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The key role of a cold electron supply on the high charge state ion production in ECR ion sources

L. SCHÄCHTER[1] , S. DOBRESCU[1], K. E. STIEBING[2]

[1] *National Institute for Physics and Nuclear Engineering (IFIN-HH), P.O.Box MG-6, Bucharest, Romania*
[2] *Institut für Kernphysik (IKF) der Johann Wolfgang Goethe-Universität, August Euler Strasse 6, D-60486 Frankfurt/Main, Germany*
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Abstract. A metal-dielectric (MD) cylindrical structure introduced in the plasma chamber of an ECR ion source has a significant positive influence on the production of highly charged state ions. The main plasma parameters: plasma potential, electron density and electron temperatures were measured using the Langmuir probe method. An increase of these parameters was observed when the MD structure was inserted in the plasma chamber of the ECRIS. The plasma potential was determined by an alternative method too, the accurate determination of the 90º analyzer magnetic field, obtaining a good agreement.
The analysis of the results lead to the conclusion that the main influence of the MD structure consists in the increase of the electron lifetime, which in turn determine the increase of the ion lifetime and togheter with the increase of the electron temperature and electron density provide a strong enhancement of the high charge state ion production.

1. INTRODUCTION

A research developed in the National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania (IFIN-HH), Bucharest, Romania and the subsequent tests carried on at the Institut für Kernphysik der J. W. Goethe Universität (IKF), Frankfurt am Main, Germany allowed to develop a new method to increase the production of highly charged ions of ECR ion sources [1]. This method allowed to increase by as much as two orders of magnitude the intensity of Ar^{16+} ion beam extracted from the IKF 14 GHz ECR ion source. The method permitted also a significant improvement of the ECRIS stability in operation, with benefic consequences on the production of very high charge state ions [2].

The method consists in the use of a special metal-dielectric (MD) cylindrical structure introduced in the plasma chamber of the ECR ion source. The MD structure (Al-Al_2O_3) had a length of 150 mm and covered the radial plasma chamber wall at the position of the resonance zone. The MD structure is a highly efficient secondary electron emitter and proved to be very resistant to the etching action of the nearby hot ECR plasma. But the important increase of the Ar^{16+} ion production that was observed can not be explained taking into account only the increase of collisional processes in the ECR plasma. As a consequence, it is necessary to suppose that the high rate of cold electrons provided by the MD structure leads to fundamental changes in the ECR plasma processes.

The main objective of the research presented in the present paper was to study some basic aspects of an ECR ion source operated with a MD structure inserted in the plasma chamber, particularly the key role of the emitted cold electrons for obtaining high intensities of high charge state ion beams. The influence of the MD structure on the main ECR plasma parameters (the plasma potential, the electron temperature and the electron density) was experimentally studied and is presented. These plasma parameters determinine the charge state distribution (CSD) [3] of the extracted ion beam from the ECRIS.

2. Experimental set- up

The IKF 14 GHz ECR ion source was operated with pure argon as working gas. The gas pressure, measured at the flange of the source pump, was varied between $1x10^{-7}$ mbar and $7.5x10^{-7}$ mbar. The microwave power was varied in the range 200-600 W. The extracted ion currents were measured in a Faraday cup after the 90°-analyzing magnet. The MD structure was inserted in the plasma chamber.

The plasma parameters were measused by the classical Langmuir plasma diagnosis method applied to the electron retardation region of the probe characteristics. The moveable Langmuir probe (tungsten wire of 0.5 mm diameter) was inserted through one of the six vacuum ports of the IKF ECRIS [4] at the microwave injection side of the source, at an inclination angle of 17^0 relative to the source axis. The probe crossed the source axis close to the maximum of the source axial magnetic field. Thus the probe was outside the very hot resonance zone of the ECR ion source plasma.

The measured voltage-current characteristics I/V of the probe (V = 0 - 180 V) allowed to derive the plasma parameters [5]. The plasma potential V_{pl} is best estimated at the maximum of the first derivative dI/dV of the probe I/V characteristics.

The mean electron temperature T_e was calculated from the equation:

$$T_e / e = -(\mathrm{d}lnI / \mathrm{d}V)^{-1} \quad (1)$$

that links this plasma parameter to the first derivative of the natural logarithm of the probe current I with respect to the probe voltage V at the plasma potential value [6].

The plasma electron density n was calculated from the Langmuir formula [5]:

$$I_{Vpl} = e\,A\,n\,(T_e/2\pi\,m_e)^{1/2} \quad (2)$$

where I_{Vpl} is the probe electron current corresponding to the measured plasma potential value, A is the area of the probe, e and m_e are the electron charge and mass.

The electron temperature and the electron density calculated by equations (1) and (2) are subject to a rather high uncertainty due to the non-Maxwellian characteristic of the low-pressure magnetoplasma of an ECRIS [3]. More than that, the calculated parameters refer certainly to their value at the Langmuir probe location, outside of the ECR zone, but they should be linked to the mean value of the same parameters in the ECR zone. For these reasons, these two parameters are given only as ratios of their value in the two modes of the source operation: without and with the MD cylindrical structure inserted in the plasma chamber. The ratios have the advantage to minimize these uncertainties and are a good estimate of the MD structure influence.

In order to check the validity of the Langmuir probe method for measuring the ECR plasma potential, this plasma parameter was determined by an alternative method too, the accurate determination of the 90º analyzing magnet field B_{AM}, that is proportional to the square root of the extracted ion energy, as a function of the source extraction voltage U_{extr}. By extrapolating the linear curve B_{AM}^2 = f(U_{extr}), the negative value of the intercept of the U_{extr} axis represents the positive potential of the ECR plasma responsible for a supplementary amount of energy gained by the ions [7]. In fact, instead of B_{AM}, the current through the analyzing magnet coils was measured and a correction of the remanent magnetic field was applied for improving the accuracy. The linear fit of the measured curve was made by the least square method.

3. Experimental results and comments

The main objective of the measurements was to determine the influence of the MD structure inserted in the plasma chamber of the source on the plasma parameters when compared to the operation of the source without the MD structure. For this, reference measurements without the MD structure and measurements with the MD structure inside the plasma chamber were made in identically conditions. The measurements were performed at different values of the RF power and of the source pressure.

In figure 1 is showed the variation of the plasma potential with the pressure, measured by the Langmuir method in both modes of operation: without and with the MD structure inserted in the source. In both cases, the

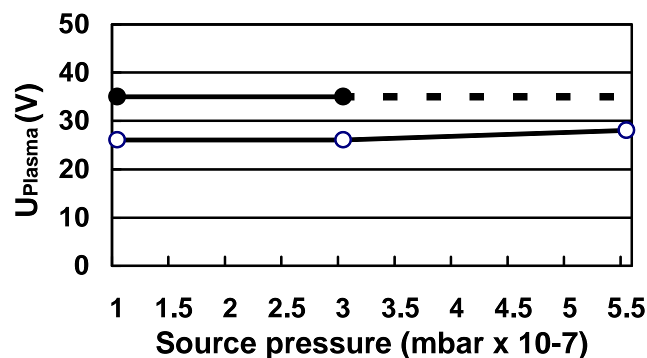

Fig. 1.- Variation of the plasma potential with the pressure, measured by the Langmuir method, in both modes of operation: without (open circles) and with (solid circles) the MD structure inserted in the source.

plasma potential is practically constant over the actual pressure range (1x10^{-7} mbar ÷ 5.4 x 10^{-7} mbar). The MD structure induced an increase of the plasma potential by about 30%, that is from 26 V to 35 V. Similar values, of 24 V and respectively 38 V, were obtained when the plasma potential was measured by the alternative method described above, the determination of the linear function B_{AM}^2 = f(U_{extr}) for Ar^{2+}.

The increase of the plasma potential indicates the complexity of the MD structure effect, because this result is in contradiction with what was considered until now [7], that the direct injection of electrons in the plasma chamber has as consequence a decrease of the plasma potential.

From spectroscopic measurements is known [8] that in the ECR plasma always exists an ultracold electron population having a temperature $T_e < 2$ eV and a density amounting to 50-80% of the total electron density. The secondary electrons emitted by the MD structure enter the plasma with an energy corresponding to

the plasma potential and are able to reach the resonance layer, resulting a shift of the ion charge state distribution toward higher charge states. The increase of the high charge state component of the ion population determines the increase of the positive charge in the plasma and the ambipolar diffusion mechanism will determine an increase of the positive plasma potential in order to reduce the electron loses.

On the plasma chamber axis, where the Langmuir probe was located, the dominant component of the collected electrons is formed by the electrons escaping from the ECR zone. As a result, the electron temperature measured by the Langmuir probe is directly related to the mean electron energy in the ECR plasma.

In figure 2 is represented the influence of the MD structure on the plasma electron temperature. This influence is given as the ratio of this parameter in the two modes of operation of the source, with and without the MD structure, at different source pressures. It can be seen that the mean electron temperature in the plasma determined by the Langmuir probe method - equation (1), increases by about 70% in the presence of the MD structure. This increase is rather constant in the pressure range that was covered in our experiments.

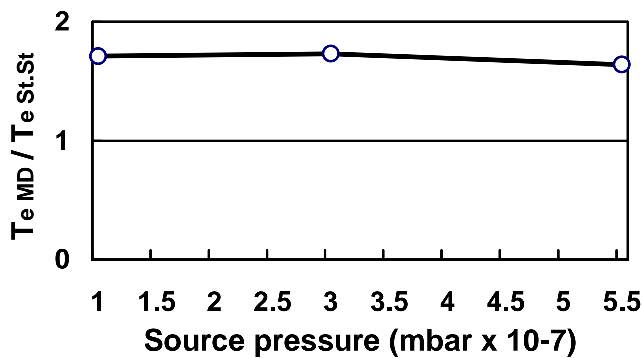

Fig. 2.-Variation of the plasma electron temperature with the pressure, measured by the Langmuir method, given as the ratio of T_e in the two modes of operation: with and without the MD structure inserted in the source.

The increase of the electron temperature in the presence of the MD structure is due to the enrichment of the electron population in the ECR plasma by the permanent supply of electrons from MD walls, that participate to the stochastic heating process starting fom an energy corresponding to the plasma potential.

As is known [9] a dominating factor for the charge state distribution of ions is the electron energy, because the dependence of the ionization cross section by ion-electron collisions on the electron energy is very strong for the highest charged states. The significant increase of the mean electron temperature that was observed when the MD structure was inserted in ECRIS explains the previous observations of a very important increase of the highest charge state ion beam intensity and a strong shift of the ion beam charge state distribution to higher charge states induced by the presence of the MD structure [1, 2].

The impact of the MD structure on the plasma electron density determined by the Langmuir probe method - equation (2) is represented in figure 3. Here all the experimental values, measured at a RF power of 400 W, have been normalized to the lowest electron density $n_{e\ min}$ measured in standard conditions of the ECR source, without MD structure, at the lowest source pressure ($1x10^{-7}$ mbar). It can be seen that the electron density strongly depends

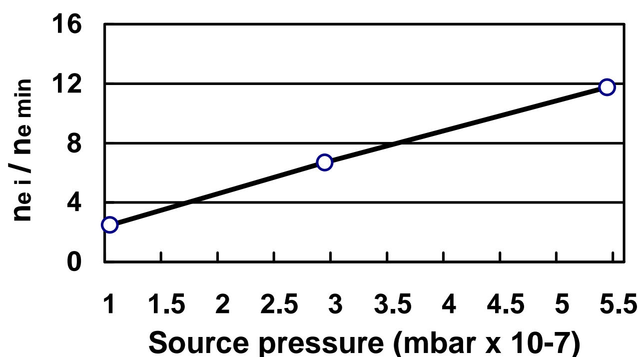

Fig. 3.- Influence of the MD structure on the electron density, measured at P_{RF}=400 W by the Langmuir method ($n_{e\ min}$ is the electron density measured without the MD structure at $p=1x10^{-7}$ mbar; $n_{e\ i}$ is the electron density in any other condition).

on the source pressure and that the presence of the MD structure induce an important increase, by a factor of about three, of the electron density, probably mainly that of the hot electron population. As a result the collisional processes are enhanced, contributing to the increase of the high charge state ion beam production.

This result is remarkable because one can not obtain a high production of highly charged ions by increasing the neutral pressure despite the increase of the plasma electron density in this case too, due to recombination that damps down the high charge state components of the ion population [9].

The variation of the electron plasma density with the RF power in the presence of the MD structure is represented in figure 4. Here the experimental values were normalized to that obtained at the lowest RF power. The plasma electron density increased by 30% when the RF power was increased from 200 W to 450 W.

The analysis of the influence of the MD structure on the ECR plasma parameters gives the possibility to outline an image about how these structures lead to very high enchancements of the high charge states in the ECR ion sources.

As is known, the production of multiply charged ions depends on the electron density and temperature and on the ion lifetime. The ambipolarity of the ion and electron currents leaving the plasma is a dominant process in the quiescent low-pressure steady-state ECR plasma of a min-B ECRIS [3, 10]. When the electron lifetime is improved through some specific techniques, the ion life time will be increased too. The main influence of the MD structure consists in an increase of the electron lifetime by the permanent emission of an intense flow of cold electrons which in turn increase the ion lifetime. This influence is correlated with higher values for the electron population in plasma increasing the collisional processes and with the increase of the electron temperature shifting the charge state distribution to higher charge states.

4. CONCLUSIONS

The influence of an MD (Al-Al_2O_3) cylindrical structure, an important electron donor, on the main ECR plasma parameters was experimentally studied using the Langmuir probe diagnosis method. A net increase of the plasma potential, from about 25 V to about 35 V, of the electron temperature by a factor of 1.7 and of the electron density by a factor of 2.5 was observed. This increase of the main ECR plasma parameters is at the basis of the strong enhancement of the highest argon ion charge states previously measured when an MD structure was utilized.

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