DESIGN OF A HIGH TEMPERATURE OVEN FOR AN ECR SOURCE FOR THE PRODUCTION OF URANIUM ION BEAMS

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Abstract

VENUS is the superconducting electron cyclotron resonance (ECR) ion source at the Lawrence Berkeley National Lab's 88-Inch Cyclotron. To generate neutral atoms for ionization, the source utilizes a resistively-heated high temperature oven that is located in a magnetic field of up to 4 Tesla and operates at temperatures up to about 2000°C. However, temperatures between 2100-2300°C are required to produce the desired 280eμA of high charge state uranium ion beams, and increased thermal and structural effects, combined with elevated chemical reactivity significantly reduce the oven's ability to operate in this envelope. The oven has been redesigned with higher thermal efficiency, improved structural strength and chemically compatible species in order to produce the desired high intensity, high charge state uranium beams. Aspects of the engineering development are presented.

INTRODUCTION

LBNL's three ECR injection systems routinely utilize resistively-heated refractory metal enclosures, called ovens, that contain a quantity of solid state material to be vaporized. From the oven, the vapor then carries into the ECR plasma where it is sequentially ionized and then extracted into an ion beam. The ovens, typically made from tantalum or tungsten, operate up to about 2100 °C.

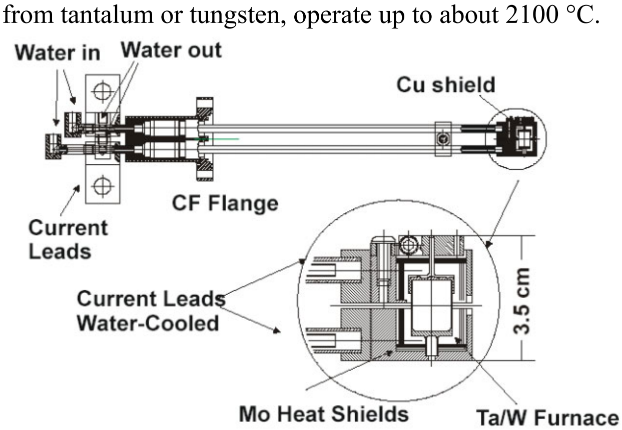

Figure 1: Compact LBNL high temperature oven.

Because the VENUS superconducting ion source is the prototype ECR injection source for a next generation radioactive ion beam facility, a key goal of the R&D program is the reliable production of uranium beam currents of up to 280eμA of any medium charge state from U^{29+} to U^{35+}.

While previous oven designs have been used successfully in the creation of lighter ion beams, high intensity uranium beams require the oven to operate at temperatures in excess of 2000 °C in order to achieve greater vapor pressures, from between $1x10^{-2}$ mbar and $1x10^{-1}$ mbar. Higher temperatures not only soften the material, making it less resistant to deformation, but also require a larger heating current and therefore result in a larger magnetic force driving that deformation. Further, a careful examination of the materials used for the ovens, containment crucibles, and source materials is crucial because chemical reactivity between species also increases, even between materials that are compatible at lower temperatures.

This study describes aspects of the oven's engineering improvements to operate at the elevated temperatures required to achieve the vapor pressures necessary for high intensity uranium beams, while maintaining chemical compatibility between heating and containment materials.

OVEN DESIGN

While the previous ECR oven performed well within its own design conditions, an improved oven was developed to meet the more stringent uranium beam requirements.

Lorentz Force Structural Effects

The oven is located within a very strong magnetic field (magnetic flux density) ranging from 3 to 4 Tesla. Since the field of the VENUS injection solenoid dominates at the oven location, the magnetic field direction is perpendicular to the oven's longitudinal axis.

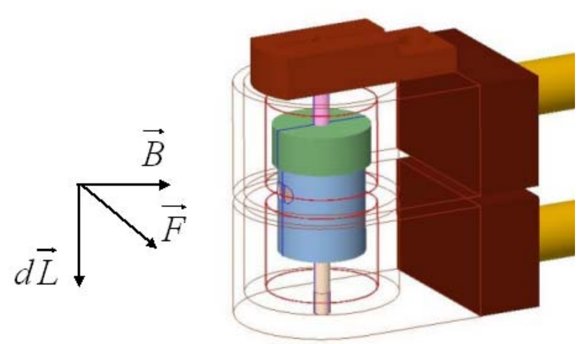

Figure 2: CAD representation of oven inside housing.

Therefore a Lorentz force acts upon the oven during operation. This force is described by the relation:

$$\vec{F} = I\int d\vec{L}\times\vec{B} \quad (1)$$

where the current density is considered uniform, and the integration is performed over the oven's unsupported length L.

*Retired

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At magnetic field strengths approaching 4T, the Lorentz force can reach sustained magnitudes of 30N or more. As the operational temperature and run time increase, the oven material's creep strength is also decreasing. For example, tungsten's creep strength was measured to decrease by 80% for 100 hr rupture time between 1482°C and 871°C alone [1].

Experimentally, several types of oven failures were observed for the high temperature oven when operated in the high magnetic field. Some ovens have experienced buckled walls. For others, the high temperature creep stresses can induce plastic deformations in the stems large enough to cause eventual operational failure by allowing thermal contact of the oven with either its surrounding concentric heat shields or its enclosure walls.

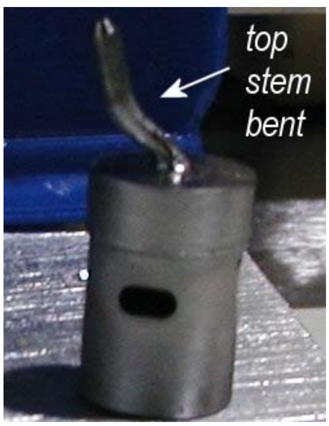

Figure 3: Tantalum oven's top stem bent after operation at 300 amps in high magnetic fields.

Such contact electrically and thermally shorts the oven, decreasing its temperature, the source material's vapor pressure and consequently the ion beam current. Figure 3 shows a tantalum oven that failed in this manner at a heating current of 300 amps.

Thermal Finite Element Analysis

The oven's geometric profile is directly correlated to performance metrics such as the maximum temperature, the temperature gradients and distribution, the supply current required to achieve a given temperature, and the oven's ability to resist structural deformation. A 2D axisymmetric thermal-electric analysis of the oven was performed in ANSYS® Multiphysics™ FEA software to determine its performance characteristics.

Figure 4 shows the temperature distribution results for three oven design variations without source material. The top picture shows the temperature profile of a tungsten oven with the original geometry. The middle picture is also tungsten, but the stem lengths have been equalized, and the body lengthened and diameter decreased. This results in a higher maximum temperature and a smaller temperature gradient in the containment zone. The third oven has the same geometry as the second but with rhenium material properties instead of tungsten.

Rhenium has a greater electrical resistivity and a smaller thermal conductivity than tungsten, both of which increase the oven's efficiency by allowing it to achieve equal temperatures at lower heating currents. Another benefit is that the system's total heat dissipation is reduced, but more importantly, the magnitude of the Lorentz force is decreased as well. Complimenting this decrease in force acting upon the oven is that rhenium has better elevated temperature creep strength characteristics than tungsten as well [2].

Note also that for the new geometry (middle and bottom ovens) the maximum temperature is located in the source material containment region, which is an improvement over the original design (top) where the maximum temperature was located in the upper stem.

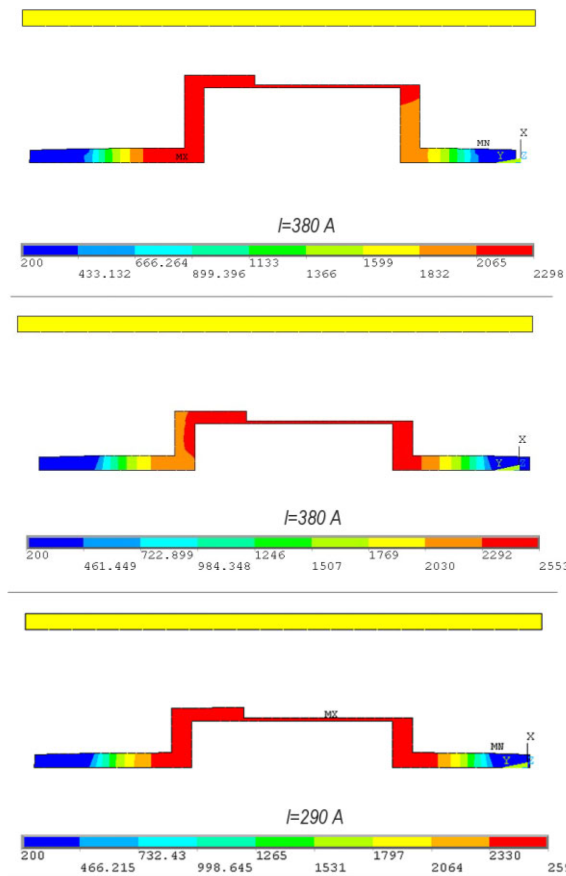

Figure 4: Temperature profiles of original size tungsten oven (top), new size tungsten oven (middle), and new size rhenium oven (bottom). All temperatures are Celsius. (Note that the color scale is different for all three profiles).

FABRICATION

LBNL ECR ovens have previously been fabricated from both tantalum and tungsten. While tantalum is much easier to machine and has higher electrical resistivity, tungsten has better elevated temperature creep resistance [2]. A method has been developed to fabricating tungsten ovens through a combination of machining and grinding, which allows them to be used in place of tantalum when the higher temperature capability is required.

But the process of making tungsten ovens is rather difficult and time consuming. And although tungsten has better performance than tantalum up to 2000 °C, FEA results indicate that rhenium has better overall performance than even tungsten at temperatures up to 2300 °C.

Unfortunately rhenium is even more difficult to machine than tungsten. However, it can be fabricated by electrical discharge machining (EDM) instead, while tungsten cannot. After a successful fabrication test of a rhenium oven using EDM, it was estimated that this method could reduce by 2/3 the time required to produce each oven, and reduce by at least the same amount the degree of difficulty. Even though rhenium stock material is much more expensive than tungsten, when the reduced labor costs are factored in, the total costs are about equal.

MATERIAL COMPATIBILITY

Uranium vapor can be produced in ECR ovens from pure uranium and from several uranium compounds. Based on calculations performed using a chemical reaction and equilibrium software program, along with the thermo-chemical database HSC, the two leading candidates for ECR oven use were identified as URe_2, and UO_2 [3].

Between the two, URe_2 is attractive because for a given temperature it has a higher vapor pressure than UO_2. The temperatures required to achieve the needed vapor pressures for URe_2 start at 1700 °C for high charge state beams and increase to over 2000 °C for high intensity runs. The URe_2 melting point is about 1950°C, so it will melt and form substantial contact with the oven walls in operation, thereby decreasing its operating temperature. The URe_2 must therefore be decoupled from the oven by containing it within a secondary ceramic crucible, such as yttria.

UO_2 has a vapor pressure between $1x10^{-2}$ and $1x10^{-1}$ mbar in the temperature range 2100-2300°C [4]. If the oven can sustain these high temperatures, it would probably be the ideal compound to use as a source material. Because its melting point is about 2820°C [4], it will sublime before melting and will have little affect on the oven's electrical resistance. It will not require a crucible and can thus be contained by the oven directly. Further, UO_2 has been shown to be chemically stable with rhenium in the temperature range 2000K -3000K [5]. In addition, its oxygen gas is used in the ECR background plasma for the production of high charge state ion beams.

ALTERNATING CURRENT HEATING

In addition to the design changes presented in this paper, the use of AC heating current instead of DC was also evaluated in order to achieve a zero time-averaged Lorentz force; the force would now oscillate with the frequency of the AC current supply. The possibility of using AC had previously been explored and tested but subsequently shelved primarily due to high amplitude vibrations at 60 Hz. The oven assembly's harmonic response was investigated in ANSYS® over the frequency range 0-800 Hz, and figure 5 summarizes the amplitude results. A resonant peak near 60 Hz is clearly seen for each spatial coordinate axis at 60 Hz, which agrees with experimental observation, while the 400 Hz response is significant only in the x-axis, at a factor 30 less than at 60 Hz. A sequence of 400 Hz tests is now under way.

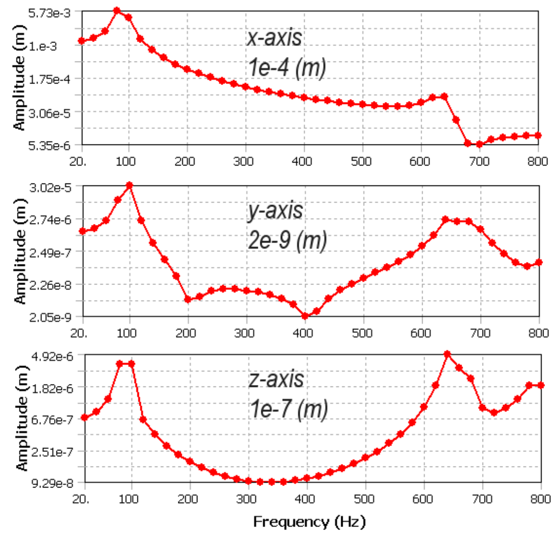

Figure 5: Amplitude harmonic response of oven system for the frequency range 0-800 Hz.

CONCLUSION

Engineering design of a new resistively-heated high-temperature ECR oven has been developed. The improved oven operates at higher temperatures than the previous design, has increased heating efficiency, decreased Lorentz forces, and increased elevated-temperature creep strength; all of which are needed to sustain reliable operation at temperatures of 2200°C. UO_2 has been identified as an ideal ion source material that is also chemically compatible with the oven and will not require use of an insulating ceramic crucible. Off-line oven performance tests and long term uranium production runs in the LBL ECR ion source have shown that the improved oven design can reliably run at temperatures up to 2300 °C. The oven is now undergoing on-line testing in the VENUS source.

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