STATUS OF THE RIKEN 28-GHZ SC-ECRIS

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Abstract

Ever since we obtained the first beam from RIKEN 28-GHz SC-ECRIS in 2009, we have been trying to increase the beam intensity using various methods. Recently, we observed that the use of Al chamber strongly enhances the beam intensity of a highly charged U ion beam. Using this method, we obtained ~180 eμA of U^{35+} and ~230 eμA of U^{33+} at an injected RF power of ~4 kW by the sputtering method. The advantage of this method is that a large amount of the material can be introduced into the plasma chamber; therefore, long-term beam production without a break is possible. In fact, we already produced intense U beams in the RI Beam Factory (RIBF) experiments for over a month without a break. For the long-term operation, we observed that the consumption rate of the U metal is ~5 mg/h. In this spring, we also produced a U beam using a high-temperature oven through two-frequency injection. In these test experiments, we observed that the beam intensity of the highly charged U ions is strongly enhanced. In this contribution, we report the results of the various test experiments on the production of highly charged U ion beams. We also report the analysis of the long-term production of U ion beams in RIKEN RIBF experiments.

INTRODUCTION

Ever since we obtained the first beam in a RIKEN RIBF project, we have been trying to increase the beam intensity of the heavy ions to achieve our final objective of 1 pμA for all target heavy ion beams [1]. Intense uranium (U) ion beam is a strong tool to produce radio isotope beams through in-flight fission reaction. For this reason, we constructed and developed a new superconducting ECR ion source at an operational frequency of 28 GHz for the production of heavy ion beams including U ions [2]. In 2011, we successfully injected 28-GHz microwaves into the ion source and produced highly charged Xe ion beams [3]. Simultaneously, we tried to produce highly charged U ion beams by the sputtering method. In 2012, we replaced the stainless steel chamber (SS chamber) with an aluminum chamber (Al chamber)). Using the Al chamber, we observed the strong enhancement of the U ion beam intensity in comparison to that using the SS chamber.

In this paper, we present the recent results of the production of highly charged U ions and analysis of the long-term operation in the RIKEN RIBF experiment.

DESIGN OF THE ION SOURCE

The detailed structure and first experimental results using 28-GHz microwaves are described in [2, 3]. The main feature of the ion source is that it consists of six solenoid coils to produce a mirror magnetic field, which produces flexible magnetic field distribution from classical B_{min} to “flat B_{min}” [4]. Using this configuration, we can independently change the magnetic field gradient and surface size of the ECR zone. Recently, we installed an additional GM-JT refrigerator, which has a cooling power of 4.2 W at 4.2 K, in order to increase the cooling power. At present, there are two GM-JT refrigerators available to cool the cryostat. Figure 1 shows the cooling power of the two refrigerators vs. aperture size of the JT valve. The cooling power is strongly dependent on the aperture size, which was optimized to maximize the cooling power. A maximum cooling power of ~7.4 W was obtained using a tow GM-JT refrigerator. Under this condition, the cooling power is ~8 W against the X-ray heat load in the cryostat.

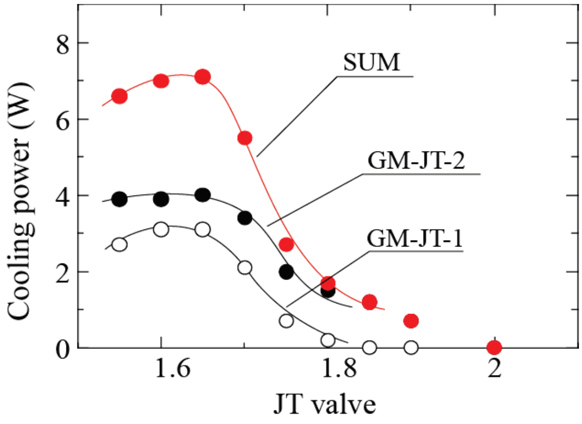

Figure 1: Cooling power of the GM-JT refrigerators vs. aperture of the JT valve.

With regard to the external ion source of the heavy ion accelerator, the production of stable beams is a critical issue, particularly for the RIKEN RIBF project. In 2011, we modified the power supply of the gyrotron to stabilize the beam intensity [5]. We observed large power ripples in the output microwaves, which render some difficulties in the operation of the ion source at an RF power lower than 1 kW. These ripples can be reduced by increasing the electric capacitance in the rectified circuit of the cathode power supply. We also observed long-wave irregularity of the beam intensity, which is correlated with the RF power. This is mainly because of the irregularity in the temperature in the room where the power supply to the

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solenoid coils of the gyrotron is installed. Fluctuation in the room temperature slightly affects the output current of the power supply to the solenoid coils. Consequently, the magnetic field strength of the gyrotron is slightly varied, which affects the output power of the gyrotron. We replaced the existing power supply with a more stable one in order to minimize this effect. After these modifications, the RF power was stabilized to within ~7% of the total power in 1-month operation

EXPERIMENTAL RESULTS AND DISCUSSION

Enhancing the Beam Intensity of the Highly Charged U Ions by the Sputtering Method

In 2011, we observed ~60 eμA of U^{35+} at an RF power of 2 kW (28 GHz) using an SS chamber [3]. In 2012, we installed an Al chamber. For comparison, we chose the same magnetic distribution as that using the SS chamber. (B_{inj} = 3.2 T, B_{min} = 0.65 T, B_{ext} = 1.8 T, and B_r = 1.85 T). The detailed experimental conditions are described in [3, 6]. The extraction voltage is 22 kV. For producing neutral U atoms, we used the sputtering method. The typical high voltage for sputtering is ~-5.5 kV. The position of the rod was remotely controlled to maximize the beam intensity. For producing plasma, we used oxygen gas as an ionized gas. At an RF power of 2 kW, we obtained ~110e μA of U^{35+}, which was almost two times as high as that obtained using the SS chamber (~60 eμA).

Figure 2 shows the beam intensity of the highly charged U ion beams at an RF power of 3~4 kW using the Al chamber. The typical beam intensities for $U^{33+}$and U^{35+} are 230 and 180 eμA, respectively. The beam intensity is strongly dependent on the consumption rate of the metal U when using the sputtering method. The beam intensity of U^{33+} ions increased from 190 to 230 eμA with increasing the consumption rate from 7 to 10 mg/h and it was not saturated at highest consumption rate. It can be suggested that higher beam intensity can be obtained at a higher consumption rate at the same RF power.

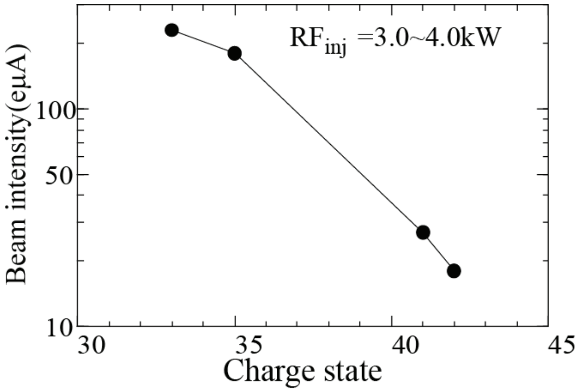

Figure 2: Beam intensity of the highly charged U ion beams at an RF power of 3~4 kW using the Al chamber.

One of the requirements for the ion source in the RIKEN RIBF project is intense beam production for a long period (1 month) without a break. For meeting this requirement, a low consumption rate is essential for the production of U ion beams. For the production of 180 eμA of U^{35+}, the consumption rate is ~9 mg/h. We installed ~20 gr of metal U rod in the plasma chamber. Under the present condition, it is possible to produce intense U ion beams (~180 eμA of U^{35+}) for three months without break.

In 2013, we supplied U^{35+} ion beams for the RIBF experiments. Figure 3 shows the beam intensity (average beam intensity of ~90 eμA) as a function of time. The injected RF power is ~1.5 kW. The magnetic field distribution is same as that in the test experiment, which was described previously. The sputtering voltage is -5.5 kV. The rod position was adjusted to maximize the beam intensity. We successfully produced intense U^{35+} beams for over a month without a break. The average consumption rate of the metal U rod is ~5 mg/h.

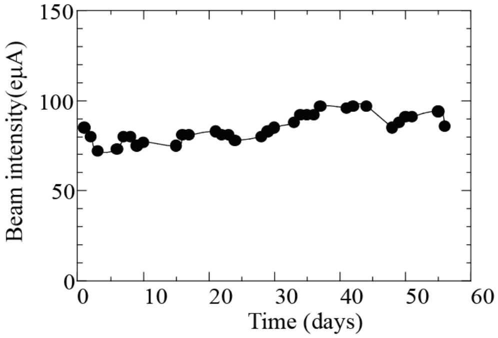

Figure 3: Beam intensity of the U^{35+} ions supplied for the RIBF experiments as a function of time.

The emitted bremsstrahlung x-rays from the plasma in the ion source add a substantial heat load to the ion source cryostat. A heat load of 6 W was observed at a microwave power of 6 kW with the 28-GHz microwaves for high-performance SC-ECRIS at LBL (VENUS) [7]. When using small refrigerators for regenerating the liquid He in the liquid He vessel, the maximum cooling power is limited by several watts at 4 K. In this case, the beam intensity is limited by the heat load. For increasing the beam intensity, the condition to obtain higher beam intensity with a lower heat load is required to be determined. For this purpose, we measured the beam intensity of the highly charged heavy ions. We measured the beam intensity and X-ray heat load in cryostat under two different condisitons(dB/dL = 1942 G/cm, S_{ecr} = 699 cm^2; and dB/dL = 2403 G/cm, S_{ecr} = 833 cm^2), where dB/dL and S_{ecr} are the average magnetic field gradient and surface size, respectively, of the ECR. The beam intensities of the U^{35+} ions are ~70 eμA for both the cases; however, the x-ray heat load (~0.5 W) in the cryostat for a steeper field gradient and a lager zone size is lower than that (~1.2 W) for a gentler field gradient and a smaller zone size. This is mainly because of the high production rate of the high energetic x-rays from the plasma at a gentler field gradient. This is one of the methods to decrease the x-ray heat load in the cryostat while maintaining the beam intensity.

Emittance Measurement of the Highly Charged U Ion Beam

Figure 4 shows the normalized RMS emittance of the highly charged U ion beams. Red and blue circles are the results with 18- and 28-GHz microwaves when using the SS chamber. Closed circles are the results with 28-GHz microwaves when using the Al chamber. We obtained almost the same emittance under all the three conditions.

In the case of the ECR ion source, the main contribution for the emittance increase is the magnetic field. In this case, the emittance is written as $\varepsilon \propto B_0(Q/M)$, where B_0, Q, and M are the magnetic field strength at the beam extraction side, charges state, and mass of the ions, respectively [7]. As shown in this formula, the emittance is proportional to the magnetic field strength at the beam extraction side. The magnetic field strength at 18 and 28 GHz are 1.2 and 1.8 T, respectively. When the emittance is proportional to the magnetic field, it is expected that the emittance at 28 GHz is 1.5 times as high as that at 18 GHz. Furthermore, the emittance decreases with increasing charge state, which is for a contradiction to the model calculation. Similar results were previously obtained with different ECR ion sources [8]. In this experiment, the emittance of U^{35+} is ~0.06π mm mrad, which is smaller than the acceptance of the accelerator.

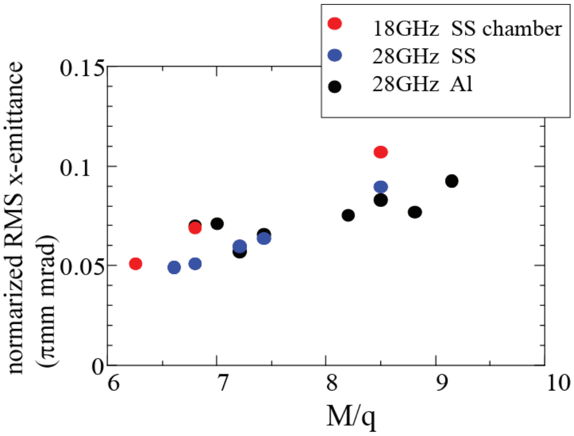

Figure 4: Normalized RMS emittance for highly charged U ion beams. Red and blue circles denote the results with 18- and 28-GHz microwaves when using the SS chamber. Closed circles denote the results with 28-GHz microwaves when using the Al chamber.

CONCLUSIONS

We produced intense highly charged U ion beams by using the sputtering method. The beam intensity was strongly enhanced by using an Al chamber instead of an SS chamber. Till date, we have obtained 230 eμA of U^{33+}, 180eμA of U^{35+} and 17eμA of U^{42+} at the an RF power of 3~4 kW. We successfully produced ~90 eμA of U^{35+} ion beams in the RIKEN RIBF experiment for over a month without a break. We also measured the emittance of the U beam. The emittance of U^{35+} is ~0.06π mm mrad, which is smaller than the acceptance of the RIBF accelerator.

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