RECENT DEVELOPMENTS OF RIKEN 28 GHz SC-ECRIS

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Abstract

In the past two years, we have attempted to improve the performance of RIKEN 28GHz SC-ECRIS for the production of an intense U ion beam. Last year, we produced ~200 eμA of U^{35+} at an injected Radio frequency (RF) power of ~2.6 kW. For the RIKEN RIBF experiment, we produced ~110 eμA of U^{35+} ions with the sputtering method for longer than one month without a break. In this case, we surely require a very stable beam to increase the transmission efficiency in the accelerators and avoid any damage to the components of the accelerator due to the high-power beam. Very recently, we tested the production of a highly charged Zn ion beam to meet the requirements of the RIBF project and to produce an intense beam with a very low consumption rate.

INTRODUCTION

To increase the beam intensity of a highly charged U ion beam for the RIKEN RIBF project [1], we attempted to improve the performance of RIKEN 28 GHz SC-ECRIS for the past several years [2, 3]. Further, to increase the output beam from the accelerator, we need to increase the U beam intensity and stabilize it because we need to avoid any damage to the components of the accelerator due to the high-power beam. To produce U vapor, we chose the sputtering method, which has two advantages:

1. We can install a large amount of material in the chamber.
2. We only need to supply a negative voltage (several kilovolts) to obtain neutral U atoms, which is simpler than the use of a high-temperature oven.

On the other hand, in general, the beam intensity with the sputtering method is weaker than that with the oven method. Furthermore, the beam intensity is not very stable, which may be due to the sputtering process. To solve these problems, we experimentally searched for the optimum conditions of the ion source. In these experiments, we obtained an intense beam with a low material consumption rate and supplied an intense beam of U^{35+} ions to the accelerators over a long period of time without serious issues. To obtain a more stable beam, we are developing a high-temperature oven. This summer, we modified the crucible to increase the volume and carried out a test experiment to produce a U^{35+} ion beam for a long period of time.

Very recently, there has been strong demand for the production of an intense beam of medium-mass heavy ions such as ^{78}Kr and ^{70}Zn ions. To meet this requirement, we tested the Zn ion beam production with RIKEN 28 GHz SC-ECRIS and successfully obtained a highly charged Zn ion beam with a low consumption rate for the first time experimentally.

In this paper, we present the recent experimental results and the experiences of the long-term operation of the ion source for the production of a U ion beam. In the next section, the experimental results related to the increase in the beam intensity of the highly charged U ion beam are presented. Then, the performance of the ion source for long-term operation is described. Next, we describe the preliminary results of a test experiment for the production of a Zn ion beam. In last section, the conclusions and the plans for future work toward improving the performance are presented.

URANIUM ION PRODUCTION

The structure of the ion source and the method for producing neutral U atoms with the sputtering method are described in Refs. [2] and [3] in detail. The main feature of the ion source is that it has six solenoid coils for producing a mirror magnetic field. Using this configuration, one can produce the so-called "flat B_{min}" [4] and "classical B_{min}."

Figure 1a) shows the beam intensity of U^{35+} as a function of the injected RF power, which was calculated using the increase in the cooling water temperature of the plasma chamber. For the production of neutral U atoms, we used the sputtering method [3]. The extracted voltage was maintained at 22 kV in this experiment. Closed circles are the results with the magnetic field strength of RF injection side (B_{inj}) ~ 3.1 T, the minimum magnetic field of mirror magnetic field (B_{min}) ~ 0.66 T, magnetic field strength of the beam extraction side (B_{ext}) ~ 1.79 T, and the radial magnetic field strength on the inner wall of the plasma chamber (B_r) ~ 1.88 T, whereas open circles are the results with B_{inj} ~ 3.1 T, B_{min} ~ 0.56 T, B_{ext} ~ 1.76 T, and B_r ~ 1.88 T. In this case, we added 18 GHz microwaves (400–450 W, double frequency injection). The typical gas pressure with B_{min} ~ 0.66 T was $\sim 7.6\times10^{-5}$ Pa, and the optimum gas pressure for maximizing the beam intensity slightly increased as the injected RF power increased. Additionally, we observed that the beam stability improved with the use of double frequency injection, which is the same as the result in Ref. [5]. The beam intensity linearly increased as the injected RF power increased for both cases. The beam intensity with a lower B_{min} (~0.56 T) is slightly lower than that with a higher B_{min} (~0.66 T).

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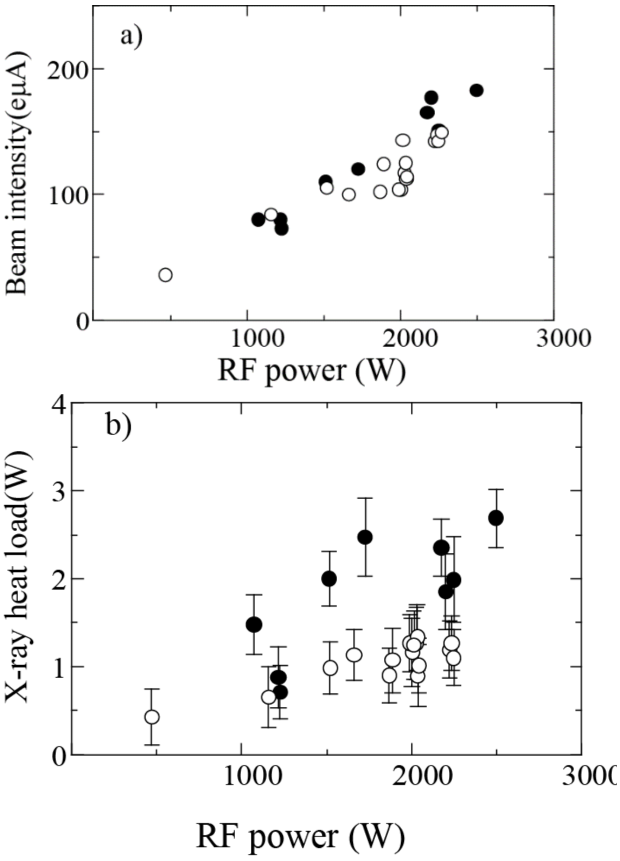

Figure 1: a) Beam intensity of U^{35+} ions as a function of the injected RF power. Open and closed circles are the results with B_{min} ~ 0.66 and 0.56 T, respectively. b) X-ray heat load as a function of the injected RF power. Open and closed circles are the results with B_{min} ~ 0.66 and 0.56 T, respectively.

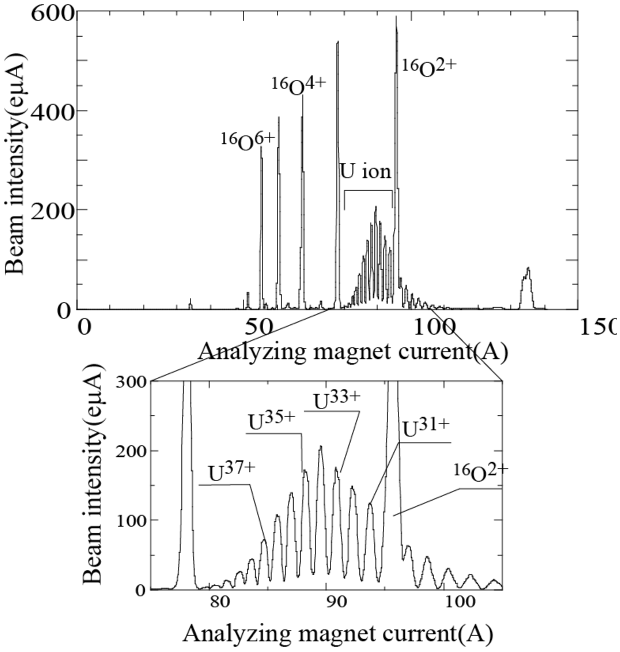

Figure 2: Charge state distribution of the highly charged U ion beam at an RF power of ~2.6 kW.

Figure 1b) shows the X-ray heat load as a function of the injected RF power under the same conditions in Fig. 1a). The closed and open circles are the results with B_{min} ~ 0.66 T and 0.56 T, respectively. The heat load for B_{min} ~ 0.56 T is significantly lower than that for B_{min} ~ 0.66 T, which is mainly due to the magnetic field gradient in the ECR zone. The average field gradient with B_{min} ~ 0.66 T is estimated to be ~2000 G/cm, which is less than that (~2400 G/cm) with B_{min} ~ 0.56 T. Generally, the energy transfer from the microwaves to the electrons in the ECR zone is inversely proportional to the magnetic field gradient. Therefore, high-energy electrons are easily produced with the lower field gradient. In this case, high-energy X rays were produced and easily penetrate the chamber walls and the wall of the cryostat. Consequently, there is an additional heat load on the cryostat of the SC-magnet owing to these X-rays emitted from the plasma.

Figure 2 shows the typical charge distribution of the highly charged U ion beam. B_{inj}, B_{min}, B_{ext}, and B_r were 3.1, 0.62, 1.78, and 1.87 T, respectively, and the RF power was ~2.6 kW.

Figure 3 shows the normalized rms emittance as a function of the focusing solenoid coil current. The beam intensity was fixed to approximately 100 eμA. In this experiment, only the focusing solenoid coil current was varied without any changes in the other parameters. The normalized X emittance dramatically decreased from 0.25 to 0.1 π mm mrad1 as the solenoid coil current increased. On the other hand, the Y emittance was almost constant. It is thought that the aberration of the analyzing magnet in the X direction (horizontal) is greater than that in the Y direction (perpendicular). Further, the beam size in the analyzing magnet becomes smaller as the magnetic convergence increases. For this reason, it may be concluded that the large X emittance with a lower focusing solenoid coil current is mainly due to the aberration of the analyzing magnet. As described in Ref. [6], the aberration of the analyzing magnet strongly affects the emittance size; that is, a larger aberration results in a larger emittance. To reduce the emittance size, we have to reduce the size of the beam using the focusing solenoid coil.

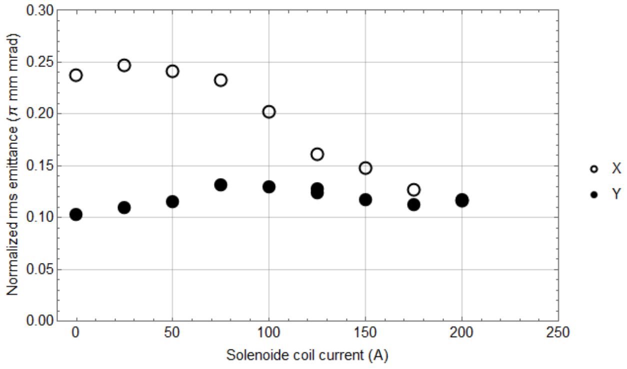

Figure 3: Normalized rms emittances as a function of the focusing solenoid coil current.

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LONG-TERM OPERATION

Figures 4a) and b) show the extraction current of the ion source and the beam intensity of U^{35+} ions, respectively. The extracted current is quite stable, as shown in Fig. 5a), and the average beam intensity of U^{35+} was ~102 eμA over a long period of time. Under this condition, a maximum beam intensity of ~49 pnA was successfully extracted from the superconducting ring cyclotron for the RIBF experiment conducted last autumn [7].

For long-term operation, it is important to minimize the material consumption rate. To obtain the consumption rate, we operated the ion source with the same sputtering voltage for approximately one month. In 2012, we produced an intense beam of U^{35+} with a sputtering voltage of approximately –5 kV. In this experiment, we observed that the consumption rate of the material is higher than that in the oven method [6]. To minimize the consumption rate while maintaining the beam intensity, we systematically studied the consumption rate for several sputtering voltages. At a sputtering voltage of –1 kV, the consumption rate was ~2.1 mg/h for the production of approximately 100 eμA of U^{35+} ions, which is a significantly lower consumption rate than that at approximately –5 kV [3].

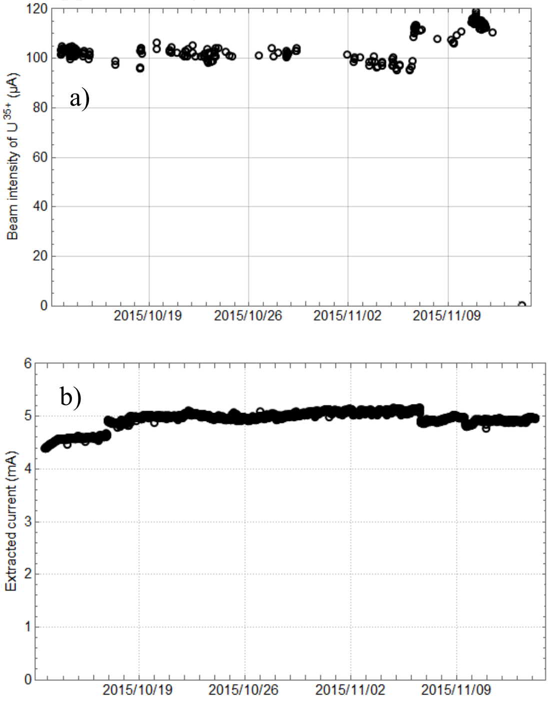

Figure 4: (a) Beam intensity of U^{35+} ions and(b) the extracted current as a function of time.

OVEN DEVELOPMENTS

When comparing the oven and sputtering methods, the oven method has several advantages, including the following:

1. We do not need to supply a high voltage to produce neutral atoms. Generally, the application of a high voltage between the plasma and metallic U increases the disturbance in the plasma. Consequently, the beam intensity may become unstable.
2. We can control the U vapor independently.

However, the oven method also has disadvantages, as described previously. In particular, we can only supply a small amount of the sample (UO_2) using the crucible (~1 g) [7]. Therefore, in this case, we have to minimize the consumption rate. In the last several years, we have attempted to maximize the beam intensity and minimize the consumption rate. In 2013, we successfully produced ~100 eμA of U^{35+} ions with a low consumption rate (~3 mg/h). However, the RIKEN RIBF experiments require the production of a beam for longer than one month without any breaks. To meet this requirement, we fabricated a crucible with a larger volume that can contain ~3 g of UO_2 and tested it this summer. Figure 5 shows the typical charge state distribution of the highly charged U ions. For the two-week experiment, we did not have any troubles and obtained a very stable beam. The consumption rate was ~2.5 mg/h for producing ~120 eμA of U^{35+} ions. Using it, we may produce a beam for longer than 1000 h, which meets the requirement.

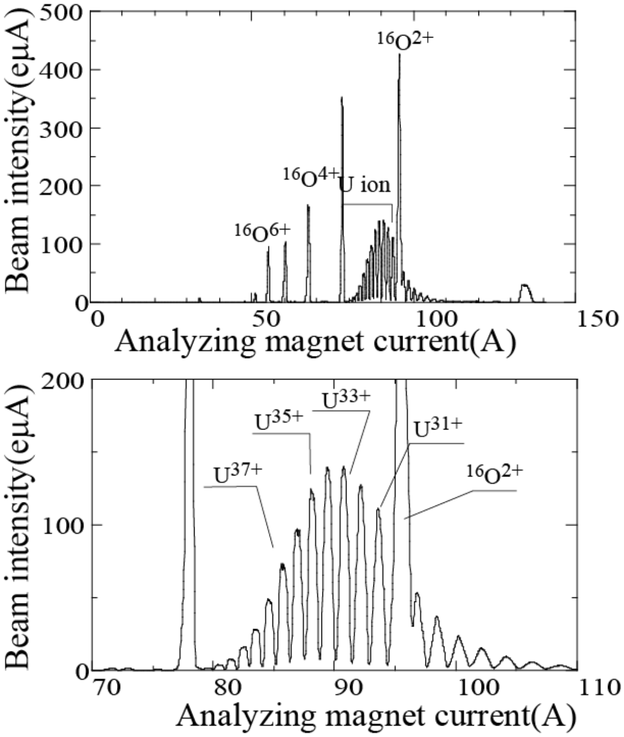

Figure 5: Charge distribution of the highly charged U ion beam.

ZINC ION BEAM PRODUCTION

For the production of Zn vapor, we used a low-temperature oven [8], which is same type as that used for 18 GHz ECRIS in RIKEN. In the test experiment, we used He gas as a support gas and ^{nat}ZnO as a sample. Figure 6 shows the typical charge distribution of the highly charged Zn ions. The injected RF power was ~1.6 kW (28 GHz + 18 GHz). B_{inj}, B_{min}, B_{ext}, and B_r were 3.1, 0.62, 1.78, and 1.94 T, respectively, and the typical gas pressure was $6.5–7.5\times10^{-5}$ Pa. The average beam intensity was ~26 eμA of $^{64}Zn^{19+}$

ions, which is the required charge state of the Zn ions for RIBF experiments. The consumption rate of Zn was ~0.20 mg/h. If we assume the use of enriched ^{70}Zn, the beam intensity will be ~60 eμA, which is the required beam intensity. Furthermore, the consumption rate for 28 GHz SC-ECRIS was almost same as that for 18 GHz ECRIS.

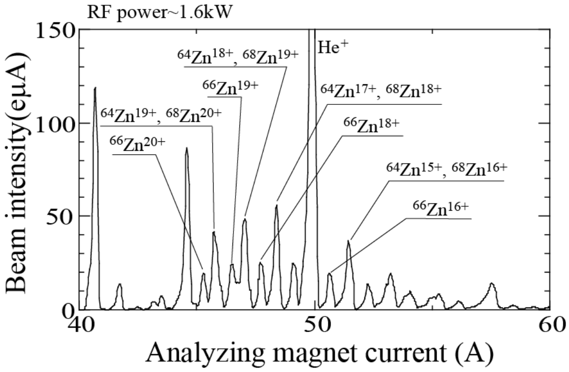

Figure 6: Charge distribution of the highly charged Zn ion beam.

CONCLUSIONS AND PLANS FOR FUTURE WORK

We produced 200 eμA of U^{35+} ions at an RF power of ~2.6 kW. We observed that the beam intensity becomes stable using double frequency injection (28 and 18 GHz). For long-term operation (approximately one month), we successfully produced a stable beam of over 100 eμA without any breaks using the sputtering method and did not observe any serious damage to the components of the accelerator. This summer, we attempted to produce a Zn ion beam with a low-temperature oven and produced ~30 eμA of $^{64}Zn^{19+}$ ions using ^{nat}ZnO in the first trial, which is the required charge state for RIBF experiments. It is estimated that the beam intensity is ~60 eμA for the ^{70}Zn ion beam when using 100% enriched ^{70}Zn. This is the required beam intensity for the ^{70}Zn ion beam from the ion source. The consumption rate was ~0.20 mg/h, which is sufficiently low for long-term operation. This autumn, we plan to produce a stable beam of U^{35+} higher than 100 eμA for long-term operation using the oven. For the production of the ^{70}Zn beam, optimization of the magnetic field, RF power, etc. will be carried out to maximize the beam intensity with a low consumption rate.

REFERENCES

[1] Y. Yano, *Nucl. Instrum. Methods Phys. Res. Sec*. B 261, 1009 (2007).

[2] T. Nakagawa *et al.*, *Rev. Sci. Instrum.* 81, 02A320 (2010).

[3] Y. Higurashi, J. Ohnishi, K. Ozeki, M. Kidera, and T. Nakagawa, *Rev. Sci. Instrum*. 85, 02A953 (2014).

[4] G. D. Alton and D. N. Smithe, *Rev. Sci. Instrum*. 65, 775 (1994).

[5] Z. Q. Xie, *Rev. Sci. Instrum*. 69, 625 (1998).

[6] O. Kamigaito *et al.*, in *Proc. IPAC2016*, paper TUPMR022 (2016).

[7] J. Ohnishi, Y. Higurashi, and T. Nakagawa, *Rev. Sci. Instrum*. 87, 02A709 (2016).

[8] K. Ozeki, Y. Higurashi, M. Kidera, and T. Nakagawa, in *Proc. HIAT2015*, paper WEPB22 (2015).

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