ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM56

DEVELOPMENT OF HELIUM GAS CHARGE STRIPPER WITH PLASMA WINDOW*

J. Gao†, F. Marti, Facility for Rare Isotope Beams,
Michigan State University, East Lansing, MI, USA
A. LaJoie, National Superconducting Cyclotron Laboratory,
Michigan State University, East Lansing, MI, USA

Abstract

The cascade arc discharge, also called “plasma window”, was proposed to be used as an interface to provide an effective separation between atmosphere and vacuum. As suggested by Thieberger and Hershcovitch at Facility for Rare Isotope Beams (FRIB) workshop in 2009, helium plasma window offers an alternative to a large pumping system used in helium gas charge stripper for high intensity heavy ion beam accelerator facilities. In this report, we present the recent progress on the development of helium plasma window with 10 mm diameter apparatus. The sealing performance of helium plasma window has been investigated. Various diagnostics tools have been developed to improve our understanding of underlying physics. Over 140 hours continuous unattended operation of helium plasma window in recirculating gas system has been achieved, which suggests our system to be a feasible charge stripper solution for heavy ion beam accelerators. We also discuss anticipated future developments of plasma window.

INTRODUCTION

For intense heavy ion beam accelerators, helium gas can be a good candidate for stripping, although offering lower charge states than liquid lithium [1]. The advantages are the helium gas has less safety concerns and contributes no contamination to superconducting cavities afterwards. The work at RIKEN has showed that a recirculating helium gas stripper with a large differential pumping system can be used for stripping U beam at an energy of approximately 11 MeV/u [2]. The pressure at the helium target is around 7 kPa and a final pressure of 5 x 10 $^{-6}$ Pa is achieved after five stages pumping system. Compared to RIKEN, the stripping energy at FRIB is about 16.5 MeV/u. A thicker stripper is required in order to achieve an equilibrium charge state distribution. According to the approximation [1], a 30 cm long with a cell pressure P_{cell} of 40 kPa can produce an average charge state of 71+, starting from 33+.

As suggested by Thieberger at 2009 Facility for Rare Isotope Beams Facility (FRIB) workshop on high power strippers and targets, plasma window contained helium cell can be used as an alternative to a large pumping system in gas charge stripper applicable for high intensity heavy ion beam accelerator facilities. The novel apparatus of plasma window used as an interface to provide an effective separation between atmosphere and vacuum was first proposed by Hershcovitch [3]. Many applications of such an effective vacuum seal device have been demonstrated [4–8].

The basic idea is to install a pair of plasma windows on both sides of helium gas chamber, so that the gas leakage to the beamline which is under high vacuum can be significantly reduced [1]. A 10 mm diameter arc flow channel is desired due to the intense beam at FRIB. Argon cascade arc with high pressure up to 9 atm and diameter from 2 mm to 10 mm has been studied previously [3–12]. However, the helium cascade arc has rarely been investigated, especially with high flowrate and large aperture. In order to develop a vacuum-atmosphere interface for the high intensity heavy ion beam at around 16 to 20 MeV/u, a recirculating plasma window test stand was developed.

In this report, we summarize recent development of helium gas charge stripper with plasma window. In Experimental Setup, a new diagnostic plate design is presented. The sealing performance of 10 mm plasma window under various experimental conditions is shown in Results. Over 140 hours long term operation of helium plasma window in recirculating gas system has been achieved for the first time. The last section discusses the future plan and concludes the results.

EXPERIMENTAL SETUP

A schematic diagram of the experiment is shown in Fig.1(a). The plasma window consisting of three cathodes, a series of eight copper disks and an anode, is inserted between a high-pressure gas cell and a low-pressure chamber. The arc can be generated between the cathodes and the anode. The whole system is cooled by water. An Omega flowmeter (not shown in Fig.1(a)) is connected to the high pressure gas cell in series. The cathode tip is made of 2% thoriated tungsten, 2.5 mm diameter and shaped into a 40-degree cone. Each floating disk is electrically insulated by G10 spacers and sealed by Kalrez made O-rings which have high temperature resistance up to 600 K. In order to better confine the cascade arc and restrict the gas flowrate, a disk with 6mm bore size is attached near the cathodes. The rest of the disks have 10 mm diameter hole. The total length is around 8 cm. After pumping through the low-pressure chamber, the gas can be recirculated in the system. The setup is similar to that described in Ref [12].

Figure 1(b) shows a newly fabricated diagnostic plate with a side viewport. A 2 mm diameter hole inside the viewport is selected so that the flow pattern disturbance can

---

[*] Work supported by NSF Award PHY-1565546

[†] gaoj@frib.msu.edu

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM56

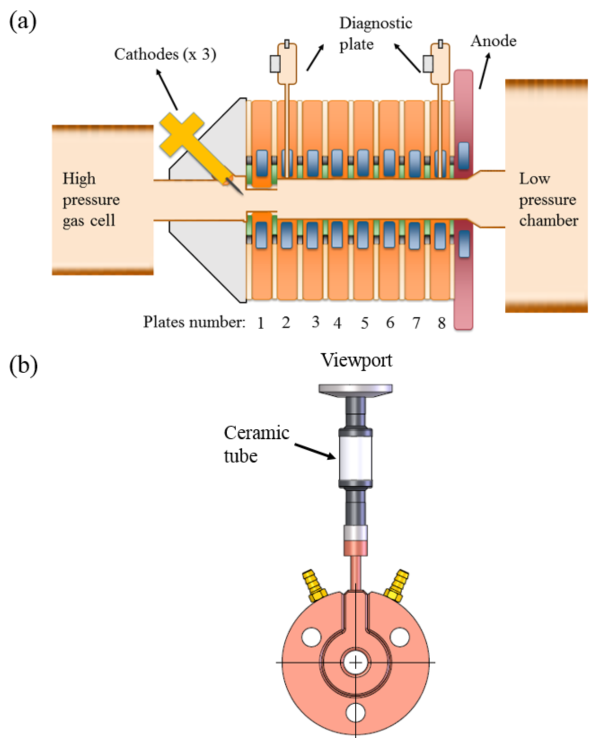

Figure 1: (a) A schematic showing the experimental setup. The plasma generated between cathodes and anode is cooled by a series of copper disks. The plasma window can be used as an interface between high pressure gas cell and the low-pressure chamber. (b) A design of diagnostic plate includes a side viewport, which allows the measurement of pressure and spectroscopy.

be minimized. A ceramic tube with about 8 mm diameter inner hole is added to provide electrical insulation for an attached pressure gauge or an optical feedthrough. A pair of diagnostic plates are installed on two sides of the plasma window, as outlined in Fig. 1 (a). This setup allows the local measurement of gas pressure and optical spectral when the arc is established between the cathodes and the anode.

In a typical experiment, the arc is first generated in low pressure argon gas flow based on Paschen's curves [13]. Then we ramp up the current up to 70 A for each cathode, and slowly feed the system with helium gas and close the argon gas supply until the system is full of helium gas. Normally we wait for a time long enough to allow the arc flow to be stable enough before recording the data. By varying the gas flowrate and the total current input, this process can be repeated.

RESULTS

The arc flow properties including the mass flowrate, current and pressure distributions are recorded. By varying the current supply for each cathode, the measured mass flowrate to sustain different cell pressure is shown in Fig. 2. It is found that the flowrate decreases as we increase the current while keeping the same cell pressure. This can be understood by the viscosity effect due to the increment of gas temperature as we increase the power source into the system. The current input is limited by the corresponding power supply unit. At P_{cell} 40 kPa and the total current of 210 A, the gas flowrate is around 90 SLM, corresponding to 0.27 g/s. Compared to the flow without arc, the gas flowrate has been reduced by over 80%. As one can see, the flowrate can be further reduced if we keep increasing the current. One should notice that higher cooling efficiency is necessary for higher current condition.

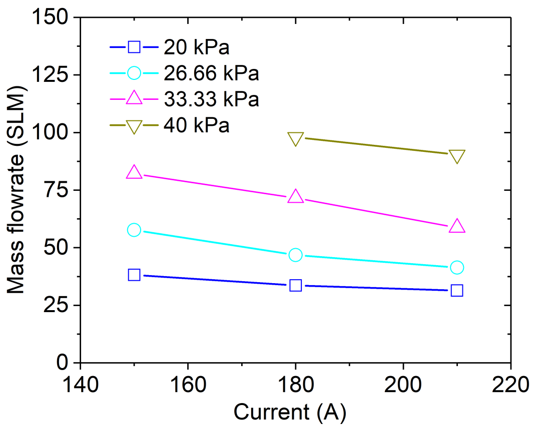

Figure 2: Measured mass flowrate as a function of current under different gas cell pressure.

It was suggested that the pressure drop through plasma window occurs in two sections: arc discharge region and the expansion chamber [14]. The first section can be explained by the increased viscosity. The choked flow condition will be established once the high temperature gas with low density enters the low pressure chamber, resulting in limiting the flow. Table 1 lists the pressure distribution under different P_{cell} with 70 A applied for each cathode. One can clearly see that the majority of the pressure drop occurs before Plate 8. It has been found that the ratio of the gas cell pressure to the chamber pressure can be over 5000.

Table 1: Pressure Drop Through Plasma Window With Constant Current (kPa)

P_{cell}	Plate 2	Plate 8	Chamber
40	21.97	13.87	0.011
33.33	15.72	9.79	0.0065
26.66	11.83	6.97	0.0047
20	9.25	5.01	0.0036

A long-lasting helium gas arc flow is very difficult to achieve, mainly due to the instability of the high temperature arc condition. When the arc is generated between the cathodes and the anode, the helium ions collide on the surface of the electrodes emitting more electrons to sustain the arc flow. Figure 3 is an example showing a picture of the elec-

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM56

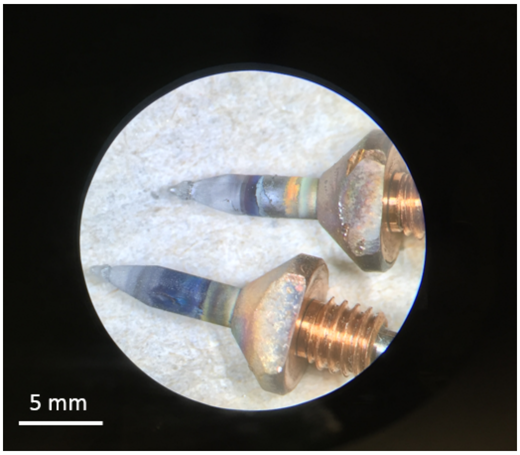

Figure 3: A picture of used electrodes after a few hours arc burning.

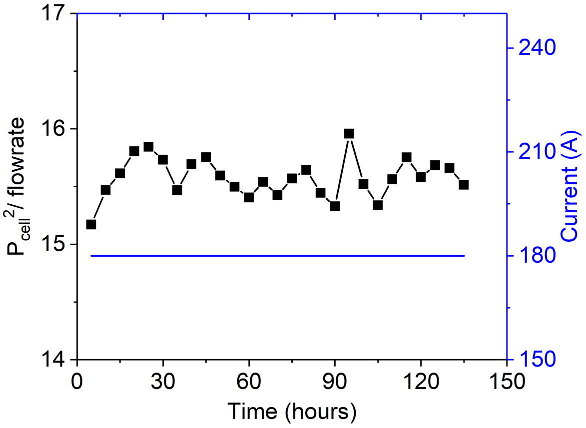

Figure 4: The ratio of the $P_{cell}{}^2$ (in kPa) to the measured gas flowrate (in SLM) in the long-term operation, over 140 hours; the total current is 180 A for the same period.

trodes after a few hours operation. Several different zones were developed on the cathode surface. A small build up of tungsten material and the changes in the shape near the electrode tip that emits electrons can be clearly seen. Also the total length of the electrodes reduces as the arc is running. Similar behavior were observed with various types of electrodes including pure tungsten, 2% thoriated tungsten, 2% lanthanated tungsten and tri-mix tungsten. More detailed study about the behavior of the tungsten-oxide electrodes can be found in Ref [15].

More recently, we have successfully run helium plasma window contained gas cell in recirculating gas system for over 140 hours. In the long-term operation, the total current supplied to the system was 180 A and the estimated total power around 23 kW. Assuming Poiseuille flow in the plasma window, if the plasma is stable leading to a constant flow viscosity, the gas flowrate is approximately proportional to $P_{cell}{}^2$. We plot the ratio of $P_{cell}{}^2$ to the mass flowrate in Fig. 4, which is more or less constant while the arc is burning. The successful operation of stable 10 mm plasma window in helium recirculating gas system provides a feasible charge stripper solution for heavy ion beams.

CONCLUSION

Current plasma window setup limits the beam size near the cathodes' side. It is always desirable to have large opening and less gas leakage to the beamline. Our plan is to explore how the mass flowrate and pressure distribution vary as we change the geometry of the plasma window. Since the focusing of the ion beam is inside the gas cell, a progressive increment of the channel size might be an option. Besides, the plasma window test stand only consists half of the gas stripper system. In order to be eligible for a gas charge stripper, a similar test stand system will be implemented on the other side of the gas cell.

The sealing performance of 10 mm plasma window device has been investigated. It has been observed that the mass flowrate decreases as the current increases with a constant cell pressure. With the aid of plasma window, the gas flowrate can be reduced by over 80%. A newly fabricated diagnostic plate allows the local pressure measurement, which reveals that the majority of the pressure drop occurs before the anode. The pressure ratio of the gas cell to the chamber can be over 5000. Over 140 hours long-term operation of plasma window contained helium gas cell in recirculating mode has been successfully achieved, which offers an alternative stripper option for heavy ion beam accelerators.

ACKNOWLEDGMENTS

We would like to thank P. Thieberger and A. Hershcovitch at Brookhaven National Laboratory for helping set up the plasma window test stand and supplying the equipment that are used for present study.

REFERENCES

[1] J. A. Nolen and F. Marti, "Charge Strippers of Heavy Ions for High Intensity Accelerators," *Rev. Accel. Sci. Technol.*, vol. 6, p. 221, 2013.

[2] H. Imao *et al.*, "Charge stripping of U 238 ion beam by helium gas stripper," *Phys. Rev. ST Accel. Beams*, vol. 15, p. 123501, 2012.

[3] A. Hershcovitch, "High-pressure arcs as vacuum-atmosphere interface and plasma lens for nonvacuum electron beam welding machines, electron beam melting, and nonvacuum ion material modification," *J. Appl. Phys.*, vol. 78, no. 9, p. 5283, 1995.

[4] A. Hershcovitch, "Air boring and nonvacuum electron beam welding with a plasma window," *Phys. Plasmas*, vol. 12, no. 5, p 57, 2005.

[5] A. de Beer *et al.*, "Performance of a plasma window for a high pressure differentially pumped deuterium gas target for mono-energetic fast neutron production – Preliminary results," *Nucl. Instrum. Methods B*, vol. 107, p. 259, 2000.

[6] A. Hershcovitch, "Non-vacuum electron beam welding through a plasma window," *Nucl. Instrum. Methods B*, vol. 241, p. 854, 2005.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM56

[7] B.Y. Pinkoski *et al.*, "X-ray transmission through a plasma window," *Rev. Sci. Instrum.*, vol. 72, no. 3, p. 1677, 2001.

[8] A. Hershcovitch, "A plasma window for transmission of particle beams and radiation from vacuum to atmosphere for various applications," *Phys. Plasmas*, vol. 5, p. 2130, 1998.

[9] S. Huang *et al.*, "Quantitative characterization of arc discharge as vacuum interface," *Phys. Plasmas*, vol. 21, p. 123511, 2014.

[10] S.Z. Wang *et al.*, "Theoretical and experimental investigation on magneto-hydrodynamics of plasma window," *Phys. Plasmas*, vol. 23, p. 013505, 2016.

[11] S. Namba *et al.*, "Development of a cascade arc discharge source for an atmosphere-vacuum interface device," *Rev. Sci. Instrum.*, vol. 87, p. 083503, 2016.

[12] A. Lajoie *et al.*, "Study of High-Flow Argon Through Cascaded Arc for Use as a Gas Target Isolator," *IEEE Trans. Plasma Sci.*, vol. 47, no. 5, p. 2752, 2019.

[13] V.A. Lisovskiy *et al.*, "Low-pressure gas breakdown in uniform dc electric field," *J. Phys. D: Appl. Phys.*, vol. 33, p. 2722, 2000.

[14] G.M.W. Kroseen *et al.*, "Description of a flowing cascade arc plasma," *Plasma Chem. Plasma Process.*, vol. 10, p. 531, 1990.

[15] A. A . Sadek *et al.*, "Effect of rare earth metal oxide additions to tungsten electrodes," *Metall. Trans. A*, vol. 21, p. 3221, 1990.