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EXPERIMENTAL STUDY OF SHEATH CURRENTS IN THE SCRAPE-OFF LAYER DURING ICRH ON TEXTOR

R. VAN NIEUWENHOVE and G. VAN OOST
Laboratoire de Physique des Plasmas—Laboratorium voor Plasmafysica,
Association Euratom-Etat Belge—Associatie Euratom-Belgische Staat,
Ecole Royale Militaire—Koninklijke Militaire School, B-1040 Brussels, Belgium

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Abstract—In our previous study on TEXTOR it has been shown that an excited Faraday-shielded fast-wave antenna draws a large DC electron current from the plasma due to the sheath rectification effect. In the present study, it is shown for the first time that this DC current (up to 400 A) extends toroidally all around the circumference of the machine and returns to the wall via conducting objects which are electrically connected to the wall. Preliminary measurements of r.f. currents in the scrape-off layer were performed using a specially designed Rogowski coil.

1. INTRODUCTION

THERE EXISTS growing evidence that the most likely candidate for providing a general explanation of most ICRH-induced edge effects seems to be based on sheath effects (see e.g. VAN NIEUWENHOVE, 1989; VAN NIEUWENHOVE and VAN OOST, 1989; PERKINS, 1989; CHODURA and NEUHAUSER, 1989). Whereas most of the theoretical studies are considering local r.f. sheaths (i.e. at the Faraday screen and the region between the antenna protection limiters), some of the authors (LAWSON, 1990; CARTER *et al.*, 1990; CHODURA and NEUHAUSER, 1989) have pointed to the possibility of nonlocal r.f. sheaths at locations where magnetic field lines cross bare conducting pieces. Until now, however, no experimental data were available to confirm these nonlocal sheath effects. The present study shows that the DC sheath-rectified currents drawn by the excited ICRF antenna extend toroidally far away from this antenna and return via conducting objects such as limiters and passive ICRF antennas to the liner (see Fig. 1) of TEXTOR. It should be mentioned here that most of the theoretical r.f. sheath models do not reproduce a sheath rectified current, in contrast to the experimental observations (see e.g. TAYLOR *et al.*, 1982; VAN NIEUWENHOVE and VAN OOST, 1989). In the study of MYRA *et al.* (1990) it is for instance assumed, as a boundary condition, that the net current collected by the antenna is zero. In what follows, the terminology "ICRF antenna sheath effect" is used to indicate that parts of the antenna behave like a Langmuir probe, with the usual static current–voltage characteristic and its ensuing DC current resulting from its rectifying effect. The present study, as well as our previous one (VAN NIEUWENHOVE and VAN OOST, 1989) is consistent with this simple picture. Note also that the r.f. sheaths at the Faraday screen blades (PERKINS, 1989) can result in sheath-rectified currents. Due to the low plasma density at this location, the contribution of these currents is expected to be less important.

The paper is organized as follows. In Section 2, the experimental set-up is described. In Section 3, the measurements are given and the parametric dependencies of the DC

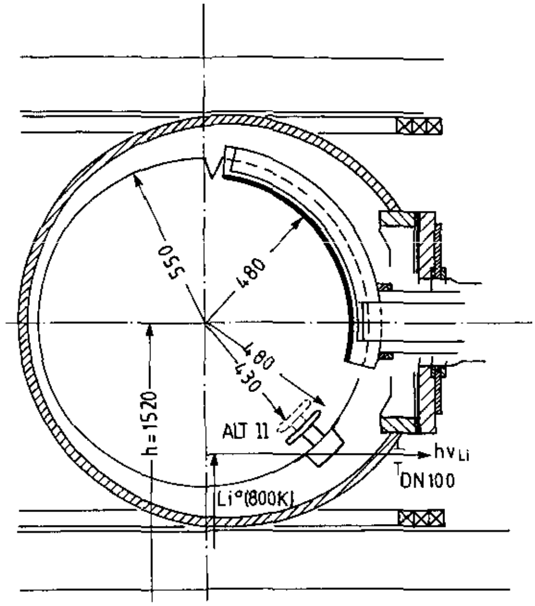

FIG. 1.—Poloidal cross-section of TEXTOR, showing the position of the antenna, the ALT-II limiter, the liner (at $r = 55$ cm), and one of the flexible V-shaped shorts which connects the antenna structure to the liner.

currents and of the current flow paths in the SOL are discussed. The toroidal extent of the r.f. sheath currents is discussed and preliminary measurements with a plasma compatible Rogowski coil are shown. An estimate of the power dissipated in sheath currents is given in Section 4. Finally, conclusions are drawn in Section 5.

2. EXPERIMENTAL SET-UP

The r.f. power on TEXTOR is provided by two pairs of low-fields side-launch antennas, located toroidally at opposite sides of the torus (VAN OOST *et al.*, 1987; DURODIÉ *et al.*, 1989). For the present experiments, Π phasing between the antennas of a pair was used. In the poloidal direction, each antenna extends from 15° below the outer midplane over 97.5° to 7.5° from the top of the machine. The antennas have a curvature, determined by a circle of radius $r = 48.0$ cm. The radial antenna position used in the subsequent text refers to the position in the equatorial plane. The radially movable antenna pairs A1 and A2 are connected to the liner by several V-shaped, flexible strips made of Inconel 625 (see Fig. 1) which serve as an r.f. short to avoid the build-up of large r.f. voltages between the liner and antenna and to reduce the r.f. fields in the region between the vacuum chamber and liner. The simplified schematic set-up for the DC current measurement between the antenna and liner is shown in Fig. 2. In the following, the term "antenna" refers to the complete mechanical wave launching structure (including the Faraday shield, side limiters, central conductor, return conductor, . . .) located inside the Tokamak vessel. An external shunt is placed over the flexible strips whereby the current through this shunt is measured by a current probe (TEKTRONIX A6302). The resistance of this shunt was chosen such that the

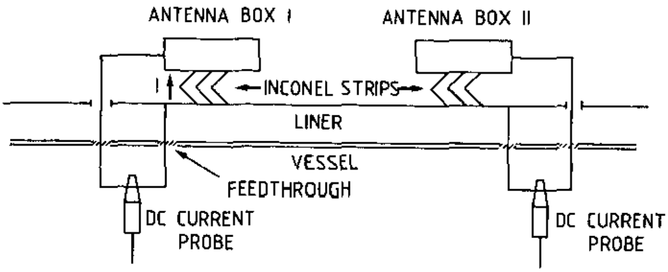

FIG. 2.—Simplified schematic set-up for the measurement of the DC current between the ICRF antenna and liner.

measured current I_m is only a small fraction (1%) of the current I between the antenna and liner (see Fig. 2), so as not to significantly perturb the actual current flow path. The total resistance of all the flexible strips (of the order of 1 mΩ) was calibrated *in situ* by connecting a constant current source (6 A) between the antenna and liner during a major opening of the machine and measuring the voltage drop over the strips. For each antenna, the external shunt consists of two thick copper wires (ϕ = 16 mm^2), one connected to the liner at the feedthrough for the electrical liner heating system, and one connected (outside of the machine) to the antenna interface system, which is electrically isolated from the mass of the r.f. generator by a DC break in the transmission line (VAN OOST *et al.*, 1987). These cables were then connected to each other at the location of the measuring system over an r.f. filter (not shown in Fig. 2) to select only the DC current component. The resistances of these cables, plus the r.f. filter were then measured, thereby completing the calibration of the system and allowing a calibrated current measurement (accuracy $\simeq \pm 5\%$) for both antenna pairs simultaneously.

3. MEASUREMENTS

3.1. *Parametric dependencies*

The measured change in DC current drawn by the energized antenna pair A2 relative to the OH level (VAN NIEUWENHOVE and VAN OOST, 1989) during a shot-to-shot power scan (transmitted r.f. power $P_{r.f.} \simeq 20$ kW–1.5 MW) is shown in Fig. 3. At low power ($P_{r.f.} \leqslant 300$ kW) there is initially a rapid increase of DC current with power, whereas at higher r.f. power levels, the increase tends to become smaller. The fact that the DC current is still increasing up to the highest r.f. power could be due to a simultaneous increase of edge density induced by the ICRF (VAN NIEUWENHOVE, 1989; VAN OOST *et al.*, 1990), because the saturated DC current is expected to be proportional to the plasma density. The dependence of the change in DC current (ΔI_{DC}), relative to the OH phase, when exciting A1 ($P_{r.f.} \simeq 500$ kW) is shown in Fig. 4, revealing a very linear relationship between ΔI_{DC} and the edge density at $r = 47.5$ cm, obtained from Li-beam charge exchange spectroscopy. This linear relationship was found to hold even for various values of the plasma current I_p. With zero phase excitation (between the antennas of a pair) the measured DC currents were found to be of the same order as for Π phase excitation.

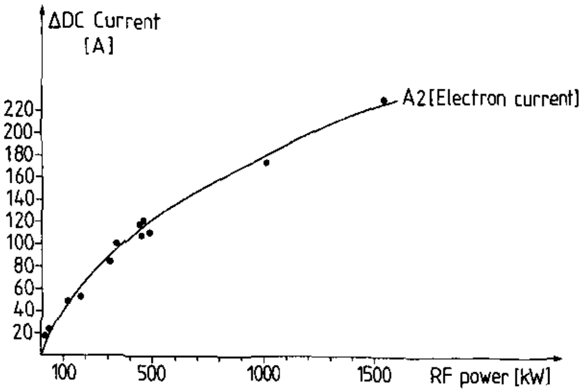

FIG. 3.—Dependence of the change in DC current relative to the OH phase on r.f. power (A2; Π phasing). The plasma parameters are: $\bar{n}_e \simeq 2.1 \times 10^3$ cm^{-3}, $I_p = 340$ kA, $B_T = 2.25$ T, H/D ratio $\leqslant 7\%$, the ALT-II toroidal belt limiter as the main limiter at $r = 46$ cm, antenna position = 49 cm, generator frequency = 32.5 MHz, wall conditioning: boronization, #40412–40426.

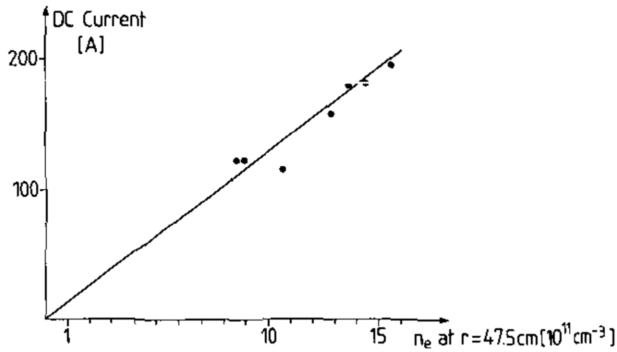

FIG. 4.—Dependence of the change in DC current on edge density when exciting A1 (Π phasing). The transmitted r.f. power was 500 kW, other parameters as in Fig. 3, #42911–42918.

3.2. *Current flow paths*

As already mentioned in the Introduction, the DC electron current drawn from the plasma by an excited r.f. antenna, is continued in the SOL plasma, and returns to the liner via conducting objects which are electrically connected to the liner. Under normal operating conditions, only the ICRF antennas and the inner toroidal bumper limiter make direct electrical contact with the liner; the toroidal belt limiter ALT-II is normally floating. Thus, when both antennas are in the standard position of $r = 49.0$ cm, and when only one ICRF antenna pair is excited, one would expect the current path to be closed through the other passive ICRF antenna. This has indeed been observed experimentally as is shown in Fig. 5a. Thus, when exciting for instance A1 (Fig. 5a), a DC current of opposite sign, carried by ions instead of electrons and hereby referred to as an "ion current", is observed to flow to the passive antenna pair A2. From these measurements it can be concluded that DC currents drawn by the excited antenna, as large as a few hundred Amperes, are flowing along magnetic field lines in the plasma SOL, even at the opposite side of the torus from the energized

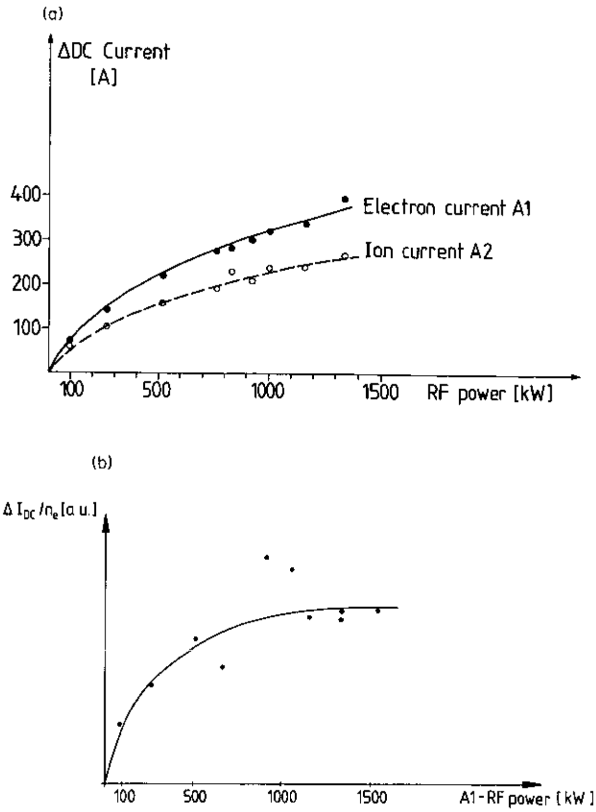

FIG. 5.—Radio-frequency power scan, when exciting A1 (a) showing simultaneously (i) an electron current drawn by the active antenna and (ii) an ion current drawn by the passive antenna. The change in DC electron current normalized by the edge density (at $r = 47.5$ cm) when exciting A1 is shown in (b). The plasma parameters are: $\bar{n}_e \simeq 3.0 \times 10^3\ \mathrm{cm}^{-3}$, both antennas are positioned at $r = 49.0$ cm, other parameters as in Fig. 3, #40816–40822.

antenna. Figure 5b shows the variation of DC current with power, when normalized to the edge density at $r = 47.5$ cm (as obtained by HCN interferometry). As expected from probe theory, the normalized DC current saturates at a higher r.f. power ($P_{\mathrm{r.f.}} \geqslant 500$ kW).

When both antennas are excited simultaneously, the current flow paths become more complicated, since the current to one of the excited ICRF antennas will, in addition to the usual electron current, also contain an ion current contribution due to the other antenna. Thus the total current collected by each antenna should be reduced significantly. This is exactly what has been observed, as is shown in Fig. 6.

As part of an edge polarization experiment (WEYNANTS *et al.*, 1990), all eight blades of the toroidal belt limiter ALT-II were electrically connected to the liner and the current through each blade was monitored separately. The variation of DC current to the eight ALT-II blades, during a ramp-down of the plasma current (from $I_p = 406$ to 322 kA), when exciting A2, revealed (i) a nonuniform distribution of the currents to the various blades and (ii) significant variations of this current distribution due to the variation of I_p. Similar strong variations in this distribution were also observed

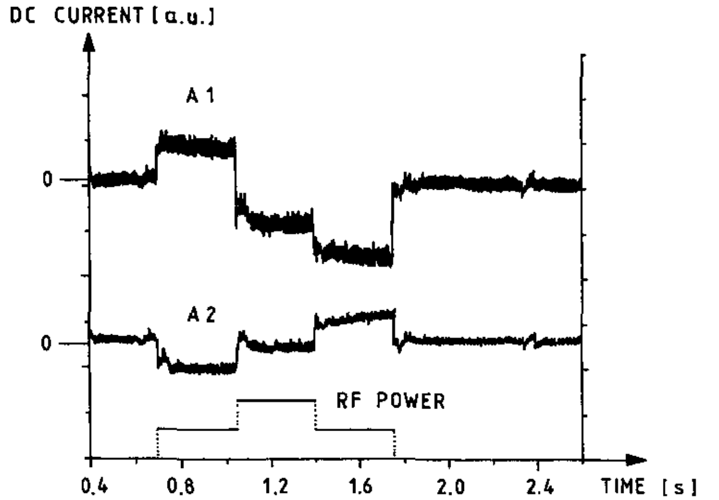

FIG. 6.—Time evolution of the DC current during a discharge when the r.f. pulse of A2 (1500 kW; from 0.7 to 1.4 s) and of A1 (1700 kW; from 1.05 to 1.75 s) are partly overlapping (from 1.05 to 1.4 s). In this figure, the A1 and A2 signals have different arbitrary units. The plasma parameters are: $\bar{n}_e \simeq 3.2 \times 10^{13}$ cm^{-3}, other parameters as in Fig. 3, #42817.

when varying only B_T. Thus the DC current seems to be guided along the total magnetic field in the SOL, as expected.

3.3. *Radio-frequency sheath currents*

The application of a sinusoidal driving voltage to a Langmuir probe leads, besides the generation of a sheath rectified DC current, also to the generation of r.f. currents at the generator frequency and its harmonics. The propagation characteristics of these r.f. currents in the SOL was first measured by GREENE (1984) on the CALTECH Tokamak by means of a plasma-compatible Rogowski coil. These experiments revealed the existence of an r.f. current tube, aligned along the total magnetic field. Even when the current monitor (Rogowski coil) was some 5 cm away in the toroidal direction from the r.f. driven probe, about 40% of the current leaving the Langmuir probe passed through the aperture of the monitor. Since the r.f. current flows equally in both directions (toroidally), nearly all the current (80%) leaving the antenna is accounted for. Preliminary measurements of r.f. currents (at the r.f generator frequency) during ICRH, using a plasma compatible Rogowski coil (similar in design to the Rogowski coil used on CALTECH), were recently performed on TEXTOR. To the knowledge of the authors, these are the first measurements of this type on an ICRF heated Tokamak. The Rogowski coil was located in the outer equatorial plane, toroidally separated by about 1 m from the exciting fast wave antenna A2. The surface of the annular ring through which the plasma and current could flow was 2 cm^2. These measurements also revealed a significant r.f. current J_z, parallel to the magnetic field. A radial profile of J_z, when exciting A2 ($P_{\mathrm{r.f.}} \simeq 400$ kW), is shown in Fig. 7. If one assumes that this current exists all along the poloidal extent ($\simeq 0.7$ m) of the exciting antenna, the integration of this current in the radial and poloidal directions leads to an non-negligible total parallel r.f. current of about 50 A. our first measure-

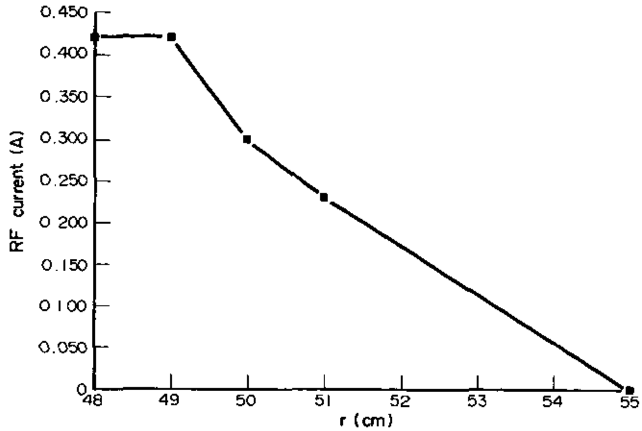

FIG. 7.—Radial profile of the r.f. current at the generator frequency, measured by a Rogowski coil, toroidally at 1 m away from the excited ICRF antenna ($P_{r.f.} \simeq 400$ kW). The plasma parameters are: $\bar{n}_e \simeq 2.0 \times 10^{13}$ cm^{-3}, $I_p = 350$ kA, H/D ratio $\leqslant 8\%$, other parameters as in Fig. 3, #44974–44980.

ments show that the r.f. current saturates at higher power ($P_{r.f.} \simeq 400$ kW), similar to the DC sheath currents. Theoretical calculations show that the r.f. currents are too large to be related to parasitically excited slow waves (SWs). This is because, for typical edge plasma parameters, SWs are strongly evanescent and would therefore have decayed to a negligible level at the toroidal location of the Rogowski coil. From the above considerations, it is tempting to conclude that we have actually observed r.f. currents generated through sheath effects at the ICRH antenna. Further measurements are required to ascertain this.

4. POWER ABSORPTION

In the saturated probe regime, when the amplitude of the driving oscillating voltage significantly exceeds T_e ($\simeq 30$ eV), it can be shown that the total absorbed power, including r.f. currents, is $P \simeq 0.6\, I_{DC} V_0$, with V_0 the amplitude of the driving voltage. Assuming $V_0 \simeq 10\ T_e$ (eV) $\simeq 300$ V and $I_{DC} \simeq 200$ A (at $P_{r.f.} \simeq 1$ MW) then $P \simeq 36$ kW, or about 3.6% of the launched r.f. power.

5. DISCUSSION AND CONCLUSIONS

It has been demonstrated that the sheath-rectified currents, generated at an ICRF antenna, extend toroidally all around the circumference of the machine and return to the liner via conducting objects which are electrically connected to the liner. The parametric dependencies of these DC currents have been further investigated and were found to be consistent with the simple picture in which the ICRF antenna has a probe-like behaviour. Preliminary measurements with a plasma compatible Rogowski coil also seem to indicate that the r.f. currents have a significant extension in the toroidal direction. These currents, and their associated electric fields, could be a possible mechanism to explain the occurrence of parametric decay processes far away from the exciting antenna, as observed on ASDEX and TEXTOR (VAN

NIEUWENHOVE *et al.*, 1988a, b). They could also lead to substantial deviations of the *I–V* characteristic of a single Langmuir probe (BOSCHI and MAGISTRELLI, 1963).

The power dissipated in the sheath currents has been estimated to be of the order of 2–4% of the launched r.f. power. As already proposed by VAN NIEUWENHOVE (1989) and more recently also by CARTER *et al.* (1990), sheath effects could be strongly reduced by allowing the ICRF antenna to float. To balance the electron current by the ion current in this case, the antenna will become very negative [in the range 100–300 V negative with respect to the wall (GREENE, 1984; TAYLOR *et al.*, 1982)]. The ALT-I biasing experiments on TEXTOR (CONN *et al.*, 1986) have clearly demonstrated that this would not cause any arcing or impurity problems.

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