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PRACTICAL USE OF HIGH-TEMPERATURE OVEN FOR 28 GHz SUPERCONDUCTING ECR ION SOURCE AT RIKEN

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Abstract

To accelerate uranium beams at the RI-beam Factory (RIBF) at RIKEN, U^{35+} ions are extracted from a 28 GHz superconducting ECR ion source by using a high-temperature oven. Our high-temperature oven uses a tungsten crucible, joule-heated with a large DC current. The crucible is heated to approximately 2000°C to achieve a UO_2 vapor pressure of 0.1–1 Pa. The high-temperature oven, which is being developed since 2013, was first used to operate the ion source for the RIBF experiments in the autumn of 2016 and was successfully operated for 34 consecutive days. The use of the high-temperature oven enables the extraction of higher intensity and more stable U^{35+} beams compared to the previous sputtering method. However, due to the vapor ejection hole of the crucible getting blocked, the beam time was interrupted in the autumn of 2017. The high-temperature oven was also used to produce high intensity vanadium beams in the 28 GHz ECR ion source. V^{13+} beams with a current of 100 μA or more were supplied to the beam time for experiments on super heavy element synthesis in 2018. This paper describes the crucible design and operation status of the high-temperature oven.

INTRODUCTION

Uranium beams are most frequently used for experiments on unstable nuclei at the RI-beam Factory. U^{35+} ions extracted from a 28 GHz superconducting ECR ion source (SC-ECRIS) [1, 2] are used for the acceleration of uranium beams. The current beam intensity supplied to the accelerators is 100–130 μA at the ion source. Previously, a sputtering method with a metal uranium rod was used in the ion source, but since 2013, we have begun to develop the high-temperature oven (HTO) method [3–5] and have practically used it for the beam time (BT) of RIBF since 2016. The HTO method makes it easier to increase the amount of vapor supplied to the plasma in an ion source and is more stable than the sputtering method. Therefore, the HTO method enables the increase of the extracted beam current. The HTO is also used to produce vanadium beams in the 28 GHz SC-ECRIS. Several production tests of V^{13+} have been made since Dec. 2016. Vanadium beams were first supplied to the BT in Jan. 2018 and experiments to synthesize the super-heavy element, whose atomic number is higher than 118, were conducted.

HIGH-TEMPERATURE OVEN AND CRUCIBLE DESIGN

Figure 1 shows a schematic of the HTO. Our HTO uses a crucible of pure tungsten in which a high-melting-point material is loaded. The crucible is directly joule-heated with a DC current of 600–700 A to around 2000°C to achieve a vapor pressure of 0.1–1 Pa for uranium oxide. Figure 2 shows two shapes of a crucible (described later). The crucibles are made by machining a tungsten rod, with body and cap fitted but not fixed.

The crucible's shape is designed with ANSYS Multiphysics [6], which can perform electric, thermal, and structural analyses simultaneously. The analyses carried out were reported in Ref. [5]. The ANSYS calculations do not converge when the voltages of the upper and lower cupper blocks, given as a boundary conditions, are increased. This is because the electric current density in the upper and lower rods is too high and beyond a cooling limit. Therefore, we needed to optimize the radius of the upper and lower rods and the crucible's body thickness. Figures 2 (a) and 2 (b) show crucible shapes of the previous R345-type and the current R692-type, respectively. Since the R692-type had to be used for a long period of BT, the capacity was designed to be approximately twice as large as that of

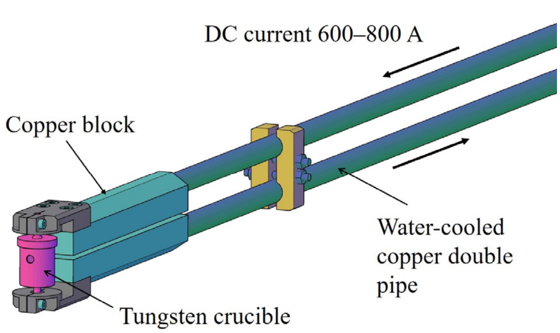
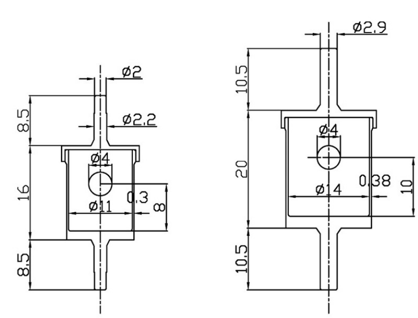


Figure 1: Schematic of the high-temperature oven.



(a) type R435 (previous) (b) type R692 (present)

Figure 2: Schematic of the tungsten crucibles.

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Table 1: Electromagnetic Force

	magnetic field	current	rod radii	electro-magnetic force	share stress	bending stress
	(T)	(A)	(mm)	(N)	(MPa)	(MPa)
LB435	3.1	507	2.2	42	11	40
LB692	3.1	679	2.9	72	11	38

R435-type. Table 1 gives the electric currents, electromagnetic forces and stresses when the two types of crucible are raised to a temperature of approximately 2000°C. Although the electric currents and the forces to which the crucibles are subjected are increased by 33%, it is found that the stresses on the upper and lower rods are almost the same. Figure 3 shows the calculated maximum temperatures of the crucible body as a function of the power of heat generation in the R692-type, and the two curves represent cases with and without a heat shield. The emissivity of the crucible and heat shield are assumed to be 0.35 and 0.15, respectively. In the heat shield case, the maximum obtained temperature was 2065°C with electric current and a power of 687 A and 893 W, respectively. In the R692-type crucible, the maximum limit of the current was around 700 A.

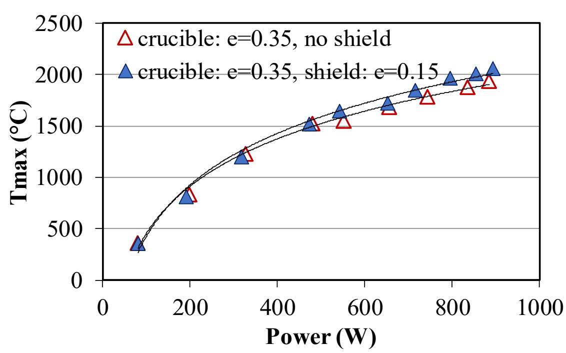


Figure 3: Maximum crucible temperatures as a function of the power of heat generation calculated with ANSYS.

ION SOURCE OPERATION USING HTO

Table 2 lists a summary of the BT, whose beams were supplied from the 28 GHz SC-ECRIS using the HTO. Ura-nium beams are accelerated to up to 345 MeV/nucleon by one linac and four cyclotrons and are supplied to the exper-iments at the RIBF. The uranium BT (U-BT) at the RIBF is executed continuously for 1–1.5 months, during which several experiments are conducted. Vanadium beams are accelerated to up to 6 MeV/nucleon by one linac and one cyclotron and used for new super-heavy element synthesis experiments. The latter experiment is also conducted for more than one month. In Table 2, where the operation time is indicated as a sum of two or three numbers a crucible was exchanged during BT.

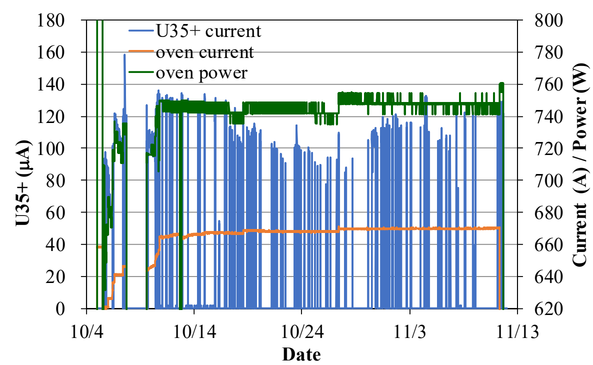
Uranium Beam Time

Figure 4(a) shows the trend of the beam current of U^{35+}, the electric current and the power of heat generation of the crucible during the U-BT in the autumn of 2016. The beam current of U^{35+} was measured with a Faraday cup posi-tioned down-stream of the analyzing magnet. The beam current can only be measured when the beams are not sup-plied to the accelerators, and changes according to the width of the slits located upstream. The power of heat gen-eration of the crucible was obtained by subtracting the Joule loss on the support pipes from the total electric power. The uranium beams were supplied to the accelerators from Oct. 10, after a few days of adjustment of the ion source. Looking at Fig. 4 (a), it is clear that the power of heat gen-eration of the crucible was almost constant for one month and that a beam current of 120 μA or more could be main-tained.

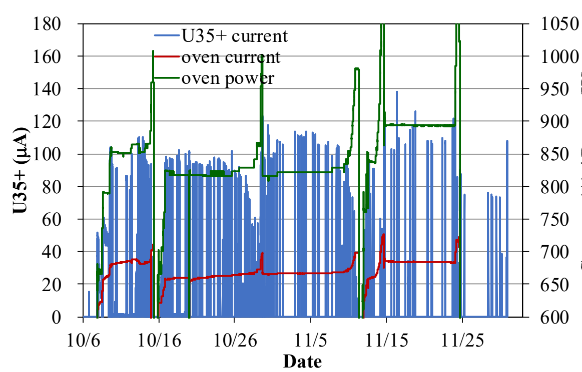
Figure 4 (b) shows the trend of the U-BT in the autumn of 2017. As can be seen from this figure, we increased the

Table 2: Summary Of Beam Time Using HTO

ion	period	beam current (μA)	operation time (d)	material	consumption rate (mg/h)	Aim
U^{35+}	10–11/2016	100–120	34	UO_2	2.4	RIBF experimen
U^{35+}	5–6/2017	60–120	35	UO_2	3.2	RIBF experimen
U^{35+}	10–11/2017	80–120	7 + 27 + 10	UO_2	4.0, 4.2, 12	RIBF experimen
V^{13+}	1–2/2018	100–210	20 + 13	metal V	2.2, 4.1	SHE serach
V^{13+}	6–7/2018	100–230	23 + 9	metal V	2.0, 3.8	SHE serach



(a)



(b)

Figure 4: Operational trend of HTO in U-BT of (a) 2016 and (b) 2017.

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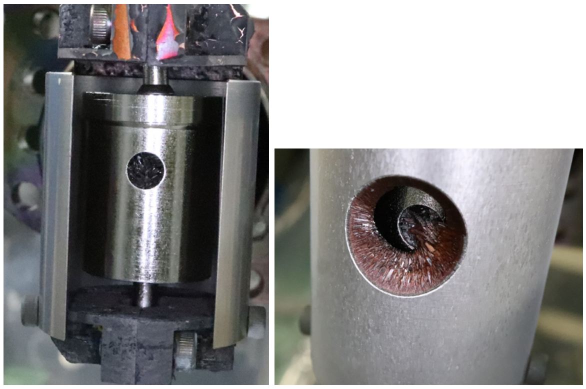


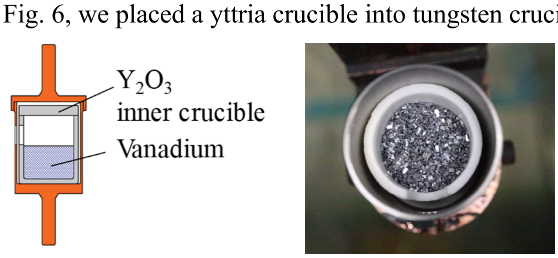
(a) Oct. 15 2017 (b) Nov. 11 2017

Figure 5: Blockage of the vaper-ejection hole of crucibles.

power of the HTO to around 1000 W five times, because the beam intensity decreased. This is because the vapor-ejection hole of the crucible was blocked. The blockage was resolved by raising the temperature of the crucible on Oct. 29 and Nov. 14. However, we had to open the ion source to exchange the crucible on Oct. 15 and Nov. 11. Moreover, we had to stop using the HTO and go back to the sputtering method after Nov. 24. Figures 5 (a) and (b) show photographs of the crucibles whose vapor-ejection holes were blocked. Figure 5 (a) is a photograph taken on Oct. 15, which shows that only the vapor-ejection hole itself was blocked within a short time, while Fig. 5 (b) is a picture taken on Nov. 11 after operation for 27 days. In the case of Fig. 5 (b), it can be assumed that UO_2 deposited on the edge of the heat shield (molybdenum), reached the va-por-ejection hole of the crucible. We later found that the heat shield shown in Fig. 5 (a), whose opening was made larger to reduce the deposition of UO_2, causes the ejection hole of the crucible to get blocked more easily. Moreover, we made a production test of U^{35+} using the HTO without a heat shield. In this test, it was found that U^{35+} beam cur-rents higher than 100 μA could be obtained by increasing the oven power to 970 W, even without a heat shield. However, after 10 days of operation, the blockage of the ejection hole occurred again.

Vanadium Beam Time

The HTO was also used to produce high intensity vanadium (V^{13+}) beams in the 28 GHz SC-ECRIS. As shown in Fig. 6, we placed a yttria crucible into tungsten crucible



(a) cross-section (b) Inside view

Figure 6: Crucibles for metal vanadium.

(R692-type) and filled it with metal vanadium (vapor pressure: 1 Pa at 1827°C). The fillable amount was approximately 2.0 g. Figure 7 shows the second half of the operational trend of the HTO in the second BT, conducted in June–July 2018. A heat shield was not used because the vapor pressure of vanadium is higher than that of UO_2. In the first half, V^{13+} was supplied at 90–120 μA. After changing the crucible on Jul. 13, the beam current was gradually increased as requested by experimenters. Figure 8 shows the relationship between vapor pressures inside the crucible, estimated from the oven power using the calculation results shown in Fig. 3, and V^{13+} beam currents during Jul. 11–20. It is found that the V^{13+} beam currents within 200 μA are proportional to the amount of vapor.

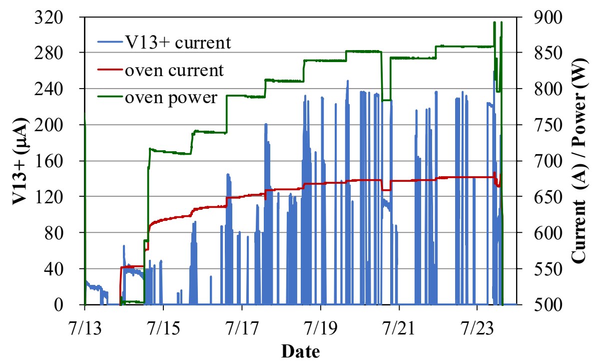


Figure 7: Operational trend of HTO in the second V-BT in 2018.

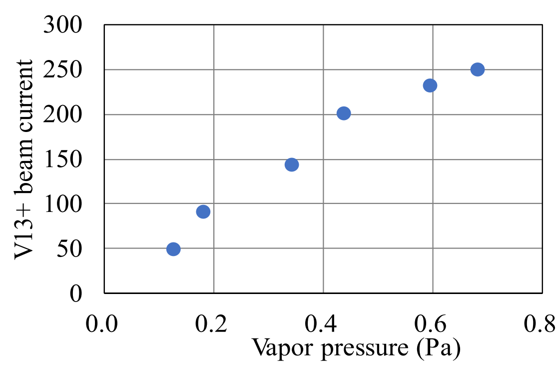


Figure 8: Relationship of vapor pressures in the crucible and beam current obtained in the V-BT during 7/11–20.

Figure 9 shows the temporal change of production efficiencies of U^{35+} and V^{13+}. The production efficiencies are obtained by dividing the number of particles, equivalent to the beam current, of U^{35+} and V^{13+} by those of the UO_2 and V vapor from the HTO, respectively. The data of V^{13+} in Sep. 2017 and U^{35+} in May 2018 are the data obtained in the pro-duction tests for approximately two weeks, and effects on the blockage of the ejection hole were removed in these efficiencies. Although the production efficiencies of

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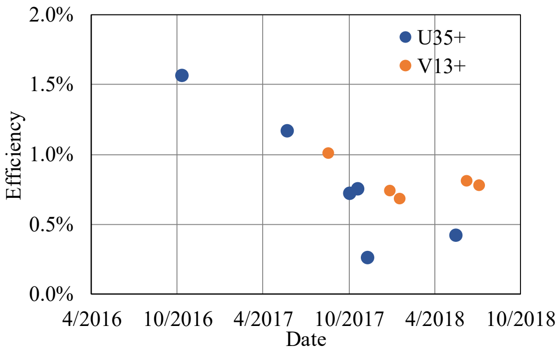

Figure 9: Production efficiencies of U^{35+} and V^{13+}.

V^{13+} do not change significantly, those of U^{35+} clearly decrease with time. Since the production tests of V^{13+} were conducted between Dec. 2016 and Mar. 2017, it is conceivable that the operation for V^{13+} production in the same ion source may be one of the causes of the decrease in the production efficiencies of U^{35+}.

OFF-LINE TEST

Tests of the HTO are performed using the off-line test stand because the 28 GHz SC-ECRIS is occupied by BT for a long time. However, since uranium is a nuclear fuel material and its use is restricted, it cannot be handled by the off-line test stand. Figure 10 shows a schematic of the off-line test stand. The test stand is equipped with a thin film deposition monitor to measure the amount of vapor. The thin film deposition monitor (INFICON) uses a crystal oscillator and is located at approximately 210 mm from the crucible. Figure 11 shows an example of the measured data during a test using vanadium. The left vertical axis dM/dt indicates an increase in the rate of mass per 1 cm^2 (deposition rate) measured by the thin film deposition monitor. The consumption rate of material in the crucible can be obtained by multiplying the measured deposition rate by 835 cm^2, which was obtained by a calibration. In these data, the consumption rate of vanadium equals to approximately 6 mg/h in an oven power of 800 W. In this measurement example, the oven power has changed in the first 30 minutes. This is presumed to be caused by a decrease in the contact resistance between body and cap of the crucible, and such unstable oven power is sometimes seen at the beginning of

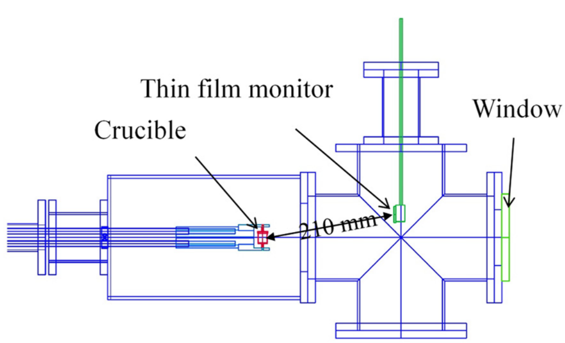

Figure 10: Schematic of the off-line test stand for HTO.

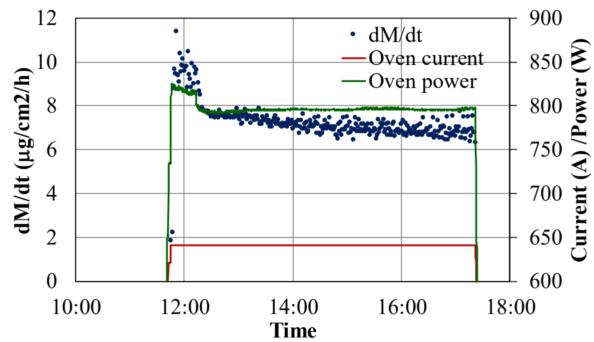

Figure 11: Example of operational trend of HTO in the off-line test stand.

excitation. Although the deposition rate, which is the average value over one minute, is scattered considerably, it is not clear whether this is a measurement problem. Figure 12 shows the deposition rates as a function of the oven power obtained for vanadium and titanium. Titanium was tested by loading metal titanium into a yttria crucible, similarly to vanadium. These results correspond to those where the temperature of metal titanium, in which a vapor pressure reaches 1 Pa, is around 1710°C, 120°C lower than that for vanadium, and show that the amount of vapor of titanium is also sufficient for operation of the ion source.

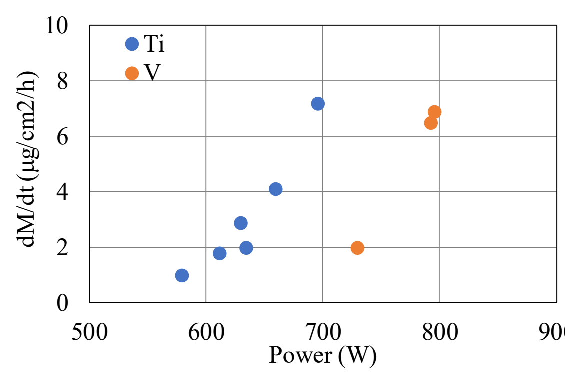

Figure 12: Deposition rate of Ti and V obtained from HTO in off-line test stand.

CONCLUSION

We produced high intensity uranium beams at the 28 GHz SC-ECRIS by using the HTO, and supplied the uranium beams to three BTs at the RIBF since autumn of 2016. In the first BT, we successfully supplied U^{35+} beams with a current of 120 μA or more, for 34 consecutive days. However, in the third BT, we had to interrupt the BT to open the ion source because the vapor-ejection hole of the crucible was blocked. Although the direct cause of the blockage of the ejection hole is not clear, it could be caused by a decrease in time of the production efficiencies of U^{35+} and an increase of the amount of vapor. The HTO could be also used for high-melting-point metals such as vanadium and titanium by placing a yttria crucible in a tungsten one. As

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a result, we successfully supplied V^{13+} beams with a current of 100–240 μA to the two BTs for the experiments of super heavy element synthesis.

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