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DEVELOPMENT OF A PENNING ION SOURCE TEST STAND FOR PRODUCTION OF ALPHA PARTICLES*

N. Savard†, University of British Columbia, Vancouver, Canada
D. Potkins, P. Jackle, J. Theroux, S. Melanson, G. Marcoux, M. Dehnel, D-Pace, Nelson, Canada

Abstract

Medical cyclotron manufacturers are seeking less-costly and more compact ion sources than Electron Cyclotron Resonance Ion Sources (ECRIS) for alpha particle production, which are currently capable of generating beam currents up to 2 mA at energies of 30 keV for axial injection into these cyclotrons. Penning Ion Sources by comparison are relatively old technologies mostly used for cheap singly-charged ion production. However, these ion sources have been used in the past for high-current multiply-charged state ion production of heavy ions up to a few mA of current, and are much smaller, cheaper, and less complex than ECRISs. Therefore, we are developing a Penning Ion source test stand to produce high-current alpha-particles for medical cyclotrons. This requires designs and simulations of all the primary components of the ion source. This system will be used to fully characterize the output beam current and internal plasma properties as a function of varying gas pressure, ion source geometries, magnetic field strength, arc voltage/current, and material properties. The result will be a source optimized for maximum alpha particle beam currents, to be used as a prototype for a commercial Penning Ion Source.

INTRODUCTION

Penning Ion Sources (referred to as PIG sources) are ion sources composed of a cylindrical anode, cathode caps at either end, and a strong magnetic field along the cylindrical axis. A plasma discharge is generated between the electrodes, and is confined predominantly by the strong magnetic field. The ions are extracted through a slit on the side of the anode with an additional electrode outside the slit (see Fig.1).

Due to their small size (few cms in height) and the need for a strong magnetic field, these ion sources are very popular for low charge state ion production in cyclotrons. However, medical accelerators are in need of higher-charge state particles, such as α-particles, to generate medical isotopes (such as Astatine-211) for radiotherapy [1]. The ECRIS (Electron Cyclotron Resonance Ion Source) is often used to produce high-charged state ions, such as for the production of α-particles, in these medical cyclotrons through an injection beamline. However, these ion sources are costly and large, and are therefore overkill when used purely for α production.

A PIG source might be used as a cheap alternative, as there have been examples of these ion sources able to achieve up to a few mA of α current [2]. In order to achieve the requirements set by manufacturers (such as IBA, Sumitomo, ACSI, and BEST) such an ion source will need to output up to ≈2 mA α-current, at energies of 30 keV, with a normalized emittance less than 1 mm-mrad. However, using PIG sources for generating α particles is rare, as very few studies can be found on this topic.

Therefore, in order to test the capability of such an ion source for α-particle production, D-Pace/Buckley Systems is designing and manufacturing a PIG source which will be able to characterize the α-particle output beam currents as a function of various input parameters. These include the gas pressure, arc voltage/current, anode size, extraction geometries, and magnetic field strength. In addition, optical emission spectroscopy and langmuir probes will be used to characterize the plasma properties such as electron density and temperature, and how they correlate to the input parameters and output current. Such information can be used to create an optimized prototype PIG source for maximal α-particle currents necessary for medical accelerators. Furthermore, PIG sources are capable of producing high-charge states of heavy ions [3] which might be of interest to ion-implanters, and are capable of producing H^- through a reversal of polarity [4], which is also applicable to medical accelerators. There is potential to also optimize the PIG source for production of these ions as well.

DESIGN

The ion source test stand's design prioritized variability in order to get a better parametric range from which to optimize high α-currents. These dynamic parameters are gas flow (source gas pressure), arc voltage/current, magnetic field strength, and anode/puller geometries. The beam currents will be measured with Faraday cups, whereas plasma density and temperature can be estimated with optical emission spectroscopy and Langmuir probes.

The design of the ion source system is presented in this paper. Unless stated otherwise, all simulations were done in COMSOL™ Multiphysics [5].

Internal Source

The primary ion source components are shown in Fig. 1. The anode is at bias (nominally 15 kV) to the grounded puller. The cathode is negatively biased (0 - 5 kV) with respect to the anode. These are clamped together with 'insulator holders', which also insulate the ion source from the grounded chamber and magnet poles. The helium gas feeds through the anode from the top and leaks through the slit into a vacuum chamber. The bottom of the anode has a hole, which currently shows a rod used to stabilize the ion source. This can also be used with a gas feed to get a more uniform gas pressure within the ion source.

* Work supported by D-Pace Inc. and TRIUMF
† nsavard@phas.ubc.ca

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Previous literature [3] mentions that PIG sources can go up to 3 kW of power, though this upper limit is usually for heavier elements than Helium. As a result, the anode was made of graphite, which has a relatively high emissivity, allowing it to cool via radiation to the vacuum chamber walls. The cathodes are made of tantalum due to its low sputtering rate, low work function (allowing for electron emission) and high melting temperature. These cathodes are water-cooled with copper tubes. The anode and cathode are separated by aluminum nitride, an electrical insulator but moderate thermal conductor to allow the anode to cool from the water tubes as well. The insulator holders are also made of aluminum nitride.

Heat transfer simulations were done combining radiative and conductive heat loss. These showed that for up to 3 kW power, the graphite will not approach its melting point (> 3500°C). However, the radiated heat is not well absorbed by the low-emissivity copper puller and aluminum chamber walls. If experiments show a power consumption of > 2.5 kW, then the inner chamber walls and puller will need to to be coated with a high-emissivity material to increase heat loss from the ion source walls. The tantalum cathodes need to remain hot, up to about 2200°C to get the estimated thermionic current of a few Amps. For 3 kW power, this means the tantalum cathodes need to have a thick (8 mm diameter) stem to increase heat loss to the water-cooling pipes (up to 3 l/s) and prevent overheating. At lower powers, the water flow speed might need to be decreased to allow the ion source to reach a stable thermionic temperature.

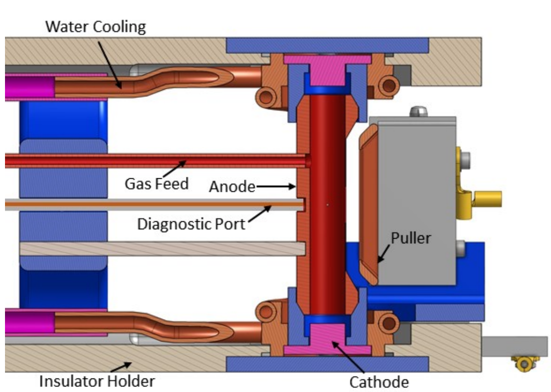

Figure 1: Cross-section view of primary PIG source components. Includes the anode, cathode, insulator holders, water cooling tubes, puller, and the diagnostic port.

The center of the anode will have a port for diagnostics, composed of an insulating cylindrical rod. An optical fiber can be inserted for measurements of optical emission from the plasma which can give the electron density and temperature, and ion temperature. In addition, a small Langmuir probe can be inserted within the plasma which can be used to measure the plasma potential, density, and temperature. These are the primary diagnostics used to determine plasma properties. The gas feeds above and below the diagnostic port can also be used for optical emission spectroscopy, in order to see how plasma properties change closer to the cathodes.

The vacuum inside the chamber will be generated by a Pfieffer HiPace^{TM}700 TurboPump. Molflow+ [6] was used to estimate the ambient pressure for gas flows of around 5 sccm. This provides vacuum levels of around 10^{-5} Torr, still high vacuum, and considering the low path length of the ions within the chamber, will lead to negligible ion collisions with the background gas.

In theory, electric fields can be very high without creating sparks in high vacuum. However, in practice sparks will still occur higher than 5 kV/mm [7]. In order to avoid that, 3D electrostatic simulations were run to ensure the spacing between HV components was appropriate.

Magnet

The magnet needs to fulfil a few conditions. Firstly, it needs to produce fields for confinement of the plasma within the ion source, which needs to be a minimum of about 0.2 T [8]. Secondly, it will be used as a 180° mass spectrometer for the particle species He^+/He^{2+} extracted from the source, to be collected with a set of movable Faraday cups (see Fig. 2) which can scan the beam currents after a 180° turn. Finally, it has to be able to operate at a range of field strengths while keeping the field uniform, in order to determine the plasma/beam properties as a function of field strength.

A C-magnet was designed with a pole gap of 78 mm, to allow for potential changes in anode length (< 5 cm) within the field. The pole diameter is 270 mm, chosen to enable beam current measurements with the faraday cup after the particles undergo a 180° turn (see Fig. 2) down to a range of 0.4 T, below which the particles travel outside the pole area. Simulations of the field show that the magnet yoke reaches saturation at about 1.1 T, therefore being the maximum field used for measurements. The ion source is placed off the pole-axis in order to allow beams at lower fields to remain within the pole diameter, allowing them to be measured by the Faraday cup.

Extraction and Measurement

The extraction voltage between the anode and puller electrode is chosen to be 15 kV nominally, though it can go up to 30 kV. The puller is allowed to move towards/away from the anode and side-to-side using stepper motors. The slit size of the anode is nominally 8 mm x 1.5 mm, and is one of the geometric properties that can be changed, along with the slit size and shape of the puller.

Extraction from the plasma is an important subject in ion source modelling, where simulation tools such as IBSIMU [9] often use assumptions of collisionless plasma sheaths within the ion source, which generates a plasma meniscus affecting the initial divergence of the beam. However, strong magnetic field perpendicular to the extraction direction make this assumption inaccurate. In this case, a flat beam was assumed, and the puller geometry was optimized to extract particles for a 0.4 - 1.1 T magnetic field strength without particles bombarding the puller. This was modelled

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using charged particle tracing including space charge effects, which allows us to follow the particle trajectories, to make sure that the particles rotate within an allowable space for measurement with the Faraday cups (see Fig. 2), and that the spread of the beam still allows us to separate the He^{+}/He^{2+} species. This requires the puller to be repositioned for various field strengths to allow all particles to pass through.

The Faraday cups can be scanned along the 180°C turn axis to measure the currents of the different species, since the ratio of He^{+}/He^{2+} can give insights to inner plasma properties. The leftmost Faraday cup is shorter than the right, and is used to measure currents at high fields, where the cup needs to fit into the space between the insulator holders due to the tight turns of the particles.

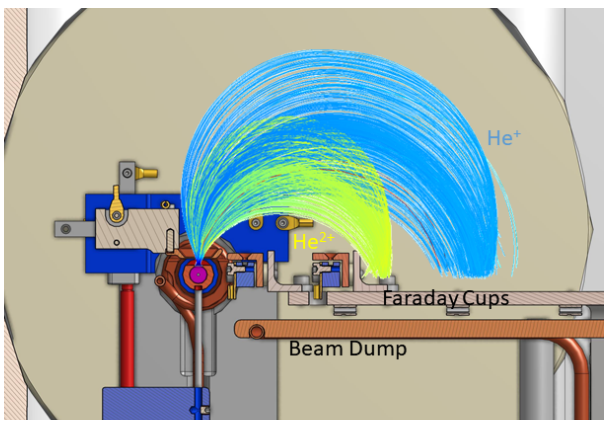

Figure 2: Simulation overlayed on a cross-sectional view of the ion source system, showing curvature of He^{+}/He^{2+} for the magnet set to about 0.71 T. The currents are collected by movable Faraday cups, and a beam dump collects the remainder of the beam.

Ignition

The plasma in PIG sources is sustained by ion bombardment of the cathode, creating electrons which are emitted into the plasma bulk. The two primary operational modes are the cold cathode and hot cathode modes. In cold cathode ion sources, an electron is released directly through secondary electron emission from ion bombardment, whereas in hot cathode ion sources the electrons are emitted due to thermal emission of the cathode material as its temperature increases from ion bombardment. Hot cathode modes usually produce higher numbers of high-charge state ions due to the increase of electron density and therefore α density. As a result, a circuit was developed to operate the ion source in hot cathode mode, shown in Fig. 3. This will be done by discharging a 100 μF capacitor up to 5 kV between the anode and cathode, used to get the plasma discharge to the hot cathode mode, after which an additional HV Glassman power supply (750 V, 4 A) can take over to maintain the discharge. The supply can be operated up to 4 A, and two can be combined in parallel in order to double the current output.

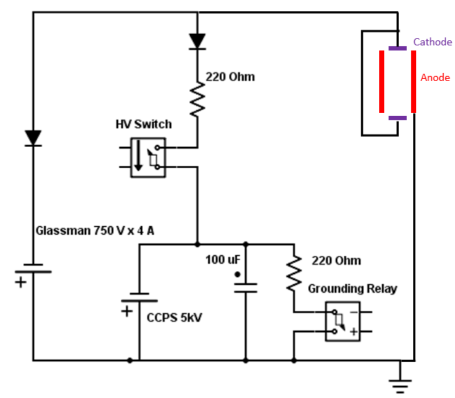

Figure 3: Simplified schematic of ignition circuit for the ion source. The CCPS (Capacitor Charging Power Supply) charges a 100 μF capacitor, which is then discharged through the ion source. As the cathodes become hot and release thermionic electrons, the ion source gets into a higher current state (> 1 A), where the main Glassman power supply (750 V, 4 A) takes over.

CONCLUSION

ECRISs are great for producing high-charge state heavy ions for nuclear physics, but costly for cyclotron manufacturers that use it only for α particles. The PIG source has potential to be a cheaper alternative to the ECRIS, and as a result, D-Pace/Buckley Systems is designing a test stand to study the output α beam-current in a PIG source as a function of several parameters, in order to fully characterize and optimize the ion source for α production. As a result, several parts of the test stand have been designed for variability, such as the ion source components and materials to allow high power operation, the magnet to allow a large range of magnetic field strengths, and the ignition system circuit to operate the ion source at several arc voltages/currents. In addition, diagnostic ports have been included to study the plasma properties of the ion source to better understand how the plasma dynamics are affected by various parameters, and how they in turn affect output beam current. This test stand is currently being manufactured, and is expected to be ready for operation in August 2019.

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