FURTHER DEVELOPMENT OF RIKEN 18 GHZ ECRIS

T.NAKAGAWA, M. KIDERA, Y. MIYAZAWA, M. HEMMI, T. CHIBA, N. INABE, M. KASE, T. KAGEYAMA, O. KAMIGAITO, A. GOTO, and Y. YANO

The Institute of Physical and Chemical Research (RIKEN) Hirosawa 2-1, Wako, Saitama 351-01, Japan

S. BIRI

Institute of Nuclear Research (ATOMKI), H-4026 Debrecen, Bem ter 18/c, Hungary

We successfully produced intense beams of highly charged ions (e.g., 300 eμA of Ar^{11+}, 18eμA of Ar^{16+}, 15eμA of Kr^{24+} and 3eμA of Xe^{32+}) from the RIKEN 18 GHz ECRIS using an electrode. To investigate the function of the electrode, we measured the beam intensity of argon ions using the electrode under pulsed mode operation. We observed that the potential dip becomes deeper by increasing negative bias voltage. It is concluded that the electrode works to optimize the plasma potential and helps to increase the beam intensity of highly charged argon ions. To obtain the information of plasma potential dip, we also measured the afterglow and steady current of highly charged Ar ions and X-rays emitted from ECR plasma simultaneously under the pulsed mode operation .

1. Introduction

Because the intense beams of medium mass heavy ions have been requested by users of RIKEN Accelerator Research Facility, a new ECRIS has been constructed as an external ion source of the RILAC(Riken heavy Ion Linear ACcelerator)-Ring cyclotron accelerator complex[1] This ECRIS will be also one of the constituents of Radioactive Ion Beam Factory (RIBF) project, whose aim is to supply the various unstable nuclei beams for the experiments in various fields.[2] According to the scaling low proposed by R. Geller, the beam intensity increases with its micro wave frequency and magnetic field strength.[3] Therefore, we had chosen the micro wave frequency of 18 GHz for the RIKEN ECRIS. It is successfully under operation now[4-6]. Recently, we have installed an electrode in the plasma chamber and observed the strong enhancement of beam intensity of highly charged ions. In this paper, we present the performance and mechanism to produce multi-charged heavy ions with electrode. We also present the measurement of x-ray from ECR plasma under pulsed mode operation for studying the basic characteristics of ECR plasma.

2. Description of RIKEN 18 GHz ECRIS with electrode

The detailed design of the ECRIS has already described in ref. 5. A single 18 GHz-1.5 kW klystron supplies RF power to the source. The axial confinement of plasma is obtained by two solenoid coils which provide magnetic mirror field. The source is completely enclosed by an iron yoke to reduce the current of the solenoid coils. The maximum electrical power consumption is 140 kW. The mirror ratio is about 3.0 (B_{max} ~ 1.4 T, B_{min} ~ 0.47 T). To confine the plasma radially, we use a hexapole magnet which consists of 36 segments, made of Nd-Fe-B permanent magnets. The field strength at the surface of the magnets is about 1.4 T. Figure 1 shows the schematic drawing of the RIKEN 18 GHz ECRIS with the stainless steel electrode. The diameter and thickness of the electrode is 13 and 1 mm, respectively. It is possible to apply the negative bias voltage between the electrode and plasma chamber as shown in fig. 1. It is also possible to use the electrode at the floating potential by disconnecting it from the electric power supply. The position of the electrode is remotely controlled with accuracy of 0.1 mm.

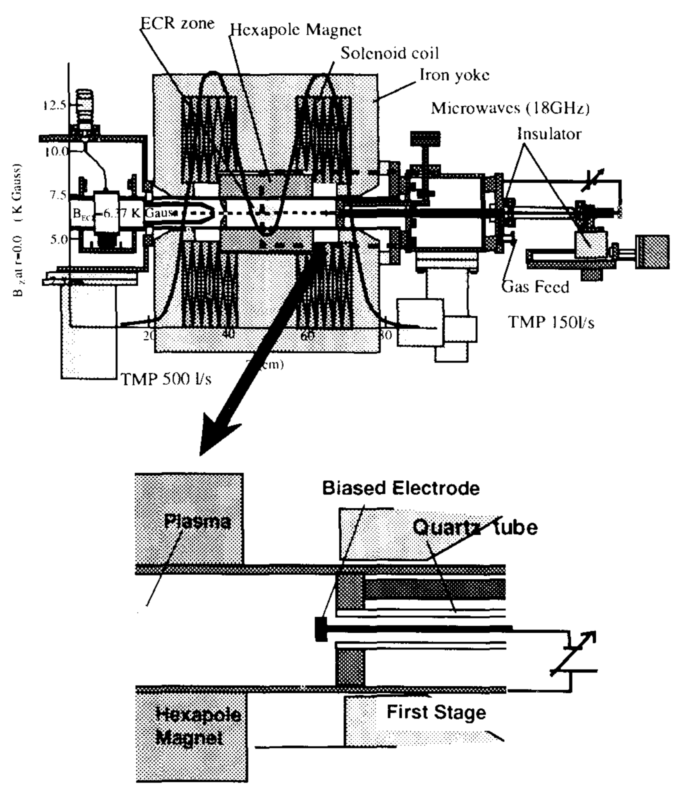

Fig.1 Schematic Drawing of 18 GHz ECRIS with electrode

3. Experimental results and discussion

3-1 Beam intensities of gaseous elements

Figure 2 shows the Ar^{11+} beam intensity as a function of electrode position. The best result was obtained when the electrode was placed at the maximum magnetic field strength in axial direction. Figure 3 a) shows the beam intensity of Ar^{11+} ions (closed circles) and current of electrode (open circles) as a function of bias voltage. We obtained the best result (160 eμA) at the negative voltage from 0 to -50 V and the electrode operated at floating potential. The beam intensity of Ar^{11+} ions decreased with increasing the negative bias voltage. The gas pressure was 5×10^{-7} Torr. The extraction voltage was 10 kV. The injected microwave power was 550 W. Total extraction current was almost constant and independent on the bias voltage. From this result, it is estimated that the density of plasma is almost constant in spite of enhancement of the beam intensity of highly charged Ar ions.

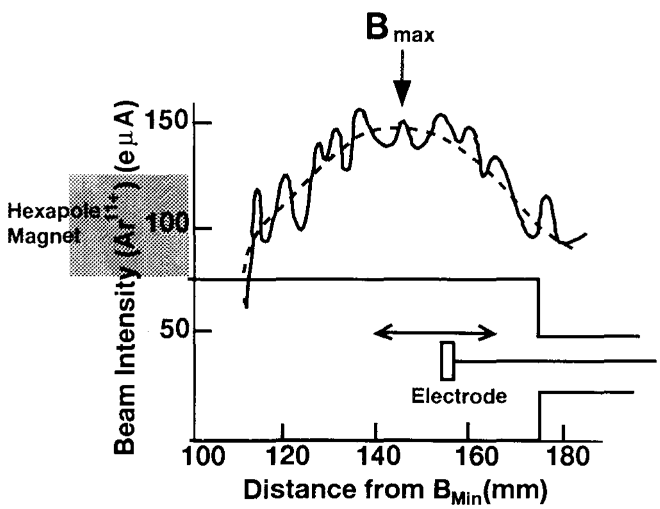

Fig.2 Beam intensity,of Ar^{11+} as a function of electrode position

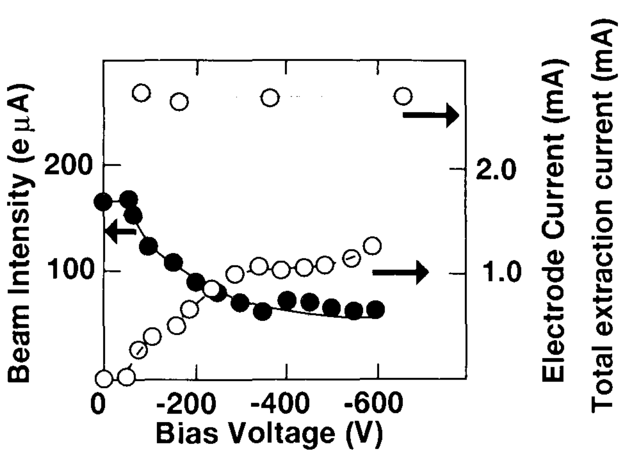

Fig.3 Beam intensity of Ar^{11+}(closed circles), current of electrode (open circles), and total extraction current as a function of bias voltage

Figure 4 shows the beam intensity as a function of the extraction voltage. The open and closed circles are the results obtained without and with using the electrode, respectively. At 15 kV, we obtained a beam intensity of 300 eμA for Ar^{11+} when using the electrode. Figure 5 shows the beam intensity of Ar^{11+} as a function of microwave power at the extraction voltage of 12 kV. The beam intensity increases upon increasing the RF power up to 600 W. Figure 6 shows the summary of beam intensity for gaseous elements. The closed circles and open circles are the results with and without using the electrode. The beam intensities of highly charged ions are strongly enhanced with using the electrode.

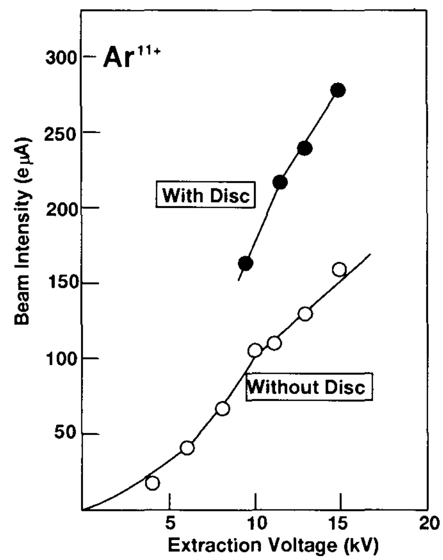

Fig. 4 Beam intensity of Ar^{11+} as a function of extraction voltage

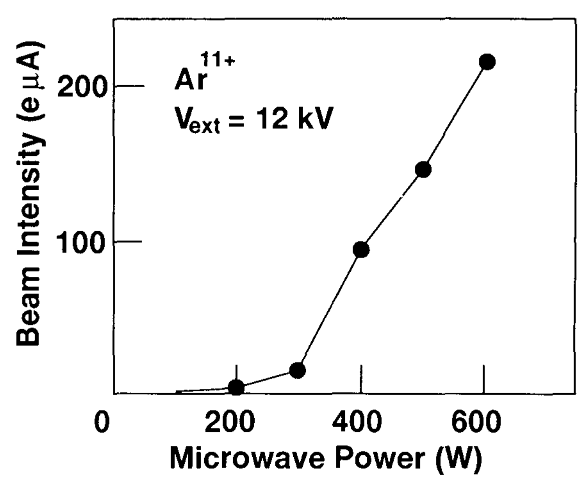

Fig.5 Beam intensity of Ar^{11+} as a function of microwave power.

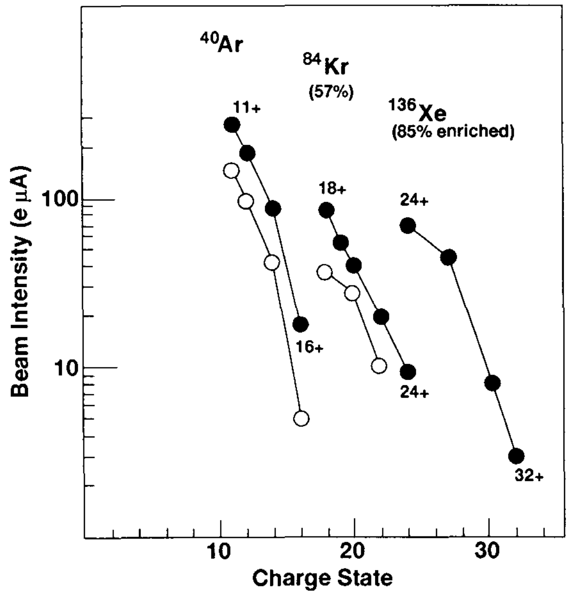

Fig. 6 Beam intensity of highly charged ions from gaseous elements. Open and closed circles are the results without and with using the disc.

3-2 Measurement of plasma potential dip

As described in the previous section, the beam intensity is strongly enhanced at 0 V or floating potential. Beam intensity decreases by increasing negative bias voltage. On the other hand, the total extraction current from the ECRIS is constant and independent on the bias voltage. These results suggest that the electrode may not work as an electron source, but instead works to change the plasma potential dip which traps the highly charged ions. The measurement of afterglow- and steady-currents under the pulsed mode operation gives information on potential dip in ECR plasma.[3)] In order to study the effect of an electrode on the plasma potential dip, we measured the afterglow- and steady-currents under the pulsed mode operation using the electrode.

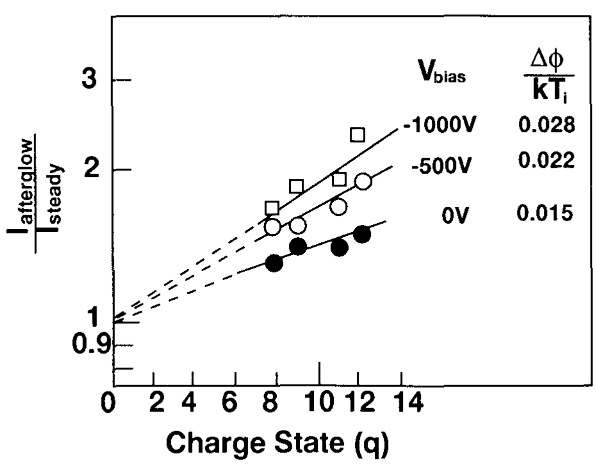

Fig.7 Ratio of afterglow current to steady current as a function of charge state.

Under the pulsed mode operation, we kept same values of gas pressure, magnetic field strength, and extraction voltage as those under the CW mode operation which we obtained the best results. The pulse length was 40 ms which is long enough to reach the equilibration for producing the highly charged argon ions such as $Ar^{11+, 12+}$. Repetition rate was 10 Hz.

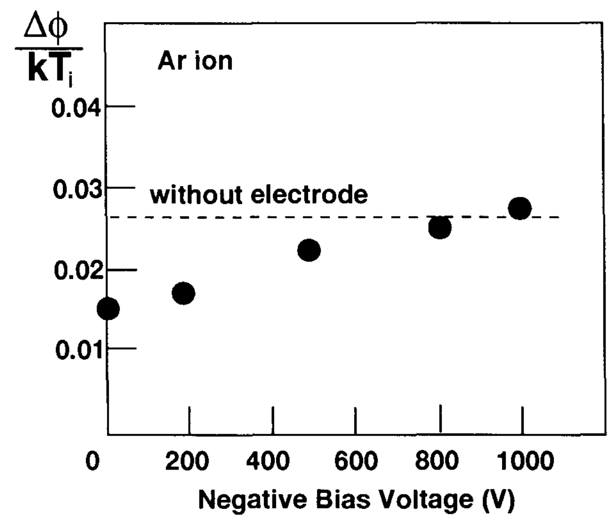

Fig. 8 $\Delta\phi/kT_i$ as a function of bias voltage

We measured ratio of the afterglow current ($I_{afterglow}$) to steady current (I_{steady}) for charge state from 8+ to 12+ as a function of negative bias voltage. As described in ref. 6, if the central plasma shows a depressed potential $\Delta\phi$, the ratio between the beam currents of steady state and the afterglow can be written as follows,

$$I_{afterglow}/I_{steady} = \exp(q\Delta\phi/kT_i) \quad (1)$$

where q, $\Delta\phi$ and T_i are the charge state of ions, depressed potential and ion temperature, respectively. Figure 7 shows the ratio of $I_{afterglow}$ to I_{steady} as a function of charge state. Closed circles, open circles, and open squares are the results at the negative bias voltage of 0, -500 and -1000 V, respectively. As shown in fig. 8, the value of $\Delta\phi/kT_i$ increases with increasing the negative bias voltage. This result suggests that the potential dip in ECR plasma becomes deeper with increasing the negative bias voltage. Dashed line shows the value of $\Delta\phi/kT_i$ without using electrode. The potential dip at floating potential or 0 V is shallower than that without using the electrode.

In ref.3, the ion confinement time of highly charged ions is written by

$$\tau_q \propto \exp(q\Delta\phi/kT_i) \quad (2)$$

The extracted ion current(I_q) can be written as follows,

$$I_q \propto n_q q r^2 L/\tau_q \quad (3)$$

where n_q, r, L and τ_q are the density of ions, average radius of plasma, length of plasma and ion confinement time, respectively. In order to obtain the higher current of ions, ion confinement time should be shorter at the fixed n_q, r, and L. The ion confinement time should be longer than the ionization time(τ_i). When we reduce the ion confinement time, but as to longer than ionization time at fixed n_q, r, and L, the ion current increases.

Using the electrode at 0 V, the ion confinement time becomes shorter compared to that without using the electrode. The ionization time seems shorter than the ion confinement time. As a result, the beam intensity of highly charged ions increases.

4. X-ray measurements under the pulsed mode operation

The measurements of ratio of afterglow- to steady-current under the pulsed mode operation give us the information of plasma potential dip ($\Delta\phi$) [3]. It is well known that the measurement of bremsstrahlung x-ray emission is a good tool to study the kinetic energy distribution and density of electrons in plasma.[3] When we combine these two methods, we may obtain the detailed information on mechanism how to create the plasma potential dip. For this purpose, we measured simultaneously x-ray from the plasma and afterglow- and steady- current under the pulsed mode operation. We tuned the ECRIS to make two extremely different ratios of afterglow- and steady-current for Ar^{9+}. i.e., Case I ratio of afterglow- to steady -current is 1:3, Case II 1:1.2, as shown in fig. 9. It is assumed that the plasma potential dip in Case I is deeper than that in Case II. We did not change any other parameters and conditions of the experiments. The duration of RF power was 40 ms. The repetition rate was 10 Hz. The microwave power was 50 W. The gas pressure of Ar gas was 1×10^{-7} Torr.

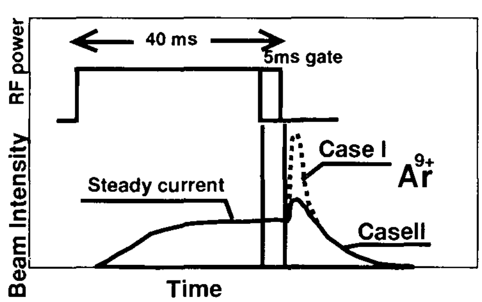

Fig. 9 Beam intensity of Ar^{9+} as a function of time under the pulsed mode operation

To detect x-rays, a collimated pure Ge detector (5cm in diameter and 5 cm of thickness) was located on the injection side of ECRIS. The diameter of the collimator and thickness were 3 mm and 150 mm, respectively. Delayed coincidence x-ray spectra were observed at selected time intervals during plasma heating. A delayed coincidence signal from microwave pulse generator is used to time gate (gate width was 5 ms) of the multichannel analyzer of the Ge detector. The obtained x-ray spectra for both case (case I and II) are shown in fig 10. In this experiment, we did not change the intensity of steady- current and just changed the intensity of afterglow current as shown in fig.9 .If we assume that the change of the intensity of afterglow current causes the change of plasma potential dip, the deference between two spectra shows the x-ray from the electrons which makes a plasma potential dip. The mean energy of subtracted spectra(CaseI-CaseII) is around 100 keV, which is commonly for the hot electrons. This experimental results and analysis is still crude, but it will help us to understand the structure of ECR plasma.

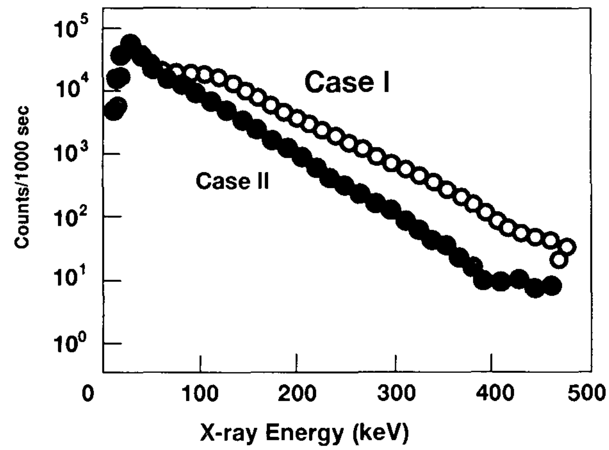

Fig. 10 X-ray spectra for Case I and II

5. Conclusion

We observed the strong enhancement of beam intensity of highly charged ions (300 eμA of Ar^{11+}, 18eμA of Ar^{16+}, and 15eμA of Kr^{24+}, 3eμA of Xe^{32+}) from the RIKEN 18 GHz ECRIS when using the electrode. We measured the beam intensity of argon ions as a function of negative bias voltage of an electrode under the pulsed mode operation. We observed that the potential dip becomes deeper by increasing negative bias voltage. We concluded that the electrode works to optimize the plasma potential and helps to increase the beam intensity of highly charged argon ions. We measured the afterglow and steady current of highly charged Ar ions and X-ray emitted from ECR plasma simultaneously to obtained the information of plasma potential dip.

References

[1] Y. Yano, Proceedings of the 13th International Conference on Cyclotrons and their Application, (World Scientific Publishing Co. 1993, Singapore) p102
[2]Y. Yano et.al, Proceedings of the 14th International Conference on Cyclotrons and their Application, (World Scientific Publishing Co. 1996, Singapore) p590
[3]R. Geller. Electron cyclotron resonance ion sources and ECR plasma (IOP, Bristol, 1996)and references therein
[4]T. Nakagawa et al., 35(1996)4077
[5]T. Nakagawa , NIM A396(1997)9
[6]T. Nakagawa et al., Rev. Sc. Instrum. 69(1998)637