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Local plasma diagnostics research on Electron Cyclotron Resonance Ion Source

L. Kenéz[1], J. Karácsony[2], A. Kitagawa[3], M. Muramatsu[3], S. Biri[4], A. Valek[4]

[1] Sapientia Hungarian University of Transylvania, Dept. of Electrical Engineering, Targu-Mures, RO-540053, 61, P-ta. Trandafirilor, Romania
[2] Babes-Bolyai University, Cluj-Napoca, RO-400084, 1, M. Kogalniceanu, Romania
[3] National Institute for Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba 265-8555, Japan
[4] Institute of Nuclear Research (ATOMKI), H-4026 Debrecen, 18/c, Bem tér, Hungary
E-mail: `l_kenez@ms.sapientia.ro`

Abstract
Electron Cyclotron Resonance Ion Sources (ECRIS) are important tools of the atomic physics research, which find applications in the field of physics, medicine etc. The most important part of the ion sources is the complex plasma, which determines their performance but is still less known. Therefore we need to make efforts to find out more about them to improve ion sources. For this reason we started local plasma diagnostics research project, at the ATOMKI-ECRIS in Hungary and continued our work at the NIRS-ECRIS in Japan. In the framework of the project we studied the cold plasma of the source, developed a new method to evaluate the ion current flowing to the probe that is useful to calculate local electron density.We designed a mechanism to position the probe and determined various electron density distributions. Using emitting probes we determined the plasma potential and its distribution.
Keywords: *ECRIS, ECR plasma, Langmuir-probe, plasma diagnostics*

1 Motivation

The Electron Cyclotron Resonance Ion Source is one of the most successful machines built for Highly Charged Ion production (HCI). ¿From their late ′70 invention, the ion sources have been developed from complex prototypes to high-performance, highly sophisticated experimental facilities. ECR ion sources can be used in diverse research fields as stand-alone machines or injectors of high-energy accelerators. They were found useful in basic research and application either (e.g. tumour therapy, production of new materials etc.). The core of the source is the ECR plasma, which is decisive factor regarding the performance of the ion source. However, the theoretical knowledge we have on ECR plasma is incomplete, therefore diagnostic research of the plasma is important. Diagnostic methods canbe divided in two groups, global and local methods. Global methods provide overall information on the plasma parameters using the intense electromagnetic radiation coming out of the source, so there is no possibility to determine the local values of the plasma parameters. However, knowledge of the local plasma parameters and their evolution during (e.g. beam optimization process, biased-disk on/off etc.) external interventions would be of great interest in better understanding of the source and explore hidden possibilities. In case of ECRIS's mainly global diagnostic methods have been applied, while physicists just nowadays started to show interest in using local diagnostic methods.

2 Short presentation of the ECR ion source

Detailed description of ECR ion sources are described by many authors (e.g. Geller 1996; Brown 1989; Wolf 1995). This paper presents the block diagram (Fig.1.) of the ECR ion source.

¿From left to right one can see the microwave system responsible for plasma ignition and support, the magnetic system responsible for the confining of the plasma, the extraction system which allow us to extract ions from the plasma using electrostatic fields, the gas feed system which allow us to introduce different gases to obtain different plasmas (eventually other mechanisms to create plasmas from solid state materials), the vacuum system which is crucial for highly-charged ion production, and the radiation protection and safety systems which are important from the user and apparatus protection point of view. There are many possibilities to make experiments in the complex ECR plasma. The plasma is created by high-frequency microwaves and confined by complex magnetic trap. The magnetic trap is formed by the superposition of two different magnetic filed configurations, an axial field created by $DC4$ solenoid coils and a radial field created by permanent magnets. It is important that in the central region of the plasma chamber, the resulted field can be imagined as constant induction egg-shaped surfaces embedded in each other. One of these surfaces play crucial role in plasma ignition and maintenance. This surface is the so-called Resonant Zone, the inner region of this surface is the so-called hot plasma, while the outer region is the cold

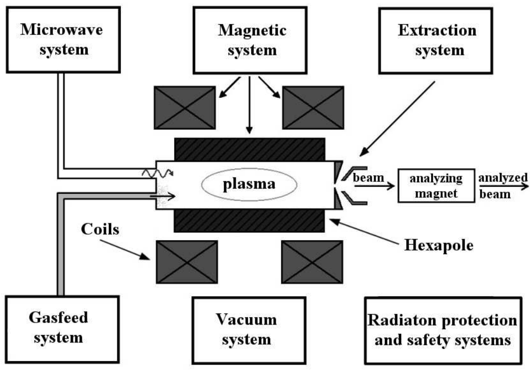

Figure 1: *Block diagram of an ECR ion source.*

plasma. The magnetic induction of the resonant zone is such that the frequency of the circular motion of the electrons equals the frequency of the microwaves introduced in the plasma chamber. When an electron goes through the resonant surface, stochastic resonant energy exchange occur between the electron and the microwaves. This is the so-called ECR heating. However, only the velocity component perpendicular to the magnetic field can be increased in this way, while the parallel remain unchanged. This way large anisotropy occur. Due to this fact, energetic electrons are trapped in the resonant zone. They collide with neutral atoms or low charged ions, which loose electrons step-by-step. These electrons form a negative cloud while ions are trapped due to electrostatic interaction between the electron cloud and ions. The final result of these processes is plasma ignition. As another result of a collision between electron and ion the anisotropy can completely or partially disappear, the electron is no more trapped and can get out of the resonant zone and get into the cold plasma. In this region electron cannot get energized by the microwaves, they cannot ionize, and most likely they escape from the magnetic trap, or mirrored back toward the resonant zone (Geller 1996).

3 Langmuir probe and ECR ion source

Depending on the particular plasma region we have to deal with and the plasma parameter we want to determine we have to choose properly the probe configuration. There are many choices, e.g. simple cylindrical probe, double cylindrical probe, emitting probe etc. Because the ECR plasma is complex there are many difficulties we have to deal with. Here we mention some of them, detailed description can be found in (Kenéz 2002a).

- the plasma is confined in a strong and inhomogeneous $B - min$ magnetic trap,
- small plasma and chamber dimensions at high frequency microwaves (> 5 GHz),
- presence of multiply charged ions of different atomic species,
- secondary electron emission of the probe,
- sputtering of the probe metal caused by energetic particles of the plasma.

By careful design of the probe and careful definition of the experimental conditions many of these difficulties can be handled or their influence can be minimized. The experimental data we obtain is the voltage-current (U-I) curve of the probe. Fig.2. shows typical probe $U - I$ curves.

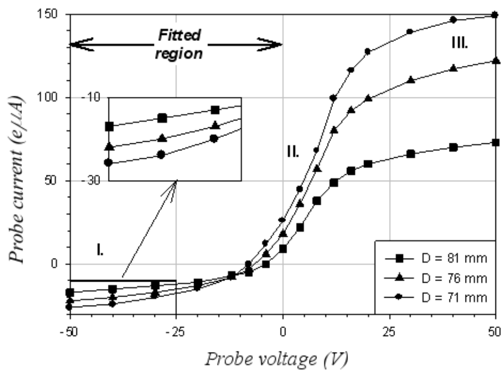

Figure 2: *Langmuir probe $U - I$ curves. D-distance between the probe and $B_M IN$ plane of the source*

These were measured in the cold region of the ECR plasma (oxygen plasma, source tuned for O^{1+} production). For the measurements we used cylindrical probe with 0.4 mm base diameter and 3 mm height. To calculate plasma parameters we fitted the [-50,0] voltage region assuming Maxwell-Boltzmann statistics for the collected electron component (Kenéz 2002a).

4 Theoretical model

The ECR plasma is confined in a magnetic mirror trap, which affects mostly the electrons of the plasma and makes the probe theory complicated. Plasmas confined in magnetic fields cannot reach a complete equilibrium state; in consequence they can be described using different temperatures for the motions perpendicular and parallel to the magnetic field. In such cases one can expect that the slope of the probe characteristics give the parallel electron temperature (Chen 1965). The particle distribution of an ECRIS is well described by a "loss-cone" distribution (Dory 1965), which presents Maxwellian character for the particle motion parallel to the magnetic field. Thus we consider Maxwell-Boltzmann electron distribution function for the parallel component. Description of a theoretical model dealing with the case of singly charged ions could be found in (Chen 1965).

4.1 Multiply charged ions

Theoretical models concerning Langmuir probes do not take into account the fact that ECR plasmas contain multiply charged ions of different atomic species, so we have to include them into the calculations to evaluate the probe data correctly. An exact ion distribution function is not available, so it has to be introduced empirically. We assume that the plasma conditions are well reflected by the extracted beam when the plasma contains mostly lower charge states (Dou 1998). The electron density can be calculated as (Kenéz 2002a):

$$n_e = \frac{I_{sat}^{ion}\overline{j^+}}{0.61Ae}\left(\frac{k_B T_e}{M}\right)^{-1/2}\left(\sum_j \alpha_j j^{3/2}\right)^{-1}, \tag{1}$$

where n_e is the electron density, M the ion mass, A the normal area of the probe with respect to the magnetic field lines, e the elementary charge, k_B the Boltzmann constant, j the charge state; I_{sat}^{ion} the saturation ion current and T_e the parallel electron temperature, determined from the mean square fit of the characteristics; $\overline{j^+}$ the average charge and α_j the percentage composition of the beam, determined experimentally from the beam spectra.

4.2 Multi-component plasma

The vacuum of the source always contain residual gas $(N, C, H...)$, while highly charged ion production needs gas mixing. All these atoms getionized in the plasma and eventually collected by the probe so they should be considered when more accurate electron density calculations are the objectives. Generalization of Eq. (1) is straightforward (Kenéz 2002a). We only have to make a summation for the different components of the plasma.

$$n_e = \frac{I_{sat}^{ion}\overline{j^+}}{0.61Ae}(k_B T_e)^{-1/2}\left(\sum_{k,j} \frac{\alpha_{k,j} j^{3/2}}{M_k^{1/2}}\right)^{-1}, \tag{2}$$

where now $\overline{j^+}$ is the estimated average charge of the multi-component plasma and $\alpha_{k,j}$ is the percentage composition of the beam (k denotes the different plasma components), determined experimentally from the beam spectra. The experiments have shown that differences between the electron densities yielded by the two models are significant when great amount of residual gas atoms are present in the plasma or two gases are used.

5 Experimental results

5.1 Axial electron density distribution. Biased-Disk effect

The current collector surface of the probe was set on the symmetry axis of the source. Probe $U-I$ curve series were taken in different plasmas tuned for different charge state production, e.g. O^{1+}, O^{3+}, O^{5+}, Ar^{4+}, Ar^{1+}, Ar^{11+} etc. During data acquisition the probe was moved step by step in the cold plasma region. Data processing was performed using all theoretical models presented in section 4. Three purposes were followed: electron density distribution along the source axis, effect of the multiply charged ions on the electron density calculated with the different models and study of the so-called Biased-Disk effect. The Biased-Disk is an internal electrode, which is negatively biased with respect to the ion source potential. When is turned on and its voltage is optimized, the extracted ion current can increase with a factor of $4-10$ depending on the optimized charge state. However, it is not completely understood the mechanism of this effect. Fig.3. presents the results of an experiment performed in Ar plasma, ion source tuned for Ar^{8+} production. Two series of $U-I$ curves were taken in Biased-Disk ON/OFF cases, respectively.

Conclusions. Moving the probe from the edge of the plasma chamber toward the resonant zone, the electron density increases. As it can be seen on the figure, withinin a relatively short distance ($20cm$) the electron density increases by one order of magnitude (true for every experiment we performed). Taking into account the different charge states of every atomic species, we calculated differences between the electron densities values calculated using SCSC and MCMC models up to a factor of 3 (Kenéz 2002b). Performing experiments increasing the charge state of the optimized ion we observed that that the calculated values of the electron density also increased. This is in agreement with the assumption that increasing the charge state of the optimized ion, the average charge state of the plasma ion component must also increase which naturally must be followed by an increase of the electron density. This result shows that for realistic description of the ECR plasma, multiply charged ions must be taken into account. We also showed that the Biased-Disk does not affect the cold plasma regions. The difference between the electron density values calculated for the Biased-Disk ON/OFF cases, are below the error limit (Kenéz 2002b).

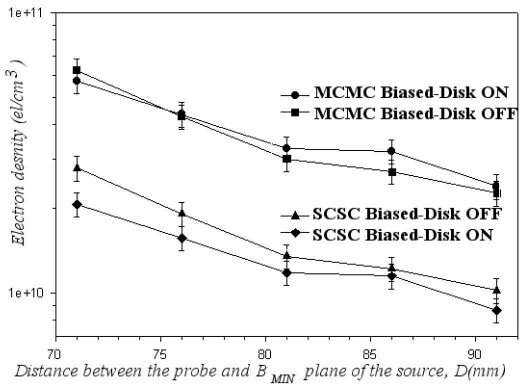

Figure 3: *Axial electron density distributions; Biased-Disk ON/OFF cases. Effect of the multiply charged ions*

5.2 Azimuthal electron density distribution

The intersection points of the end plane of the plasma chamber and those magnetic field lines which cross the resonant zone is a star-shaped configuration. Due to the cylindrical symmetry of the coils and the hexapole permanent magnet, the stars have three identical branches at each end of the chamber, but 60 degrees rotated. The purpose of the next experiment was to determine the electron density distribution in the branches of the stars. The holder of the probe was introduced on the axis of the source, so its current collector surface could be rotated on a given radius circle (e.g. $14mm$). Measurements were performed in the cold plasma region, in different axial planes, in a 100-degree angle region of only one branch of the injection side star. For this experiment low ionized O plasma was generated. We calculated the electron density using the models presented in section 4, but due to the low average charge of the plasma ion component (close to 1) no relevant differences we observed. But it is important to note, that using MCMC model the differences were larger than the error limit. It can be seen on Fig.4., that the electron density has maximum value in the middle plane of the star, than falls rapidly.

Outside the star-shape no electron current could be measured, only a little ion current, which proves that ions are electrically confined. Moving toward the resonant zone the electron density increase as we showed at the axial measurements, while the angular region where the plasma is located widens. The result of this experiment is the first three-dimensional electron density distribution of the ECR plasma in the literature (Kenéz 2004).

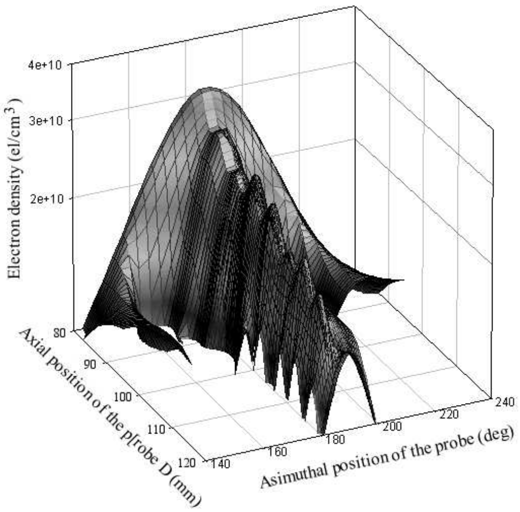

Figure 4: *3D - electron density distribution*

5.3 Plasma potential measurements using emitting probe

The experiments presented in this section were performed at the all-permanent NIRS-ECRIS, Japan. For well-known reasons, e.g. electron current suppression caused by the confining magnetic field, in case of ECR plasmas simple Langmuir-probes are not suitable for plasma potential measurement (Kenéz 2002a, Chen 1965). However, another type of probe, the emitting probe is available for this purpose. Let's see what makes possible to use emitting probes for plasma potential measurement. Curve 1 in Fig.5. is a typical cold probe characteristic curve.

There are two important points in this curve, one is the so-called floating potential (V_f) where the total probe current is zero and the other one is the plasma potential (V_p) where the plasma and the probe are on the same electric potential, there are no electric fields, the number of the collected charged carriers is determined by their energies. Due to the larger mobility of the electrons, V_f is negative for simple Langmuir-probes used in the cold regions of the ECR plasma. When a probe is heated (Fig.1. curves 2,3 and 4) it starts emitting secondary electrons. Due to the secondary electron emission, the shape of the probe voltage-current ($U - I$) curve changes in some regions. When the probe potential is above the plasma potential, the low energy secondary electrons are trapped by the positive potential barrier of the probe so they cannot leave and do not contribute to the total current. Decreasing the probe voltage below the plasma

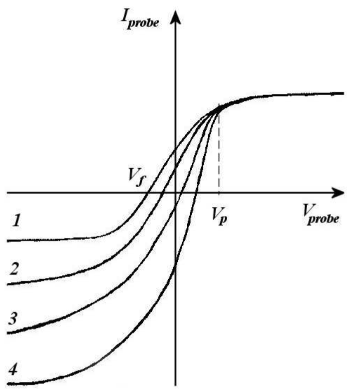

Figure 5: *Probe voltage-current curves; curve 1 - cold probe, curves 2,3 and 4 - heated, emitting probe (increasing heating current)*

potential, the secondary electrons are repelled by the probe and enter into the plasma contributing to the total current. It can be seen on the figure, that proportionally to the heating current, the steepness of the transition region of the curves is emphasized. Of course, the number of the secondary electrons increases proportionally with the probe temperature. This means, heating continuously up the probe, the floating potential gets higher and higher closing to the plasma potential, which is the saturation value of this process. Taking into account these considerations, ensuring sufficiently high secondary electron emission, the emitting probe can be used to determine the local plasma potential and consequently its distribution in ECR the plasma. Emitting probes can be simply realized making a loop of tungsten (or other material) of little dimensions and insulating it properly from other conducting parts of the ion source. The probe must have a heater electrical circuit and another circuit to bias it to different voltages with respect to the plasma chamber (which is on high voltage) and to measure the current. The emitting probe used at the present experiments was made of $0.1mm$ diameter tungsten wire and approx. 1 mm length. The emitting probe was made splicing one 0.1 mm diameter tungsten wire with two 0.1 mm diameter copper wires (Kenéz 2002b) and introduced inside a two-bored (2×0.4 mm) ceramic insulator tube. For test experiments different kinds of plasmas were generated at different microwave power using Ar, N and O as working gas. The ECR plasma contains highly charged heavy ions, which collide with the probe sputtering it. Due to this effect, the lifetime of the probe is limited. However, carefully controlling the experimental conditions we reached lifetimes as long as 10 hours. The behavior of the emitting probe and ion source was tested. During heating when the probe was kept in fixed position the plasma was only slightly disturbed. The disturbance was slightly higher when the heated probe was moved inside the plasma chamber. The heated probe was used only in the cold regions of the ECR plasma. To determine the local plasma potential, $U-I$ curves were taken while the heater current was step-by-step increased to get higher and higher emission. Using these curves the behavior of the floating potential was analyzed. It was observed that corresponding to the theory, the floating potential increased as the probe temperature increased and finally saturated (Fig.6.).

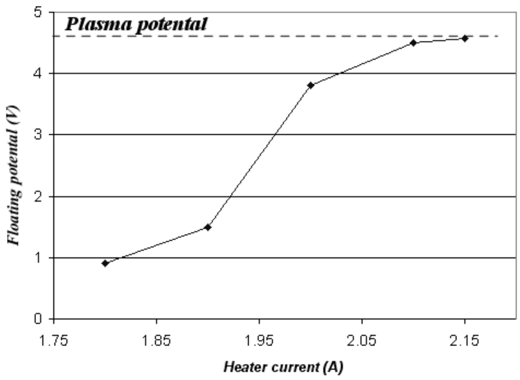

Figure 6: *Evolution of the floating potential during continuous heating of the probe; the saturation value is the local potential*

Under these circumstances we consider that the saturation value of the floating potential is the local plasma potential.

6 Conclusions

We adapted a method well known in the filed of plasma physics and successfully applied to calculated local plasma parameters and parameter distributions in the complex ECR plasma even though many difficulties are encountered. Both theoretical and experimental work has been done. We developed new theoretical model to take into account the multiply charged nature of the ECR plasma. We also measured the first three-dimensional local electron density distribution. Using the emitting probe method, we measured local plasma potential. Further experiments are needed to build the three-dimensional plasma potential map of the cold ECR plasma.

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