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Influence of the biased electrode on the plasma potential in ECRIS

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Dedicated experiments have been carried out at the Frankfurt 14 GHz electron cyclotron resonance ion source (ECRIS) by using a special double biased-electrode assembly, which consists of a conventional disk electrode and a separately biased ring electrode installed in front of it. In this assembly, the ring can be used to modulate the fluxes to the disk and allows a detailed study of the role of secondary electron fluxes in ECRIS operation. It was found that these fluxes contribute more than 50% to the total disk currents. However, blocking them did not result in a drop in the extracted ion currents. Instead, it was observed that, under certain operational conditions, the injection of secondary electrons results in a decrease in the extracted currents by up to 20%. Parallel to the double disk measurements, Langmuir probe measurements have been performed close to the position of B_{max}. From the probe characteristics, plasma potentials were determined to be about +30 V at the conditions of the experiment. Applying a negative voltage to the double disk electrodes leads to a decrease of the plasma potential by approximately 5 V. Changes in the plasma shape were observed when the biased electrode voltage was changed. We conclude that the main effect of the biased electrode is a decrease of the plasma potential by reflecting a sufficient amount of electrons back to plasma, which otherwise would have been lost.
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I. INTRODUCTION

The biased electrode effect[1–5] in electron cyclotron resonance ion sources (ECRIS) has attracted renewed attention. This is now more and more connected with the possibility of getting detailed information about the basic processes in electron cyclotron resonance (ECR) plasmas. In recent publications,[5–7] we described the fast reaction of the extracted ion currents to a modulation of the bias voltage, demonstrating that the disk has an important influence on the ion dynamics during their transport from the dense, hot region of the ECR plasma to the extraction area. Biasing the electrode obviously allows one to compact the plasma near the extraction, keeping the total ion production rates almost unchanged. The mechanism of this positive influence of the biased electrode is not fully understood yet. In this article, we report on a study where the emphasis was placed on the separation of the effects of the secondary electron emission from the electrode and reflection of plasma loss electrons by the electrode potential. The experiments have been supplemented by measurements with a Langmuir probe.

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II. EXPERIMENTAL SETUP

The experiments have been performed at the Frankfurt 14 GHz ECRIS.[8] The source was operated with pure argon, helium, and oxygen as working gases. The microwave power was kept constant at 300 W. The gas pressure, measured at the flange of the source pump, was varied between 1×10^{-7} and 1×10^{-6} mbar. The extracted ion currents were measured in a Faraday cup in front of an analyzing magnet.

A "double electrode" assembly[7] was inserted axially into the source from the microwave injection side. The assembly consists of a coaxial ring- and a disk-shaped electrode, which both could be biased separately. The ring (⌀36×9 mm, thickness 4 mm) was mounted at a distance of 3 mm in front of the disk (⌀36 mm). The assembly was positioned at 5 cm outside from the maximum of the magnetic field at the injection side.

The moveable Langmuir probe was inserted through one of the six vacuum ports at the microwave injection side of the source. These ports are oriented with an inclination angle of $\vartheta_{incl}\approx17°$ relative to the source axis. A tungsten wire of 0.5 mm diameter was used as probe. The length of the sensitive area was chosen to be 4 mm. It was oriented in two ways, parallel to the port axis and vertically down. With respect to the magnetic field, these two ways of mounting resemble probe orientations (almost) parallel and perpendicular to the magnetic field lines. The probe crossed the source axis close to the maximum of the magnetic field. The probe position was measured relative to this crossing point. The orientation of the probe relative to the plasma with its three-armed geometry was chosen such that the probe completely crossed the plasma region radially. The axial position at the maximum of the magnetic field was still well outside the resonance zone of the ECRIS.

III. EXTRACTED ION CURRENTS AS A FUNCTION OF THE ELECTRODE VOLTAGES

The main motivation for using the double electrode structure was to control the electron fluxes to and from the disk by the ring voltage. If the voltage on the ring electrode is chosen sufficiently negative with respect to the disk voltage, both the fluxes of secondary electrons from the disk electrode to the plasma and the fluxes of loss electrons from the plasma to the disk can be blocked completely. At the operational conditions of the source, the optimal value of the disk voltage was $U_D = -300$ V, i.e., the extracted ion currents increased with negative electrode voltages and saturated at disk voltages of $U_D \leqslant -300$ V. Almost identical ion currents could be obtained by biasing only the ring or only the disk electrode.

The biased-electrode effect was stronger for argon plasma than for the case of helium. For argon, a change in the ring voltage from $U_D = 0$ to $U_D = -300$ V increased the ion current by a factor of 3, for helium by a factor of 1.5.

At $U_D = U_R = 0$ V, the disk electrode collected up to 1 mA of electron current. Setting negative ring voltages quenched this current down to a saturation value of (100–200) μA, when a voltage of $U_R \approx -200$ V was reached. At still more negative ring voltages, no further influence onto the extracted ion currents was observed besides some small changes, which depended on certain source conditions. They will be discussed later.

In Fig. 1, currents to the electrodes are shown for a fixed ring voltage of $U_R = -500$ V as a function of the disk voltage for a pure oxygen plasma at a gas pressure of 6×10^{-7} mbar. This value was optimized to obtain highest ion currents. If the disk voltage is increased from $U_D \approx (U_R + 100)$ to $U_D \approx U_R$, the disk current changes rather abruptly from a smoothly increasing shape to a distinctly enhanced level, from where it further tends to saturate smoothly. The ratio between these two saturation levels is constant for all investigated plasmas and amounts to a factor of 2. This transition has to be attributed to the opening of the potential barrier for the secondary electrons emitted from the disk. The extracted ion currents are not influenced by this rather dramatic change inside the source. Therefore we conclude that in the given saturated state of the plasma, the injection of cold electrons does not further improve the source performance.

At lower gas pressures, this opening of the potential barrier and injection of secondary electrons into the plasma results even in a decrease of the extracted currents (Fig. 2). The extracted ion current drops by 20% if the disk voltage is set equal or exceeding the ring voltage.

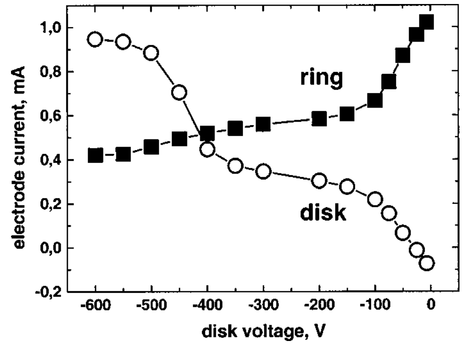

FIG. 1. Currents to the electrodes as a function of the disk voltage U_D for a fixed ring voltage U_R of -500 V. The discharge was sustained in a pure oxygen with a pressure of 6×10^{-7} mbar. The extracted ion current is constant and amounts to 310 μA.

IV. LANGMUIR PROBE MEASUREMENTS

The insertion of the Langmuir probe into the plasma of the ECR discharge resulted in a significant disturbance of the plasma and manifested itself in strong variations in the extracted ion currents. This perturbation was especially pronounced for the probe orientation "perpendicular" to the magnetic field lines. Indeed, when the negatively biased perpendicular probe entered the central, denser part of the plasma near the source axis, the extracted currents increased by a factor of two and more, if the biased electrode voltages were set to zero. A positive bias on the probe quenched the ion beam by factor of 2. The "parallel" probe did not influence the extracted currents as much. Its influence on the extracted ion currents only appeared when the probe entered the central part of the plasma and amounted to some 25%–30%, depending on the gas composition and operational conditions.

Being positioned at the crossing point with the source axis, the perpendicular probe collected up to 500 μA of saturated electron current and 150 μA of the saturated ion current from an argon plasma. For the parallel probe, these values were 150 μA and 50 μA, respectively. The ratio of the electron currents for the two orientations is close to the theo-

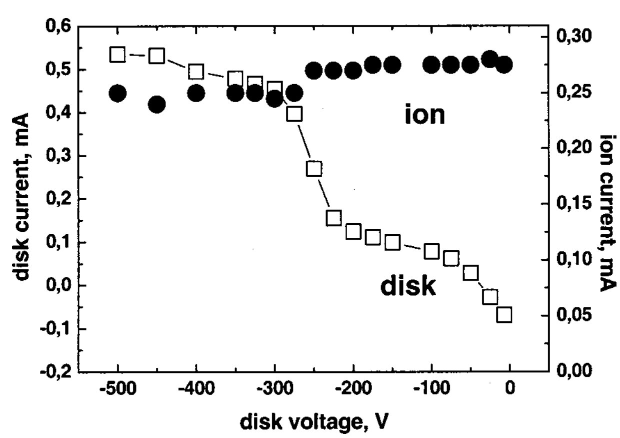

FIG. 2. Extracted ion currents (right-hand side scale) and currents to the disk electrode (left-hand side scale) as function of the disk voltage at a fixed ring voltage of -300 V. The discharge was sustained in a pure oxygen plasma at a gas pressure of 3.5×10^{-7} mbar.

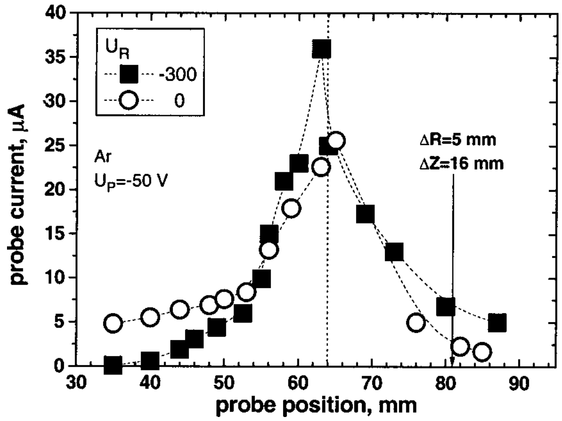

FIG. 3. Probe currents as a function of the probe position for an argon plasma with $U_R = -300$ V and 0 V, and $U_D = 0$ V. The probe voltage is -50 V. The point where the probe crosses the source axis has a calibration value of 64 mm and is marked by the dotted line. The radial position of the probe can be calculated as $\delta R = \sin(17°) \times (x\text{-}64)$, where x is the probe position in mm.

retically expected value[9] of $4R/\pi L \times \ln(L\pi/4R) = 0.2$, where R is the radius of the probe and L is the probe length.

In Fig. 3, the currents to the negatively biased parallel probe are displayed as a function of the probe position for two values of the bias at the ring electrode for the case of argon plasma. The bias on the disk electrode of the double electrode assembly was set to zero for both measurements. The probe voltage was set to (-50) V ensuring a saturation of the ionic currents to the probe. It can be seen that the probe currents increase substantially when it approaches the region near the source axis. From the measured slopes, the radial extension of the plasma can be estimated. The full width at half maximum values are 3 mm for helium and oxygen plasmas, and slightly wider for an argon (about 5 mm). Biasing the ring electrode results in an increase of the probe currents at the source axis. For argon and oxygen, in addition, a ''rotation'' of the profile is observed (see Fig. 3). Here, one has to keep in mind the total axial movement of the probe of 60 mm. The probe currents at one side of the plasma star decreased whereas those at the other side increased, which was especially pronounced for the case of argon and oxygen gases.

By analyzing the measured voltage–current characteristics of the probe, values for the plasma potentials have been deduced. If no bias voltage is applied to the double-electrode assembly (i.e., setting $U_R = U_D = 0$ V) plasma potentials of 35 V, 30 V, and 20 V were extracted for argon, oxygen, and helium plasmas, respectively, not depending significantly on the gas pressure and probe position. If the double-electrode assembly was biased to negative values, the plasma potentials decreased and saturated when the electrode bias exceeded $U_R = U_D \leqslant -200$ V. At optimal values of voltage on the biased electrode ($U_R = U_D \leqslant -300$ V), the plasma potentials changed to 30 V, 25 V, and 15 V, which means they decreased by 5 V for all investigated plasmas.

V. CONCLUSIONS

The experiment demonstrates that the most important mechanism of the biased electrode operation is the reflection of plasma electrons back to the plasma, reducing in this way the electron losses from the plasma. This mechanism shows a saturation effect which obviously is connected with the energies of the loss electrons and hence the properties of the plasma itself. The experiments have demonstrated that the secondary electrons, generated at the disk, do not improve the source performance over the effect gained by blocking the plasma losses. Therefore, one can conclude that shape and elemental composition of the biased electrode are not of great importance. We even found indications that secondary electrons may be harmful for the source performance.

The values of the plasma potential and its dynamics, when the biased disk is set to negative voltages, are consistent with dedicated determinations of the plasma potential[10] and with measurements of the radial plasma potential distributions at the Q_T-upgrade mirror machine.[11] The decrease of the plasma potential compensates the blocking of axial electron losses from the plasma to the electrode. Keeping in mind that the plasma total properties are not changed with biasing the electrode,[5] this change of the plasma potential has to be accompanied by a redirection of the ion currents inside the source chamber resulting in an enhancement of the extracted currents. Possible explanations, in which way the plasma potential influences the radial transport in plasma, are discussed in Refs. 11 and 12. Changes in the plasma shape have clearly been observed for the argon and oxygen gases. They are most probably connected with change of the $\mathbf{E} \times \mathbf{B}$ drift of plasma induced by the plasma potential.

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