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COMPARISON OF THE EFFECTS OF AN ICRF ANTENNA WITH INSULATING SIDE LIMITERS WITH AND WITHOUT A FARADAY SCREEN ON THE EDGE PARAMETERS OF A TOKAMAK PLASMA

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ABSTRACT. The PHAEDRUS-T tokamak was operated with radiofrequency power near the ion cyclotron frequency at 90° phasing between two current straps with and without a stainless steel Faraday screen covering the antenna. In both cases, the sides of the antenna were protected by insulating limiters. The plasma parameters in the scrape-off layer were measured and were shown to be essentially the same when radiofrequency power was applied from the Faraday screen covered antenna as compared with the antenna without a Faraday screen. The intensity of Fe(XVI) light dropped an order of magnitude after the screen was removed.

1. INTRODUCTION

In the past, a large increase in the numbers of impurities was commonly observed when an ion cyclotron range of frequency (ICRF) antenna was operated in a tokamak. Much effort [1] has been spent on understanding this. Considerable progress has been made and, under appropriate conditions, the RF specific impurity increase has been eliminated in present day machines [2]. However, clean operation is not necessarily guaranteed under non-optimal conditions, such as low absorption or 90° phasing.

Experiments on the model C stellarator [3] demonstrated that covering an ICRF antenna with a Faraday screen (FS) led to better heating results. For operation without an FS, the loading resistance was higher than expected because the antenna coupled electrostatic fields to the plasma. Axial electric fields penetrated the edge plasma and were responsible for the large increase in the numbers of impurities. By adding an FS, the axial electric fields were shorted out, thereby decreasing the impurity rise. In vacuum, the axial RF magnetic field was not changed with the addition of the FS. The loading resistance was lower with the FS, but it had the expected resonance behaviour when the ratio of the wave frequency to the ion cyclotron frequency was near unity and it had a magnitude within the calculated range. A higher temperature was reached because fewer impurities were present to radiate energy. The tokamak DIVA [4] also gave better heating efficiencies with an FS covered antenna.

One current area of research focuses on finding techniques to diminish the increase in the number of impurities when RF power is applied. Two methods that have been successful are using a limiter made of a low Z conducting material, such as carbon [5] or beryllium [6] instead of a high Z metal, and periodically coating the machine with a low Z conducting material, such as beryllium [6], carbon [7] or boron [8]. Another technique uses current phasing of 180° between the two straps [9]. This phasing produces fewer impurities because most of the near fields from the antenna cancel owing to the symmetry of the current straps. However, this technique is incompatible with RF current drive experiments, which require phasings different from 0 or 180°. Use of low Z material limiters, coating the machine with a low Z material and modulating the current in the straps at 180° yield a lower baselevel of impurities than was observed in the past. This new, lower, baselevel makes what were previously minor sources of impurities much more significant.

On several machines the FS has been identified as a major source of iron impurities. One theory [10, 11] is that when a magnetic field line connects two different FS blades most of the electric field between the blades is shorted out by the electrons. Except in the narrow sheaths near the blades, charge quasi-neutrality must be satisfied in the gap. The plasma potential on the field lines between the blades rises and accelerates ions into the FS. Impurity production can be decreased by aligning the blades of the FS with the total magnetic field.

An experiment on JET [12] demonstrated that impurity production was less for a small angle between the FS blades and the total magnetic field than for a large angle. However, the alignment angle is dependent on the safety factor, so flexibility in operating the machine was limited.

As the internal environments of the new, larger, machines become harsher for the plasma facing components, researchers are faced with the task of designing an FS that is able to perform adequately, or of finding an alternative solution that would allow machines to operate RF power without an FS.

In a recent experiment, TEXTOR [13] has performed ICRF heating from antennas with and without an FS for coupled power up to 2 MW. They obtained the same heating efficiencies for the two cases and slightly higher radiated power for the antenna without an FS. However, impurities were still not a serious problem. In contrast to the experiment described here, they used 0 or 180° phasing between the current straps, had conducting (carbon) side limiters and covered the antenna feeders with carbon tiles.

In another recent series of experiments, PHAEDRUS-T operated an ICRF antenna with various configurations of FSs and insulating boron nitride (BN) side limiters on the antenna. These configurations were an antenna: (i) with an FS and no BN side limiters, (ii) with an FS and BN side limiters and (iii) with no FS but with BN side limiters. For a plasma with ~150 kW of Ohmic power and an FS covered antenna with no BN side limiters, 40 kW of coupled RF power was enough to cause significant changes in the edge plasma [14, 15]. The addition of BN side limiters greatly reduced the change in the edge plasma potential due to RF power and reduced the intensity of Fe(XVI) light by a factor of 2 [16]. This is in contrast to other small machines, which typically have large impurity increases during RF power application. The addition of BN side limiters to the PHAEDRUS-T antenna makes its characteristics similar to those of a large tokamak in terms of RF–edge coupling.

Both with and without an FS, the density rise during RF power application (less than ~50%) was about the same. This density rise limited the amount of coupled power by causing a disruption at approximately 100 kW of RF power. Forty kilowatts of RF power were used in this experiment because the plasma could be quite well controlled when the RF power was turned on (the position was stable and the density rise not too large) and there should be enough power to show if removing the FS had adverse effects on the edge plasma or impurities.

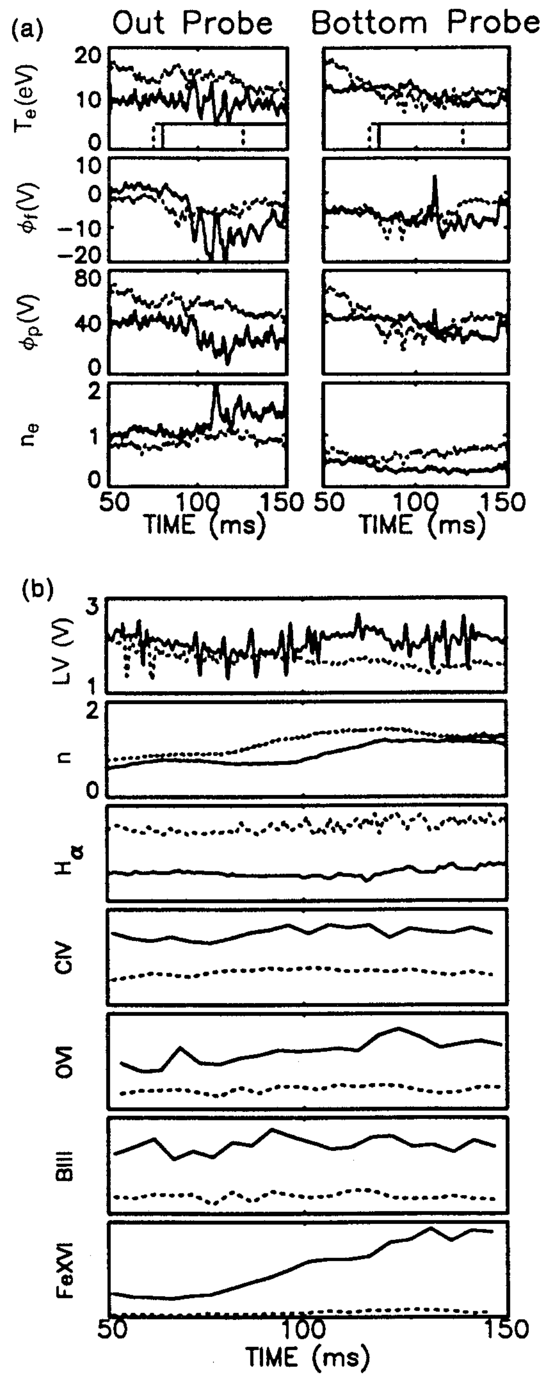

FIG. 1. In each plot the x axis is the time from 50–150 ms. Solid lines are for the case with FS data and the dotted lines for the case without FS data. The times during which RF power was applied are shown in the T_e plots by the solid and dotted rectangles for the cases with and without an FS, respectively. (a) On the left are shown T_e, ϕ_f, ϕ_P and n_e (10^{12} cm^{-3}) for the out probe; the corresponding measurements for the bottom probe are shown on the right. (b) These plots show the loop voltage (LV), the line average density (n (10^{13} cm^{-3})) and the light intensities of H_α from the limiter, C(IV), O(VI), B(III) and Fe(XVI). All light intensities except that for H_α are normalized to the line average density.

In this paper, a comparison of the effects of an RF antenna with and without an FS is made of plasma edge parameters as measured by triple probes. The intensities of VUV emission light are also compared.

The data compared were taken from two different days separated by three months and a vent of the tokamak. Operating conditions (line average density, plasma position, toroidal magnetic field, plasma current, RF power and phasing, gas and conditioning procedure (boronization and helium glow)) were kept the same or nearly so for each day. The only difference in machine hardware was that the FS was removed and the current straps were covered with BN tiles.

The surface conditions of the machine were not exactly the same. This was shown during the Ohmic phase by the slightly different edge parameters. Also, the recycling of deuterium at the limiter changed, as evidenced by the difference in intensity of H_α light from the limiter (see Fig. 1) and the different fuelling required.

Nevertheless, in terms of a change in edge parameters and impurity production when the RF power is turned on with and without an FS, similar results have been obtained during several different operating regimes. The data for this paper are for 40 kW RF power in the fast wave current drive regime. This is only one of several configurations that have been tried. The cases have also been investigated with and without an FS covering the antenna, with RF frequencies below and one above the ion cyclotron frequency, with a different toroidal magnetic field, with different gases and with RF power up to 150 kW. The minor radius at which the absorption of most of the RF power is expected to take place and the absorption efficiency vary for these different regimes.

2. MACHINE

The PHAEDRUS-T tokamak is an ISX class tokamak. The major radius, minor radius, plasma current, toroidal field and pulse length are 0.93 m, 0.26 m, 100 kA, 1 T and 150 ms, respectively. A typical line average density is $\sim 1 \times 10^{13}$ cm^{-3} and on axis $T_e \sim$ 500–800 eV. The minor radius is defined by a carbon poloidal ring limiter. The RF antenna is on the low field side and is capable of coupling 250 kW to the plasma, and the phasing between the two current straps, which are made of copper, can be varied between 0 and 180° for a frequency range of 7 to 19 MHz. The machine is boronized weekly and helium glow discharge cleaned daily.

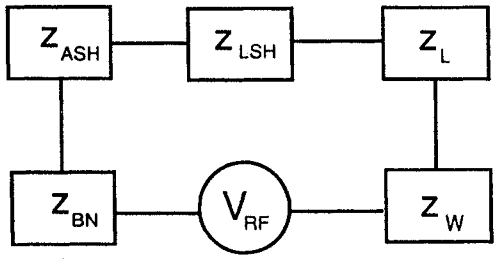

FIG. 2. Schematic representation of current flow between the antenna and plasma edge. Here, Z_{BN} is the impedance of BN side limiters, Z_{ASH} is the impedance of the sheath next to the antenna, Z_{LSH} is the impedance of the sheath next to the limiter, Z_W is the impedance of the vacuum vessel wall from the probe port box to the antenna port box, Z_L is the impedance of the carbon limiter and V_{RF} is the oscillating voltage from the antenna.

The sides of the antenna were covered with BN [16] side limiters both with and without the FS in place. The material BN is an insulator that can reduce the direct coupling of RF power to the edge. The increased sheath potential due to the RF power causes increased sputtering because of the higher energy of escaping ions to the sides of the FS and the carbon limiter. The impedance of the BN is much larger than the sheath, wall or limiter impedances, so with the addition of an insulating side limiter almost all the voltage drop occurs across the BN instead of across the sheath near the antenna (see Fig. 2). However, the BN does not prevent a wave generated by the antenna from interacting with the edge plasma and directly depositing energy.

3. EXPERIMENT

Measurements of electron temperature (T_e), floating potential (ϕ_f) and ion saturation current were taken in the edge and measurements of the light intensities of Fe(XVI) (335 Å), C(IV) (384 Å), B(III) (518 Å) and O(VI) (1032 Å) were made in a pure deuterium plasma operated at 90° phasing with an RF frequency of 19 MHz and a toroidal magnetic field for which $3\Omega_D$ (Ω_D is the cyclotron frequency of deuterium) occurs on axis. For PHAEDRUS-T this is a fast wave current drive regime with low pass electron absorption and negligible ion absorption. Measurements were first made with the FS on the antenna. Several months later, after the FS had been removed and the current straps had been covered with BN tiles during a vent of the tokamak vessel, the same measurements were made under similar operating conditions.

Plasma parameters were measured by two triple probes separated 40° toroidally from the antenna, and thus only far field RF effects would be seen. Radial scans were taken for minor radii r = 26 to 29 cm. From these data, the electron density (n_e) and plasma potential (ϕ_p) were calculated. The latter was calculated from the following equation (see Ref. [17]):

$$\phi_p(V) = \phi_f(V) + 0.5(T_e(\mathrm{eV})/e)\ln(m_i T_e/m_e T_i) \qquad (1)$$

No measurement of T_i, the ion temperature, was made, so it was assumed that $T_i = T_e$. The 'out' probe was mounted horizontally on the midplane. It mapped to the top half of the antenna owing to the rotational transform. The 'bottom' probe was mounted vertically and mapped to the bottom of the antenna, near the radial feeder.

4. RESULTS

Typical plasma edge parameters are shown in Fig. 1(a). The solid lines correspond to the antenna with an FS, and the dotted lines to the antenna without an FS. The times during which RF power was applied from the antenna with and without an FS were 80–150 ms and 75–125 ms, respectively. These data were taken at a minor radius of 27.4 cm, 1 cm behind the leading edge of the BN side limiter and 0.5 cm in front of the current strap.

Before the RF power is turned on, differences are evident in the T_e profiles. The initial difference in T_e for the probes, especially the out probe, for with and without an FS is probably due to the different surface conditions, in particular, the recycling coefficient of deuterium from the carbon limiter. The recycling rate was different for the two days, as shown by the difference in H_α light from the limiter and the difference in the way the operator was required to release neutral gas into the tokamak to obtain a good plasma. Also, there was a difference in the vertical plasma position of 2 mm. The gradual decrease of T_e with time without the FS for the out and bottom probes is partly due to a change in the horizontal plasma position by a few millimeters during the shot and the difference in fuelling. This is also true for the gradual change in the calculated plasma density as a function of time for both probes with and without an FS.

The biggest change due to the application of RF power is seen in the ϕ_f of the out probe with and without an FS, where ϕ_f decreased approximately 15 and 5 V, respectively. Part of this may be due to the slow temporal response of the probes [18]. The actual change in floating potential during RF power application is less than this measured value. Less change was seen on the bottom probe than on the out probe, where ϕ_f dropped approximately 5 V for the cases with and without an FS. The electron temperature T_e changed by at most a few electron volts due to the RF power. In general, because of the insulating side limiters on the antenna, the application of RF power had little effect on the edge parameters that were on field lines connected to the antenna, and even less when the difference with and without an FS was examined.

The intensity of H_α light from the carbon limiter is shown in Fig. 1. The intensity of H_α light for the no FS case is a factor of two higher, mainly because of the different recycling coefficient of deuterium from the limiter. With and without the FS, little change is seen when the RF power is turned on. The H_α intensity from the limiter is dependent on the flux of hydrogen or deuterium ions to the limiter, the recycling coefficient and the values of n_e and T_e near the limiter. A nearly constant intensity of light when the RF power is turned on indicates a lack of global n_e and T_e changes in the edge.

Plots of the time evolutions of the C(IV), O(VI) and B(III) light intensities in Fig. 1 do not show a noticeable change when the RF power is turned on either with or without an FS. However, their magnitudes were reduced by approximately a factor of 2–4 by the removal of the FS. Although the FS is made of stainless steel, during boronization with TMB ($(CH_3)_3B$) it becomes partially coated with boron and carbon. Oxygen is also present on the FS and other surfaces. Because of the proximity of the FS to the plasma, its removal can eliminate a significant source of high and low Z impurities. The flat carbon and boron signals during RF power application indicated that RF enhanced sputtering at the BN and carbon limiters does not take place.

The Fe(XVI) light intensity data (see Fig. 1) show that after the FS was removed the iron emission dropped by a factor of 10 throughout the discharge. These data imply that, with the FS, most of the iron is produced by plasma ions falling through the plasma sheath potential (Eq. (1)) into the FS face, which is the closest piece of iron to the plasma, and causing sputtering. In addition, iron originating from the FS and wall is continuously deposited and eroded from the carbon limiter throughout the discharge. After the FS was removed, the nearest sources of iron were the limiters of the bellows at r = 32 cm, as compared with r = 26.4 cm for the FS. Much less sputtering takes place at these surfaces because of the lower plasma density at the bellow limiters. For both the cases with and without

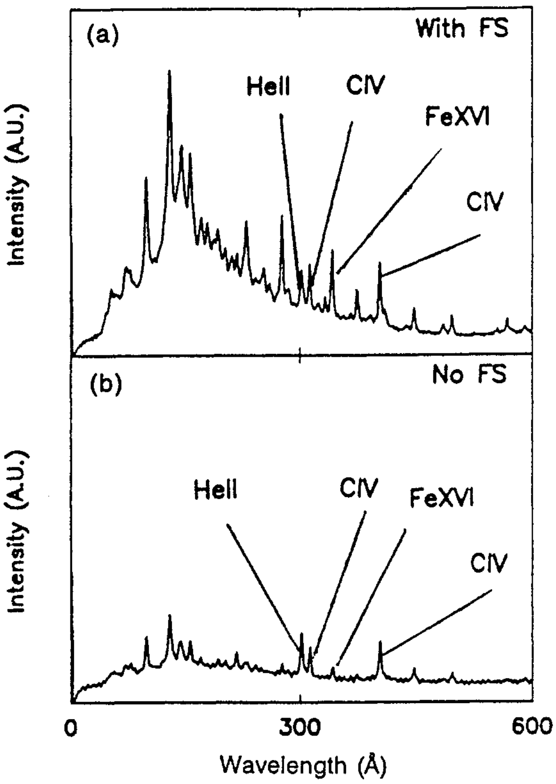

FIG. 3. Relative intensity of VUV spectral emission at t = 110 ms: (a) with an FS, (b) without an FS. The lines He(II) (304 Å), C(IV) (312 Å), Fe(XVI) (335 Å) and C(IV) (384 Å) are labelled.

an FS, the intensity increases by a factor of 3-4 during RF power. The reason that this happens is not clear at this time. The absolute intensity of Fe(XVI) light dropped by a factor of 10 with the removal of the FS but the relative increase during RF power application was about the same for the two cases.

Figure 3(a) shows a plot of the VUV emission spectra with an FS during RF power application and Fig 3(b) shows a plot without an FS. The with FS case shows an iron dominated spectra because of the relatively intense iron continuum from ~100–300 Å and the Fe(XVI) line as compared with the He(II) and C(IV) lines. With no FS, the spectra are dominated by low Z particles (helium, carbon and oxygen). This is seen by the reduction in the magnitude of the iron continuum and the low intensity of the Fe(XVI) line as compared with the He(II) and C(IV) lines. The low Z impurity intensity and the entire spectrum were lower after the nearest piece of iron, the FS, was removed.

Figure 1(b) shows that, before the RF power is turned on, the loop voltage is slightly lower for the antenna without an FS. This is consistent with the lowering of high Z impurity production by the removal of the FS. The loop voltage increases for the with FS case and remains flat with no FS when the RF power is turned on. Using the Spitzer resistivity for the plasma resistance, this rise can be caused by an increase in Z effective ($Z_{\rm eff}$) and/or a drop in T_e due to the power radiated by impurities from the FS. For no FS, the high Z impurity rise was much less, so $Z_{\rm eff}$ would undergo a smaller increase. The radiated power and the subsequent change in loop voltage would also be less. (Although no direct measurement of radiated power was available, the absolute intensity of the VUV spectral emission was lower after the FS was removed.)

Spikes were seen in the loading resistance as the density was ramped up. These were indicative of eigenmodes, which show that the RF power was coupled to the core plasma but was not absorbed very well. In spite of the low absorption of RF power by the plasma, after the FS was removed a plasma was produced that had a VUV emission spectrum dominated by radiation from low Z particles.

Removal of the FS allowed the voltage stand-off to reach a level near the limit of the matching capacitors.

5. CONCLUSION

The electron temperature, plasma potential and plasma density showed no significant changes after the FS was removed from the ICRF antenna. Both with and without an FS, the RF power had little effect on the edge plasma parameters. This was mainly because for operation with and without an FS, the antenna had BN insulating side limiters. The intensity of impurity light emission was lowered, especially for Fe(XVI), after the FS was removed.

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