28GHZ SC-ECRIS AT RIBF

T. Nakagawa, Y. Higurashi, J. Ohnishi, H. Okuno, K. Kusaka, M. Kidera, E. Ikezawa, M. Fujimaki, Y. Sato, Y. Watanabe, M. Komiyama, M. Kase, A. Goto, O. Kamigaito, Y. Yano, RIKEN, Wako, Japan
T. Aihara, M. Tamura, A. Uchiyama, SAS, Ohsaki, Japan.

Abstract

The next generation heavy ion accelerator facility at RIKEN, requires an intense beam of high charged heavy ions. To meet the requirements, we constructed and tested the RIKEN new SC-ECRIS. After producing the first beam in the spring of 2009, we tried to optimize the ion source condition for maximizing the beam intensity with 18GHz microwave. We observed that the gentler field gradient and lager ECR zone size give higher beam intensity. Based on these studies, we produced 500μA of Ar^{11+} and 350μA of Ar^{12+} at the RF power of 1.8kW. We also produced highly charged U ion beam with sputtering method for RIBF. In this article, we describe the structure of the ion source, test experiment and future plan.

INTRODUCTION

Since middle of the 1990s, RIKEN has undertaken construction of new accelerator facility so-called Radio Isotope Beam Factory (RIBF) [1] and successfully produced 345MeV/u U beam (~0.4pnA on target) in 2008[2]. Using it, more than 40 new isotopes were produced with the in-flight fission reactions for only 4 days experiment.[3] It is clear that the intense U beam is strong tool to produce new isotopes in the region of medium mass nuclei and to study the mechanisms of the r-process in nuclear synthesis. For these reasons, the intense U beam is strongly demanded. To meet the requirement, we started to construct the new superconducting ECR ion source (SC-ECRIS) which has an optimum magnetic field strength for the operational microwave frequency of 28 GHz. In the end of 2008, we obtained the 102% of the designed value for the magnetic field strength. In the spring of 2009, SC-ECRIS produced first beam with 18GHz microwaves.[4] Since we obtained first beam, we made various test experiments to increase the beam intensity of highly charged heavy ions with 18 GHz microwave. During the test experiments, we tried to produce U ion beam with sputtering method and produced 0.75~2pμA for highly charged U ions (27~35+) at the RF power of ~1.2kW. In the summer of 2010, the ion source was moved from high voltage terminal to the new ion source room. From this winter, it will be used as an external ion source as a new injector system of RIBF to produce intense U and Xe ion beam[5].

DESIGN OF SC-ECRIS

Detailed structure of the ion source was described in ref. [4]. In this section, we briefly mention the structure and excitation test of the SC-coils

Sc-coils

The schematic drawing and photograph of the Sc-coils are shown in Figs.1 and 2. Inside radii of the hexapole and solenoid coils are 102 mm and 170 mm, respectively. Four coils (SL2 ~SL5) can be used for creating a flat magnetic field region between the mirrors. The hexapole magnetic field in the central region is increased by using iron poles, which is same structure as the VENUS.[6] A NbTi-copper conductor is used for coils and these are bath-cooled in liquid helium. The magnetic stored energy is 830 kJ at the design current. 3D calculations of the deformation of the coil assembly were performed with ANSYS [7]. The hexapole coils were dry-wound to work for turn transitions and was vacuum impregnated with epoxy. On the other hand, the solenoid coils were wet-wound with warm epoxy and cured. The ends of the hexapole coils were fixed with a stainless steel ring to support the large radial magnetic force acting on the current return sections. The six solenoids were assembled with stainless steel spacers and tightened with sixty-four long aluminium-alloy bolts that support a repulsive force of approximately 800 kN at the maximum.

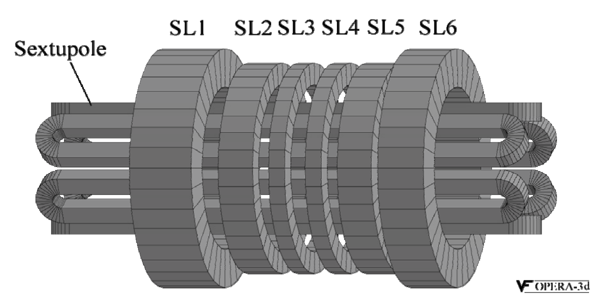

Fig.1 Schematic drawing of the Sc-coils

Using this coil configuration, we can create various shape of mirror magnetic field with six solenoid coils. This magnetic system allows us to produce both of "conventional B_{min}" and "flat B_{min}"[8] configurations. Figure 3 shows the typical axial and radial magnetic field distributions. The maximum axial magnetic fields are 3.8 T at the RF injection side (B_{inj}) and 2.2 T at the beam extraction side (B_{ext}). The maximum hexapole magnetic field (B_r) is 2.1 T on the inner surface of the plasma chamber (r = 75 mm).

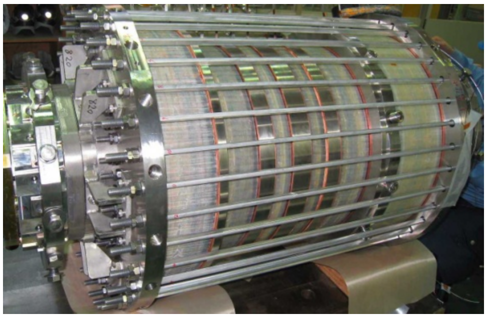

Fig.2 Photograph of Sc-coil assembly for RIKEN SC-ECRIS.

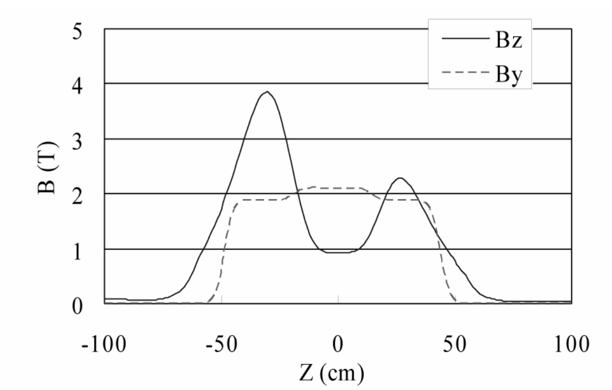

Fig.3 Axial and radial magnetic field distribution

Cryostat

Amount of the liquid-He in the cryostat is ~500 L. The cryostat is equipped with three small GM refrigerators with 4 K, 20K and 70 K stages. Figure 1 shows the schematic drawing of the system. In addition, to increase the cooling power at 4.2K, we use GM-JT refrigerators, which has a cooling power of 4.2W at 4.2K. The nine current leads made of high temperature superconducting material are used to minimize the heat load to 4 K stage. The estimated heat load to 70 K stage is 128 W caused by copper current leads, supports of a cold mass and radiation through the multi-layer insulation.

The maximum electromagnetic force between the magnetic shields and the cold mass is estimated to be 8 tons in axial direction. The cold mass is supported with the belts from an outer tank in room temperature. Four belts with a cross-section of 300 mm^2 are used for the axial direction to support the axial force up to 10 tons. On the other hand, eight belts with a cross-section of 80 mm^2 are used for each of the vertical and horizontal directions to support up to 5 tons. The six solenoids and the hexapole coils are excited individually with seven power supplies. The solenoid coils are excited through seven high temperature superconducting current leads.

Excitation Test

After the solenoid and hexapole coils were assembled, the excitation tests were performed in the cryostat. Figure 4 shows the results of the excitation test. Each solenoid coil achieved the design current without a quench. Next, the hexapole coils was tested. In the combination tests in which the hexapole and one or two of the solenoids were excited at the same time, the hexapole coils quenched in all cases. The hexapole quenched at low currents ranging from 65 A (24%) to 115 A (42%) when the SL1 and the SL2 were excited at their design currents in advance (run #3~#7). The hexapole coils also quenched similarly when the SL6 was excited in advance (run #9, #11). A cause of these quenches was presumed to be a coil motion at the ends of the hexapole coils from the voltage signals, which observed in some of these runs. In run #10, the SL6 was ramped after the hexapole coils was excited at 220 A.

In run #12 and #14~#17, the solenoids and the hexapole coils were excited simultaneously keeping a ratio of the currents. In this case the direction of the force acting on the hexapole coils did not change during the excitation. The quench current of the hexapole increased to more than 85% of the designed value in this way. It, however, was difficult to reach the design current. We have thus concluded that it is necessary to reinforce the structure at the ends of the hexapole coils. After modification, we made a same excitation test as shown in Fig.4. Finally we obtained 102% of designed value without quench.

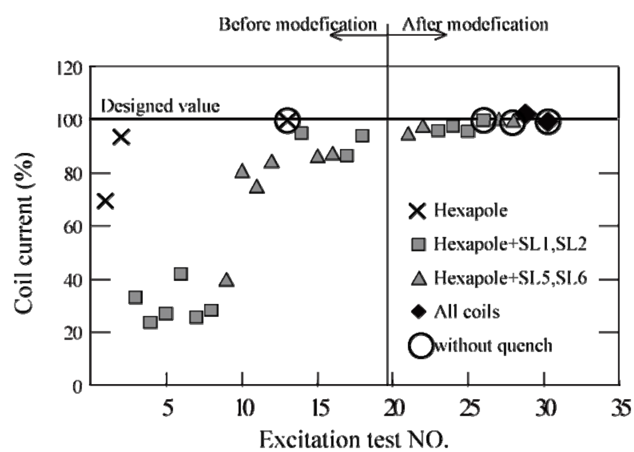

Fig.4 Results of excitation test

Plasma Chamber

Two turbo-molecular pumps (1100L/sec) are placed at the RF injection side and beam extraction side to keep the high vacuum of the plasma chamber. The position of extraction electrode is remotely controlled. The high temperature oven is inserted from the RF injection side. To set the oven on the optimum position, the position of oven is also remotely controlled. The negatively biased disc is placed in the axial direction and its position is remotely controlled with the accuracy of 0.1 mm.

The inner diameter and outer diameter of the plasma chamber are 150 and 164 mm, respectively. The chamber is made of double wall stainless steel tube with the water cooling channel in between. To keep the high voltage (40kV max), the kapton sheets (total thickness of 1.2 mm) covers the plasma chamber. Actual extraction voltage for injecting the ions into the RFQ linac is 22kV, which is lower than the maximum extraction voltage of 40kV.

LBL group demonstrated that the temperature of the cryostat increases with increasing the RF power with 28GHz.[8] It is due to the high energetic X-ray form the ECR plasma. To minimize the X-ray effect when using 28GHz microwave, the plasma chamber will be covered by Ta sheets (total thickness is ~2mm). Figure 5 shows the schematic drawing of the plasma chamber.

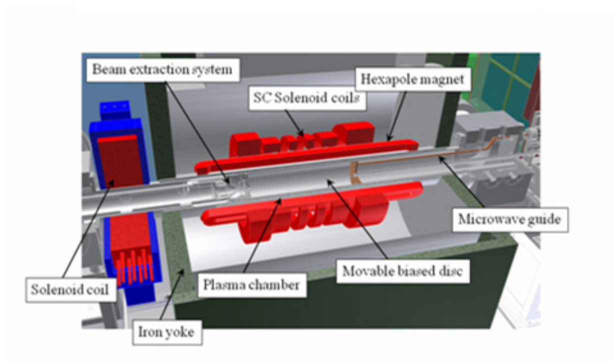

Fig. 5 Schematic drawing of the plasma chamber

LEBT

After the extraction of the beam at 22kV, the solenoid coils is used for focusing the beam. Design of the 90-degree analyzing magnet is based on the LBL one [9]. The vertical gap and bending radius are 150 mm and 510 mm, respectively. The solenoid coil is used to focus the extracted beam. The ion source, solenoid coil, and bending magnet were installed in the ion source room.

The Xe^{20+} and U^{35+} beams are injected into the RFQ linac and then new heavy ion linac for accelerating up to ~0.6 MeV/u.

EXPERIMENTAL RESULTS

Magnetic Field Configuration

To maximize the beam intensity, the optimization of the magnetic field configuration is very important. In the early stage of test experiments, we investigated the effect of the magnetic field configuration on the beam intensity of highly charged heavy ions.[4] In this sub-section, we show the part of these results.

Figure 6 a) shows the beam intensity of Xe^{24+} as a function of B_{min} at the RF power of 300W. The beam intensity gradually increased with increasing B_{min} up to ~0.5T from 15 to 60 eμA. Figure 6 b) shows the charge state distribution of Xe ions for various B_{min}. The average charge state of Xe ions increases with increasing B_{min}. This is mainly due to the effect of the magnetic field gradient at the resonance zone. The gentler field gradient gives lager kinetic energy to the electrons at the resonance zone. As a results, the average kinetic energy of the electron plasma increases with increasing the B_{min}. Therefore the mean charge state of the distribution increases with increasing the B_{min}. To evaluate it, we calculated the field gradient distribution at the resonance zone for several B_{min}. Figure 6 c) shows the field gradient distribution for several B_{min}. It is clearly seen that the field gradient increases form ~700 to ~1800G/cm with decreasing the B_{min} form 0.5 to 0.3T.

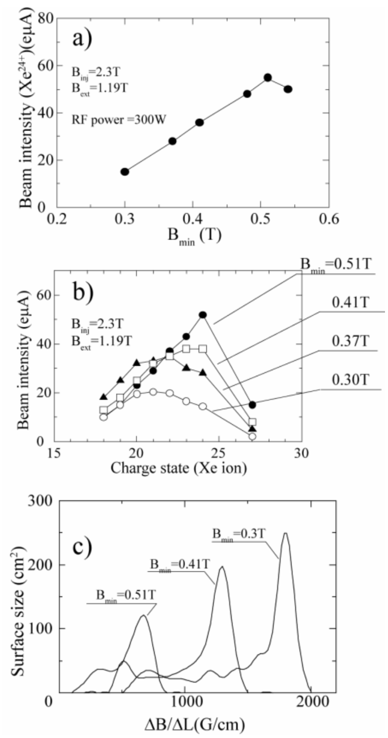

Fig.6 a) beam intensity of Xe^{24+} as a function of B_{min}, b)charge state distribution of Xe ions for several B_{min}. c)Magnetic field gradient distributions for several B_{min}

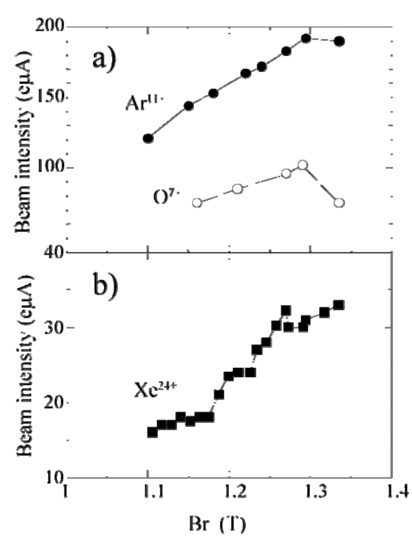

Fig.7 Beam intensity of highly charged heavy ions as a function of B_r

Figure 7 a) shows the beam intensity of Ar^{11+} and O^{7+} as a function of *B*r. The beam intensities seems to be saturated at *B*r~1.3T. On the other hand, the beam intensity of Xe^{24+} gradually increased with increasing the *B*r up to 1.32 T and is not saturated (see Fig. 7 b)). It seems that we need higher *B*r to optimize the beam intensity of highly charged heavy ions.

Effect of Field Gradient and ECR Zone Size

The strong interests for increasing the beam intensity of highly charged heavy ions are the effect of the resonance surface size and field gradient at ECR zone. As described in refs.[10-12], the lager zone size(multiple frequency heating, or broadband microwave radiation) gives higher beam intensity of highly charged heavy ions. As described in the previous section, the ion source has six solenoid coils for creating the mirror magnetic field. Using these coils, the average field gardient at resonance zone (or B_{min}) and surface size of the ECR zone can be changed, independently. It means that one can study these effects on the beam intensity cleraly.

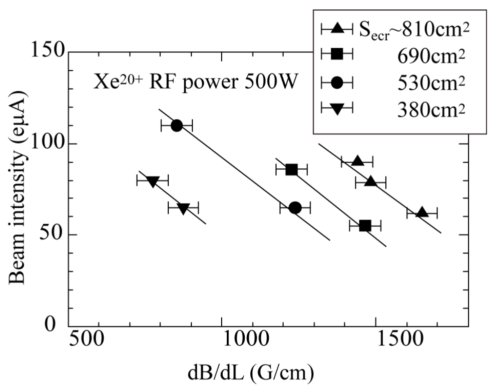

Fig.8 Beam intensity of Xe^{20+} as a function of average field gradient for several ECR zone size

Figure 8 shows the beam intensity of Xe^{20+} as a function of the average magnetic field gradient for several ECR zone sizes at the RF power of 500W. For investigating these effects, B_{inj}, B_{ext} and B_r were fixed to 2.3, 1.2 and 1.3T, respectively. It is clearly seen that the beam intensity increases with decreasing the field gradient. It seems that the beam intensity is higher for larger zone size at same field gradient.

Figure 9 a) and b) show the ratio of highly charged Xe beam intensity between two conditions. The ratio between two different field gradients increases with increasing the charge state (Fig.9 a)) on the other hand, the ratio between different zone sizes are almost constant and independent on the charge state (Fig.9 b)). It is well-known that the energy transfer from microwave to electron increases with the gentler field gradient. The electron temperature becomes higher at the gentler field gradient. For this reason, the production rate of the higher charge state Xe ions increases with increasing the electron temperature.

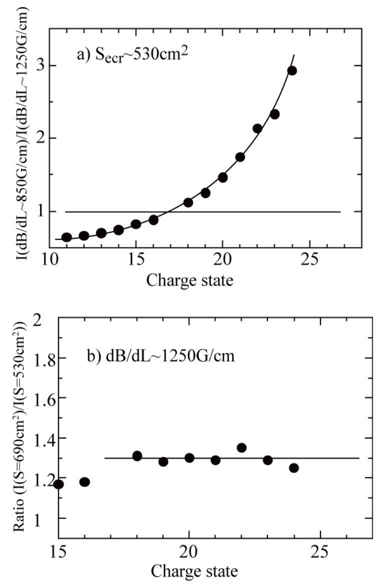

Fig.9 a)Ratio of beam intensity between two different magnetic field gradients ,b)two different ECR zone sizes.

Figure 10 shows the beam intensity of Ar^{11+} as a function of average magnetic field gradient for several ECR zone size. We can see the same tendency as Xe^{20+} case except for the beam intensity at the gentler field gradient (dB/dL < 800G/cm). Figure 11 shows the beam intensity of Ar^{11+} as a function of RF power under two conditions (A and B). The conditions (field gradient and ECR zone size) A and B are indicated in Fig.11. The beam intensity increases with increasing RF power up to 1.8kW and we obtained 500 eμA of Ar^{11+}

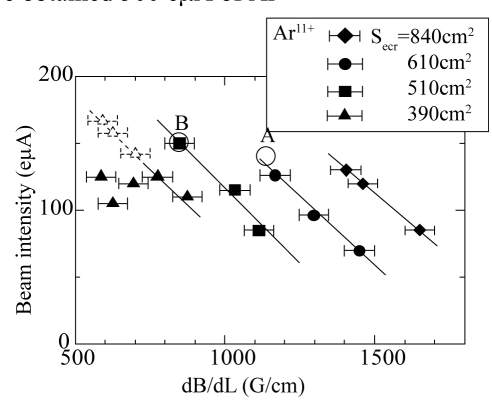

Fig.10 Beam intensity of Ar^{11+} as a function of average field gradient for several ECR zone size

We observed that the beam intensity was almost saturated at the gentler field gradient (dB/dL<800G/cm) as shown in Fig.12. The estimated beam intensities are shown as the dashed line. Simultaneously, we measured the heat load of the cryostat form the X-rays emitted from plasma. We observed that the heat load increases decreasing the field gradient. The heat load of the cryostat is strongly dependent on the X-ray energy, i.e., higher energy X-ray gives large heat load. It means that the very high energetic electron was generated at *dB/dL*<800G/cm. We observed same tendency for Ar^{12+} and higher RF power (>1kW)(see figs. 13 and 14). It is still unclear why we do not obtain higher beam intensity in this region. To understand this phenomenon, we need further investigations.

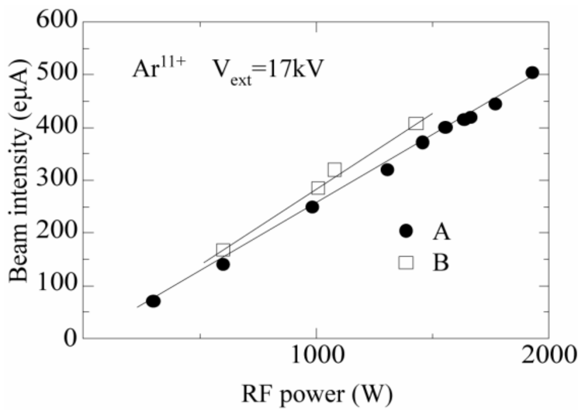

Fig. 11 Beam intensity of Ar $^{11+}$ as a function of RF power.

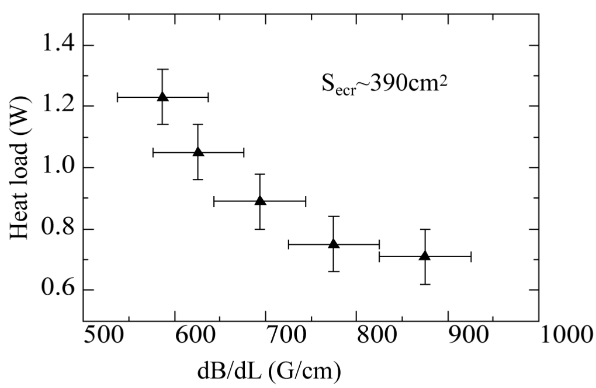

Fig.12 Heat load of X-ray as a function of magnetic field gardient.

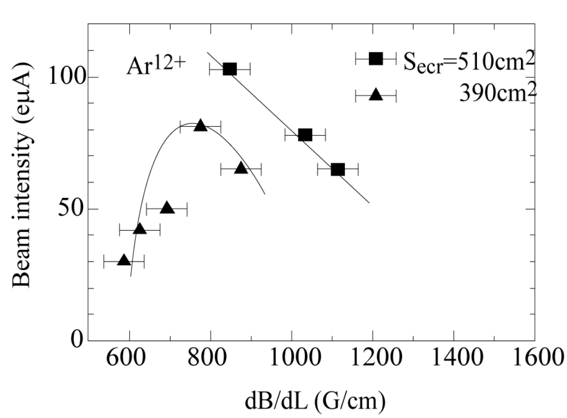

Fig.13 Beam intensity of Ar $^{12+}$ as a function of magnetic field gradient.

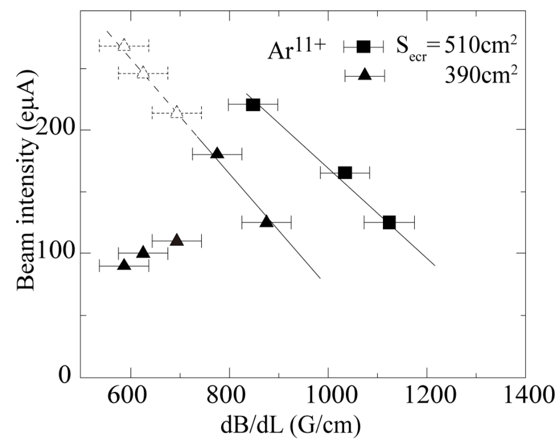

Fig.14 Beam intensity of Ar $^{11+}$ as a function of magnetic field gradient at the RF power of 1kW.

U Beam Production

To produce highly charged U ion beam, we used the sputtering method. Figure 15 shows the beam intensity of U ion as a function of RF power(upper) and the beam intensity of highly charged U ion beam at the RF power of 1.2kW. The extraction voltage was 15kV. The beam intensity of U^{35+} was ~25eμA, which is 12 times as high as that for RIKEN 18 GHz ECRIS.

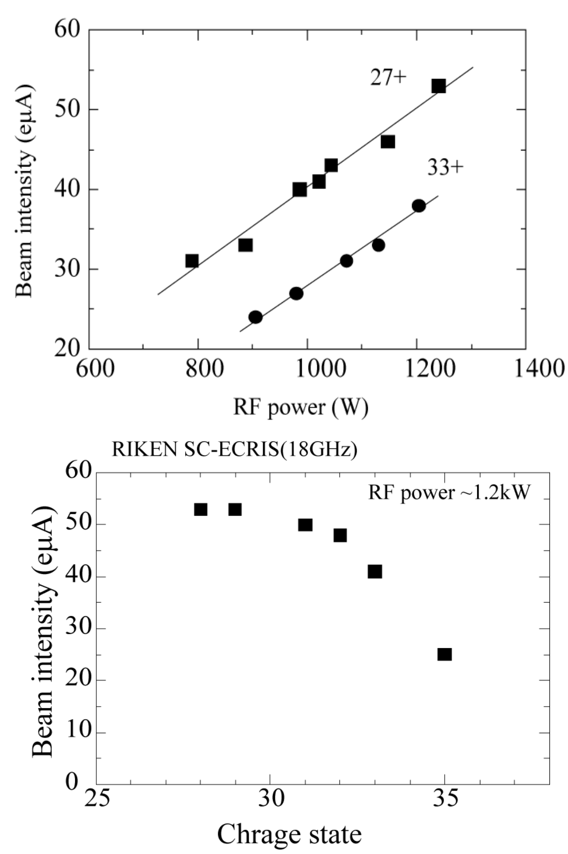

Fig.15 Beam intensity of U $^{27+ \text{ and } 33+}$ as a function of RF power(upper) and beam intensity of highly charged U ion at the RF power of 1.2kW(lower)

It is noted that the beam intensities were not saturated in this test experiment as shown in Figs.15. Because the power density of RF power in this experiment was very low (~100W/L). We may obtain higher beam intensity at the higher sputtering voltage and RF power.

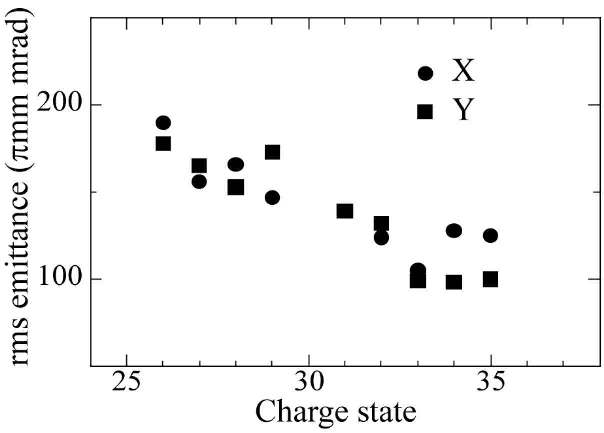

Fig.16 4rms emittance for highly charged U ion.

Figure 16 shows the X and Y emittance (4rms) for highly charged U(26~35+) ions. The emittance decreased with increasing the charge state at same extraction voltage. In this experiment, we obtained the ~ 100πmm mrad for U^{35+}. This is smaller than the acceptance of the accelerator of the RIKEN RIBF (~160 πmm mrad). It means that we can accelerate almost of the U^{35+} beam produced form RRIKEN SC-ECRIS at present.

FUTURE PLAN

It is obvious that the higher frequency gives higher beam intensity of highly charged heavy ions, if we can make optimum magnetic field distribution for higher frequency. To increase the beam intensity of highly charged U ions, we will operate the new SC-ECRIS with 28GHz microwave instead of 18GHz after moving the ion source to the ion source room for new injector system of the RIBF in the summer of 2010. The 28GHz gyrotorn was already installed and tested at RIKEN in this spring of 2010. In the winter of 2010, the test with uranium will be made to meet the requirement of the RIKEN RIB factory project

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