PLASMA WINDOW AS CHARGE STRIPPER COMPLEMENT*

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Abstract

Modern ion accelerators, particularly heavy ion accelerators, almost universally make use of charge stripping. A challenge facing facilities, as the demand for higher intensity beams rises, is a stripping media that's highly resistant to degradation, such as a recirculating He gas stripper [1]. A method of keeping the He gas localized in a segment along the beamline by means of a Plasma Window (PW) positioned on both sides of the gas stripper has been proposed and the initial design set forth by Ady Hershcovitch [2]. With a cascaded plasma arc being the interface between high pressure stripper and low pressure beamline, the goal is to minimize gas flowrate from the stripper to the beamline in order to maintain sufficient isolation of the He gas. We present the initial results from the test stand developed at Michigan State University and the planned experimental program that will follow.

INTRODUCTION

Pushing the frontier of intensity and energy of Heavy Ion Beams requires facilities to employ some form of charge stripping. Solid thin carbon foils, while relatively easy to prepare and employ, suffer from often impractically short lifetimes when used with a high intensity heavy ion beam [1]. Alternatively, gaseous stripping media must be maintained at pressures much greater than those of the beamline to present a reasonably high degree of beam-gas interaction. In the case of the Facility for Rare Isotope Beams (FRIB) for example, the pressure of such a stripping gas would be on the order of 300 torr, and beamline pressure would be on the order of 10^{-8} torr. Inclusion of some structure to support such a large pressure differential while maintaining a flowrate low enough to not excessively load the vacuum system, presents a significant challenge with the Plasma Window being one possible solution.

During the R&D for FRIB a helium stripper and a liquid lithium stripper were considered. The first phase of development of the helium stripper contained by plasma windows was performed at Brookhaven National Laboratory (BNL) by Hershcovitch, Thieberger, and collaborators. The liquid lithium stripper was finally selected as the preferred choice because of the expected higher charge states obtained. As the potential applications in other accelerators as strippers or targets were interesting we pursued the development of a test stand at MSU to improve the performance and study the scaling laws of the different design parameters.

The Plasma Window is a wall stabilized DC arc discharge [3] that greatly inhibits the flow of gas between high (~300 torr) and low (~1 torr) pressure regions that the window connects, so provides an interface between high and low pressure without the need for solid material. This is the primary application for the PW under consideration in this work, with the high pressure gas representing a He gas charge stripping media, for example, ideal for use in a heavy ion accelerator. Hershcovitch has mentioned a great deal of other possible applications all stemming from the function of the PW being a pressures interface, such as electron beam welding, non-vacuum material modifications, transmission of high energy synchrotron radiation, and to isolate gas targets for use in fast (fusion) neutron generation or nuclear physics experiments. These will not be further mentioned in this work [2, 4].

Currently, the scaling laws for the PW's operation are not wholly understood. Different mechanisms have been proposed and obtaining some general relationship between flowrate and geometric, plasma, and fluid properties. Minimization of the PW's flowrate in terms of geometry and current supplied relies critically on a thorough understanding of the plasma and fluid processes within. Relevant plasma parameters can vary substantially with respect to initial conditions [5].

PREVIOUS EXPERIMENTS

The functionality of the window as separator of vacuum and atmospheric pressures is attributed primarily to the high temperature of the plasma relative to the inlet gas. Assuming the pressure within the channel is on the order of that in the high pressure inlet gas cell, the density of the gas in the arc must be significantly lower than that at atmosphere, by the ideal gas law. Additionally, viscosity of ions, electrons, and gas exhibit strong (through different mathematical expressions) dependence on temperature [2].

$$\eta_i = 2 * 10^5 \mu^{1/2} \frac{k}{\lambda_i} T_i^{5/2}$$

$$\eta_e = 2.5 * 10^7 \frac{k}{\lambda_e} T_e^{5/2}$$

$$\eta_g = a T_g^x$$

In the above equations, η_i, η_e, and η_g are ion, electron, and gas viscosities respectively, similarly for T_i, T_e, and T_g for temperatures. The respective Coulomb logarithms are

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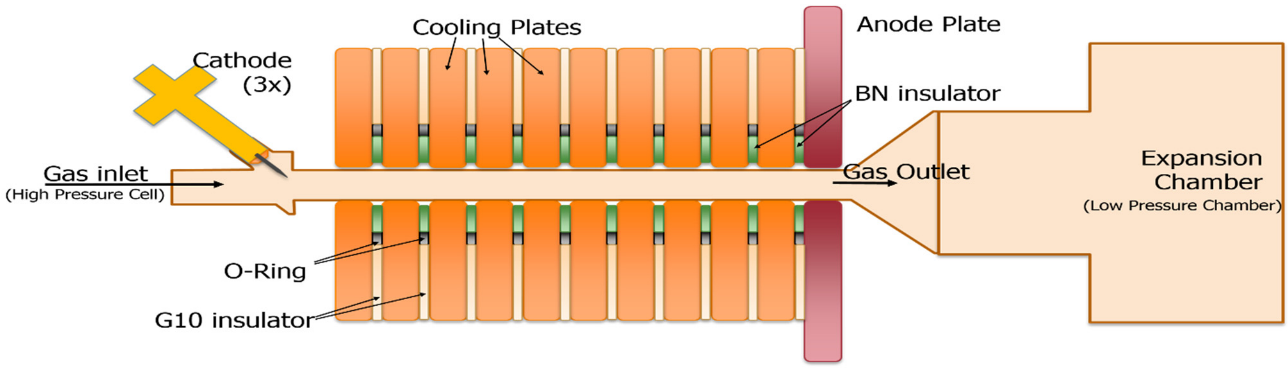

Figure 1: Schematic (not to scale) of the Plasma Window. Ten cascaded arc cooling plates of floating potential are each 1 cm in width and separated by 1mm of O-ring, boron-nitride spacers, and G10 spacers to insulate them from their neighbors. Three thoriated tungsten needle cathodes collectively deliver up to 90 amps.

given by λ_i and λ_e, k is Boltzmann constant, μ is ion mass in proton mass units, and finally a and x are constant characteristics for a given gas. This then acts to effectively lessen the flowrate [2]. Another suggested mechanism for the observed flowrate reduction is a choked flow condition being reached in the Plasma Window at high inlet pressures.

Other authors have performed different forms of analysis to determine an overall temperature for the plasma in the channel, but these rely on the assumption of Local Thermodynamic Equilibrium (LTE), a feature very unlikely for this plasma [6, 7, 8].

Huang et al [6] investigated a variety of geometric arrangements of their own design of the Plasma Window, finding that their data fit reasonably well to a fit curve of a normalized pressure vs input power, following similar analysis conducted by Vijvers et al, motivated by the assumption of Poiseuille Flow [6, 9]. A spectroscopic analysis was conducted to determine an integral electron temperature, but no additional measurements were provided which may have given some indication as to the axial profile of this and other plasma parameters.

Krasik et al [10] used a similar spectroscopic method to obtain an average temperature of the plasma (heavy particles) by assuming it was a blackbody radiator. This method, also employed by Ben-Liang et al [11], was found to be in good agreement with temperature obtained by averaging presumed plasma conductivities and comparing with a collection of theoretically calculated values to obtain corresponding temperatures. Vijvers, in addition to the Optical Emission Spectroscopy mentioned above, performed a Thomson Scattering measurement to obtain a radial profile of electron temperature and density [9].

PRELIMINARY RESULTS

Although the ultimate desired pressure difference to maintain spans roughly ten orders of magnitude, the MSU-housed assembly is currently outfitted and operates with only the first stage of the differential pumping system. Additionally, this PW has been only used so far with Ar gas due to the relative ease with which the arc can be established. This allows us to more easily characterize the properties of the plasma and surrounding gas chambers during operation.

The window is comprised of ten 1cm thick floating voltage metal plates separated by O-rings, boron-nitride spacers, and G10 spacers to insulate them from adjacent plates, each 1 mm thick. A final grounded anode plate of 10.6 cm diameter is added at the end and in contact with the expansion chamber. The ten metal cooling plates have outer diameter of 6.1 cm, and every plate has an inner hole of diameter 6 mm. The Plasma Window schematic in Fig. 1 illustrates the arrangement. Each plate, cathode, cathode-holding structure, and anode are cooled by a continuous flow of water. Temperature probes are affixed to the return-side of the coolant tubing to determine the amount of heat removed by the water in each individual plate.

Figure 2 shows a comparison between the measured flowrates of an Ar gas flow without arc and with arc, at three different current values.

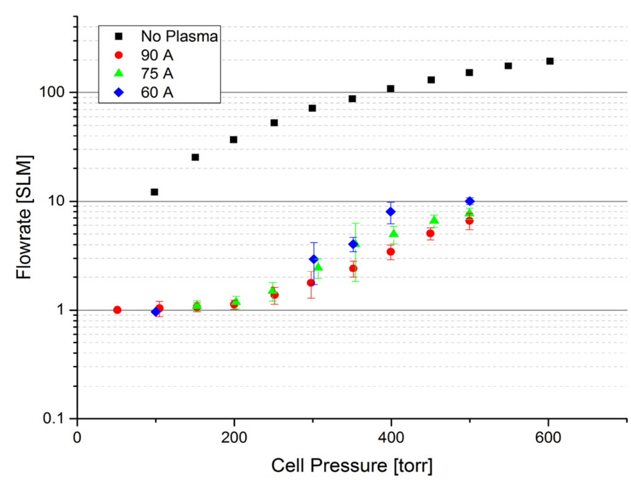

Figure 2: Flowrate values for both un-ionized gas flow and plasma at multiple current values. Error bars are the standard deviation of all points (between 50 and 150 points) during the collection time for a specific pressure setpoint.

A value of inlet pressure is set and a MKS Mass Flow Controller 1579 adjusts the gas flow such that this pressure

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is maintained. This illustrates the large pressure gap resulting from the arc, in addition to an apparent difference in scaling of flowrate with respect to Cell pressure.

Comparisons of gas flowrate with the arc on and off have been made for a series of pressures and arc currents. An initial experiment has been carried out using Ar gas. The PW has been used to reduce flowrate by a factor of up to 40 at 90 A total supplied current and inlet pressure (cell pressure in this work) of 300 torr, from the case of un-ionized flow. This is shown in Fig. 3.

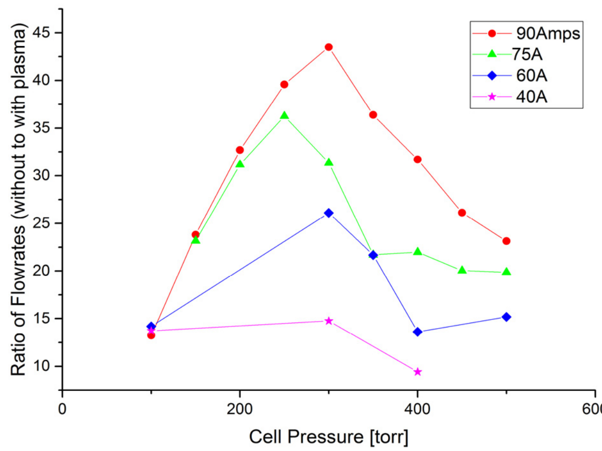

Figure 3: Ratio of flowrates (arc OFF to arc ON) as the cell (inlet) pressure is varied between 100 and 500 torr, for multiple current values. 90 A and 75 A curves show a shifting of the maximum ratio. There is a current lack of data points for 60 A and 40 A in expected pressure range to indicate continuation of shift.

Ongoing and Future Work

The next operation we will be undertaking with the PW is to initiate arc with 100% Ar, and gradually transition to 100% He so that all characteristics measured up to this point will be repeated with He.

Ben-Liang et al [11] studied the effects of two plasma window geometries with different dimensions than ours, being only six plates in length, and of channel diameter 3mm and 6mm. The authors measured the potential of the plates, finding a steep potential fall near the cathodes, followed by a nearly linear decrease up to the anode, for both the 6mm and 3mm diameter arrangements. Such measurements can be useful for determining an axial form of plasma properties within the channel.

The next inclusion for our investigation of the functionality of the Plasma Window is a means of measuring the floating voltage on each of the metal plates encompassing the plasma channel. Since each is electrically and thermally insulated from its neighbors, these floating voltages would give some indication of the relative number of electrons being pushed to each plate. This can then inform us of an idea for axial electron density, which would dictate axial temperatures and collision frequencies. This can then indicate the degree to which these interactions impact the flowrate.

We will additionally employ a UV-Vis spectrometer positioned along the PW axis to observe the spectra of the excited atoms and ions within. A wealth of literature exists on the interpretation and analysis of such spectra, and analyzing the broadening and shifts of the emission peaks allows for determination of an integral value of electron density and temperature.

Also under current investigation is the possibility of including on our assembly a laser and detection system to allow for the possibility of Thomson Scattering measurements to be performed in the radial dimension of the plasma channel, as in the work of Vijvers et al [9]. However, due to our inability to include diagnostics in the immediate vicinity of the exit of the plasma channel, this type of measurement may not be possible without significant renovation of our current apparatus.

Finally, we hope to use data from all the above components to put together a reliable detailed theoretical model for operation of the PW with which flowrate predictions for different parameters can be investigated, and so, optimized.

CONCLUSIONS

A review of existing literature on the performance of pressure-separating cascaded arc plasma devices, of similar form to the discussed PW, has indicated that, while there is a fairly large amount of literature on devices using Ar gas, each publication describes a different geometry and performs a different set of measurements. The ongoing work introduced here seeks to provide a more thorough description of the underlying mechanisms for the greatly reduced flowrate observed with the PW arc, and how its performance can be optimized with respect to controllable geometry and arc parameters.

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