Development of ECR ion sources at RIKEN

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The electron cyclotron resonance ion source (ECRIS) is one of the best choices for the RI Beam Factory (RIBF) project[1)] for the production of radioisotope beams using projectile-like fragmentation and for super-heavy element search experiments.[2)] Since the first beam was produced with the RIKEN 10 GHz ECRIS,[3)] we have continuously improved the performance of the existing ECRIS and constructed new ECRISs to produce intense beams of highly charged heavy ions to meet the requirements of the RIKEN accelerator facility. For these purposes, we have constructed three types of high-performance ECRISs (18 GHz ECRIS, Liquid-He-free SC-ECRIS, and 28 GHz SC-ECRIS) in the last three decades. In particular, we have attempted to produce intense beams of heavy ions, such as uranium (U) ions for the RIKEN RIBF project 1) and super-heavy element search experiment 2) since the early 2000s. Figure 1 shows the time evolution of the beam intensity of highly charged heavy ions produced at RIKEN. In the last three decades, the beam intensity has been dramatically increased, as shown in the figure. For example, the beam intensity of Ar^{8+} has been increased from $\sim$100 μA to 2 mA. For heavier ions, the intensity of the U^{35+} ion beam increased from a few μA to $\sim$180 μA in the last 10 years.

The 18 GHz ECRIS,[4)] which consists of two room-temperature solenoid coils and a hexapole permanent magnet to confine the plasma for producing mainly medium-charge-state heavy ions such as Ar^{8+} and Xe^{20+} and works as an external ion source of the RIKEN linear accelerator (RILAC), was constructed in 1995 and produces intense beams of various heavy ions ($\sim$2 mA of Ar^{8+}, $\sim$200 μA of Xe^{20+}). To increase the variety of ion species, we adopted the various methods[5,6)] to produce intense beams of metallic ions. In the early 2000s, intense beams of highly charged Zn ions were required to perform a new super-heavy element ($Z = 113$) search experiment. To meet the requirement, we adopted the insertion method and successfully produced an intense beam of highly charged Zn ions ($\sim$2 pμA) for a long term (longer than one month) without a break.

Liquid-He-free SC-ECRIS[7)] has a unique feature in that it uses a small refrigerator to achieve the superconductivity of the magnet without using liquid He. It produces a high mirror magnetic field (maximum magnetic field of $\sim$3 T) with low electric power consumption. It is suitable for producing higher charge states of heavy ions. For this reason, it is used as an external ion source of the AVF cyclotron, which only accepts higher-charge-state heavy ions ($A/q < 4$) for acceleration.

A fully superconducting ECRIS with 28 GHz microwaves[8)] was constructed in 2007. The RIKEN SC-ECRIS can be operated at flexible axial field distributions from the so-called classical $B_{\rm min}$ to flat $B_{\rm min}$.[9)] In 2013, U^{35+} ion beams of $\sim$180 μA were produced at an injected RF power of several kW for a short-term test experiment using the sputtering method.[10)] It produced a U^{35+} beam of $\sim$120 μA for the RIKEN RIBF experiment with a high-temperature oven.[11)] Figure 2 shows a schematic of the ion source. Figure 3 shows the charge-state distribution of the highly charged U ion beam when tuning the ion source to produce U^{35+} ions.

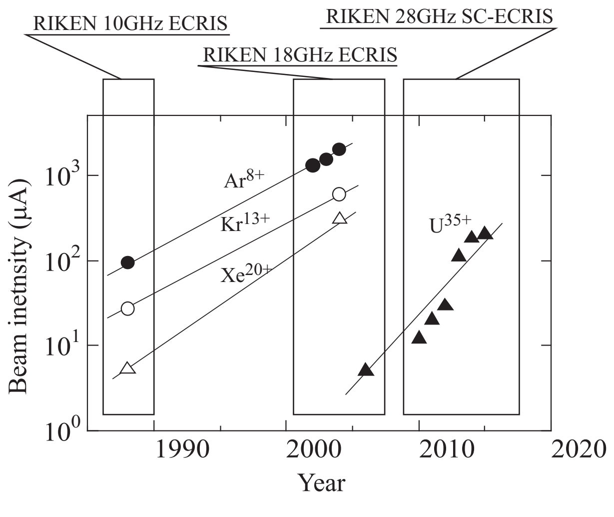

Fig. 1. Time evolution of the beam intensity of highly charged heavy ions produced at RIKEN ECRISs.

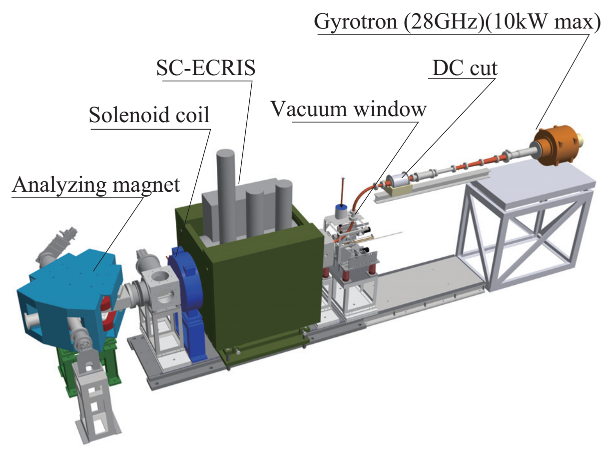

Fig. 2. Schematic drawing of the RIKEN 28 GHz SC-ECRIS.

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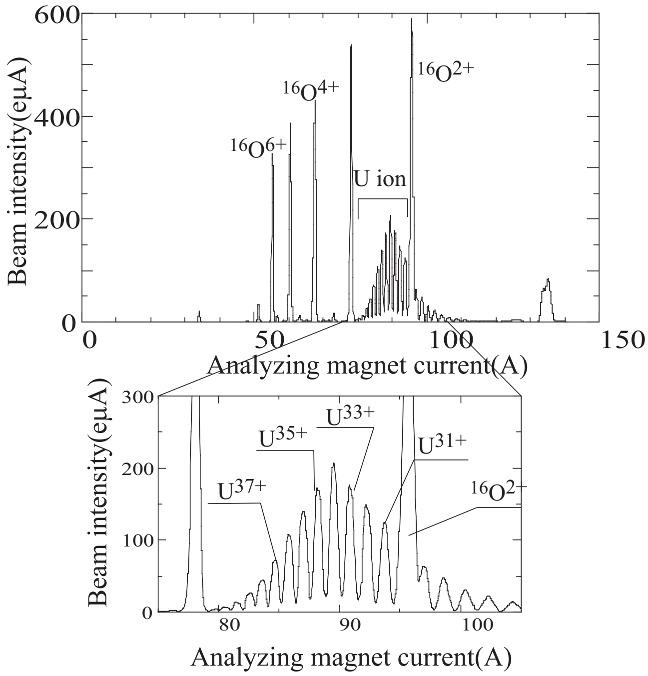

Fig. 3. Charge-state distribution of the U ion beam. The ion source was tuned to produce the U^{35+} ion beam.

For the new super-heavy element ($Z = 119$) search experiment, an intense beam of highly charged V ion beams was required. We therefore attempted to produce a highly charged V ion beam using the RIKEN 28 GHz SC-ECRIS and produced a $V^{12+,\ 13+}$ ion beam of a few hundred μA for a short-term test experiment; its intensity is almost ten times higher than that of the Zn ion beam.

References

1) Y. Yano, Nucl. Instrum. Methods Phys. Res. B **261**, 1009 (2007).
2) K. Morita et al., Nucl. Phys. A **944**, 30 (2015).
3) K. Hatanaka et al., RIKEN Accel. Prog. Rep. **22**, 219 (1988).
4) T. Nakagawa et al., Nucl. Instrum. Methods Phys. Res. B **226**, 392 (2004).
5) T. Nakagawa et al., Nucl. Instrum. Methods Phys. Res. A **396**, 9 (1997).
6) K. Ozeki et al., Rev. Sci. Instrum. **86**, 016114 (2015).
7) T. Kurita et al., Nucl. Instrum. Methods Phys. Res. B **192**, 429 (2002).
8) T. Nakagawa et al., Rev. Sci. Instrum. **81**, 02A320 (2010).
9) G. Alton, D. N. Smithe, Rev. Sci. Instrum. **65**, 775 (1994).
10) Y. Higurashi et al., Rev. Sci. Instrum. **85**, 02A953 (2014).
11) J. Ohnishi et al., Rev. Sci. Instrum. **87**, 02A709(2016).