ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOC2

A NOVEL INDUCTIVE OVEN DESIGN FOR THE PRODUCTION OF HIGH CURRENT, METAL ION BEAMS*

D. S. Todd†, J. Y. Benitez, LBNL, Berkeley, CA, USA

Abstract

Essential to the proposed search for element 120 at LBNL's 88-Inch Cyclotron is the continual delivery of over a particle microamp of ^{50}Ti for weeks-long campaigns spanning many months. The fully-superconducting ECR ion source VENUS will be the injector source for these runs, and we have developed a new inductive oven design that can survive VENUS' high magnetic fields while injecting metallic gas into the plasma with high efficiency. The new oven employs a vertical susceptor to permit use with metals that melt before outgassing sufficiently, while also allowing a rotation of the oven's material exit toward the plasma center for better conversion efficiency to the produced beam. The performance of VENUS with this oven has been outstanding. As reported here, ^{50}Ti^{12+} beams with stable currents between 1.0 and 1.5 pμA from this oven were used to produce two element 116 particles: the first time titanium beams have been used to have been used to create superheavy elements.

INTRODUCTION

Superheavy elements beyond copernicium (element 112) have been discovered by bombarding transuranic targets with high-current ^{48}Ca beams. For element 113, a plutonium target was used, and the target atomic number was increased for each successive element discovery. The short half-lives of target material with atomic number greater than californium (element 98, used to discover element 118) mean that there isn't enough material, nor would it last long enough, to serve as targets for the months-long experiments necessary for superheavy element production. A potential way to move forward is to use as projectile beams elements with higher atomic numbers for these searches .

Earlier this year (2024), researchers at LBNL announced they were able to use ^{50}Ti beams from the 88 Inch Cyclotron incident upon a plutonium target to produce two atoms of element 116 [1]. This was the first time that a titanium beam was used to produce superheavy elements, and this result opens the door to extending the periodic table by using ^{50}Ti beams on californium targets in the search for element 120.

The production and delivery of more than 1 pμA ^{50}Ti beams from the 88-Inch Cyclotron was no small feat: not because the cyclotron couldn't produce this high of currents (it has delivered over 2 pμA ^{48}Ca beams previously [2]), but because titanium beams are notoriously difficult to produce from an ion source. Titanium is highly reactive with other atoms, therefore any deposited on the walls of a plasma source producing these beams will affect plasma stability by pumping background gas in an unpredictable manner. Additionally, for sources relying on outgassing from pure titanium, sufficient partial pressures typically require heating the titanium to over 1600 °C.

Using a novel inductive oven within LBNL's superconducting electron cyclotron resonance (ECR) ion source VENUS, we were able to deliver 80–120 μA ^{50}Ti^{12+}; beams to the cyclotron with excellent stability and a relatively low material consumption rate. The inductive oven used for this work is described as are some of the difficulties overcome en route to its successful deployment.

ION SOURCE AND OVENS

Electron cyclotron resonance (ECR) ion sources produce ion beams from a magnetically confined plasma. This confinement is typically in the form of solenoids for axial confinement and a multipole (typically sextupole) for radial confinement. The superposition of these fields produces a net magnetic field magnitude whose minimum is at the source center and which grows in all directions about this center. Closed surfaces of constant magnetic field surround the source center, and by injecting microwaves with frequency that matches the electron cyclotron frequency on one or more of these surfaces, electron energies can be raised to the point that they can ionize atoms and confined ions. The ion beam species produced are determined by the material injected into the plasma, and these sources have the distinct advantage that beams can be formed from any material introduced to the plasma without destroying it. The easiest means of beam production is the injection of gas into the plasma, and a common means of producing beams from metals is to raise the temperature of the metals to the point its vapor pressure emits sufficient material quantity into the plasma.

Raising the temperature of metals is often performed through the use of ovens. The general oven has some sort of a crucible whose temperature is raised to outgassing temperatures for the material it holds, and often some sort of outlet directs that vaporized material toward the plasma. The low-temperature oven used at LBNL is an example of this, where a heater cartridge conductively heats a crucible containing the material of interest [3]. A series of channels then directs the evaporate toward the plasma. This oven has been extremely successful at efficiently delivering ^{48}Ca to the plasma, primarily as a result of the aiming channels. Consumption rates of this expensive material are typically 0.5 mg/hr. This oven is limited to low temperatures, however, reaching a practical maximum of approximately 700 °C.

Higher temperatures have been reached at LBNL and at other laboratories using resistive ovens [4, 5]. Here, a high

* This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract number DE-AC02-05CH11231 (LBNL).

† dstodd@lbl.gov

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOC2

current is run along the length of a thin walled, typically cylindrical, crucible and ohmic heating is used to reach the desired temperature. These ovens are typically operated vertically so that material may be easily contained, and this orientation allows the use of materials that melt before reaching temperatures providing sufficient partial pressures. These ovens have two real shortcomings: the vertically-run currents are nearly perpendicular to the magnetic fields at the injection end of the source where they are typically installed. For advanced superconducting sources, these fields reach 3–4 Tesla and can produce strong forces perpendicular to the axis of the oven. These forces can be particularly damaging for high temperature ovens as the chemistry that takes place between the crucible and desired material at high temperature can be corrosive and affect the oven's structural integrity. It should be noted that there have been successes with high-temperature resistive ovens in high-field sources, such as with RIKEN's production of high-current vanadium beams in their 28 GHz ECR ion source, but this required research to find an insulator to separate the hot vanadium from their resistive oven to prevent the oven damaging hot chemistry between the vandadium and the oven [6].

As titanium is particularly corrosive and resistive ovens used with it in VENUS were frequently destroyed, we opted to use inductive technology for the oven that would provide high-current ^{50}Ti beams for superheavy element research. Inductive ovens have been successfully used at China's Institute of Modern Physics in and the Facility for Rare Ion Beams in Michigan [7, 8], primarily for the production of high-current uranium beams which require bringing the uranium to temperatures exceeding 2000 °C. These ovens utilize cylindrical coils whose axes are parallel to and offset ~4 cm from the central extraction axis of the source. The susceptor holding the material of interest is coaxial with the coil and nested within an insulator that isolates the susceptor from the coil both thermally and electrically. The susceptor has a hole in the end closest to the source plasma, and it is through this that material escapes in gas form and feeds the plasma. The offset and alignment of this oven mean its output is usually not directed toward the plasma center, so it is expected that a substantial fraction of the ejected material is not ionized by the plasma and deposited on the chamber walls.

As ^{50}Ti, unlike the uranium used at the labs mentioned above, is a low-abundance, expensive isotope, efficient transfer from oven to plasma to beam is a necessity, and titanium's high reactivity means deposited material on the plasma chamber walls typically leads to source instability. For this reason we strove to produce an inductive oven whose output could be aimed at the plasma center to enhance the probability of ionization. To do so, we designed an inductive oven that uses a vertically-aligned coil. Again, the susceptor and surrounding insulator are nested within the coil, but the exit aperture in the susceptor is located in the side of the cylinder rather than the end as is the case with an horizontal oven. The hole in the susceptor is aligned with a larger hole in the surrounding insulator, and these align with a gap between two turns of the inductive coil. The direction of the hole is rotated about the vertical axis so that the output material is directed toward the center of the plasma.

To reach near VENUS' confined plasma, the oven is attached to the end of a 1.1-meter-long shaft. So that the oven may be changed or refilled rapidly, this shaft and the oven at its end must pass through a 38.1-mm- diameter port.

OVEN DESIGN

The goal of the project was to produce an oven capable of delivering >100 µA $^{50}Ti^{12+}$ continually for at least ten days straight at a time while keeping material consumption rates below 5 mg/hour as this low-abundance isotope is expensive. The scale of the inductive oven was set primarily by the fact that it had to pass through the 38.1-mm-diameter port and the idea that the typical oven has a susceptor nested within an insulator nested within the inductive coil.

The coil tubing is 3.97-mm-outer-diameter copper tubing with 0.36-mm-wall-thickness. It is wound on a 3D printed winding fixture so as to produce five full turns with minimum spacing between turns of 1 mm and a tube center radius of 12.5 mm. As shown in Fig. 1, there are two larger gaps at the front side of the oven. The upper gap allows for material to exit the oven while the lower gap serves as a support location for an insulating post that prevents the insulator and susceptor from falling through the coil. This support post is the weak point of the design as if the post breaks the hot oven would fall onto and possibly damage the plasma chamber. For this reason, an aluminum mesh structure was added that surrounds the oven to act as a catch should the insulator fail, though it has yet to do so. This cage and the oven within are outside the plasma.

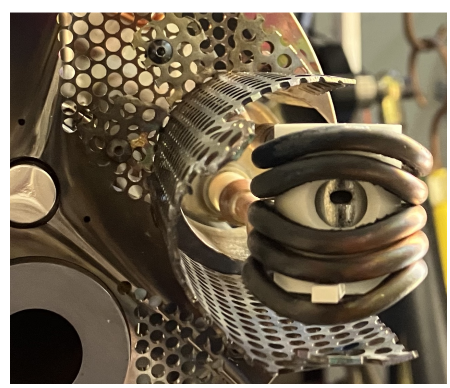

Figure 1: End-on view of the inductive oven when installed in VENUS. The perforated aluminum sheet that acts as a preventative catch should the ceramic support rod (bottom) fail surrounds the oven.

The coil is brazed onto an RF vacuum feedthrough that is welded to the 1.4-m-long shaft used to position the oven an axial distance of approximately 22 cm away from the plasma center. As the feedthroughs are at the plasma end of the shaft, the inside of the shaft is maintained at atmospheric pressure. Hollow, copper tubes run the RF and provide water

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOC2

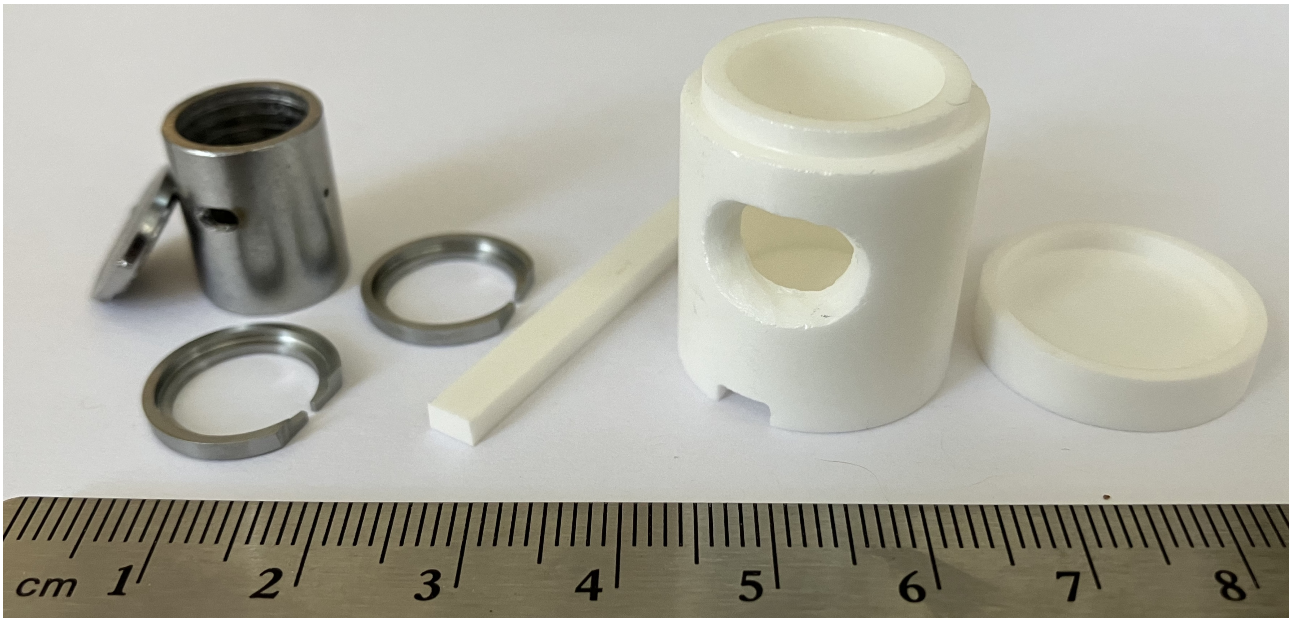

Figure 2: From left to right, the molybdenum susceptor and lid, molybdenum slotted susceptor support rings, yttriated zirconia support rod, slotted cylindrical insulator, and insulating lid.

cooling to the coil. The coil is driven by a commercially-available, 2.4 kW inductive power supply that operates in the 150-400 kHz range. The power supply is maintained at high voltage within the source cage.

The insulating post and the insulator body/lid combination are made from yttria-stabilized zirconia. The insulator thickness is 3 mm with an outer diameter of 21.8 mm. A relatively large hole is placed in one side of the insulator to allow the exit of material from the susceptor housed within it, as shown in Fig. 2. As discussed below, in the final version of the insulator a slot was added to the bottom of the insulator body in which the support post nested which ensured alignment of the insulator was maintained relative to the coil opening, as shown in Fig. 3.

The final susceptor design was a 12.7-mm-diameter, molybdenum cylinder with 1.1-mm-wall-thickness. At 200 kHz operation, this is equivalent to approximately four skin depths so that nearly all flux passing axially through the center is countered by eddy currents in the susceptor body. The susceptor height is 16.5 mm and provides a total capacity of approximately 0.75 cm^3. More typically the susceptor is filled to below the 2.0-mm-tall, 3.8-mm-wide material exit opening in the side, located 9.4 mm from the bottom of the cylinder. This leaves a fill volume of approximately 0.44 cm^3, equivalent to about 2 grams of titanium: enough for ~16 days operation at 5 mg/hour consumption.

The susceptor is thermally isolated from the insulator by molybdenum stand-off rings, shown in the exploded view of Fig. 4. The rings have been machined with angles that keep point-like contact with both the susceptor and the insulator to prevent heat transfer between the two, and the rings maintain a 1-mm-gap between the susceptor and the insulator.

Figure 3: Inductive oven viewed from below. The support post rests on the bottom turn of the coil and a slot in the insulator prevents rotation of the insulator relative to the coils.

RESULTS

The inductive oven has been found to stably produce $^{50}Ti^{12+}$ beams of ~90–120 µA for multiple days without intervention, and did so for the 22 days of running with the cyclotron that led to the production of two elements of 116. During these runs the beam current extracted from the cyclotron was between 1-1.5 pµA, and titanium consumption rates were typically in the range of 2.5–4.5 mg/hr. More

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-MOC2

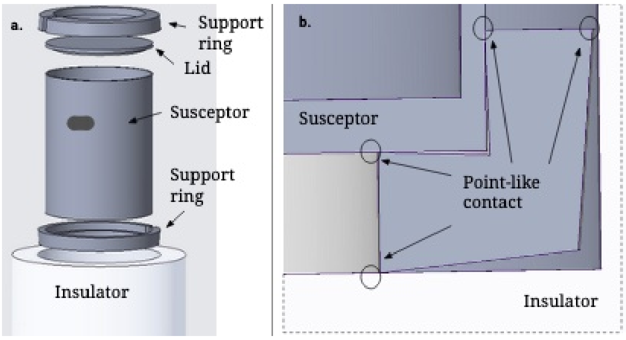

Figure 4: An exploded view of the oven assembly, left, and detail showing the point-like contact the ring makes with both the susceptor and the insulator.

recent runs have consistently been in the low end of this range.

For every run, the insulators become gray and develop cracks, but they hold their shape until the end of the run and haven't caused problems. The body and lid insulators can only be used for one run while the support posts can typically be used multiple times. We have only used one susceptor/lid combination for all of our ^{50}Ti runs to date, and these show no signs of damage.

The coils do collect titanium near the material exit opening. It is not a significant amount and this can be chipped away easily. It should be noted, however, that for one run where the titanium-coated coil had been exposed to atmosphere for three months before its next use, there was significant outgassing inside the source when the coil was energized to a low level. This caused a few hour delay on start up, and could likely be avoided by protecting the coil between runs.

PROBLEMS AND OTHER DEVELOPMENT NOTES

The susceptor itself has clogged twice, and both times were due to suddenly turning the coil power supply off when at high temperature. The reason for this is believed to be the fact that the insulator provides a good thermal barrier from the cool outside world except at the exit aperture, therefore this location would be expected to cool fastest when the power is suddenly turned off. It has been found that as long as the oven is ramped down in a steady manner (as high as 10s of W per minute), no clogging has occurred.

Early iterations of the oven allowed the insulator to rotate relative to the coil and the susceptor relative to the insulator. Both of these caused reduced beam production and usually led to clogging. The addition of a slit to the insulator body, mentioned above, that eliminated the ability of the insulator to rotate stopped rotation clogs. Wedging thin (0.02-mm-thick) strips of molybdenum between the susceptor and the insulate prevented rotations of the susceptor.

An early iteration of the oven used a thin-walled 0.5-mm-thick) tantalum susceptor. At 200 kHz inductive heating, this represented less than one skin depth. As a result, the eddy currents formed in the susceptor were not enough to counter the magnetic flux and eddy currents were formed in the titanium inside the oven. The titanium was heated more quickly than the susceptor, and though we surpassed the desired partial pressure temperature and melted the titanium, the susceptor walls remained colder than the titanium and the titanium condensed and solidified there. Additionally, there was evidence of chemical reactions taking place between the titanium and tungsten. The change to the thicker-walled molybdenum susceptor mentioned above has prevented these problems. An advantage inductive ovens with thick-walled susceptors have over resistive ovens is that nearly all of the inductive power goes into the susceptor. Unlike the resistive oven whose resistance can change as material shifts within the oven itself, the inductive oven temperature is very stable as all the heat goes into the susceptor regardless of the quantity of material inside it.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of Brian Bell in winding the inductive oven coils and other machining efforts on this project.

REFERENCES

[1] J.M. Gates *et al.*, "Toward the discovery of new elements: Production of livermorium (Z=116) with ^{50}Ti", *Phys. Rev. Lett.*, accepted for publication, 2024.

[2] D.S. Todd *et al.*, "High current beam extraction from the 88-Inch Cyclotron at LBNL", in *Proc. Cyclotrons'13*, Vancouver, Canada, 2013, paper MO2PB02. `https://jacow.org/CYCLOTRONS2013/papers/MO2PB02.pdf`

[3] D.J. Clark and C.M. Lyneis, "The production of beams from solid materials at the LBL ECR source", *J. Phys. Colloques*, vol. 50, no. C1, pp. 759–766, 1989. `doi:10.1051/jphyscol:1989180`

[4] D. Leitner *et al.*, "High intensity production of high and medium charge state uranium and other heavy ion beams with VENUS", *Rev. Sci. Instrum.*, vol. 79, p. 02C710, 2008. `doi:10.1063/1.2816790`

[5] J. Ohnishi *et al.*, "Development of a high-temperature oven for the 28 GHz electron cyclotron resonance ion source", *Rev. Sci. Instrum.*, vol. 85, p. 02A941, 2014. `doi:10.1063/1.4849655`

[6] Y. Higurashi *et al.*, "Intense vanadium ion beam production for superheavy element research experiments", *J. Phys.: Conf. Ser.*, vol. 2743, p. 012052, 2024. `doi:10.1088/1742-6596/2743/1/012052`

[7] W. Lu *et al.*, "Production of metallic ion beams by electron cyclotron resonance ion sources equipped with inductive heating ovens at the Institute of Modern Physics", *Rev. Sci. Instrum.*, vol. 92, p. 033302, 2021. `doi:10.1063/5.0041671`

[8] H. Ren *et al.*, "Development and status of the FRIB 28 GHz SC ECRIS" *J. Phys.: Conf. Ser.*, vol. 2244, p. 012008, 2022. `doi:10.1088/1742-6596/2244/1/012008`