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HIGH-INTENSITY VANADIUM-BEAM PRODUCTION TO SEARCH FOR A NEW SUPER-HEAVY ELEMENT WITH *Z* = 119

T. Nagatomo†, Y. Higurashi, J. Ohnishi, H. Nakagawa, O. Kamigaito,
RIKEN Nishina Center, Wako, Japan

Abstract

We have begun synthesizing a new super-heavy element (SHE) with an atomic number, *Z*, of 119 using a very powerful vanadium-beam (V-beam) to overcome the very small production cross section. We investigated the correlation of the V-beam intensity, the total power of 18- and 28-GHz microwaves, and the consumption rate of metallic V powder that was proportional to the amount of the vapor in the plasma chamber. Consequently, we obtained approximately 600 eμA at a microwave power of 2.9 kW and a consumption rate of 24 mg/h. In addition, we found that the position of the crucible used as an evaporator of the V sample and the strength of the mirror field at the extraction side B_{ext} from 1.34 to 1.51 T did not have a significant effect on the beam intensity.

INTRODUCTION

A new project for the synthesis of new super-heavy elements (n-SHEs) with an atomic number greater than 118 has been conducted at RIKEN heavy-ion linear accelerator RILAC [1] since 2016. As the first step of this project, we attempt to produce an SHE with *Z* = 119, through the nuclear reaction between a vanadium-beam (V-beam) and a curium target. In order to achieve a higher acceleration energy than previously possible, we have installed ten superconducting acceleration cavities that were newly developed to generate a gap voltage of more than 2 MV [2,3] despite the spatial constraints in the existing facility. The cryosorption of the cavity surface, which is cooled by liquid helium, cannot be ignored, because the particulate matter adsorbed on the surface increases the surface resistance, which in turn reduces the acceleration voltage. In order to minimize the generation of the particulate matter due to the ion beam sputtering on the beam duct, we efficiently controlled the transverse emittance of the beam by the "slit triplet" in the LEBT [4]. After the first beam acceleration test this year [5], we successfully accelerated argon- and vanadium-ion (V-ion) beams with a 4 rms emittance of approximately 80 π mm*mrad ($\beta = v/c \sim 0.3\%$). However, the emittance limitation using the slit triplet reduces the beam intensity by approximately 1/3 compared to that of the beam separated by the analyzing the magnet, and it is desirable to obtain the highest intensity beam possible. Furthermore, it is not easy to increase the "brightness" of the beam extracted from the electron cyclotron resonance ion source (ECRIS). In addition, the synthesis of SHE requires a long experimental period that lasts approximately one month without interruption. Therefore, we focused on the effects of V vapor and microwave power on the beam intensity and investigated the optimal parameters that would allow long-term experiments with the highest possible beam intensity.

EXPERIMENTAL

Experiments were performed using the two superconducting ECRISs at RIKEN Nihina center, both of which have essentially the same ion-source structure [6,7]. One superconducting ECRIS is used as the ion source for RILAC, renamed as RIKEN 28-GHz SCECRIS "*KURENAI*" (R28G-K) [4], and the other for the RIKEN Radioactive Isotope Beam Factory (RIBF) [8], renamed as RIKEN 28-GHz SCECRIS "*SUI*" (R28G-S) [6,7]. The main feature of both of the ion sources is their ability to generate the mirror field with "classical" or "flat" B_{min} [9] using six superconducting solenoids and a superconducting hexapole magnet. The 18- and 28-GHz microwaves, which were used for the ECR plasma heating, were generated by a 1.5-kW klystron power amplifier and a 10-kW gyrotron system, respectively. The microwave power was estimated from the temperature rise and flow rate of the cooling water flowing through three channels in the plasma chamber wall.

The V vapor was produced by a high-temperature oven HTO heated by Joule heating using high-power direct currents [10]. The amount of vapor was proportional to the consumption rate of the solid V sample, which was measured as a function of the heating power of the HTO. The HTO crucible can be operated up to ~2,000 K using a high current DC power supply. The crucible had a double structure, namely, a thin tungsten crucible containing a second crucible made of yttrium oxide. The yttrium-oxide crucible contained 2.2 g of granular metallic V sample and suspends the chemical reaction between the sample and the crucible. In the present study, we modified the injection flange in order to use two HTO crucibles (three crucibles at maximum) at the same time, as shown in Fig. 1. Both of the crucibles were placed at positions where the plasma could not reach in order to avoid the additional heat inflow from the plasma. This straightforward modification doubled the amount of the stable V vapor supply. In order to observe the dependence of the beam intensity on the position of the HTO crucible, we compared the optimized $^{51}V^{13+}$-beam intensities obtained using HTO 1 and 2 crucibles individually.

The intensity of the $^{51}V^{13+}$-ion beam was measured by a Faraday cup located near the focal point of the analyzing magnet as a function of the total microwave power and consumption rate. The extraction voltage was also fixed to 12.6 kV, which accelerated the V^{13+} ion to an adequate speed for the following accelerator in RIBF. For each of the experimental conditions, the maximized beam intensity was recorded by adjusting the support gas pressure and the

† nagatomo@riken.jp

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position and voltage of the biased disk. In order to avoid the admixture of the $^{16}O^{4+}$-ion beam, which is close to the mass-to-charge ratio of $^{51}V^{13+}$, we chose $^{14}N_2$ gas as a support gas, which stabilized the ECR plasma.

In addition, the mirror field at the beam extraction region B_{ext} was changed from 1.31 to 1.51 T in order to observe the effect on the beam intensity.

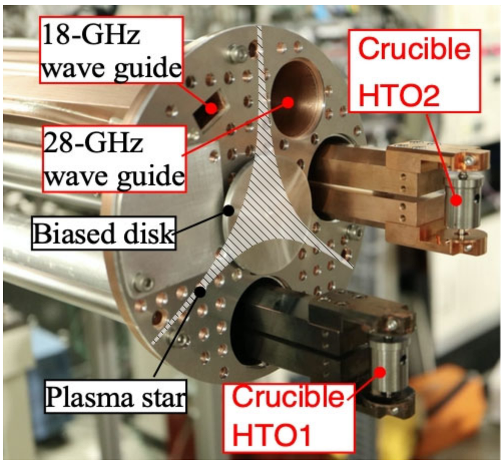

Figure 1: Two HTO crucibles, HTO1 and HTO2, stuck into the plasma chamber. The biased disk was located at the center of the flange and was movable along the axis of the ion source. The rectangular and circular outlets were the ends of the 18- and 28-GHz microwave guides, respectively.

RESULTS AND DISCUSSIONS

Figure 2 shows obtained contour plots of the optimized V^{13+}-beam intensity as a function of the consumption rate and the total microwave power by individually using differently positioned HTO 1 and 2 in Fig. 1 using R28G-K. The mirror fields B_{inj}, B_{min}, B_{ext}, and B_r were fixed as 2.3, 0.48, 1.4, and 1.47 T, respectively. As shown in Fig. 2, the beam intensity increases with increasing consumption rate and microwave power. For example, the beam intensity of 260 eμA was obtained at a consumption rate of 6.6 mg/h and a microwave power of 1.5 kW for HTO 1. For HTO 2, we obtained almost the same beam intensity of 262 eμA under the same conditions. Comparing the contour lines in the panels of Fig. 2, the beam intensity appears to be independent of the oven position.

Using the two crucibles of HTO 1 and 2 simultaneously, we could extend the contour plot to a higher consumption rate region, as shown in Fig. 3 using R28G-S. The mirror fields B_{inj}, B_{min}, B_{ext}, and B_r were 2.3, 0.48, 1.4, and 1.47 T, respectively, and were almost the same as those for the case of Fig. 2. Due to the double ovens, the total amount of the V sample increased to 4.4 g. Thus, for a month of uninterrupted beam supply, the consumption rate should be limited to approximately 6 mg/h. According to Fig. 3, an approximately 400-eμA (30-particle-μA) V^{13+} beam is available for the long-term experiment with microwaves of approximately 2.5 kW.

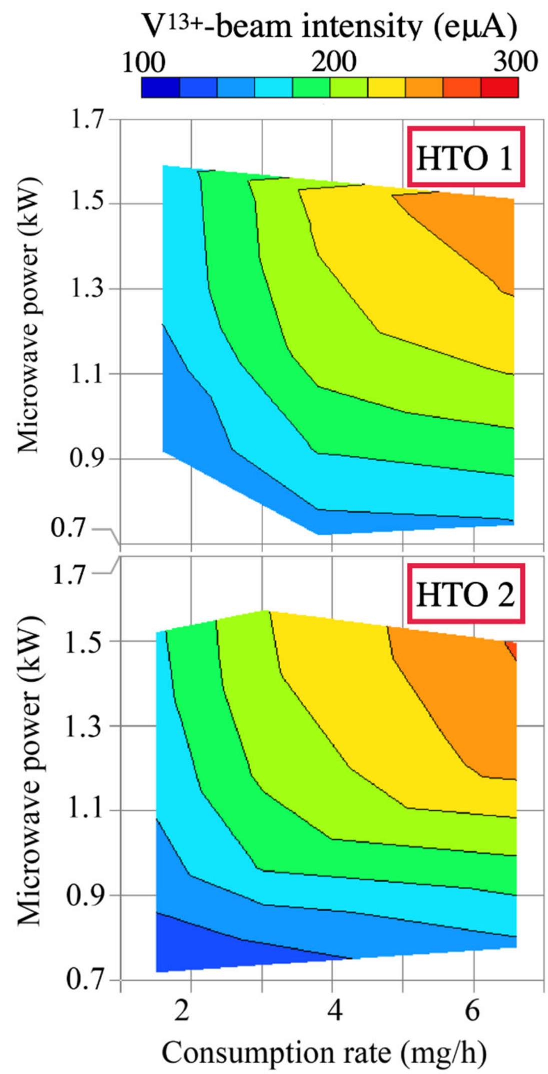

Figure 2: Obtained contour plots of the $^{51}V^{13+}$-beam intensity as a function of the total power of the 18- and 28-GHz microwaves and consumption rate of the V sample using HTO 1(top) and HTO 2 (bottom).

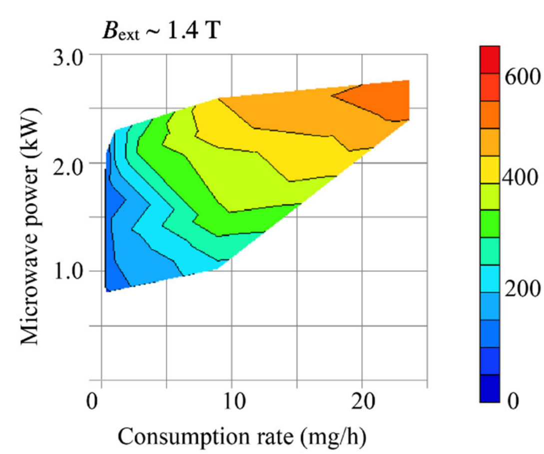

Figure 3: Expanded contour plot of the 51V13+-beam intensity using both HTO 1 and 2 crucibles.

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Furthermore, from Fig. 3, the intensity appears not to be saturated yet and increases as the microwave power and the consumption rate increase. By increasing the microwave power and consumption rate to 2.9 kW and 24 mg/h, respectively, we obtained a V^{13+} beam with a very high intensity of 600 eμA, as shown in a mass-to-charge-ratio spectrum in Fig. 4. Such a high-intensity beam, which lasts approximately one week, is also essential for the development of the production targets that require high-intensity exposure.

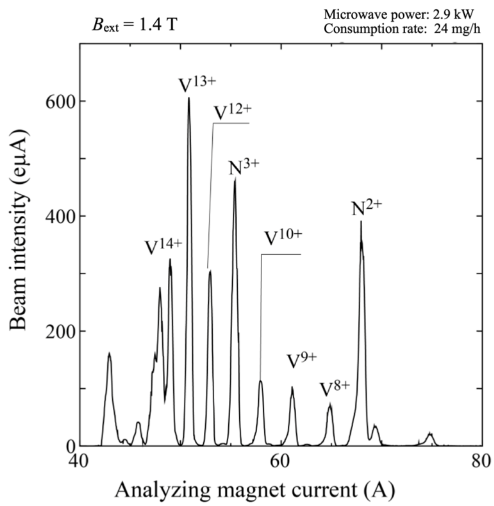

Figure 4: A mass-to-charge-ratio spectrum was obtained with a total microwave power of 2.9 kW and a consumption rate of 24 μg/h

Figure 5 shows the beam intensity of V^{13+} as a function of microwave power for different magnetic field strengths using R28G-K. The consumption rate was fixed to be 6.5 mg/h for all cases. The beam intensity increases linearly with increasing microwave power and is independent of the magnetic field strength for three cases of B_{ext} of 1.34, 1.41, and 1.51 T. Comparing these results, no significant effect of B_{ext} on the V^{13+}-beam intensity was observed in the experimental condition. However, it is possible that some beam quantities, such as the density distribution of the beam in the phase space, which was not observed in this measurement, may have changed by changing the B_{ext} and/or position of the crucible mentioned above. Thus, we plan to measure the ion beam distribution in the transverse phase space $\{x, x', y, y'\}$ using a pepper-pot-type emittance meter while changing B_{ext} and the position of the crucible.

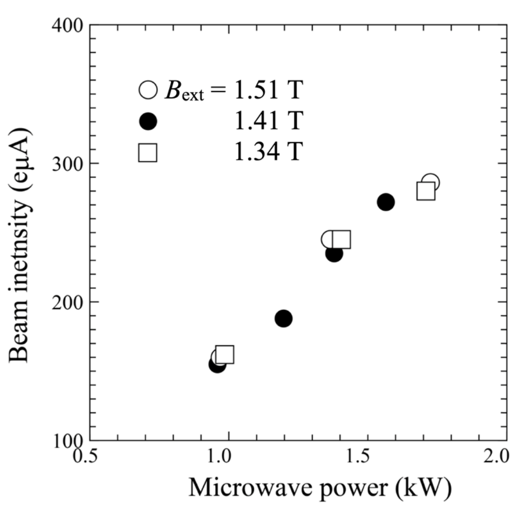

Figure 5: Beam intensity of V^{13+} as a function of microwave power for mirror fields for extraction regions B_{ext} of 1.51 T (open circles), 1.41 T (closed circles), and 1.34 T (open squares).

CONCLUSIONS

We measured the beam intensity of V^{13+} as a function of both the consumption rate of the vanadium sample and the microwave power. The optimized beam intensity was found to clearly depend on these two parameters. In the two-dimensional space of these parameters, the beam intensity is plotted as contour lines. As a consequence of the dependencies, it was found that a V^{13+}-beam with an intensity of 400 eμA can be produced at a consumption rate of approximately 6 mg/h and a microwave power of 2.5 kW. Simultaneously using both HTO crucibles allows us to execute SHE synthesis, which lasts approximately one month without interruption. Furthermore, we also obtained a V^{13+} beam with an intensity of 600 eμA at a consumption rate of 24 mg/h and a microwave power of 2.9 kW. The extra-high-intensity beam lasts for one week, and is suitable for experiments such as the essential development of the production target.

On the other hand, significant effects by changing the oven position and varying B_{ext} between 1.34 and 1.51 T on the beam intensity were not observed within the scope of the simple measurement using only a Faraday cup.

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