Highly Charged Ion Production Using an Electrode in Biased and Floating Modes

S. Biri[2], T. Nakagawa[1], M. Kidera[1], L. Kenéz[2], A. Valek[2] and Y. Yano[1]

1) The Institute of Physical and Chemical Research (RIKEN) Hirosawa 2-1, Wako, Saitama 351-01, Japan,
2) Institute of Nuclear Research (ATOMKI), H-4026 Debrecen, Bem tér 18/c, Hungary

Abstract

One of the most popular ways to obtain higher beam intensities in ECR ion sources is to install an electrode (usually disc) into the plasma chamber. Examined this method in detail we found that majority of the groups observed the beam intensity improvement by supplying a suitable biased voltage to the electrode and an electron current was injected into the plasma. A few groups observed the enhancement, however, when the electrode operated at floating potential – without being an electron donor. Only a few (and sometimes contradictionary) information was found on the optimised properties of the electrodes, i.e. position, dimension, shape, material.

In spite of the great success of the "biased-disc" method, the mechanism is still not completely clear. In this contribution, as a step of understanding, we examine what condition we observed the above mentioned two modes. The experiments were performed at the 18 GHz RIKEN and at the 14.5 GHz ATOMKI ECR ion sources.

1. Introduction

Examined the popular "biased disc" method in detail, we categorised the published experimental data into two groups [1]. The majority of the groups reported that improved beam intensities were observed when supplying a negative biased voltage (several tens ~ several hundreds volts) to the electrode in respect to the plasma chamber and an electron current in the order of mA was injected into the plasma. A few groups observed the enhancement, however, when the electrode operated at floating potential – without being an electron donor.

In spite of the great success of this method, the mechanism is still unclear. In this paper, as a step of understanding, we examine the conditions how to observe the above mentioned two modes. The secondary goal was to enhance the beam intensity of highly charged ions by using the electrode. Most of the experiments were performed at the 18 GHz RIKEN-ECRIS and some tests and simulations at the 14.5 GHz ATOMKI-ECRIS.

2. Experimental apparatus

2.1. The 18 GHz RIKEN-ECRIS

In the 18 GHz RIKEN ECRIS the plasma chamber wall is covered up with a thin aluminium tube (of thickness 1 mm) to emit secondary electrons which helps to increase the plasma density. The plasma chamber has the feature that its axial length is much longer at the injection side than the hexapole magnet. The maximum of the axial magnetic field (1.3 T) is also outside the hexapole volume at the injection side. For symmetrical point of views we placed the electrode holder rod and the tested electrodes themselves on the chamber axis. Other details on the 18 GHz RIKEN ECRIS (including the effect of the electrodes on the highly charged ion currents) are shown by T. Nakagawa in this workshop [2].

2.2 The 14.5 GHz ATOMKI-ECRIS

Since 1997 the 14.5 GHz ECR ion source of ATOMKI [3] produces beams of multiply charged ions on a very reliable and stable way. In spite of the relatively weak magnetic trap (mirror ratio is less than 2 at any direction) highly charged ions with medium intensities can be easily obtained (e.g. 100 μA of Ar^{8+} and 1nA of Ar^{16+} at 10 kV source potential). Several disc and 'star'-shape electrodes have been tested successfully to increase the ion currents.

3. Magnetic field lines and electron movement simulations

In order to get some initial information on the dimension and position of electrodes to be tested we visualised in 3D the magnetostatic field line structure in the chamber by the TrapCAD code [4].

First those field lines were only considered which crossed the closed resonance surface for 18 GHz (B=0.63 T). In Fig. 1 the well known 'stars' or 'triangles' are drawn at two axial position. The stars are formed by the points of those magnetic field lines (when crossing the actual axial position) which also passed through the closed B=0.63 T surface. It can be seen that the field line number versus radius ratio changes at different axial positions. We believe that plasma particles mainly follow these 'high-energy' field lines and hit the electrode or the end-wall of the chamber. The electrode can deliver seconder electrons effectively only if (1) it is placed to suitable position and its surface covers most part of the star at that position and (2) the emitted new electrons can join quickly the high energetic field lines.

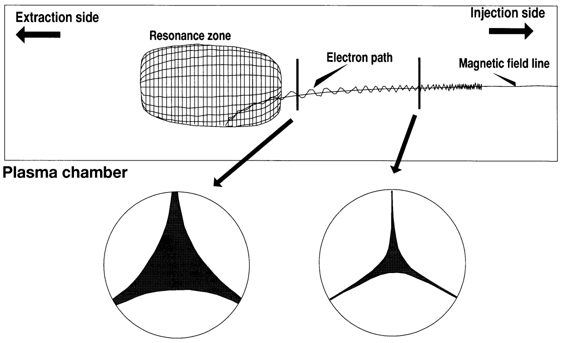

Fig. 1. High energy magnetic field line calculation. Upper part: the closed resonance surface in the plasma chamber (side view) and a portion of an electron path with its guiding magnetic field line. Lower part: 'stars' are formed by the cross sectional points of those field lines which crossed the resonant surface. Left star: close to the resonant zone, right star: around Bmax.

In a second series of simulation we started electrons with constant total energy (200 eV) from many different positions. 200 V is a typical voltage of the biased electrodes. The energy components (parallel and perpendicular to the actual magnetic field line) were varied in a wide range. We observed that all the electrons which were started outside the above mentioned ‘stars’, lost quickly (within several ns) at the cylindrical surface of the chamber. These parts of the electrodes seem to be completely redundant for both points of views. The other electrons which were started from within the stars, however, had a much longer lifetime.

Based on the above modelling and also fulfilling some technological requirements we chose 8, 13 and 26 mm diameter of discs made of stainless steel (SS). We made two other 13 mm discs made of copper and aluminium and one SS 'star-shape' disc for the axial position, where the magnetic field has the injection peak. The thickness of all the electrodes was 1 mm. The axial position of the electrode was remotely controlled. The negative bias voltage was applied between the electrode and plasma chamber.

4. Optimised electrode parameters

We studied the effect of some electrode parameters on the current of highly charged ions (in most cases it was Ar^{11+}). The axial position, the electrode dimension (diameter) and shape and the material were investigated and comparised.

We scanned the electrode several times between the chamber wall and the resonant zone. We measured a curve which is roughly a 'hill' with a maximum around the magnetic peak while there are several local maximums and minimums “sitting” on this hill. The average distance of these local maximums and minimums is in some kind of connection with the wavelength of 18 GHz (17 mm), however, we were not able to find a more exact rule.

We tested discs with diameters 8, 13 and 26 mm and the highest Ar^{11+} current at 10 kV source potential was 140, 165, 160 μA, respectively (see Fig 2.). From this experiment the disc with diameter of 13 mm proved to be the best and chose for further tests.

The tested circular and ‘star’-shape electrodes gave exactly the same result at both ECRIS. This means that only that part of the electrode is important and this fits well with the above TrapCAD simulations.

We tested Cu, Al and SS electrodes without observing any differences. Because Cu and Al melted quickly (if the electrode was too close to the resonant zone), SS electrode is recommended. Obviously the seconder electron emission ability of the applied material is not important here.

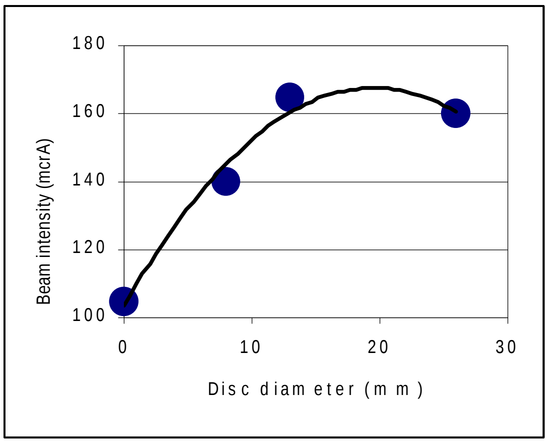

Fig. 2. Dependence of the highly charged ion production on the disc diameter.

5. Observation of two working modes

We studied the effect of the electrode using different bias voltages and electrode currents. At the ATOMKI-ECRIS we found the well-known biased behaviour of the electrode. Depending on the plasma conditions we clearly found, however, two operation modes of the electrode at the RIKEN-ECRIS.

5.1. The biased or Electron Donor (ED) mode

The applied magnetic field was far below the maximum (it was about 1.0…1.1 T) and the RIKEN-ECRIS was tuned to obtain the maximum beam intensity of the Ar^{11+} ions at 10 kV source potential. The gas pressure was $8x10^{-7}$ mbar and the injected microwave power was 550 W. Figure 3a) shows the beam intensity of Ar^{11+} ions and current of electrode as a function of bias voltage. Similar curves were measured in ATOMKI and in many laboratories. At this magnetic field the argon beam intensity increased with increasing the bias voltage up to -160 V and then gradually decreased. The current of electrode also increased with increasing the bias voltage up to -160 V and then nearly saturated. Figure 3b) shows the charge state distribution of argon ions when the ion source was tuned for producing the Ar^{11+} ions. We note the CSD seems to be not shifted! All of the ion currents increased by approx. the same factor. The total beam current increased from 2.7 mA upto 4.0 mA when adding 1.2 mA of disc current.

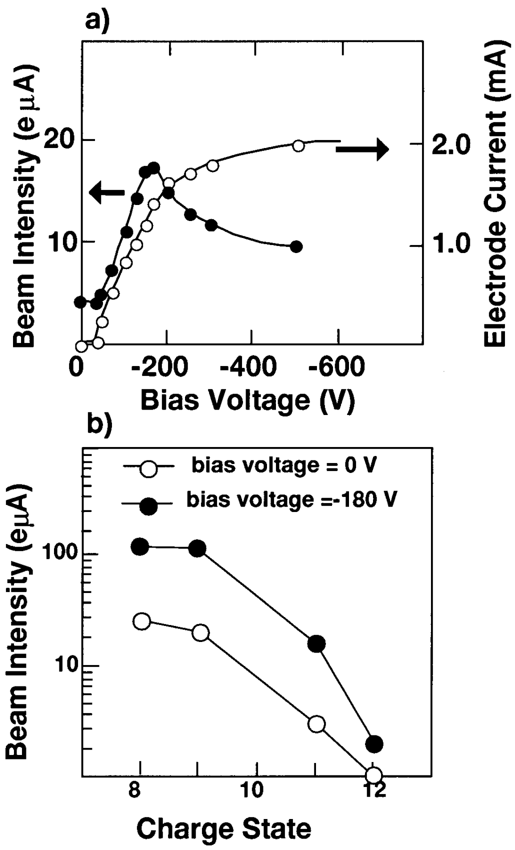

Fig. 3. Operation in Electron Donor (ED) mode.
a./ Beam intensity of Ar^{11+} ions (closed circles) and current of electrode (open circles) as a function of negative bias voltage. b) Charge state distribution of Ar ions when applying voltage of 0 and -160 V

The same result was obtained in pulsed mode. We measured the ratio of the argon afterglow current to the steady-state current for charge state of 8+, 9+ and 11+ as a function of negative bias voltage. The pulse length was 40 ms which is long enough to reach the equilibration for producing the highly charged argon ions such as $Ar^{11+,12+}$. The repetition rate was 10 Hz. The plasma parameters (magnetic field, gas pressure etc.) were kept near the values as in CW mode. Both (steady-state and afterglow) currents increased by the same factor between –20 and approx. –100 V electrode voltages.

Because the best result was obtained when the electrode operated at a several hundreds of volt negatively biased potential and the plasma seemed to require electrons from the electrode further we call this arrangement as Electron Donor (ED) mode.

5.2. The floating or Potential Tuner (PT) mode

Searching for the highest Ar^{11+} current at the RIKEN source the best result was obtained when the magnetic field was high (about 1.3 T) and the electrode was placed around the maximum magnetic field at axial direction. Figure 4a) shows the beam intensity of Ar^{11+} ions and the current of the electrode as a function of bias voltage. We obtained the best results at electrode voltage of zero volt without any current through the electrode. Between zero and -100 V the ion current output was unchanged. Then the beam intensity of Ar^{11+} ions decreased with increasing the negative bias voltage. Figure 4b) shows the charge state distributions of argon ions when the ion source tuned for production of Ar^{11+} ions without using the electrode, with using it at the bias voltage -160 V and at the floating potential. The mean charge state seems to be shifted to higher charge state when using the electrode at floating potential! The total beam current did not change by tuning the disc voltage.

The beam intensity of Ar^{11+} ions was 165 μA it is almost 50 % increase compared to that without using the electrode ever before at this ECRIS (at 10 kV ion source potential). To check the beam intensity of Ar^{11+} ions without using the electrode again, it was removed from the plasma chamber without changing any other parameters. We got only 105 μA current.

This strange mode was also observed in pulsed mode at the RIKEN–ECRIS, it was not found, however, at the ATOMKI-ECRIS.

Because the best result was obtained when the electrode operated at zero (floating) potential without emitting any electrons into the plasma the electrode seems to effect via changing or tuning the plasma potential further we call this arrangement as Potential Tuner (PT) mode.

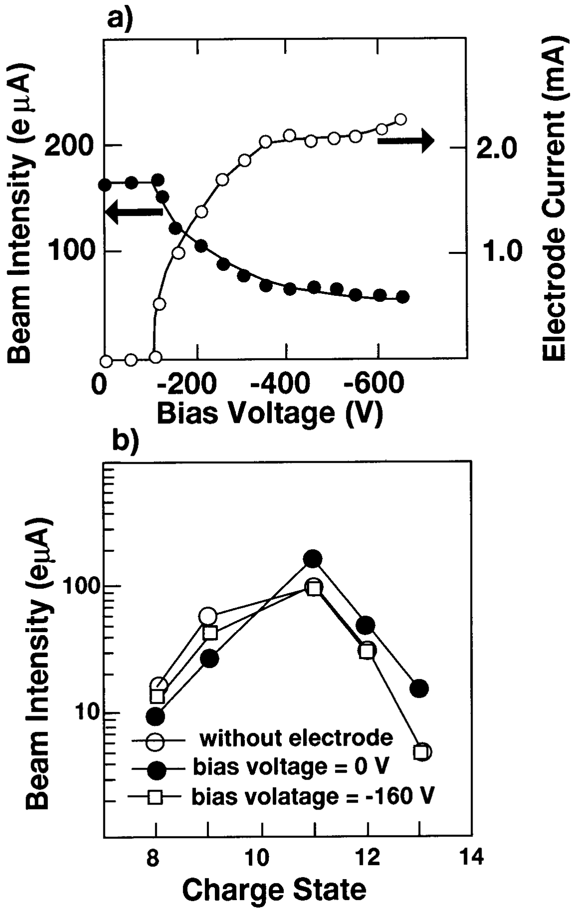

Fig.4. Operation in Potential Tuner (PT) mode.
a) Beam intensity of Ar^{11+} ions (closed circles) and current of electrode (open circles) as a function of negative bias voltage. b) Charge state distribution of Ar ions without using the electrode, with using it at -160 V and at floating potential

6. Discussion

Table 1 summarises the measured currents and the difference between the two modes.

Most published data seem to fit to ED mode, with other words most ECR plasmas require external electrons in order to increase the ion currents. The biased disc effect is frequently explained by an increase of the electron density. However, as it can be seen from Fig. 3b the CSD did not change in our case. The selected Ar ion intensity simply increased together with the increase of the total current. A recent experiment at the Frankfurt University [5] also showed that the plasma respond is too fast to the electron injection so the most possible explanation is that the electron injection in ED mode improves the extraction conditions for all the ion components.

It is much more difficult to explain the PT mode found only at the 18 GHz RIKEN-ECRIS. Here we can give only one possible qualitative explanation. To obtain higher HCI beam intensities it is crucial to increase the density of ionising electrons and to prolong the confinement time of the ions in the electron cloud. For an effective extraction, however, sometimes we need to shorten the ion confinement time (keeping its value, of course, higher than the ionisation time). As a result, there exists an optimal confinement time for every ion species. We assume in PT mode the metallic electrode regulates the plasma potential dip that traps the positive ions. By means of moving axially the disc an optimal confinement time is generated. The plasma potential dip changes but it still remains strong enough to trap the highly charged ions and it becomes optimal for extraction at the same time. As a result the beam intensity of highly charged ions increases.

MODE:	BASIC	POTENTIAL TUNER (PT)		ELECTRON DONOR (ED)	
Magnetic field	High B	High B	High B	Low B	Low B
Electrode mode	No	Floating	Biased	Floating	Biased
Electrode voltage (V)	-	0	-160	0	-160
Electrode current (mA)	-	0	1.5	0	1.2
Total beam current (mA)	5.6	5.7	5.7	2.7	4
Ar^{11+} current (μA)	110	165	105	5	17

Table I. Comparison of the two modes of electrode at the 18GHz RIKEN-ECRIS.

7. Conclusion

We successfully observed the enhancement of highly charged ions using an electrode in the ECRIS plasma chamber. We found that the effect of electrode is strongly dependent on the plasma parameters and on the position of the electrode.

At certain parameters we need a few tens or hundreds volt and few mA of electron current to increase the beam intensity of highly charged ions. The extraction current increases with increasing the current of electrode. The electrode works as an electron source (Electron Donor or ED mode). At higher axial magnetic field the best results are obtained at floating electrode potential. The electrode works to tune the plasma potential dip (Plasma Tuner or PT mode).

We continue these investigations to understand the exact mechanism of electrode-plasma interaction in the electron cyclotron resonance (ECR) ion sources and traps.

Acknowledgement

This work was partly supported by the National Scientific Research Foundation (OTKA) of Hungary under the contract Nr. T26553.

References

[1] Biri S., Nakagawa T., Kidera M., Miyazawa Y., Hemmi M., Chiba T., Inabe N., Kase M., Kageyama T., Kamigaito O., Goto A., Yano Y., Nucl. Instr. Methods B152 (1999) pp. 386-396.

[2] Nakagawa T. et al., Recent Developments of RIKEN ECRISs, see this proceedings.

[3] Biri S., Vámosi J., Review of Scientific Instruments 69 (1998) 646-648. See also: http://www.atomki.hu/atomki/ECR/

[4] Vámosi J., Biri S., Computer Physics Communications 98 (1996) 215-223. See also: http://www.atomki.hu/atomki/ECR/trapcad.htm

[5] S. Runkel, K. E. Stiebing, O. Hohn, V. Mironov, G. Shirkov, A. Schempp and H. Schmidt-Böcking, see this proceedings.