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An interchangeable-cathode vacuum arc plasma source

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A simplified vacuum arc design [based on metal vapor vacuum arc (MeVVA) concepts] is employed as a plasma source for a study of a ^{7}Be non-neutral plasma. The design includes a mechanism for interchanging the cathode source. Testing of the plasma source showed that it is capable of producing on the order of 10^{12} charges at confinable energies using a boron-carbide disk as the cathode target. The design is simplified from typical designs for lower energy and lower density applications by using only the trigger spark rather than the full vacuum arc in high current ion beam designs. The interchangeability of the cathode design gives the source the ability to replace only the source sample, simplifying use of radioactive materials in the plasma source. The sample can also be replaced with a completely different conductive material. The design can be easily modified for use in other plasma confinement or full MeVVA applications. © *2010 American Institute of Physics.* [doi:10.1063/1.3291982]

I. INTRODUCTION

We are preparing to analyze the half life of a beryllium-7 (^{7}Be) ion by examining a ^{7}Be non-neutral plasma confined with a Malmberg–Penning trap.[1] ^{7}Be is a radioactive isotope that has been found in unexpectedly high concentrations at orbital altitudes.[2] It is peculiar in that it is the lightest known isotope whose radioactive decay only occurs through electron capture, and it has been shown to have a half life that changes depending on the electrochemical configuration of its electrons.[3,4] Ionizing the atom may have a significant impact on its half life, and may possibly explain its abundance in the atmosphere.

^{7}Be can be created by bombarding a boron-10 atom with a proton beam. We create our ^{7}Be on the surface of a sample of enriched boron carbide. Because ^{7}Be as well as boron-carbide are conductive, we can effectively employ vacuum arc techniques, as used in metal vapor vacuum arc sources[5] or by MacGill *et al.*,[6] for generating ^{7}Be ions, though the properties of the ions and nature of the experiment require some unique features in a ^{7}Be plasma source.

The half life of ^{7}Be is about 53 days. To get an accurate measurement, the plasma is confined for a period on the order of one half life. To use a plasma source for multiple experiments, the sample material needs to be replaced after it decays through the duration of the experiment. Our design accommodates the radioactivity of the source by employing a mechanism for interchanging the boron carbide sample attached to the cathode of the source. This interchangeability provides the added benefit of being able to use the same plasma source for multiple experiments using a variety of conductive materials exchanged for the boron carbide sample.

The source design employs a number of other useful features to accommodate the peculiarities of this particular experiment. The creation of ^{7}Be on the boron carbide surface occurs only in a small region, and so the surface is masked to restrict the arc discharge to only the region where the ^{7}Be is located. The study will occur in an ultrahigh vacuum environment, and so the materials used are compatible with this type of vacuum, and all parts are threaded for direct attachment rather than using cements. The cathode assembly is directly removable to allow sample exchanging to occur in a small, isolated chamber, rather than re-evacuating the entire trap assembly. Cathode removal and insertion is accomplished with a manipulator arm structure.

II. SOURCE DESIGN

Our design focused primarily on the need to have an easy way to remove the source from the chamber without repressurizing the entire trap. The source, then, is built from two separate parts—a removable cathode assembly and a fixed mounting assembly (Fig. 1). The cathode assembly is trivial to disassemble to replace the cathode target material. Cylindrical symmetry is used in the design for ease of production and use. The assemblies are made from oxygen-free high-conductivity copper and Macor®.[7] A photo of the completed parts is seen in Fig. 2.

A. Cathode assembly

The copper base of the cathode assembly is hollowed to reduce weight and provide a mechanism for removal and insertion. The tapered sides help align the cathode with the mounting assembly. Slits in the back give the taper some flexibility, helping to ensure good electrical contact with the mounting rings. A groove above the taper is used to hold the cathode in position. The target material (boron carbide with ^{7}Be) is placed on the end, along with a 1/16-in.-thick Macor mask (a disk with a small hole that exposes the ^{7}Be spot) to restrict arc discharges to the ^{7}Be location. A thin layer of

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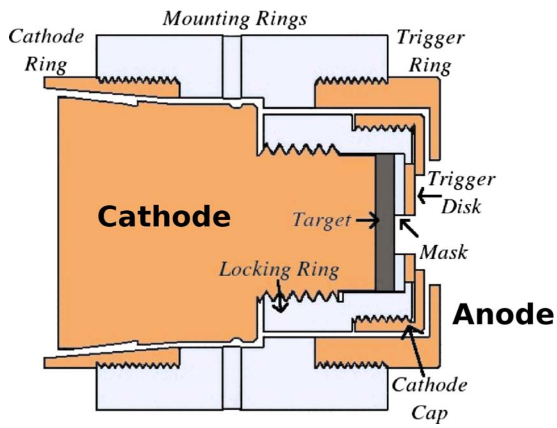

FIG. 1. (Color online) Schematic of the plasma source assembly. Materials are color coded, with the lightest color as Macor®, the midtone as copper, and the dark shade as boron carbide. Not pictured is the interior of the cathode base, hollowed out and grooved to accommodate insertion and removal from the trap. Note that although the piece locking the cathode assembly together is labeled "cathode cap," it is electrically part of the anode of the circuit. The misnomer is a result of conflicting descriptions of the part's mechanical and electrical purposes.

graphite is applied to the inner surface of the mask to help initiate the discharge.[8] A copper trigger disk is cut to match the mask so that the discharge occurs along the 1/16 in. inner surface of the exposed region. The three pieces are attached and held to the cathode base with a Macor locking ring. A copper cap threads onto the locking ring to give an electrical connection to the trigger disk, securely holding all the pieces in place.

B. Mounting rings

The mounting ring assembly consists of three pieces, two copper rings to provide electrical connections to the base and the trigger and a Macor ring to hold the assembly together. A set of spring-loaded ball bearings in the Macor ring align with the locating groove in the cathode base. The trigger ring is cut precisely to ensure good contact with the cathode cap and trigger disk, and the cathode ring is carefully tapered to match the cathode base. Copper extensions on the rings provide a base to which wires from high voltage feedthroughs into the trap can apply the high voltage pulse needed to generate the vacuum arc.

FIG. 2. (Color online) The assembled mounting rings (left) and ion source (right).

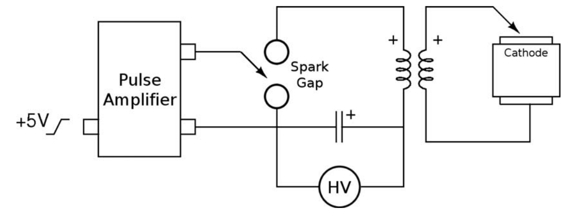

FIG. 3. Schematic of the electrical circuit used on the source.

C. Electrical system

The major simplification of this design from typical vacuum arc sources is the absence of a high-current arc and a high-voltage extraction grid. This source is designed only as a plasma source, not to generate high energy ion beams, and so the arc discharge normally used as a trigger is itself sufficient for releasing a relatively small number of ions and does not impart unnecessary energy to them that would make confinement more difficult. The arc is provided by a high-voltage pulse transformer that initiates the discharge of a 0.22 μF capacitor with 1–10 kV applied potential (Fig. 3). The current is transferred to the plasma source through a step-up air core transformer, providing the voltage and energy needed to create the vacuum arc and release the ions from the cathode surface. A positive bias ($\sim$100 V) is also applied to the trigger disk of the cathode relative to the grounded base. The bias helps to direct the ions away from the source and remove some of the electrons from the stream of material flowing away from the source, which provides a cleaner signal in testing.

III. TESTING

The source was tested in a $\sim$6 μTorr environment with 4 kV applied to the capacitor and using a 4:10 turn ratio for the step-up transformer. This configuration resulted in a 7 kV peak discharge at the source. A copper Faraday cup was used to view the output by using an integrator circuit measured with an oscilloscope. The circuit is done without active components due to the amplitude and high frequency of the signals. A typical signal is shown in Fig. 4. Varying the source-

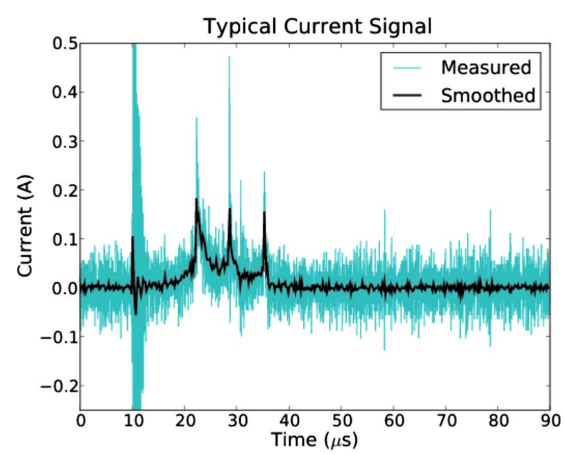

FIG. 4. (Color online) Typical current in the Faraday cup, measured 25 cm from the source with a 50 V bias applied to the cathode. Smoothed data overlayed to see overall structure over the noise.

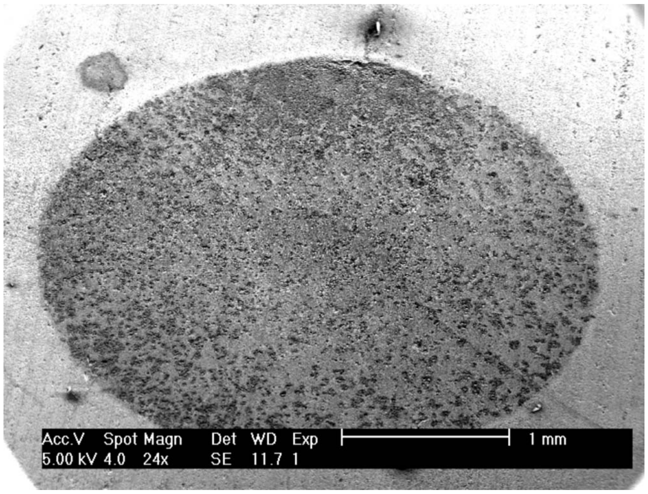

FIG. 5. SEM photo of the unmasked region of the target surface.

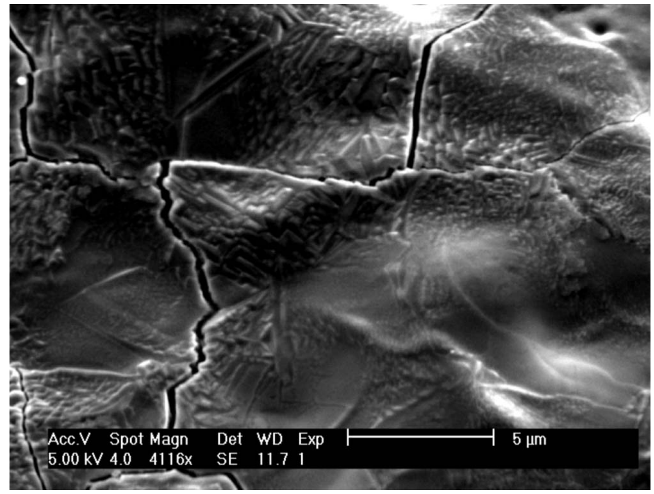

FIG. 6. SEM photo of the primary ablation region, showing melting, fracturing, and crystal formation.

cup distance revealed typical ion velocities of ~ 25 km/s, consistent with results shown by other designs such as that of MacGill *et al.*[6]

The energy of released ions is between 20 and 25 eV, a good range for confinement in our trap. The thermal spread of the ions can be estimated at 1 eV in each shot. Analyzing the integrated signal reveals a total charge output of 6.2×10^{-7} C per shot, on average. Assuming the output is mostly singly ionized atoms, that correspond to an average of 3×10^{12} ions. Even considering the likelihood that a portion of the ions are doubly ionized, the source output is more than sufficient for the experiment.

A sapphire window placed between the source and the Faraday cup to block released ions while allowing UV light to pass through gives us the amount of signal seen at the Faraday cup due to photoelectron emission. In this configuration, the signal seen is exactly the noise signal seen on all other equipment (including empty oscilloscope channels) due to the arc discharge in the electronics. The cup itself is designed to recapture any secondary electron emission from ion collisions. We therefore conclude that the signals seen in testing are entirely ion output and not electron emission effects.

Varying the distance to the Faraday cup provided a view of the expansion of the stream of ions from the source. The profile turned out to exhibit a linear expansion with positive bias applied to the source cathode (near linear with the cathode grounded). The rate of expansion implied the ions would reach the radius of the trap wall at about a 30 cm distance from the source. For our experiment, the ions would enter the trap injection system much earlier than that, and so loss of ions to collisions with the trap wall or other undesirable results of beam expansion will be negligible.

The behavior of the cathode surface was also examined by viewing a target with a scanning electron microscope (SEM) as well as an optical microscope. The SEM photo in Fig. 5 shows the unmasked region of the target after 25 shots. Ablation occurs primarily at the edge where the discharge occurs along the graphite layer, consistent with the observations of Oates *et al.*[9] Ablation also occurs to some extent over much of the exposed region, and so ^{7}Be can be extracted from the entire spot where it is created in the target. Estimates from the microscope images imply ablation occurs to a depth of as much as 10 μm. At this depth, a large quantity of boron and carbon will also be released, requiring some type of mass discrimination in the trap injection system for the experiment. Closer views of the surface reveal the surface in the ablation region to have melted and cracked from cooling after discharges, and also exhibit some evidence of crystallization through the process. (Fig. 6) The composition of these crystals was examined briefly, but no conclusive results were obtained.

IV. CONCLUSIONS

Our testing shows this new design is an effective plasma source for experiments. The interchangeability is simple to implement and use, and provides for a flexibility not present in previous designs. Using only the trigger spark, we are able to produce a sufficient number of ions for our study, though a similar design could be implemented with the vacuum arc system for high output studies.

Masking the target surface is effective, and, since ablation occurs throughout the unmasked region, allows us to maximize the amount of ^{7}Be released by the source while restricting arcs to just the region of interest. A quadrupole mass discriminator is used to remove other material (particularly boron, carbon, and copper) from the output and insert the ^{7}Be into our trap.

ACKNOWLEDGMENTS

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