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DEVELOPMENT OF RIKEN 28 GHz SC-ECRIS FOR PRODUCTION OF INTENSE METAL ION BEAM

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Abstract

To produce intense metal ion beams (e.g., Ti^{13+}, $V^{12+,13+}$, Cr^{13+}) for synthesizing new super heavy elements (Z=119,120) at RIKEN, we tried to optimize the performance of RIKEN 28 GHz SC-ECRIS. Based on the "scaling law" and the "high B mode" operation, we systematically measured the beam intensity of various heavy ions as a function of B_{inj}, B_{r} and B_{ext} with 28 and 18 GHz micro-waves. We observed that B_{ext} is dependent on the charge state of heavy ions as predicted by the "scaling law". Using these systematics, we obtained ~400 eμA of V^{13+} at the mi-crowave power of 2 kW (28 GHz) and B_{ext} of ~1.4 T with 28 GHz. For long term operation, we produced very stable beam of 100-200 eμA of V^{13+} ion. Following this, we con-structed new 28 GHz SC-ECRIS for new elements synthe-sis.

INTRODUCTION

At RIKEN, we planned to synthesize new elements, which have atomic number higher than 118, after the experiments for synthesizing the super-heavy element (atomic number of 113).[1] For this purpose, production of intense and stable highly charged metallic ion beams, such as $V^{12+,13+}$ ions, is required. Therefore, we conducted test experiments to produce these beams and studied the opti-mum structure of the ion source to increase the beam in-tensity and, especially, the effect of magnetic mirror ratio on plasma confinement, for several years. It is well-known that the "scaling law" [2,3] and the "high B mode" opera-tion [4-6] provide some of the important guidelines to op-timize the magnetic mirror ratio of ion sources for produc-tion of various charge states of heavy ions. Model calcula-tion based on the Fokker-Planck equation also shows the same tendency as the "scaling law". [7,8]

As a first step to improve the ion source performance for production of these metallic ion beams, we also conducted a systematic study to optimize the magnetic mirror ratio using the RIKEN 28 GHz SC-ECRIS and the liquid-He-free SC-ECRIS on the bases of these laws. Using the results of the systematic study, we attempted to produce intense metallic ion beams last year.

In addition, to further expand this project, new superconducting RF cavities are now under construction in the downstream of RIKEN heavy-ion linac (RILAC) to increase the beam energy. [9] In this project, we also planned to construct a new 28 GHz SC-ECRIS. Based on the experimental results, we completed the design and the construction last year. The ion source, the low energy beam transport line and first results for the ion source have been reported in ref. [10]. In this contribution, we present in de-tail the results of the systematic study and production of highly charged V ion beam.

SYSTEMATIC STUDY

In the test experiments, we used two different types of ion sources, Liquid-He-free SC-ECRIS [11] and RIKEN 28 GHz SC-ECRIS [12]. The main feature of the RIKEN 28 GHz SC-ECRIS is that it has six solenoid coils to pro-duce a flexible mirror magnetic field in the axial direction and can produce both "classical" and "flat" B_{min}. [13,14]

In the middle of 1980s, the "scaling law" was proposed for describing the effect of the main ion source parameters (microwave power, magnetic field strength, microwave frequency, mass of heavy ions, etc.) on the output beam of highly charged heavy ions. In these papers [2,3], it was reported that the strength of the magnetic mirror affects the optimum charge state, i.e., a higher mirror ratio yields higher charge states of the output ion beam.

It is obvious that the maximum magnetic mirror field at the microwave injection side (B_{inj}), the maximum magnetic mirror field at the beam extraction side (B_{ext}), and the radial magnetic field (B_{r}) work as parts of the magnetic mirror to confine the plasma. In the middle of 1990s, the "high-B" mode that employs a high magnetic mirror ratio to confine the plasma was proposed to increase the beam intensities of highly charged heavy ions. This principle was adopted by many laboratories in the design of their ECR ion sources. Intense beam of highly charged heavy ions was successfully produced using this method.

In this section, the experimental results (effect of B_{inj}, B_{r} and B_{ext} on the beam intensity of highly charged heavy ions), which were obtained on the bases of these laws, are presented.

B_{inj} and B_r Effect

Figure 1 a) and b) show the two-dimensional contour plots (B_{r} vs. B_{ext} and B_{inj} vs. B_{ext}) for the beam intensity of Xe^{22+} produced with RIKEN 28 GHz SC-ECRIS. In these figures, red and blue colors indicate the highest and lowest beam intensity, respectively. In this study, we used the 18 GHz microwave instead of 28 GHz. The minimum strength of the mirror magnetic field (B_{min}) was set to ~0.5 T. The extraction voltage and the microwave power were 21 kV and ~500 W, respectively. The gas pressure and biased disc condition (negative voltage and position) were slightly changed to maximize the beam intensity at the measurement points.

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As shown in the figures, the beam intensity increases with increasing both B_r (or B_{inj}) and B_{ext} and becomes maximum at certain values of these parameters. The values of B_r and B_{ext} to maximize the beam intensity were ~1.5 and ~1.2 T, respectively (Fig. 1 a)). The corresponding B_{inj} and B_{ext} values were ~2.2 and ~1.2 T, respectively (Fig. 1 b)). As mentioned in ref. [6] (High B mode operation), B_{ext}~ B_r~$2.0B_{ecr}$ and B_{inj}~$4B_{ecr}$. Therefore, we obtain B_{inj}/B_{ext}~2.0 and B_r/B_{ext}~1.0, which is almost the same as the results obtained in the test experiments (B_r/B_{ext}~1.2 and B_{inj}/B_{ext}~1.8).

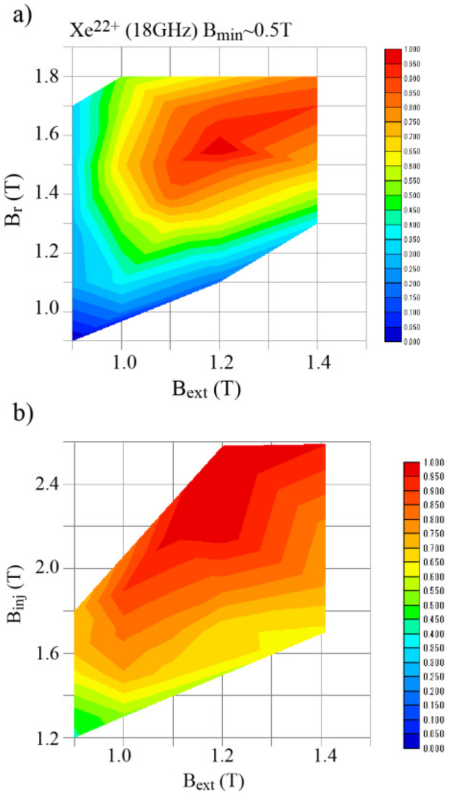

Fig. 1. Two-dimensional contour plot of the beam intensity of Xe^{22+} ion: a) Br vs. B_{ext} and b) B_{inj} vs. B_{ext}.

To study the relation between B_{ext} and B_{inj} (or B_r) in more detail, we measured and plotted the beam intensities for various charge states of heavy ions as a function of B_{inj}/B_{ext} and B_r/B_{ext}. Figure 2 a) and b) show the normalized beam intensities as a function of B_{inj}/B_{ext} and B_r/B_{ext} with RIKEN 28 GHz ECRIS (18 and 28 GHz microwaves) and Liquid-He-free SC-ECRIS (18 GHz microwave). In Fig. 2, it appears that the beam intensity of various charge state heavy ions produced with our ECR ion sources are saturated at B_r=1–1.2B_{ext} and B_{inj}=1.6–2.0B_{ext}. The tendency for the results of RIKEN 28 GHz SC-ECRIS looks similar to that for liquid-He free SC-ECRIS. These results are well-reproduced in the "High B mode" operation (B_{inj}/B_{ext}~2.0, B_r/B_{ext}~1.0).

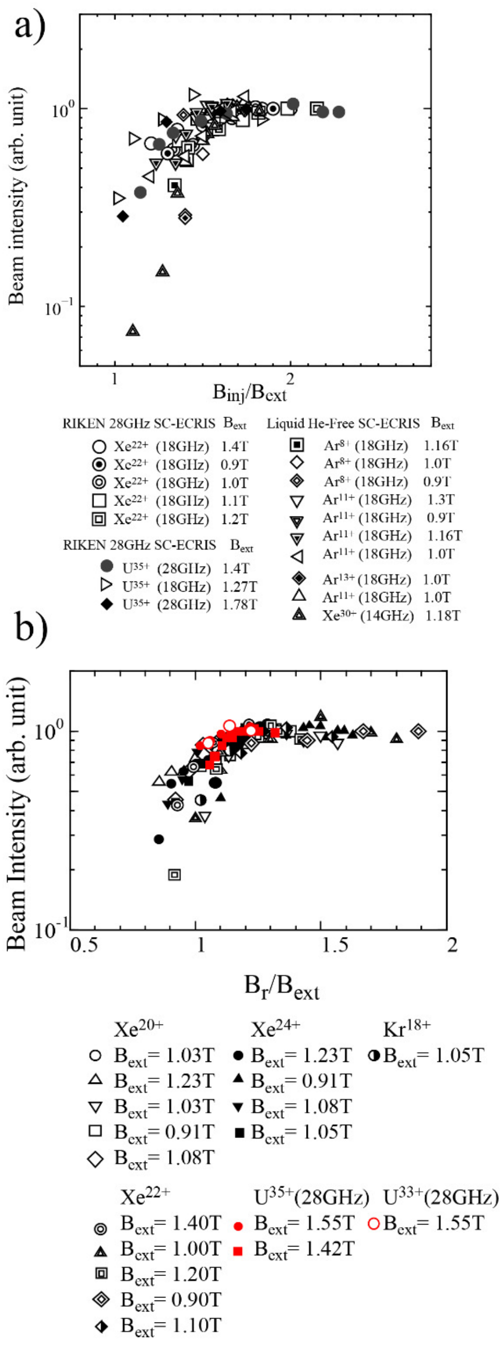

Fig. 2. Beam intensity of highly charged heavy ions as a function of B_{inj}/B_{ext} (a) and B_r/B_{ext} (b).

B_{ext} Effect

To investigate the effect of B_{ext} on the beam intensity, we measured the beam intensity under various combinations of B_r (or B_{inj}) and B_{ext}. Figures 3 a) – c) show the two-dimensional contour plots of the beam intensity (B_r vs. B_{ext}) for highly charged Xe ions. Similar to Fig. 1, the beam intensity increases with increasing B_r and B_{ext} and becomes maximum at certain values of these parameters. As shown in these figures, the beam intensity gradually changed in the highest beam intensity region; therefore, it is difficult to determine B_{ext} for maximizing the beam intensity accurately. As a reference, we choose the B_{ext} value, which yields ~95% of the maximum intensity, as the optimum B_{ext}. The optimum B_{ext} for Xe^{27+} is higher than that for Xe^{22+} with 18 GHz microwave. It is also shown that the optimum B_{ext} becomes higher with higher frequency (28 GHz). In this experiment, we choose B_{min} as ~0.5 T for 18 GHz and as ~0.63 T for 28 GHz.

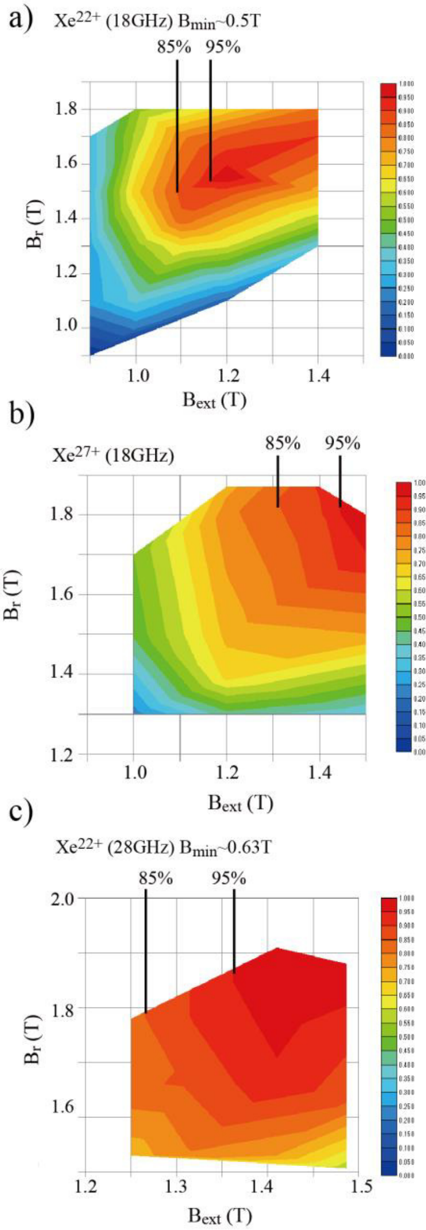

Fig. 3. Two-dimensional contour plot of the beam intensity (B_r vs. B_{ext}): a) Xe^{22+} ion with 18 GHz, b) Xe^{27+} ion with 18 GHz, and c) Xe^{22+} ion with 28 GHz.

Using the same procedures as that for Fig. 3, we measured the optimum B_{ext} for various charge states of Ar and Xe ions with 18 and 28 GHz. Figure 4 shows the optimum B_{ext} for RIKEN 28 GHz SC-ECRIS with 18 GHz microwave as a function of the charge state of Xe ions. The optimum B_{ext} increases from 1.2 to 1.6 T with increasing the charge state from 22 to 30. We observed the same tendency for the highly charged Ar ions with the liquid-He-free SC-ECRIS. The optimum B_{ext} increases from ~1.1 to ~1.25 T with increasing the charge state from 8 to 13.

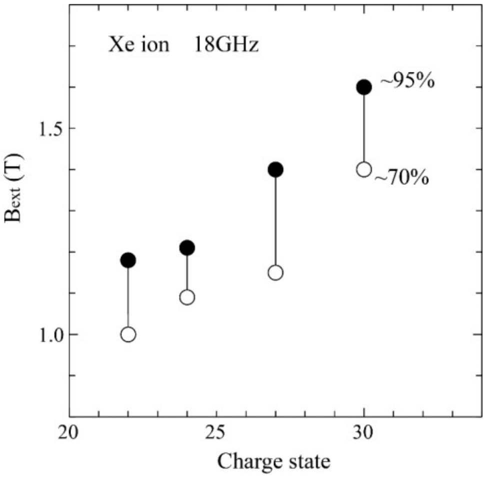

Fig. 4. Optimum B_{ext} for the highly charged Xe ions. Open and closed circles indicate the B_{ext} value, which yields 70 and 95% of the maximum beam intensity, respectively.

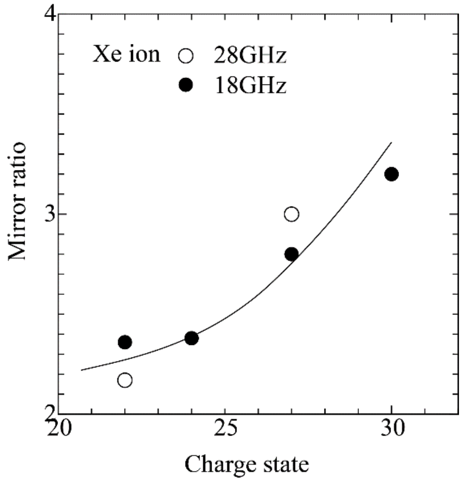

Fig. 5 Optimum mirror ratio (B_{ext}/B_{min}) for highly charged Xe ions as a function of charge state.

As described in ref. [2, 3], the optimum charge state is dependent on the mirror ratio, when B_{min} is fixed. Therefore, we plotted the experimental results of Xe for 18 and 28 GHz microwave (Fig. 5) and Ar ions (Fig. 6) as a function of the charge state. The mirror ratio increases with increasing the charge state. In Fig. 5, the open and closed circles are the results obtained for 28 and 18 GHz microwave, respectively. The mirror ratio increases from ~2.2 to ~3.2 for both 18 and 28 GHz microwaves with increasing the charge state from 22 to 30. Figure 6 shows the results for Ar ions produced with liquid He-free SC-ECRIS. We also observed that the optimum mirror ratio increases with increasing the charge state. These results can be qualitatively reproduced with the "scaling law" [2, 3].

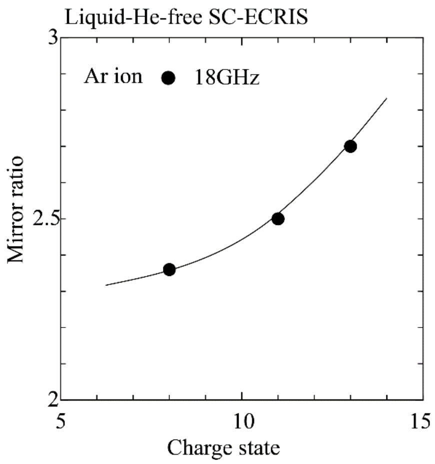

Fig. 6. Optimum mirror ratio ($B_{\mathrm{ext}}/B_{\mathrm{min}}$) as a function of charge state of Ar ions.

However, these experimental results were obtained for a low microwave power density (below several 100 W/L). At a higher RF power (~1 kW/L), we may observe different tendency.

VANADIUM ION BEAM PRODUCTION

We tried to produce intense beam of highly charged vanadium (V) ions on the bases of the results described in the previous section. For production of the V vapor, we used the high-temperature oven [15]. For long-term operation, we fabricated a new crucible, which has almost two times larger volume than the old one [16]. To obtain sufficient temperature for evaporating the materials, detailed simulation was carefully performed and sufficiently high temperature was obtained to produce the vapor. The detailed results are presented in ref. [15]

As described in refs. [2,3,17], the optimum charge state of the heavy ions is strongly dependent on the electron density (n_e), ion confinement time (τ_i) and electron temperature. For these results described in refs, [2,3,17], it is assumed that V^{13+} ion is in the same region of Xe^{24-27+} ions. As described in ref. [18,19], $n_e \tau_i$ is dependent on the mirror ratio. The magnetic mirror ratio ($B_{\mathrm{ext}}/B_{\mathrm{min}}$) for 18 and 28 GHz microwaves is assumed to be 2.2–2.7 from the results described in the previous section and these papers. If we choose B_{min} ~0.6 T for 28 GHz, the optimum B_{ext} might be 1.3–1.6 T for V^{13+}. Figure 7 shows the beam intensity (upper figure) and X-ray heat load (lower one) as a function of B_{ext}. The extraction voltage was 12.6 kV. Oxygen gas was used to produce plasma. The beam intensity was slightly changed from B_{ext}~1.6 to ~1.4 T.

Figure 8 shows the typical charge state distribution of highly charged V ion beam at a microwave power of ~2 kW(18+28GHz). The ion source was tuned to produce V^{13+} ion beam. Figure 9 shows the beam intensity and X-ray heat load as a function of microwave power for B_{ext}~1.4 T. We used the double frequencies (18GHz (several 100 W)+ 28GHz) injection [20] for obtaining the stable beam. Both the beam intensity and heat load increase with increasing microwave power. At 2 kW, the X-ray heat load was ~1.2 W, which is sufficiently low for safe operation of our ion source. The oven power was tuned to maximize the beam intensity at each microwave power. Generally, to maximize the beam intensity, the oven power increased with increasing microwave power. At the microwave power of 2 kW, we need almost 1 kW of the oven heating power. For lower microwave power (~1.2 kW), lower oven power was sufficient to maximize the beam intensity; in this case, the consumption rate of the material was ~2.4 mg/h, which is sufficiently low to operate the ion source for long term.

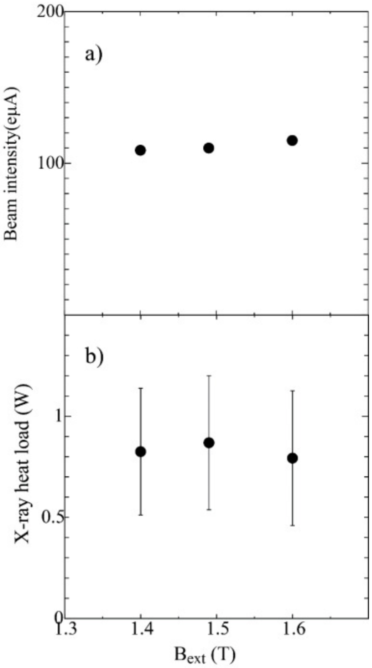

Fig. 7 a) Beam intensity of V^{13+} as a function of B_{ext}. b) X-ray heat load as a function of B_{ext}.

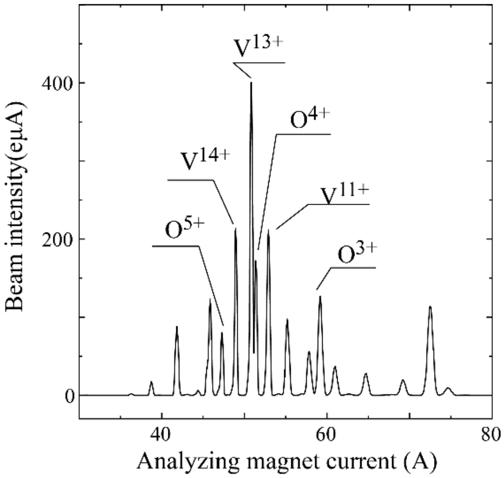

Fig. 8. Charge state distribution of the highly charged V ions.

For long-term operation, we successfully produced an intense beam (100–200 eμA) of V^{13+}. However, we still need to achieve improvement of the high-temperature oven performance at higher material consumption for long-term operation, as described in ref. [16].

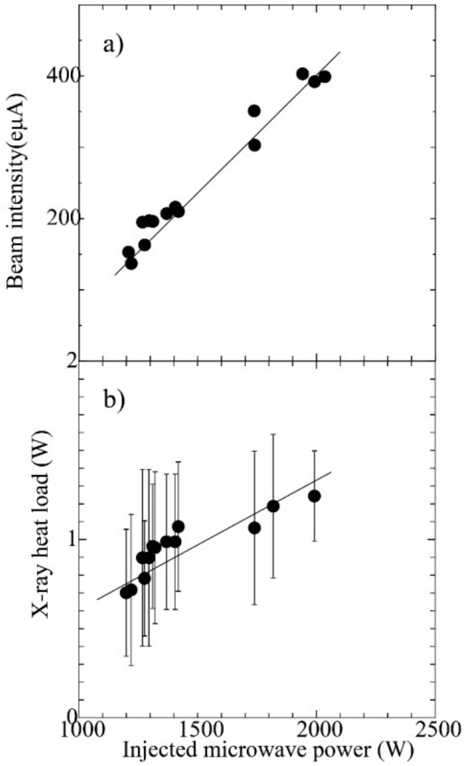

Fig. 9 a) Beam intensity of V^{13+} as a function of microwave power. b) X-ray heat load in the cryostat as a function of microwave power.

CONCLUSION

We systematically studied the effect of the magnetic mirror ratio on the beam intensity of various charge state heavy ions with 18 and 28 GHz microwave. The beam intensity was saturated at B_{inj}=1.6–2.0B_{ext} and B_r=1–1.2B_{ext}, which is the same tendency as in the “high B mode” operation. The optimum B_{ext} to maximize the beam intensity is dependent on the charge state of heavy ion. It can be qualitatively reproduced by the “scaling law”. We produced intense V^{13+} ion beam on the bases of the systematic study. We obtained ~400 eμA of V^{13+} ion beam with microwave power of ~2 kW and B_{ext}~1.4 T. For long-term operation, we produced 100-200 eμA of V^{13+} ion with the new high-temperature oven.

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