Title

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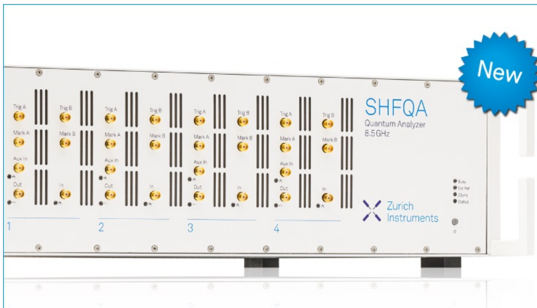

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## ABSTRACT

High Temperature Ovens (HTOs) have widely been used to evaporate refractory materials in electron cyclotron resonance ion sources to produce hundreds of microamperes of multiply and highly charged metal ion beams. To meet the demands of milliamperes of multiply charged uranium and other heavy metal ion beams for future accelerators, a new and low-cost HTO is under development at Lawrence Berkeley National Laboratory for better long-term stability at high evaporation rates. ANSYS simulations have been carried out to optimize the new HTO with low heating current to reduce the electromagnetic forces as an HTO is immersed in the strong ECRIS magnetic fields. A larger loading volume is employed to deal with higher material consumption. Off-line tests have shown that the unloaded new HTO operates stably up to 1800–1900 °C with low temperature gradients and good repeatability. This paper presents and discusses the conceptual design features of the new HTO and off-line tests.



## INTRODUCTION

High Temperature Ovens (HTOs) are often used in Electron Cyclotron Resonance Ion Sources (ECRISs) to vaporize refractory metals for the production of hundreds of electrical microamperes of multiply and highly charged metal ion beams. A metal vapor pressure of about $10^{-3}$ to $10^{-2}$ Torr is required inside the HTO, with an oven aperture of a few mm$^2$, to supply the needed atom flow to the ECR plasma.[1] Higher atom flow typically results in increasing heating current to achieve higher oven temperature, which exacerbates the oven stability.

The future Electron Ion Collider (EIC) supported by the US Department of Energy and other intense heavy ion beam facilities, such as the High-Intensity heavy ion Accelerator Facility (HIAF) project,[2] requires electrical milliamperes of uranium ion beams of charge state preferentially ≥30+ in the cw or pulsed mode, which is feasible but yet to be demonstrated. The present record of intense uranium beams is 400 e$\mu$A of $U^{34+}$ produced by the LBNL VENUS ECR ion source for hours with an HTO made of rhenium, off-line tested stably to ≥2100 °C, which was found completely deformed afterward. During the operation, the rhenium HTO was operating at ~1800 to 1900 °C with heating current up to ~400 A, which resulted in an electromagnetic (em) force of up to ~30 N.[3] Other HTOs made of tantalum and tungsten also suffer severe damages resulted from the em force at substantially lower operating temperatures than the off-line tested temperature of 2100 °C. The unsatisfactory lifetime, essentially used once only, and poor long term stability of these HTOs have led to an exploration of a reliable HTO to improve the VENUS performance and meet the future demands.

A high performing HTO for the ECRIS should not only mitigate the em force but also deal with the possible alloying and wetting which may occur between the material to be vaporized and the oven body/crucible at elevated temperatures.[4] In addition, a large material loading is needed for the long term operations for the production of more intense metal ion beams.

Mitigations of the aforementioned issues could be achieved by (1) lowering the HTO heating current as much as possible to reduce the em force and employing an oven vapor exit aperture as large as possible to lower the temperature requirement for the same atom flow rate; (2) employing additional supports to mechanically mitigate the em forces; and (3) employing crucibles that are chemically stable even at elevated temperatures and have large loading capacity and high thermal conductivity to reduce the temperature gradients.

Based on the guidance stated above, a new HTO has been under exploration at LBNL. This paper presents a brief theoretical justification, the design features of the new HTO, ANSYS analyses on the temperature distributions and the em forces exerted by the VENUS magnetic fields, and the off-line test results.

## EVAPORATION TEMPERATURE AND APERTURE

The HTOs used in the physical vapor deposition (PVD) process usually have a large material loading operating with a low current. However, the structure of this HTO needs to be modified for application in the ECR ion source as the operation of the HTO for PVD is in pure vacuum without a strong magnetic field. The large-aperture crucible with a large loading capacity can proportionally lower the required temperature for the same atom flow rate.

The maximum evaporation flux per second of a substance from the condensed form to its gaseous form in vacuum near its surface can be expressed by the Hertz-Knudsen equation,[5]

$$\Phi = \frac{p \cdot N_A}{\sqrt{2\pi MRT}}, \tag{1}$$

where $p$ is the saturation vapor pressure of the element, $N_A$ is the Avogadro constant ($N_A$ = 6.022 141 × $10^{23}$ mol$^{-1}$), $M$ and $T$ are the relative molecular mass and temperature of the element, respectively, and $R$ is the ideal gas constant.

Take uranium as an example. $UO_2$ was determined to be the most promising compound as a result of the tests conducted at LBNL.[6] The saturation vapor pressure of $UO_2$ can be expressed by the following formula[7]:

$$\ln[p(\text{Torr})] \sim -\frac{37\,195}{T} + \frac{3\,516\,200}{T^2} + \frac{2.6178 \times 10^9}{T^3} + 13.298. \tag{2}$$

With the substitution of (2) into (1) and $M_{UO_2} = 270$, we obtain

$$\ln[\Phi(\text{cm}^{-2}\,\text{s}^{-1})] \sim \ln\left(\frac{2.137\,79 \times 10^{21}}{\sqrt{T}}\right) - \frac{37\,195}{T} + \frac{3\,516\,200}{T^2} + \frac{2.6178 \times 10^9}{T^3} + 13.298. \tag{3}$$

Assume that the area of the aperture of the crucible for those HTOs discussed above is $A_0$ (~10 mm$^2$) and the required temperature of $UO_2$ is 1800 °C. If the aperture can be enlarged to $A$ with the ratio of this area being $a = \frac{A}{A_0}$, then the relationship between the area ratio $a$ and the required temperature of the oven for the same atom flow rate can be calculated by Eq. (3), as shown in Fig. 1. For example, if the aperture of the crucible can be enlarged to 5 times its original size, the required temperature of the crucible will be decreased to ~1600 °C with the same atom flow rate, which will decrease the em force with lower power consumption during operation.

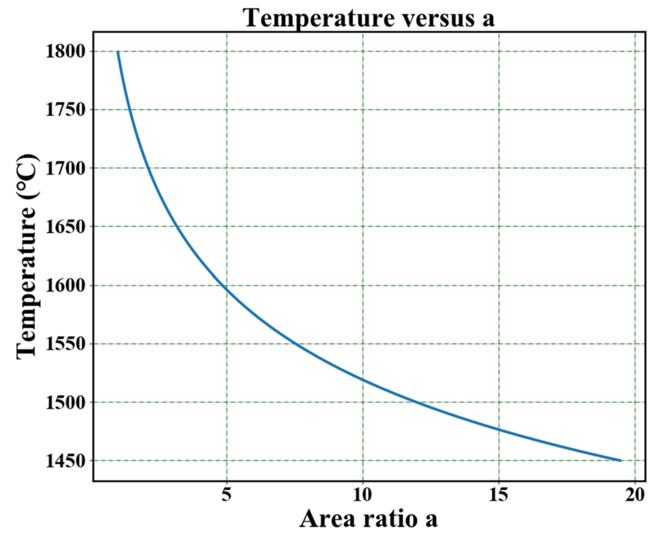


**FIG. 1**. The temperature of the crucible vs area ratio *a* for the same atom flow rate.

The aperture of the oven can be considered as a small surface evaporator. According to Ref. 8, an approach for the description of the vapor stream density distribution on surface evaporators is as follows:

$$\Psi(\alpha) = \Psi_0 \cos^n \alpha, \tag{4}$$

where $\Psi_\alpha$ is the vapor stream density in a direction with an angle $\alpha$ ($0 \le \alpha \le \pi/2$, shown in Fig. 2) to the normal of the vapor delivery surface and $\Psi_0$ is the vapor stream density for $\alpha = 0$. $n$ is the exponent that depends on the evaporation rate with $n > 1$. Equation (4)

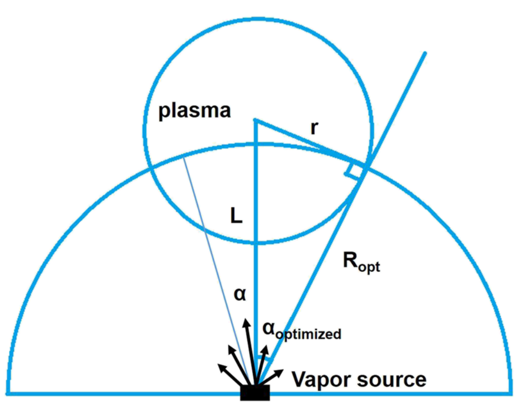


**FIG. 2**. The illustration of the vapor molecule path through the plasma area (assumed to be a sphere with radius $r$). Here, $\alpha$ is the trajectory angle of the vapor molecule to the vertical direction. $R_{opt}$ is the radius of the half-sphere when $\alpha$ reaches $\alpha_{optimized}$. $L$ is the distance between the vapor source (vapor exit aperture of the crucible) and the plasma center.

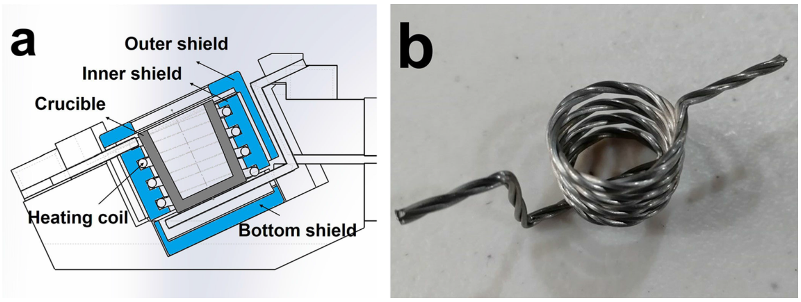


**FIG. 3**. (a) The 2D structure of the new type of HTO. (b) The picture of the heating coil.

with $n$ ~2.5 is valid up to an angle of $\alpha = 30^\circ$ for the vapor stream density.

Here, we assume $n = 2$ to simplify the problem. The vapor stream density at radius $R_{opt}$ with an angle α is subjected to the equation $\int_0^{\pi/2} \Psi_{R_{opt}}(\alpha) \cdot 2\pi R_{\rm opt} \sin\alpha \cdot R_{opt} d\alpha = \Phi \cdot A$, where $A$ is the area of the aperture of the oven. Then,

$$\Psi_{R_{opt}}(\alpha) = \frac{3\Phi \cdot A}{2\pi R_{opt}{}^2} \cos^2\alpha. \tag{5}$$

Apparently, the vapor stream density $\Psi_{R_{opt}}$, reaches maximum when $\alpha = 0$, according to Eq. (5).

In order to estimate the ionization efficiency of the vapor, some simplifications are made as follows.

1. All the vapor molecules within an angle between 0 and $\alpha_{\rm optimized}$ that travel through the plasma will be trapped and ionized. The other moving direction of the vapor molecules will be lost.
2. The distance between the aperture of the crucible and the plasma center is $L = 10$ cm, and the plasma area is a sphere with a radius $r$ of 5 cm.

Then, the total ionization efficiency of the vapor molecules ejected out of the crucible can be estimated as follows:

$$f = \int_0^{\alpha_{optimized}} \Psi_{Ropt}(\alpha) \cdot 2\pi R_{opt} \sin\alpha \cdot R_{opt} \cdot d\alpha/(\Phi \cdot A) \sim 35\%. \tag{6}$$

## ANSYS SIMULATION RESULTS

The structure of the new HTO is shown in Fig. 3(a). The aperture (~80 mm$^2$) of the oven is tilted to increase the vapor ionization efficiency. $ZrO_2$ thermal shields, inner and outer, are employed as shown. An R.D. Mathis tungsten coil made of 3 twisted strands of a diameter of 0.030″ each, Part No. ME18A-3x0.030W, is used as the heating element, as shown in Fig. 3(b). The inner surface of the inner thermal shield is pitched to hold the heating coil in place to mitigate the em force. A BeO crucible (melting point: 2530 °C) is used for its high thermal conductivity [>200 W/(m K) at room temperature] and chemical stability (inert to the heating coil and the loading materials).

This new HTO is designed to operate at a maximum current of 70 A. Thermal conductivity, thermal radiation emissivity, and electrical resistivity of all the components vs temperature are taken into account in the simulations. The cooling water in the terminal leads is of 22 °C with a heat transfer coefficient of 2000 W/(m$^2$ K). Due to the complexity in modeling, the 3-stranded tungsten heating coil is simplified to a single strand with the same total cross section. The simulated temperature distributions on the coil and the BeO crucible are shown in Figs. 4(a) and 4(b); as the heating coil reaches ~2300 °C (a), a maximum temperature of ~1800 °C inside the BeO crucible is achieved (b). The BeO crucible is heated by thermal radiation from the coil. The thermal conduction between the coil and the crucible is neglected in the simulations. The temperature gradient of the crucible is related to the thermal conductivity of the material, which will decrease at high temperature.

The HTO is to be placed inside the VENUS plasma chamber at a distance of 17.5 cm from the injection magnetic peak. The oven centers one of the six poles where there is no plasma and is immersed in a magnetic field of ~3.2 T. At a heating current of 70 A and mechanically fixed current terminals, the total em force exerted on the oven heating coil is ~2.65 N, which is substantially lower than that on HTOs discussed above. The calculated von Mises stress on the heating coil is shown in Fig. 5(a). The maximum stress on the heating coil is 274 MPa around the top 90° turning, and that could be an issue as the maximum tensile strength of tungsten decreases

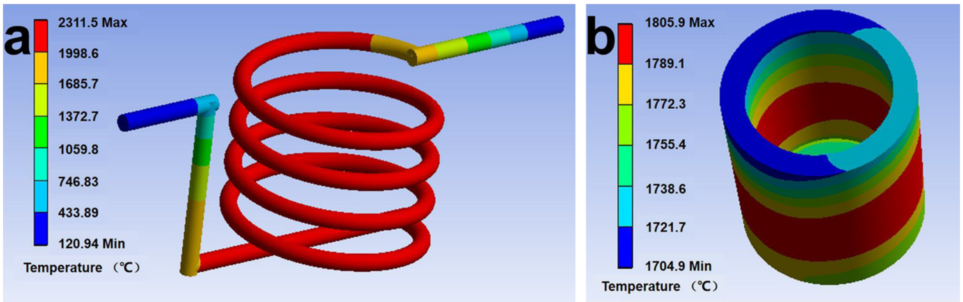


**FIG. 4**. Simulated temperature distributions on the coil (a) and the BeO crucible (b) by ANSYS.

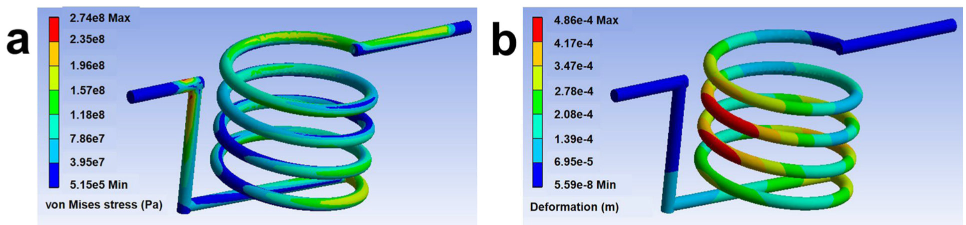


**FIG. 5**. Calculated von Mises stress distributions (a) and deformation distributions (b) on the heating coil.

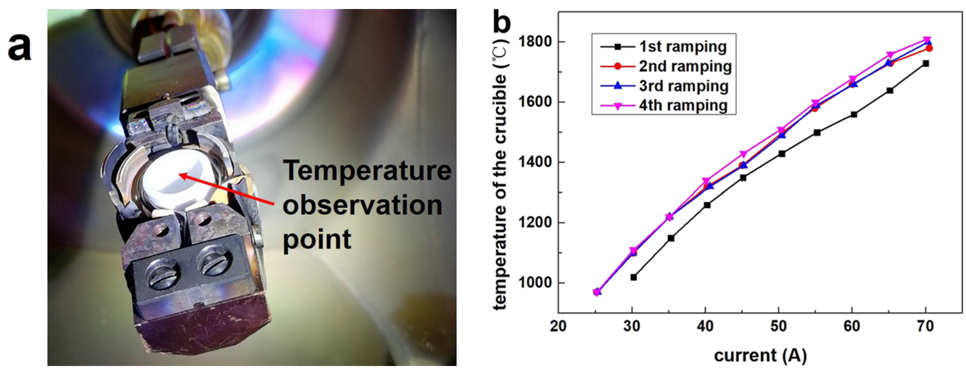


**FIG. 6**. (a) The temperature observation point at the off-line test bench. (b) The temperature of the crucible at the observation point vs the loading current.

to 436 MPa at 600 °C.[9] The calculated maximum deformation of the coil is ∼0.5 mm, as shown in Fig. 5(b), which should be addressed. The pitched inner thermal shield is thus designed to address the deformations.

The current terminals connecting the heating coil are also subjected to a force/torque per terminal due to the em forces. Such a force/torque can be mitigated by using ceramic supports. The em force exerted on the heating coil can be reduced by inserting the HTO further into the plasma chamber where the magnetic fields are lower.

## OFF-LINE TEST AND DISCUSSION

The oven was tested unloaded at an off-line apparatus and the tests were carried out without the top thermal shield for measuring the temperature distributions with an optical pyrometer. The off-line test bench is shown in Fig. 6(a). The oven was energized to 70 A in each test run for a few hours, and the temperature inside the BeO crucible reached above 1800 °C at a total electric power of 630 W. The temperature inside the BeO crucible vs the oven current at different tests is shown in Fig. 6(b). The oven was shown stable with good repeatability for ∼15 h at 70 A throughout the tests with little damage to both the tungsten heating coil and the BeO crucible. The vacuum was ∼5 × $10^{-7}$ Torr and kept stable during these stability tests.

The off-line tests are consistent with the simulations, which is very promising for this new design. The temperature of the crucible in off-line tests can be further increased with an optimized thermal shielding structure. However, once the oven is immersed in the magnetic fields, its characteristics could change substantially as the force/torque exerted by the em force results in different operating conditions. Tests of this new oven with the VENUS ion source have been planned in the near future, and it is anticipated that there will be a number of modifications to go through before a new HTO is successfully developed.

## ACKNOWLEDGMENTS

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