per cm^2 per shot is then given by

$$En = \left[D_{Fe}\ Y_{Fe\rightarrow Au} + D_O\ Y_{O\rightarrow Au}\right] \frac{n}{n_m} \tag{2}$$

where n_m is the number of gold atoms in a monolayer, $n_m = 2 \times 10^{15} cm^{-2}$, the Y's are the sputtering yields, and deuterium sputtering has been neglected. Assuming that oxygen and iron ion energies are comparable (~ 150 eV), and taking the sputtering yields from the literature [19] ($Y_{Fe\rightarrow Au}=0.5$, $Y_{O\rightarrow Au}=0.3$), we can calculate the ratio between oxygen and iron fluxes from eq. (2). Using the value of $\alpha = E/D_{Fe}$ obtained from the data presented in Fig. 6 we find $D_O/D_{Fe}=3$. This result agrees with spectroscopic and bolometric estimates [6] of global oxygen and iron concentrations in TCA.

4. Effect of the limiter

In view of the large iron impurity concentrations observed the stainless steel limiter on TCA was replaced by a carbon limiter. A detailed analysis of the preformance of various limiter designs will be given elsewhere [20]. Here, we shall briefly summarize the main results: Fig. 7. shows the radiated power density divided by the ohmic power density, in the center of the plasma, for two similar discharges with RF heating, using steel and carbon limiters. The carbon limiter gives a considerable reduction in the radiated power loss, but spectroscopic measurements [6] indicate that the remaining power loss is still predominantly due to iron impurity radiation. This is confirmed by the collection probe measurements (Fig. 8) which show that the iron flux in the scrape-off layer is reduced, but not eliminated, by using a carbon limiter.

5. Discussion and conclusions

The measurements presented in this paper show that for the present impurity levels, sputtering by impurities is the main erosion mechanism in the TCA edge plasma. Previous measurements [6] indicate that the maximum iron concentration in the plasma can reach 1% in a discharge with Alfvén wave heating, using a steel limiter. If we now assume that the iron seen in the plasma is produced by sputtering in the scrape-off layer, we can estimate the surface area, S, involved in the process:

$$N_{Fe} = S \left[D_{Fe} \, Y_{Fe \rightarrow Fe} + D_O \, Y_{O \rightarrow Fe} \right] \tag{3}$$

where N_{Fe} is the total number of iron ions in the discharge. We find $S \approx 1000 \text{ cm}^2$, an area which is larger than the surface of the limiters, but smaller than the total antenna surface. We conclude that impurity sputtering can easily explain the iron injection observed in TCA. There are, of course, other mechanisms for impurity production in tokamaks, e.g. arcing, and we cannot exclude the possibility that they also contribute to the observed iron contamination.

Bolometric measurements (e.g. Fig. 1) have shown that the radiated power density in the center of the plasma increases typically by a factor of 5 during RF heating. Taking into account a slight increase in the electron denstiy, it has been estimated [6] that the central iron concentration increases by a factor 4. On the other hand, the iron impurity flux on the edge increases only by a factor 2. We conclude that Alfvén wave heating in TCA has a tendency to accumulate impurities in the center of the plasma. This may be related [8] to the negative plasma potential observed during the RF pulse (Fig. 2).

Finally, the electron temperature increase seen in the scrape-off layer (Fig. 2) may explain the enhanced iron injection during RF heating [4, 21], since the sputtering yields increase rapidly with impact energy in the range of interest (~ 100 eV).

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Figure Captions

Fig. 1: Radial profiles of radiated power loss in a discharge with RF heating (stainless steel limiter, B=1.51T, D_2 ,P_{RF}=100kW).

Fig. 2: Electron density, electron temperature and plasma potential in the scrape-off layer, a) with and b) without RF heating. Plasma current loop voltage and line averaged electron density, are also shown (carbon limiter, B = 1.16 T, D_2).

Fig. 3: Electron density and temperature as functions of radial distance from the limiter surface, a) with and b) without RF heating (carbon limiter, B = 1.51T, D_2).

Fig. 4: Iron retained on a gold probe as a function of the number of shots (carbon limiter, B = 1.16T, D_2).

Fig. 5: Iron impurity flux as a function of radial distance from the limiter surface, with and without RF heating (stainless steel limiter, B = 1.16T, D_2).

Fig. 6: Erosion constant vs. Deposition rate at a fixed position, for various RF heating powers (P_{RF} = 0-120 kW, B = 1.16T, D_2).

Fig. 7: Ratio between radiated and ohmic powers in discharges with RF heating. Comparison between stainless steel and carbon limiters (B = 1.51T, D_2).

Fig. 8: Iron impurity flux as a function of radial distance from the limiter surface, with RF heating. Comparison between stainless steel and carbon limiters ($B = 1.16T$, D_2).