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EXTRACTION OF HIGH-CHARGE STATE ARGON AND α-PARTICLES FROM D-PACE PENNING ION SOURCE TEST STAND

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Abstract

At the D-Pace Ion Source Test Facility (ISTF), we measure the extracted current of high-charge state ions from a hot cathode Penning ion source. Producing high-charge states of boron, arsenic, and phosphorous is of interest to the ion implantation community. Higher-charge states allow these doping agents to be accelerated to higher energies within the same accelerating electric fields. When used for doping silicon semiconductors, this allows for deeper implantation of the ions. We use helium and argon gas as a proxy (non-toxic gases) to determine whether the Penning ion source could be used for high-charge state production in ion implanters. The ability to reach charge states of greater than 4+ with argon and 1+ with helium leads to the possibility of producing high-charge state ions used in the ion implantation industry. This paper shows the extracted beam currents of Ar^{3+} - Ar^{6+} and α-ions for the hot cathode Penning ion source with variations in the confining magnetic field ($|\vec{B}|$ = 0.4 – 0.95 T), inlet gas flow (Q = 0.3 - 10 sccm), and arc discharge current (I_{arc} = 1 - 3 A).

INTRODUCTION

D-Pace Inc has developed a self-heated hot cathode Penning ion source for studying the production of α-particles as a function of operational parameters such as magnetic field strength, inlet gas flow, and arc current [1]. The purpose of this test stand is to determine how to optimize the ion source for α-particle production. It is believed that an optimized Penning ion source could be a potential replacement for Electron Cyclotron Resonance ion sources used to axially inject α-particles into medical cyclotrons; due to the existence of high-current α-particle producing Penning ion sources developed in the past [2]. However, Penning ion sources can also be used for producing high-charge state ions of other gases and metal vapors [3]. The production of high-charge state ions is especially beneficial to the ion implantation sector, as it allows ions to be accelerated to higher energies without increasing the size and cost of an accelerator [4]. Therefore, the Penning ion source could potentially be used for ion implanters looking to produce high-charge states of boron, arsenic, and phosphorous. As these are toxic elements, we use the inert gases of helium and argon as substitutes, with the assumption that the production of α-particles (ionization energy = 54.42 eV [5]) and charge-states higher than Ar^{4+} (ionization energy > 59.58 eV) would correlate to the production of high-charge state ions useful for ion implanters.

In this paper, we show how the extraction of α-particles from the ion source is correlated with each operational parameters: inlet gas flow, arc current, and magnetic field strength. In addition, similar experiments are performed using argon as the inlet gas, and the measurable currents for each high-charge state ion are shown. In addition, some comments are made on the experimental setup, and how the Penning ion source can be improved in the future to optimize high-charge state production.

EXPERIMENTAL SETUP

The general setup up of the Penning ion source test stand is shown in the disseration by Savard [1]. The simplified schematic of this test stand is shown in Fig. 1. This schematic presents the ion source within the pole gap of a C-Magnet, which produces a uniform magnetic field of 0.4 - 0.95 T. The ions are extracted by raising the ion source body up to 15 kV with respect to the grounded static puller and vacuum box walls. These extracted ions undergo a curved trajectory in the magnetic field, and are measured by a moving Faraday cup after undergoing a 180° turn.

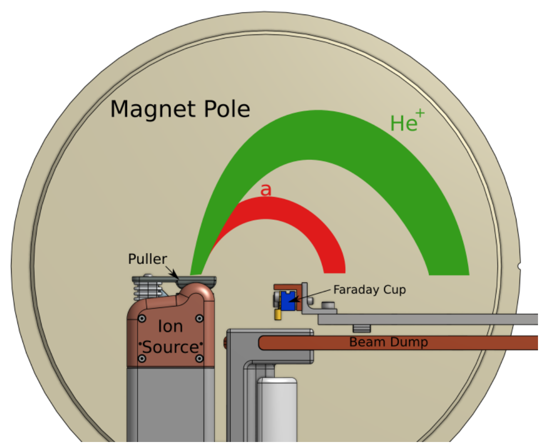

Figure 1: Simplified schematic of the experimental setup. Shown is the Penning ion source and the trajectories of the extracted ions (for helium operation) within the C-Magnet. A movable Faraday cup measures the current.

The Faraday cup is shielded by a grounded plate with a 62×2 mm slit. The measured current is fed through a load resistor (2.2 kΩ for helium), and the voltage across this resistor is measured by a NI USB-6001 data acquistion system. An example of the resultant peaks for a scan using helium is shown in Fig. 2. The upper estimate of current for each charge state is calculated by integrating the entire peak between their baselines, whereas the lower estimate is calculated by integrating over the full-width half-maximum of the peak. The appropriate peaks are found by converting the distance from the ion source extraction slit to the estimated

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mass-to-charge ratio (M/Q) of an ion given a particular extraction energy and magnetic field strength.

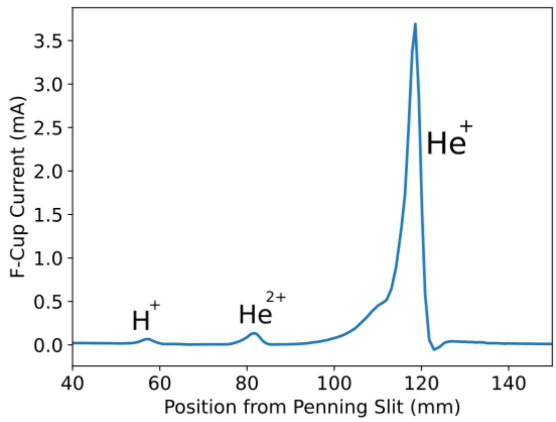


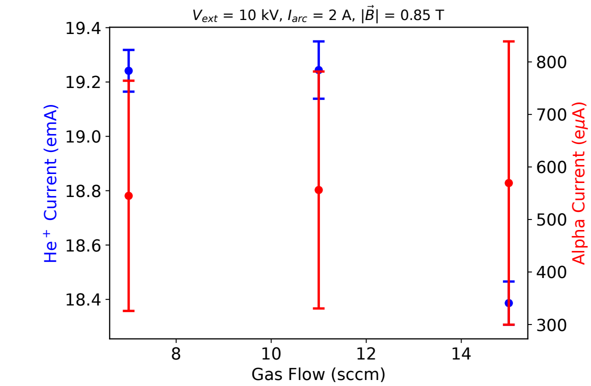
Figure 2: Example scan of measured currents as function of distance from ion source slit. Peaks labeled with its respective ion. Measurement taken at 11 kV extraction, 7 sccm gas flow, 2 A arc current, and 0.5 T magnetic field strength.

OPERATION WITH HELIUM

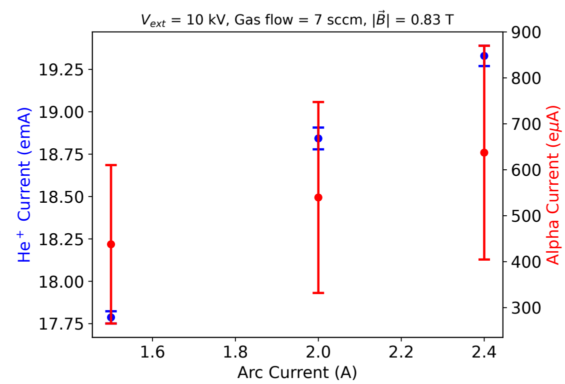
The Penning ion source was operated using helium gas (99.999% purity) which is fed into the ion sourch chamber at 5 - 15 sccm. Extraction voltages had to be set to less than 15 kV for most operational parameters since the total bias current will otherwise overload the 40 mA limited power supply (Glassman EQ series) used to supply the extraction voltage. It is unknown how much of this current is due to secondary emission. The He^+ and α-particle currents are shown as a function of gas flow, arc current, and magnetic field in Fig. 3. For each variation, the other operational parameters are kept constant as shown in the figure titles. It should be noted that the arc voltage is dependent on these operational parameters since the power supply driving the plasma discharge operates in current-control mode.

When increasing gas flow (Fig. 3a), the He^+ current seems to increase due to increased ionization collisions, but then rapidly drops. However, the total current on the high voltage power supply increases steadily, so it is likely that the ion current actually increases. With increased gas flow, the combination of increased space charge within the beam along with increased ion-neutral collisions increases the divergence of the beam, thus resulting in more of the beam to hit grounded components outside the Faraday cup. The α-particles have no clear dependence on gas flow. However, measurements of current on the puller showed an increasing current as a function of gas flow, which makes it difficult to determine whether α-particle production is truly independent of gas flow.

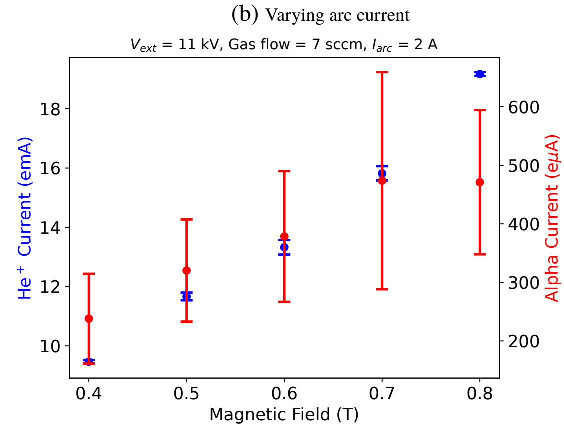
Figure 3b shows an increase in arc current results in an increase in measured current for both ions, likely due to an increased electron density required to maintain the higher currents at the cathode, which corresponds to an increased re-



(a) Varying gas flow



(b) Varying arc current



(c) Varying magnetic field

Figure 3: He^+ and α-particles currents read on Faraday cup for variations in (a) gas flow, (b) arc current, and (c) magnetic field strength.

action rate for ionization of neutral and ionic helium. Figure 3c shows that an increasing magnetic field also generally corresponds to higher current readings for both ions, likely due to the increased arc voltage that the power supply requires to maintain the set current when increasing the magnetic field. This means each electron emitted from the cathode has higher energy to contribute to ionization of the netural and ionic helium atoms.

From these measurements, it seems that in order to optimize the Penning ion source for high-charge states, one must

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increase the magnetic field and arc current of the plasma discharge. It is expected that lower gas flows would be beneficial as well, and it may be we cannot go to low enough gas flow to see this effect due to an over-cooling of the cathode. However, it is clear that future prototypes of the Penning ion source could potentially achieve up to 1 mA of α-particle current output.

OPERATION WITH ARGON

The Penning ion source was also run with argon in order to determine the amount of high-charge state argon ions that could be extracted. The gas flow is much lower compared to the helium case since the heavier atomic weight allows the inner chamber gas density to reach values similar to those of helium for lower gas flows. These experiments allowed for extraction voltage of 15 kV due to the lower total currents. An example plot of a measured mass spectrum using argon gas is shown in Fig. 4.

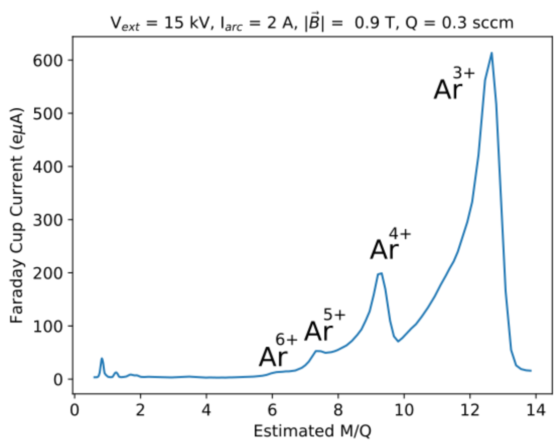

Figure 4: Example mass spectrum from the Penning ion source running argon gas.

Figure 5 shows the measured currents of various charge states of argon for different gas flows. The high charge state currents ($Ar^{>3+}$) increases at lower gas flows. This is expected as decreased neutral gas density means an electron is more likely to collide with ionic argon, hence producing greater densities of high-charge states through step-wise ionization. The high-charge state ion currents also increase as a function of magnetic field and arc current, just like the α currents in the helium case. These similarities imply that lower gas flow is expected to increase high-charge state production for helium as well. It is possible that increased α-particle bombardment on the puller as gas flow is increased is what causes the relative independence of measured α-current as a function of gas flow.

CONCLUSION

The Penning ion source test stand at the ISTF has been operated with various gas flows, arc currents, and magnetic field strengths using helium and argon as the inlet gas. It was

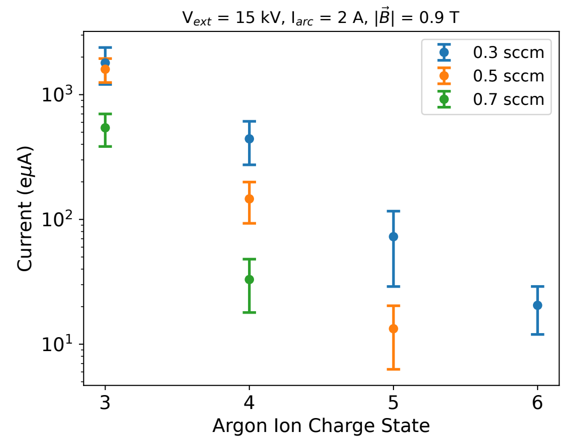

Figure 5: Measured argon ion currents of various charge states for various gas flows.

shown that low gas flows, high arc currents, and high magnetic field correlate to increased production of α-particles and Argon ions with charge states higher than 4+. The ion source can currently achieve α-currents up to 900 uA, with currents of Ar^{6+} up to 20 uA. It is expected that future prototypes of this Penning ion source could produce these particles at higher beam currents. This would correspond to increased beam currents of high-charge state ions when operated with elements used in ion implanters. This could allow future versions of the Penning ion source to be used for high-energy ion implantation.

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