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EXTRACTION OF HIGH-CHARGE STATE NEON AND KRYPTON FROM THE D-PACE PENNING ION SOURCE TEST STAND

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Abstract

D-Pace has a self-heated hot-cathode Penning ion source test stand at their Ion Source Test Facility (ISTF). High-charge state production of boron, arsenic, and phosphorous is interesting to the ion implantation industry, as it allows for higher energy implants of these dopants using the same accelerating gradient in a given accelerator system. We use Neon and Krypton as proxy gases to investigate whether the Penning ion source could be used for high-charge state production in ion implanters. We were able to produce charge states up to Ne^{3+} (> 200 $e\mu$A) and Kr^{6+} (> 7 $e\mu$A). The obstacles in using the current Penning ion source test stand are discussed, with comments on how to potentially increase the current output, stability, and lifetime of this ion source.

INTRODUCTION

D-Pace Inc has a self-heated hot cathode Penning ion source test stand. This was initially used for investigating the production of α-particles as a function of experimental parameters such as magnetic field strength, inlet gas flow, and arc current [1]. However, the Penning ion source has been used often in the past as a source of high-charge state ions for various gases and metal vapors [2]. The compact size of these sources means they have potential as a cost-effective replacement for Electron Cyclotron Resonance ion sources used in high-charge state ion production. Producing these high-charge states is advantageous to the ion implantation community, as these ions can be accelerated to higher energies at the same voltage gradient without increasing the size, and therefore cost, of an accelerator [3]. Therefore, the Penning ion source could possibly be used in ion implanters needing high-charge states of boron, arsenic, and phosphorous for doping semiconductors. Due to the toxicity of these dopants, inert gases are used as substitutes. It is assumed that producing high-charge states of these inert gases with similar masses and higher ionization energies would lead to similar high-charge state production of the dopants. These experiments have been performed in the past for Argon, showing that charge states of Ar^{6+} can be readily generated by this ion source [4].

In this paper, we extend the experiments to Neon and Krypton. We show the maximum currents of the various charge states of Neon and Krypton produced by the Penning ion source. We also comment on the experimental setup, and what changes would be required for the test stand to optimize the production of high-charge state dopants.

EXPERIMENTAL SETUP

A schematic drawing of the test stand is shown in Fig. 1. This presents the ion source projected onto one of the magnet poles of the C-magnet, which produces a uniform magnetic field of 0.4-0.95 T. This field provides plasma confinement within the ion source and also acts as a mass spectrometer for the extracted ions. Ion extraction is done by a grounded puller held in place by an insulator, with a separation of 2.3 mm from the extraction slit on the anode body. The ion source body can be raised up to 15 kV for ion extraction. These ions are measured by a moving Faraday cup after undergoing a 180° turn. The Faraday cup is shielded by a grounded plate with a 62×2 mm slit. The current is measured by a NI USB-6001 data acquisition system across a resistor. The scan distance for the Faraday cup is converted to an estimated mass-to-charge ratio of an ion based on the set magnetic field strength and extraction voltage. More information about the general setup can be found in the thesis by N. Savard [1].

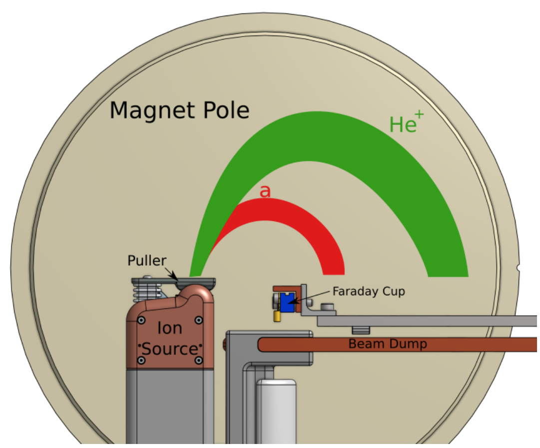

Figure 1: Schematic drawing of the experimental setup. Shown is the Penning ion source projected onto the C-magnet pole. Example trajectories of helium ions being rotated by the field to a movable Faraday cup is shown.

RESULTS

The ion source was operated using Neon and Krypton as inlet gases. The purpose of these measurements is to show the maximum output of each high-charge state. Previous experiments showed that high-charge state currents are maximized at higher magnetic fields and lower gas flows, due to higher confinement times and higher ionization percentage of the gas [1,4]. For this reason, several runs were done with the magnetic field at 0.9 T, while attempting to decrease the inlet gas flow as low as possible. The arc current was var-

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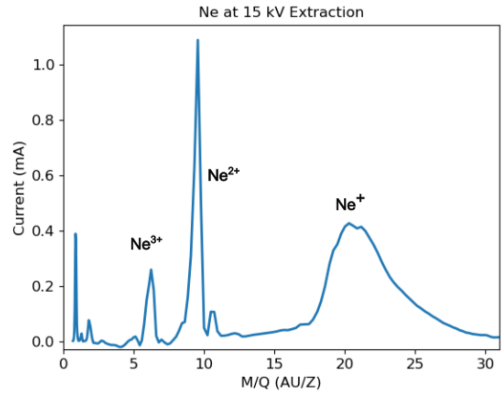
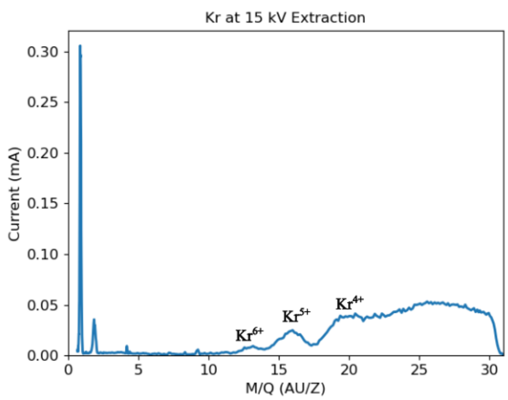


(a) Neon operation



(b) Krypton operation

Figure 2: Measured spectrums for Neon and Krypton. X-axis is estimated mass-to-charge ratio based on magnetic field strength and energy of each species due to the extraction voltage.

ied between 1 - 3.5 A, with the dependent voltage typically between 200-400 V.

An example plot of Faraday cup measurements taken for a Neon and Krypton beam are shown in Fig. 2. Due to the overlap of different species on the Faraday cup, and the presence of other anomalous peaks (to be discussed in the next section), the upper estimate of each charge-state is determined by manually finding the troughs of each peak, and integrating between the two. The lower estimate is an integration over the peak within a few samples of the troughs.

Fig. 3 shows the maximum particle-currents for each measured charge-state of Neon and Krypton. In order to achieve these currents at 0.9 T, the inlet gas flow had to be brought down to about 0.85 sccm for Neon, and 0.2 sccm for Krypton. Lower gas flows led to an unstable discharge which was eventually extinguished. We were able to measure up to a charge state of 3+ (237 $\pm$ 4 $e\mu$A) for Neon, while for Krypton we were able to measure up to 6+ (8 $\pm$ 2 $e\mu$A).

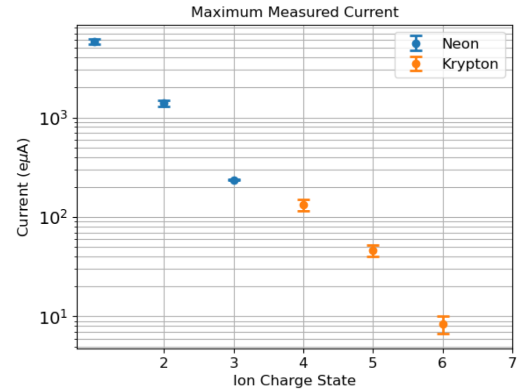


Figure 3: Measured maximum particle-currents of each charge-state of Neon and Krypton.

DISCUSSION

One will notice in Fig. 2 that there are many peaks at low M/Q, which corresponds to particles with a small turn radius. While it is possible these are hydrogen ions coming from remnant water within the source, this is unlikely due to the large measured currents relative to the gas ions (gas bottle is 99.999% purity), the existence of several of these peaks, the reproducibility of these peaks on longer runs, and their correlation with high magnetic field strengths. Therefore, these are more likely to be high-charge ions which curve in the magnetic field and miss the puller entirely. This could happen due to a combination of a large divergence of the extracted beam due to plasma meniscus effects, along with the curving trajectory due to the strong magnetic field. For this reason, it is believed that the charge states we are currently measuring with the static puller is likely underestimating the total amount of ions that can be extracted from the ion source. Future experiments could use a grounded electrode along the ion source to block these ions. However, the best method to maximize the extraction of various high-charge state ions would be an adjustable puller.

It should be noted that this ion source suffers from typical instabilities found in Penning discharges when the gas flow (and hence internal pressure) is low and the magnetic field is high [5]. This instability is found to be magnified when applying an extraction voltage, likely because the additional extraction of positive ions from the inner plasma leads to increased plasma losses, and may lead to a reduction of ion bombardment on the cathode necessary for thermionic electron emission. An indirectly heated cathode would allow for the thermionic emission to be independent of ion bombardment from the plasma. This could allow for a more stable plasma discharge at lower gas pressures, which could lead to higher charge state extraction.

Finally, an important caveat to these ion sources is the sputtering due to the ion collisions on the cathode. Though the ion source was designed so that the insulators separating the anode and cathode potentials are shielded from the line-of-sight of the cathode surface facing the plasma, the

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sputtered cathode material (Tantalum) will still condense onto this surface creating a conducting path. This is the primary reason for the short lifetime of the source. Additionally, the sputtering increases with ion mass, and the operation with Krypton specifically led to the tantalum material stacking on the anode and shorting directly with the cathode. This collection of cathode material on the anode, as shown in Fig. 4, only takes about an hour. This means that for heavy particles, the separation between the cathode and plasma chamber would need to be increased to prevent this.

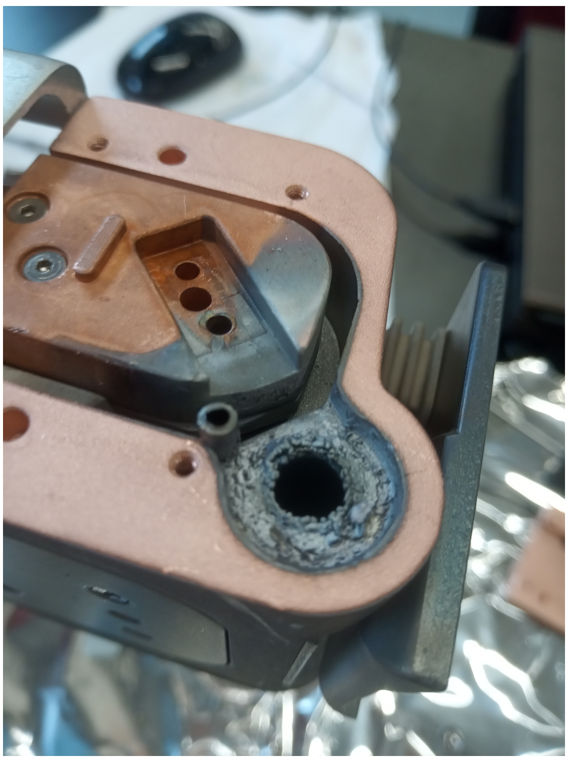

Figure 4: View of Penning ion source after Krypton experiments. The tantalum sputtered from the cathode collects on the anode and eventually makes contact with the cathode, creating an electrical short.

CONCLUSION

The Penning ion source at D-Pace's Ion Source Test Facility has been operated with Neon and Krypton gases. This ion source can produce the 1-3+ charge states of Neon and the 4-6+ charge states of Krypton. Maximum currents for each charge state are shown, with currents of 237 $\pm$ 4 $e\mu$A for Ne^{3+} and (8 $\pm$ 2 $e\mu$A) for Kr^{6+}. Ways to improve upon these results are discussed. Specifically, we mention that optimizing the beam current outputs and ion source lifetime could be achieved by using an adjustable puller, converting the design to an indirectly heated cathode, and by modifying the design to reduce sputtered material collecting on insulators and the anode body.

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