CHARACTERIZATION AND PERFORMANCE OF PLASMA WINDOW FOR GAS FLOW RESTRICTION IN DIFFERENT GEOMETRIES [*]

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Abstract

The plasma window (PW) is a DC cascaded arc whose function is to restrict gas flow from a high pressure (order of 100 torr) region to a low pressure region (order of 100 millitorr) without the use of any solid separation. As a result, the PW allows a greater pressure to be maintained than otherwise would be possible, a beneficial characteristic for gas targets such as charge strippers for heavy ion accelerators, since the higher pressures enable the gas stripper to be shorter while allowing the same amount of interactions in the stripping region. The reduction in flow rate is directly related to the increase in gas temperature resulting from the power deposition into the plasma (order of 10 kW) via the cathodes, resulting in a dramatically increased viscosity. The flow rate reduction, depends upon the properties of the plasma, including the electron density and temperature, pressure, and electrical conductivity. As a result, understanding these plasma properties in multiple cascaded arc geometries – in this work having either 6 mm or 10 mm channel diameter – provides a means of understanding how the PW can be optimized for a given design choice. Determinations of these plasma properties for different conditions are shown, and results are compared with a simulation created in PLASIMO, which has been shown to yield comparable properties to measurements in an argon arc.

INTRODUCTION

One challenge facing high intensity heavy ion charge strippers is the need for charge stripping media that are able to sustain continuous high energy depositions over durations in excess of a week. Due to the energy deposition being so high in facilities that are pushing the beam intensity frontier, such as the upcoming Facility for Rare Isotope Beams, traditional solid strippers do not meet this survival time criterion and liquid or gas stripping alternatives must be sought [1]. Gas charge strippers require some design constraints which make their implementation challenging. Studies performed by RIKEN's charge stripper group indicate that generally lower mass gases yield the highest equilibrium beam charge state distributions, as summarized in Table 1 [2, 3].

Table 1: Equilibrium Charge States (Q_e) for ^{238}U

Material	Q_e at 11 MeV/nucleon
He	66+
Ar	56.6+
N_2	56+
CO_2	55.7+
C (solid)	72+

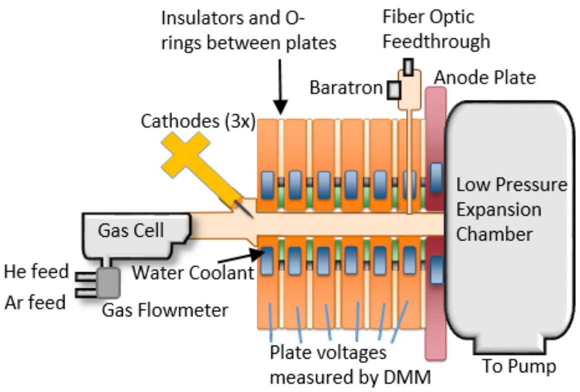

Figure 1: Key components of the plasma window. The gas cell represents the gas charge stripper chamber. Plasma and ion beam travel coaxially through the channel. The final plate before the anode illustrates the diagnostic plate setup with pressure and optical emission measurement ports.

The chamber must be at a high pressure to give a target thickness great enough to achieve charge state equilibration [1, 3], and the chamber entrance large enough to accept the beam without scraping. However, the combination of these features results in a high gas flow rate which must be recycled by pumps so as to transition to beamline pressures of 10^{-8} torr. This challenge is greatest for the low mass gases like helium due to their high diffusion rate. The PW is a device that can in part mitigate this by heating the gas, increasing viscosity [4]. This work focuses on argon and helium and investigates the nature of the effectiveness of the flow rate reduction phenomena. Flow rate in this work is measured in standard liters per minute (SLM).

EXPERIMENT

The plasma window is a DC cascaded arc whose channel is coaxial with the beam, in which a plasma significantly heats and plugs the flow of gas out of the charge stripping chamber. It is comprised of three needle cathodes, several stacked metal plates, and finally an anode plate for a total length of about 7 cm. More details on the components and structure is described in [5]. This work will also briefly

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introduce several channel length and diameter configurations as will be mentioned later. In a beamline, this PW structure would be set on both sides of a high pressure charge stripping chamber, which is referred to as the gas cell in this work. For ease of study, the test stand at the National Superconducting Cyclotron Lab (NSCL) has only one plasma window.

A major addition to the PW over that reported in [5] is the replacement of two of the plates with diagnostic plates. A narrow tube connects the PW channel to a Baratron pressure gauge and optical feedthrough connected to an Ocean Optics HR4000 spectrometer, as illustrated in Fig. 1. Additionally, the potential of the plates which are floating with respect to the plasma are measured by DMM to determine the plasma's electrical conductivity using the well known relation

$$j = \sigma E \tag{1}$$

in which the conductivity σ is taken as an average over the channel's cross sectional area since current density j is assumed uniform.

In this experiment, a diagnostic plate was positioned at the second plate on the cathode-side as well as the final plate, adjacent to the anode (only the latter is shown in the diagram). Measurements were made with several different PW configurations in which the plate count and their channel sizes were varied. The notation used in this work to denote these configurations is (plate count)x(channel diameter in mm), e.g. "1x6mm_7x10mm" denotes one 6 mm channel diameter plate followed by seven 10 mm channel diameter before the anode. In all cases, the anode's aperture is the same size as the plate immediately upstream of it.

In addition to the conductivity, two other properties that characterize a plasma are its electron density n_e and electron temperature T_e. Electron temperature is calculated based on relative spontaneous emission intensities from the plasma using the Boltzmann line method [5, 6]. The relationship is

$$I_{ul} \propto \frac{g_u A_{ul}}{\lambda} exp\left[-\frac{E_u}{kT_e}\right] \tag{2}$$

where subscripts u and l denote upper and lower states of the emission, I the measured intensity, g the degeneracy, A the transition rate, λ the wavelength, and E the energy of the upper state.

Electron density is calculated based on Stark broadening of a selected emission. The presence of numerous plasma electrons and ions in the vicinity of an emitting gas particle exposes it to an electric microfield which perturbs the excited state energies. This manifests as broadening of the emission proportional to the density of the perturbing charged particles is thus used to extract the electron density [7, 8].

These properties are determined at two locations: plates 2 and 6 from the cathodes. Results of the latter are shown in Fig. 2. For the near-cathode location, electron temperatures are slightly smaller, and electron densities are generally about twice the corresponding value in the figure. These, along with pressures and conductivity, comprise the main properties that determine a plasma's behavior. So if these match with values from a computational model, then it is assumed that the model's representation of the arc is reasonably accurate.

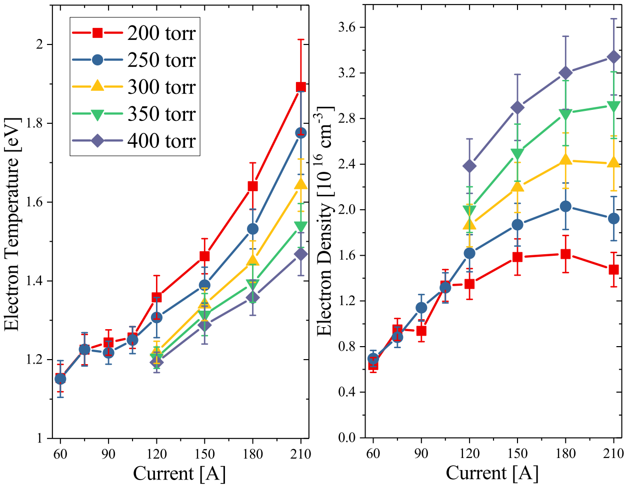

Figure 2: Electron temperature and density as a function of cell pressure and arc current, for 6x6mm PW in argon.

Table 2: Comparisons of Measured and PLASIMO Plasma Properties in Argon 6x6mm PW

Property	Measurement	PLASIMO
T_e (p2) [eV]	1.30	1.26
T_e (p6) [eV]	1.34	1.36
n_e (p2) [cm^{-3}]	3.5x10^{16}	4.0x10^{16}
n_e (p6) [cm^{-3}]	2.2x10^{16}	4.2x10^{16}
σ (p1-2) [(Ω m)$^{-1}$]	3850	4340
σ (p5-6) [(Ω m)$^{-1}$]	5080	5600
Pressure (p2) [torr]	256	256
Pressure (p6) [torr]	148	171
Flow Rate [SLM]	11.2	7.7

RESULTS

One such model is PLASIMO, which contains an arc module [9, 10]. Table 2 shows these comparisons for a sample case of an argon arc in the 6x6mm configuration with gas cell pressure at 300 torr and current at 150 A. the plate locations where the measurements and model data are taken are in parentheses, with the conductivities being taken in between the two plates listed. Most of the measured values are reasonably close to the modeled values, with the notable exceptions of the pressure near the end, and the flow rate. However, as can be seen in Fig. 3, PLASIMO maintains the same trend with respect to current as observed in measurement. The discrepancy between measured and modeled values can perhaps be attributed to PLASIMO's inability to accurately model the more complicated near-cathode behavior of the plasma.

Figure 3 shows the gas flow rate through a PW that consists of six 6 mm channel diameter plates. At the pressures

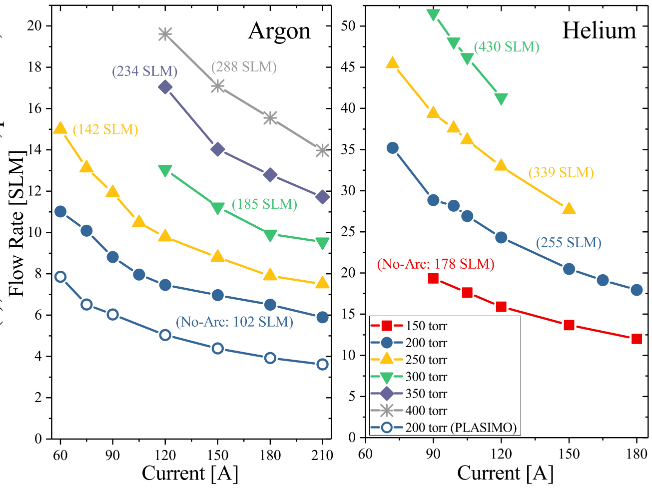

Figure 3: Gas flow rates through 6x6mm PW for both argon and helium as a function of arc current at several cell pressures. Values in parentheses are the no-arc flow rates for that cell pressure.

indicated, the arc is not very stable at currents less than 60 A, but even at this current, the benefit provided by the PW over the corresponding no-arc case is substantial and increases with greater current. The no-arc flow rates indicated are obtained by a quadratic fit to data in the accessible pressure range that is only up to about 100 torr without arc.

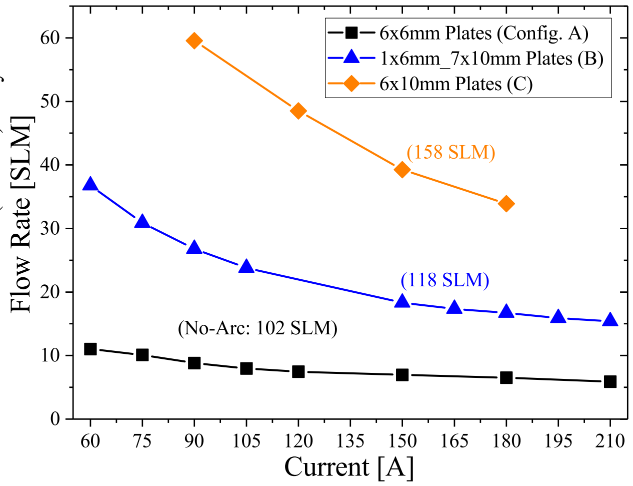

Figure 4: Argon flow rates through several PW configurations. All points are taken at gas cell pressure of 200 torr.

Figure 4 shows flow rates in several different PW configurations, labeled A, B, and C. Each data point corresponds to flow rates observed with the gas cell at 200 torr. Config. C has a substantially higher flow rate than the Config. A due to its larger channel size. However, it is interesting to note that even the presence of a single 6 mm plate in an otherwise 10 mm diameter channel confers a dramatic reduction in flow rate as seen by comparing the Config. B. The length change from the two additional plates is expected not to contribute as significant a reduction as observed, but this will be verified in future studies. The reason for this large flow rate reduction by using the narrow entry is likely related to the fact that by the time the gas has traversed the first plate which has the smaller aperture, it has already been heated to about T_e, its maximum possible temperature.

CONCLUSION

The plasma window is a viable means of substantially reducing the flow of gas from a high pressure charge stripping chamber, allowing for higher target thickness than otherwise would be achievable. Low mass gases such as helium allow for a higher final charge state to be achieved, but the tradeoff is a greater flow rate that must be pumped out to return to beamline pressures after the stripper. Larger diameter channel plasma windows result in much greater flow rates, but this can be largely mitigated by using a slightly smaller aperture over even just a short distance at the beginning of the window.

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REFERENCES

[1] J. A. Nolen and F. Marti, “Charge strippers of heavy ions for high intensity accelerators,” *Rev. of Accel. Sci. and Tech.*, vol. 6, pp. 221-236, 2013.

[2] H. Kuboki *et al.*, “Development of plasma window for gas charge stripper at RIKEN RIBF,” *J. Radoanl. Nucl. Chem.*, vol. 299, pp. 1029-1034, 2014.

[3] H. Okuno *et al.*, “Low-Z gas stripper as an alternative to carbon foils for the acceleration of high-power uranium beams,” *Phys. Rev. Spec. Topics - Accel. and Beams*, vol. 14, 2011.

[4] A. Hershcovitch, “A plasma window for transmission of particle beams and radiation from vacuum to atmosphere for various applications,” *Physics of Plasmas*, vol. 5, May 1998, pp. 2130-2136

[5] A. LaJoie *et al.*, “Study of high-flow argon through cascaded arc for use as a gas target isolator,” *IEEE Trans. on Plas. Sci.*, vol. 47, pp. 2752-2758, 2019.

[6] J. Cooper, “Plasma Spectroscopy,” *Rep. Prog. Physics*, vol. 29, pp. 35-130, 1966.

[7] V. Milosavljević and G. Poparić, “Atomic spectral line free parameter deconvolution procedure,” *Phys. Rev. E*, vol. 63, p. 036404, 2001.

[8] H. R. Griem, *Spectral line broadening by plasmas*, New York, NY, USA: Academic Press, Inc., 1974.

[9] G. M. W. Kroesen *et al.*, “Description of a flowing cascade arc plasma,” *Plas. Chem. and Plas. Proc.*, vol. 10, pp. 531-551, 1990.

[10] G. M. Janssen *et al.*, “PLASIMO, a general model: I. Applied to an argon cascaded arc plasma,” *Plas. Sources Sci. and Technol.*, vol. 8, pp. 1-14, 1999.