Study of ion and electron fluxes to the walls in very low-pressure electron cyclotron resonance plasmas

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Abstract: Electron cyclotron resonance (ECR) plasmas are high-density plasmas where charged particles are confined thanks to a strong static magnetic field. However, it is well-known that ions and electrons are lost at the magnetic cusps. In a very low-pressure helium ECR plasma, we show that important electron and ion current densities are also transported to the walls at the magnetic corners. These fluxes are discussed in relation with peculiar plasma-surface interactions arising at this location.

Keywords: ECR plasma, electron and ion transport, wall current probe.

1. INTRODUCTION

Electron cyclotron resonance (ECR) reactor has been borrowed from fusion and electric propulsion plasmas [1]. Such very low-pressure plasmas use strong static magnetic fields as a key feature. It provides the necessary conditions for the ECR heating of electrons [2,3]: the frequency of the 2.45-GHz microwaves matches the natural gyration frequency of the electrons bathed in an 875-G magnetic field intensity. Thus, electrons locally see a constant accelerating electric field. In addition, the \( \mathbf{B} \)-field also acts as a magnetic mirror inverting the momentum of primary electrons and allowing their confinement. This is crucial to increase the electron mean free path which enables plasma generation, maintenance and stability. Finally, in such discharges, primary electrons drift longitudinally due to the magnetic gradient, the magnetic curvature and the \( \mathbf{E} \times \mathbf{B} \) drifts. Hence, ECR plasmas present a high plasma density with a good homogeneity even at very low-pressure [4].

Due to the electron drift, it is needed to close the magnetic racetrack [3] in order to considerably reduce the electron collection loss area. However, magnetic corners (MCs) induce anisotropies leading to a specific charged particles transport as described in rectangular magnetrons [5]. In addition, a specific cone loss exists at the cusps: depending on their incident angle, energetic electrons can escape the magnetic mirror. Even if such behaviour is deeply acknowledged and theorized, the discrepancies between theory and experimental results, especially on the measured loss area, is still poorly understood [6].

In this study, we investigate the loss of charged species on surfaces in strong magnetic field regions of very low-pressure ECR plasmas. Electron and ion current densities have been measured in helium at cusp and MC for different pressures using a specifically conceived wall current probe (WCP), analogous to that of [7]. From the ion current measured at the walls, we obtain an image of the charged species transport. Both ion and electron current densities are compared with the local magnetic field topographies. The prevalence of a high charged particles flux at the MC could induce strong modifications in the local plasma-surface interactions.

2. MATERIALS AND METHODS

The reactor used in this study is depicted in Fig. 1 and similar to the one described in several articles [3, 8, 9]. It is a 110×16×12 cm³ (along the X, Y and Z-directions, respectively) non-magnetic stainless steel vessel with several ports and a top-window that allows for optical and electrical plasma characterizations. The magnetic racetrack consists in 2×2×2.2 cm³ Sm-Co magnets arranged in a 94-cm long 14-cm large external ring (north) and an 84-cm long interior magnet (south). The distance separating centre-to-centre magnets is 6 cm but obviously varies at the MCs. The resulting magnetic field at the bottom of the vessel directly above a magnet is about 3300 Gauss.

A linear applicator is placed on the side of the vessel at \( Z = 8 \) mm from the bottom of the reactor. For all experiments, the 2.45 GHz solid state Sairem© microwave generator injected 150 W with a reflected power (reduced using a triple stub) below 1 W.

The base pressure was obtained using a rotary and a turbo molecular pumps leading to a pressure below \( 10^{-5} \) Torr. The experiments were carried out at 0.1, 0.3 and 1 mTorr.

Fig. 1. The ECR linear reactor used in this study. Dashed inset depicts a cross section of one of the plasma lobes. Dotted inset shows the magnets polarity and the 2 locations of the WCP measurements (1: cusp, 2: MC). Dot-dashed inset represents the area modelled in Fig. 3.
3. RESULTS AND DISCUSSION

In order to understand the variations of the measured charged species fluxes, the results have been compared to the local magnetic field topography. Part of the racetrack geometry (dot-dashed inset of Fig. 1) has been reproduced using ANSYS MAXWELL to obtain the magnetic field cartography at \( Z = 0 \) (Fig. 3.a). The magnetic field lines have been calculated with COMSOL Multiphysics© using a 2D radial \([ r = \sqrt{x^2 + y^2}, Z ]\) modelling of the same area (Fig. 3b).

At the cusp, the magnetic field is maximum right above the magnet \((Y' = 0, Z = 0, B = 3300 \text{ G})\) and decays exponentially with increasing \( Z \), which provides a good mirror ratio. At the MC and in between magnets, \( B \)-intensity first increases with \( Z \) (up to \( Z = 10 \text{ mm} \)) then decreases slowly, preventing any mirror effect at low \( Z \). In Fig. 3, the magnetic map of the MC shows a strong impact of the increased inter-magnet distance: the area is characterized by a large zone combining low \( B \)-field magnitude and recombination of certain magnetic lines on the walls.

\[ I_s = 0.6 n q A_{probe} \frac{k}{\sqrt{T_e}} \frac{1}{m_i} \]  

with \( n \) the plasma density, \( q \) the elementary charge, \( k \) the Boltzman constant, \( T_e \) the electron temperature, \( m_i \) the ion mass and \( A_{probe} \) the area of collection of the charged particles by the probe. However, when the value of the difference between plasma potential \( (V_p) \) and the probe potential is increasing, \( A_{probe} \) increases as well in a near-linear fashion due to edge effects [11]. To counteract this issue, tests measurements have been performed with a guard ring (8 adjacent patches surrounding the central electrode) biased at the same varying potential as the one of the measuring electrode (central electrode). Both methods giving similar results for \( I_s \), the standard procedure has been applied to all measurements.

**Fig. 3.** a) Magnetic field intensity (in Gauss) at \( Z = 0 \). The two positions of the WCP measurements are shown in green. The red oval indicates the area where the carbon deposit may become incandescent at very low pressure [12]. Red dashed lines highlight the edges of the magnets. \( X' \) and \( Y' \) axes are parallel to \( X \) and \( Y \), respectively. Grey and blue lines are found in b) where \( B \)-field intensity (at \( Z = 0 \)) and field line profiles are detailed.

The WCP has first been positioned on the central magnet to assess the charged species current densities at the cusp. The measured ion and electron current densities as well as the magnetic field magnitude are plotted in function of the distance from the centre of the central magnet \((Y' = 0)\) in Fig. 4. Note that throughout the whole manuscript, the
electron current density is taken as a positive value.

For both charged species, the fluxes to the walls decrease with the distance from the magnet centre. The maxima are found at 1 mTorr with 3.8 and 17 mA cm\(^{-2}\) for the ion and electron current densities, respectively. One has to note that the electron current density is far greater than the ion one since the floating potential is well below 0 V.

Fig. 4. Electron a) and ion b) current densities measured at the cusp for different pressures and Y’ positions (Y’ = 0 at the magnet centre). The B-field intensity is also shown.

Moreover, the ion and electron current densities diminish with decreasing pressure which goes along with an increase of the confinement. Indeed, any collision with the surrounding gas would break the primary electron trapping on the magnetic lines. Thus, a greater pressure also means less confinement and more losses.

Finally, the electron flux seems to be more affected by the magnetic field since it presents a maximum at Y’ = -3.5 mm from the magnet centre, where the magnetic field intensity is at its highest value. Electrons and ions are trapped on specific magnetic lines that recombine on the magnet of opposite polarity [13]. Note that due to the probe thickness, the current densities are measured at Z = 7 mm. Such discrepancy between charged particles fluxes may thus be explained by their different Larmor radii. The ionic or electronic Larmor radius is defined as [6]:

\[
r_{Le} = m_{Le} v_{Le} / q B
\]  

with \(v_{Le}\) the average transverse velocity of the charge particle—deduced from the electron temperature for electrons and equal to the Bohm velocity for ions [14], and \(B\) the magnetic field intensity. Considering an electron temperature between 5 and 10 eV, a B-field intensity of 3500 G at \(Z = 0, Y' = -3.5\) mm on the cusp leads to \(r_{Le} = 1.3-1.8\) mm and \(r_{Le} = 15-21\) µm. Note that the electron width leak may be approximated to \(w_{Le} \approx 4 \sqrt{r_{Le}/r_{Li}}\) [6], which gives a smaller value than the one we observed experimentally.

The WCP has also been positioned at the centre of the magnetic corner (MC), where the inter-magnet spacing is the greatest and field lines cross the bottom of the reactor, as depicted in Fig. 3b. A map of the measured electron current density for \(p = 0.1\) mTorr is depicted Fig. 5a. The specific topography observed is similar to the ones measured for other pressures and for the ion current density. All data for the WCP patches 2, 8, 14 and 20 are plotted in Fig. 5b, for each pressure. The origin \(X_{probe}, Y_{probe} = 0\) corresponds to the position of the white ring in Fig. 3a.

The first interesting result is that a strong electron current density is lost to the walls in this area, up to 21.5 mA cm\(^{-2}\) at 0.3 mTorr, which is slightly greater than the one found at the cusp (Fig. 4a, Y’ = 3.5 mm, 1 mTorr). Furthermore, the flux evolution with respect to the pressure is different: we observe at the MC a maximum for ions and electrons at low pressure (0.3 and 0.1 mTorr). Knowing that increasing the pressure shorten the ion and electron mean free paths, this means that these strong fluxes are due to a better magnetic confinement. Moreover, the ratio between ion and electron current densities \((J_e/J_i \sim 10)\) is far greater than at the cusp \((J_e/J_i \sim 5)\). The electron \(J_e\) and ion \(J_i\) current densities can be respectively written as [7]:

\[
|J_e| = q n_e \exp(-V_e/a_e) \sqrt{e T_e/2 \pi m_e}
\]  

\[
J_i = q n_i \sqrt{e T_i/m_i}
\]

\[
(3)
\]

\[
(4)
\]

with \(n_e, n_i\) the charged species density at the sheath edge, \(V_e\) the potential at the sheath edge (slightly lower than the plasma potential \(V_p\)), \(V_w\) the potential at the walls (0 in our case). Thus, \(J_e/J_i\) is proportional to \(\exp(-V_e/T_e)\). Our results show that \(V_p\) at the MC is slightly greater than at the cusp. Such an increase of \(J_e/J_i\) then means that \(T_e\) greatly increases at the magnetic corner. Besides, contrary to the cusps, the magnetic field at the magnetic corner does not act as a magnetic mirror along the Z axis. It confirms that the WCP collects an important amount of high-energy (primary) electrons and thus that the losses at the magnetic corner are due to recombination of B-lines on the walls.

Secondly, one may observe that the highest values are found at the intermediate pressure of 0.3 mTorr. This is due to a combination of two effects. On the one hand, decreasing the pressure implies an increase of \(T_e\) [8, 15] and thus of both fluxes. On the other hand, the current densities also depend on \(n_e, n_i\) (slightly lower than \(n\)) which has been shown to reach a maximum at about 0.4 mTorr.
especially conceived wall current. The energetic electrons are recombined on the magnetic corner due to the recombination of magnetic field lines at the wall. The results reveal the existence of important losses at the magnetic corner due to the recombination of magnetic field lines on the wall. By the increase of the $J_e/J_i$ ratio, we can deduce that a higher proportion of energetic electrons are lost at the magnetic corners than at the cusps.

It has been shown that decreasing the pressure implies greater electron fluxes at the corners but less at the cusps. This means that the electron loss areas can be controlled by changing the pressure.

Additionally, the strong plasma leak revealed at the magnetic corners seems to explain the incandescence observed under very low-pressure conditions and may be used to remobilize [12] and/or thermally desorb [16] hydrocarbon deposit into the discharge.

5. REFERENCES

4. CONCLUSION
In this study, the electron and ion current densities have been measured at the magnetic cusp and corner of a linear ECR reactor using a specially conceived wall current probe.

The results reveal the existence of important losses at the magnetic corner due to the recombination of magnetic field lines on the wall. By the increase of the $J_e/J_i$ ratio, we can