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Windowless targets for intense beams

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Abstract

Earlier results have shown that a plasma window can effectively separate vacuum from a pressure of close to 3 atm. Present results indicate that a plasma window enhanced by a venturi facilitates a rather effective vacuum separation from a 9 atm gas target. Utilization of the plasma arc as the window for gas targets removes all of the limitations on beam current, energy, and energy focusing imposed by solid windows. Various applications and the new results are discussed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

High-energy particle beams and radiation are usually generated in vacuum. For many applications these beams must be transported from high vacuum to atmosphere or to a poor vacuum region for interactions with various targets. In these applications various windows are employed to separate vacuum and atmosphere, or to separate high and low pressure regions. Although presently used "conventional" windows like thin solids, or foils are not problem free, they function adequately when low intensity, high-energy particle beams propagate through them. However, these windows may be destroyed in systems with high-intensity beams where large amounts of energy will be deposited in windows. Consequently, in some machines beams are expanded before traversing windows to reduce their power density at the window surface. The end result is often degraded performance from the experiment.

Plasma windows can separate between vacuum and atmosphere (and even higher pressures), offering many advantages over presently used windows because the interaction of high-energy particles and photons with these plasmas is negligible, due to their low target thickness. A plasma window can have an effective target thickness 10^{-4} smaller than that of the 250 μm thick Be windows often used at synchrotron light sources. In addition to fewer interactions with beams, plasma windows are impervious to thermal damage.

An atmospheric arc plasma has been used to establish a vacuum–atmosphere interface without any intrusive solid structures, forming a 'plasma

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window' [1]. A hot plasma discharge is created in order to separate a high-pressure region from the accelerator vacuum. Plasma windows can separate vacuum and atmosphere, or high and low vacuum, in a way that facilitates transmission of various particle beams and/or radiation from the low- to high-pressure regions [2]. Prior to this work, the best test results with high-pressure targets were achieved with argon as target as well as arc gas. First, a 5 bar cell was separated from atmosphere [2]. Later, a gas target cell at 2.85 bar absolute was effectively separated across a 2.36-mm diameter 40-mm long arc from the three-chamber differentially pumped system, with the pressure in the first chamber reaching 0.57 mbar [3]. These (and other) experimental results confirm that the plasma window reduces the gas flow significantly and allows for high target gas pressures.

In another experiment, a 175 keV electron beam was transported from vacuum into the atmosphere through the plasma window [1,2]. Further, a series of Electro-Magnetic Interference (EMI) experiments revealed that RF emission from the arc is negligible, suggesting that plasma windows can be used near sensitive detectors [2]. X-ray transmission experiments through a plasma window were performed at the National Synchrotron Light Source (NSLS) at BNL. As expected, transmission of X-rays was excellent [4]. More recently, a 2 MeV proton beam was successfully transmitted through a plasma window with negligible energy losses [5].

Clearly, the results thus far indicate that plasma windows have a wider range of uses in accelerator-based research. In this paper a possible number of target embodiments for various applications, as well as new experimental results are described. In earlier experimental results [3], the plasma window separated a high-pressure gas cell from vacuum. The new configurations involve a venturi nozzle, a gas heater, and a flow constrictor between the plasma window and the high-pressure gas cell.

2. Gas target improvement

Prior testing of a pressurized gas target system [3] clearly shows the viability of the plasma window as alternative to solid windows. Utilization of the plasma arc as the window for the gas target removes all of the limitations on beam current, energy, and energy focusing, that a solid window creates. But, further improvements, involving venturi nozzles, are possible.

Venturi nozzles are utilized in commercially available compressed air-driven vacuum pumps referred to as (depending on the manufacturer) vacuum transducer pumps or ejector vacuum pumps. Compressed gas is forced to flow through a venturi, where it acquires forward momentum, expands, and it creates suction behind the expanding gas flow direction.

To prevent corrosion and damage to the arc itself, inert gas is usually supplied rather than using ambient atmosphere. The arc gas can be supplied as backflow from a venturi [2] that has the additional benefit of enhancing the plasma window pressure differential by a factor of 3 due to the pumping action of the venturi. It also reduces the power required to sustain the discharge by 25%. Additionally, the venturi nozzle creates a high-pressure boundary preventing undesirable gases as well as liquids or small solid grains from entering the vacuum chambers. This venturi property expands the variety of targets that can benefit from plasma windows. Venturi use has the drawback of higher gas consumption; however, in many situations this is outweighed by the advantages accrued. When expensive and/or flammable target gases (e.g., deuterium) are required, a gas recirculating system is needed. A venturi can be readily incorporated into such a system.

In previous configurations [2,3] the high-pressure gas cell opening faces a plasma window. For this work, a high-pressure gas cell (the target) faces a small chamber separating the plasma window from the target. Gas from the target will flow into this gap. To reduce the mass flow rate from the gas cell a 'flow constrictor' was developed. Its function is to convert the flow from laminar into turbulent, thereby increasing the resistance to flow. The constrictor can be heated to warm the exiting gas, increasing its effective viscosity, which in turn reduces the flow from the target cell.

3. Experimental setup

Fig. 1 displays the experimental arrangement. The plasma window is mounted on an evacuated 4″ cross. The cross is divided into two chambers separated by a skimmer with a 2 mm aperture. A Varian TriScroll 300 roughing pump (pumping speed of 300 l/min) pumps each section of the cross. The plasma window is a segmented wall-stabilized plasma arc forming an interface between the high gas pressure region of the target section and the vacuum (i.e., accelerator vacuum). The arc is a wall-stabilized type cascade arc discharge. A centimeter of plasma separates the gas cell from a 4-cm long plasma window channel. The plasma is formed by striking a DC arc from a set of cathodes to a single anode held at ground potential. The potential difference between the cathode and the anode is distributed across several intermediate 'cascade plates' made of copper that were allowed to float to their own potential. The arc used in these experiments has three sharp tip cathodes that are equally spaced around the beam path and just outside of its aperture. In this way a clear optical path 2 mm in diameter exists down the axis of the window. Each cathode has its own power supply for convenience in operation. The power dissipated in the arc can be substantial (the order of several kW) so all of the arc components are water cooled. More details on the arc can be found elsewhere [1–3].

A venturi is mounted on the arc cathode housing which is separated from the gas target cell by a ceramic insulator, since the cathode housing is usually at potential of about -100 V (for many applications the target must be at ground or other potentials). The gas target cell is a pressurized, 3.8-cm diameter, 11.8-cm long, stainless-steel cylinder with a 6-mm opening aperture. In the last experiment, a 5-cm long, 2.36-cm diameter molybdenum constrictor was installed at the target cell entrance. The molybdenum can be heated, thus heating the gas enclosed in it.

Convectron gauges measure pressure in the vacuum chambers. Mechanical Bourdon tube pressure gauges monitor pressure on either end of the gas cell.

4. Results

Venturi pumping action requires proper flow through the venturi. In the first set of measurements the exhaust section and the target gas feed (of Fig. 1) were not included in the experimental setup. Motivation for this set of experiments was to explore a gas flow scenario that allows for sufficient gas flow to facilitate venturi action. But, flow rate should be low enough to sustain a high target pressure. With the needle valve closed, the experimental configuration is equivalent to an

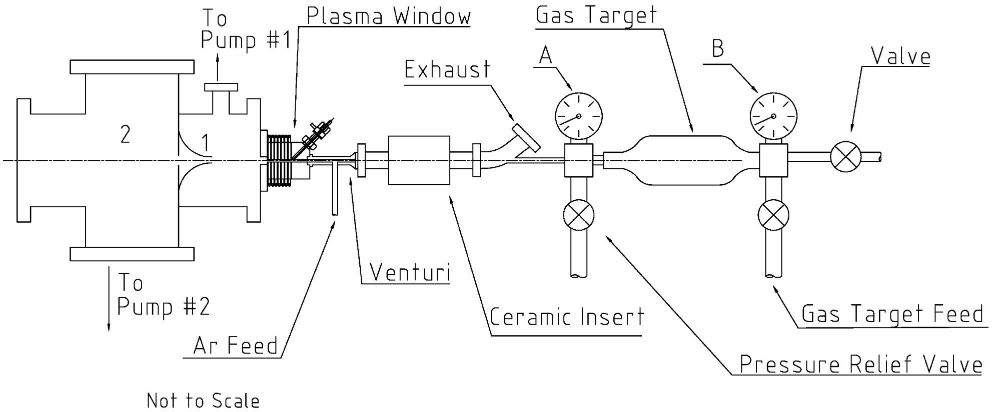

Fig. 1. Experimental schematic diagram of the apparatus used to measure the plasma window high-pressure/vacuum separation performance.

earlier setup [3] except for a factor of 60 lower pumping speed in this configuration.

Attempts to adjust the needle valve to allow for sufficient flow to enable venturi action and yet maintain adequate pressure in the gas target failed. No such operating mode was found. With the valve closed, at a target pressure of 3 bar, the pressures in chambers 1 and 2 were 22 and 2 mbar, respectively. Total arc current was 45 A, for an arc power of 6.4 kW. These measurements were conducted in argon. Consistency with early observations [3] exists. The factor of close to 40 difference in pressure is a result of the poorer pumping capability of this system (10 l/s versus 500 l/s of the roots blower).

With the exhaust open, the arc operated in its normal venturi gas feed mode. For an arc power level of about 5 kW in argon (50 A of total arc current), the pressures in chambers 1 and 2 were 0.66 and 0.036 mbar, respectively. Variations in gas target pressure did not affect arc operation. With the exhaust open a maximal target pressure of 3 bar could be sustained. Pressurizing the target with either argon or nitrogen in the range of 1–3 bar had little affect on the arc, gas target performance, or the vacuum chambers' pressure.

Next, a 5-cm long, 2.36-cm diameter molybdenum flow constrictor was installed at the target cell entrance. The molybdenum can be heated, thus heating the gas enclosed in it. With the flow constrictor, a target pressure exceeding 9 bar (pressure gauge limit) was reached. The target pressure was measured by pressure gauge B, while the constrictor exit pressure was monitored by pressure gauge A. At the maximum target pressure, gauge A read 2.7 bar. In this target pressure range (of up to 9 bar), the pressure at A varied linearly with the target pressure (at B). Again, variations in target pressure did not affect arc operation, or pressure in either of the vacuum chambers.

Heating the molybdenum constrictor, with a current of up to 30 A, resulted in a proportional pressure increase in both the target and at the exhaust side of the constrictor. Variations in applied target pressure (gauge B) lead to similar variations in pressure readings at A, which were identical to the case where the molybdenum constrictor was not heated. The pressures in chambers 1 and 2, as well as the arc operation, were unaffected by the heating of the molybdenum constrictor. The data strongly suggests that gas heating was not confined to the gas cell opening, the rest of the target gas heated up as well.

Finally, a flow meter was installed in the exhaust line to measure gas consumption by the venturi and the gas target. Gas consumption by the venturi alone was 0.8 l/s. Applying pressure to the gas target resulted in linearly proportional gas flow, as shown in Fig. 2. Small deviations from

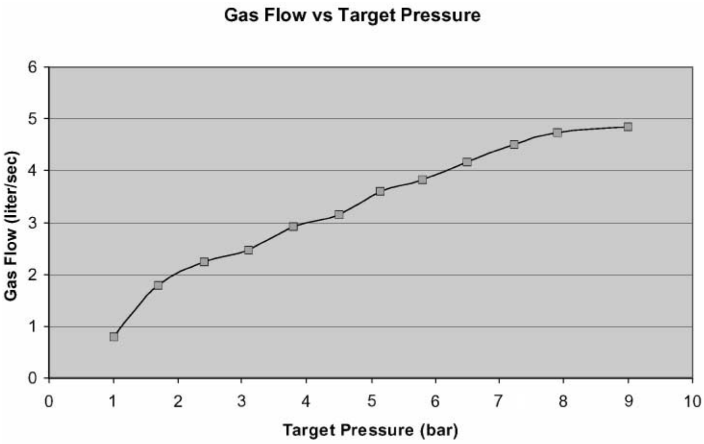

Fig. 2. Gas flow versus gas target pressure. The pressure in chamber 2, which stayed constant at 0.036 mbar, was unaffected by gas target pressure variations.

linearity are most likely due to instrumental limitations of the flow meter at low flow and of the pressure gauge at high pressure. For a target pressure of 9 bar, the gas flow was 4.8 l/s (due to target and venturi). And, for a set target pressure, gas flow was identical regardless on whether the molybdenum constrictor was heated up or not.

Since gas flow through the plasma window is minute by comparison (2.7×10^{-3} l/s), total gas consumption for a target pressure of 9 bar is under 5 l/s. In all experiments, dependence of vacuum chambers' pressure on plasma arc current was, as expected, consistent with earlier experiments [1–3], i.e., vacuum pressure drops as arc current increases.

To summarize the results, plasma window operation and performance was successfully decoupled from a high-pressure gas target by a venturi. A gas target pressurized to 9 bar was separated from vacuum by the plasma window system at a total gas consumption of under 5 l/s.

5. Applications

Several different types of accelerator systems can benefit from the utilization of the Plasma Window system. These systems can be broken into four general categories: pressurized gas targets, liquid targets, high- and low-pressure internal targets, solid targets in atmosphere or in special environment.

5.1. Pressurized gas targets

Earlier [3] testing of the closed target cell clearly shows the viability of the pressurized gas target system. Even with the small pumps of the Fig. 1 system, present experimental results demonstrate that feasibility. Future generations of this system can achieve higher target pressures while maintaining the required vacuum pressure for the accelerator. The utilization of the plasma arc as the window for the gas target removes all of the limitations on beam current, energy, and energy density, that a solid window creates. As an example, a pressurized target for an accelerator based neutron source is shown next.

Ideally, an intense source of monoenergetic neutron beam based on the reaction D(d,n)^{3}He would have a D^+ beam of a few mA, and a windowless [6,7] D_2 target with a pressure of a few bars. The plasma window can potentially facilitate such a target. High target pressure, however, requires high arc power, due to high gas pressure at the cathodes. Operation in a high-power, high-pressure mode increases plasma window and first chamber cooling needs, as well as first chamber pumping requirements. Employing a venturi greatly reduces pumping, power, and cooling requirements. As stated in Section 2, the enhanced gas flow resulting from venturi utilization is a relatively small drawback.

Windowless neutron source targets for generating an intense, fast, monoenergetic neutron beam can benefit from a configuration similar to the present experimental configuration. Fig. 3 is a schematic representation of a high-pressure D_2 target. It can be used with expensive, flammable, or any target gases requiring a gas recirculating system. Of course, for all other gases, the pipe leading to the recirculating system can be simply vented, and the target gas can be different from the venturi fed gas.

5.2. Liquid targets

Fig. 4 is a schematic diagram for a liquid target. Liquid is enclosed in a cooled solid container with an opening for an intense beam. High-pressure gas prevents the liquid from escaping through the aperture. In pulsed systems, cyclical target heating occurs. Pulsed gas valves can be employed to raise the container pressure when the liquid is hot. Some valves, like gas-puff Z-pinch valves [8,9], can operate at pressures exceeding 200 bar. Like the high-pressure gas target, Fig. 4 target system can be enclosed when toxic materials are used.

Mercury is used in this example because of its interest to the Spallation Neutron Source (SNS) and to the muon collider. Present SNS design [10] employs a broad, low power density beam. Window cooling sets the beam power density

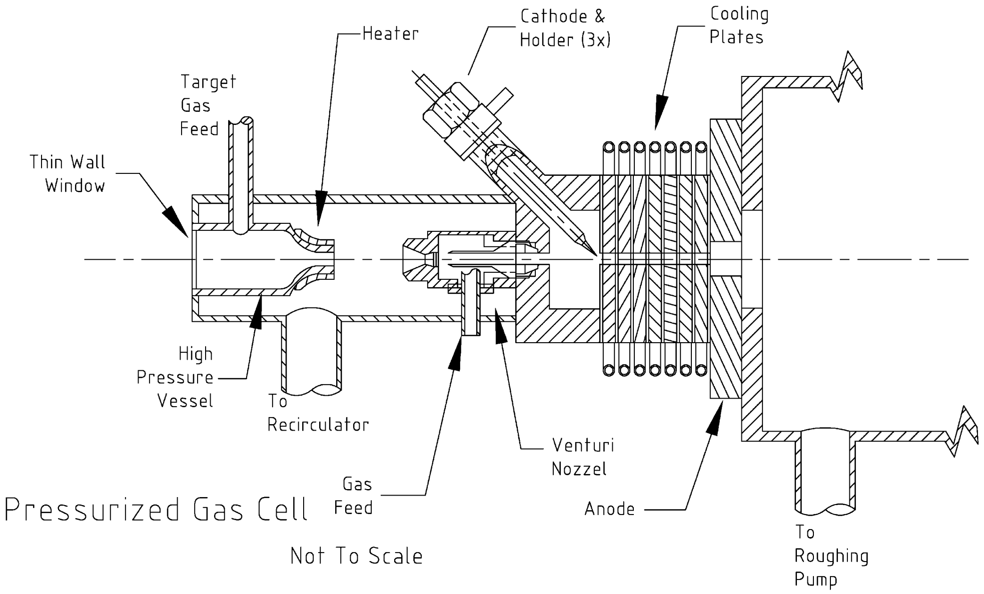

Fig. 3. Schematic diagram of a closed system high-pressure gas target system.

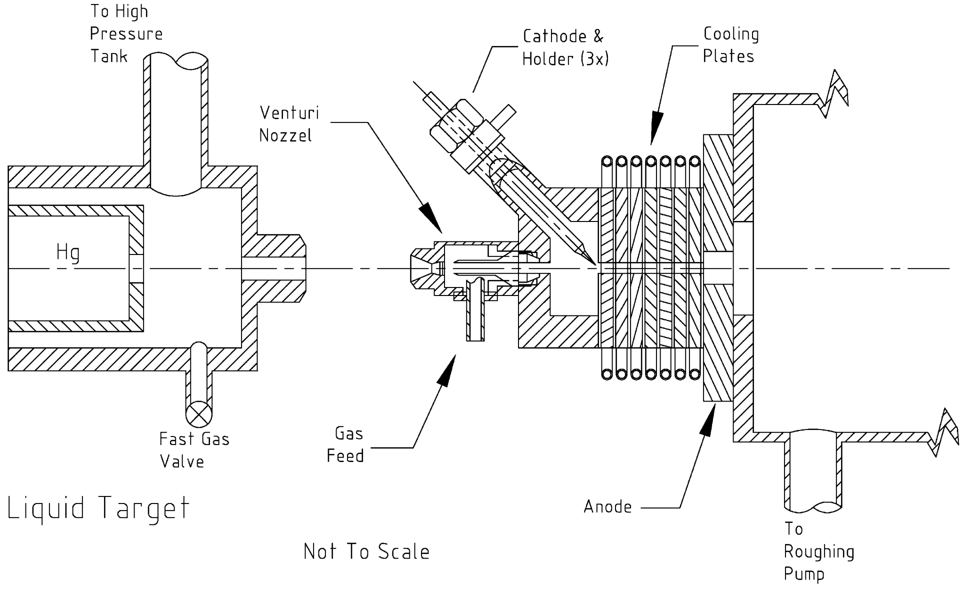

Fig. 4. Sketch of a high-pressure liquid target configuration.

limit. Obviously, a plasma window can eliminate any solid window cooling problem.

With plasma windows, the SNS can utilize higher current density beams yielding higher neutron brightness.

5.3. Internal targets

Plasma windows offer viable scheme for maintaining a highly localized, high pressure, cells inside storage rings. A plasma stripper/lens or an internal gas target "sandwiched" between two plasma windows could achieve the desired vacuum separation. High-pressure internal targets in high-vacuum accelerators or storage rings would need a system based on Fig. 3 with the "thin wall window" replaced by an additional heater and constrictor followed by another plasma window and venturi.

Lower-pressure discharges are more suitable as plasma windows for low-pressure internal targets (of 13 mbar or less). Fig. 5 is a schematic diagram for a low-pressure internal target based on plasma sheets. Beam apertures are plugged by plasma sheets similar to those generated for ion source applications [11]. Gas atoms or molecules cannot cross the plasma sheet. A typical thickness of a plasma sheet [11] is about 2–3 mm. Ionization mean-free-path [given by $(n_e\sigma)^{-1}$, where σ is the effective ionization cross-section] for gas target atom or a molecule entering that sheet is about 0.15 mm. Also, a quick calculation of $P = nkT$ (in MKS units $10^{20} \times 1.38 \times 10^{-23} \times 1.16 \times 10^{5} = 160$ Pa, ≈ 1.6 mbar) reveals that a plasma sheet can withstand a static pressure of 1.6 mbar. However, over 13 mbar can be supported, since the gas is free to flow parallel to the plasma sheets.

5.4. Solid targets

Energetic particle beams can pass from vacuum through a plasma window into atmospheric pressure [1,2,5]. The plasma window and venturi nozzle arrangement can be used to allow beams to pass from the vacuum chamber and strike a target in atmosphere. If a solid target requires a special environment to avoid corrosion, or any safety issue, an arrangement similar to Fig. 3 is suitable. The solid target can replace the high-pressure cell in this figure. A compatible sacrificial gas is needed in this case to maintain the plasma window arc.

6. Discussion

Even though testing of the closed target chamber had already shown the viability of the pressurized gas target system, present results are a substantial improvement. While the present system

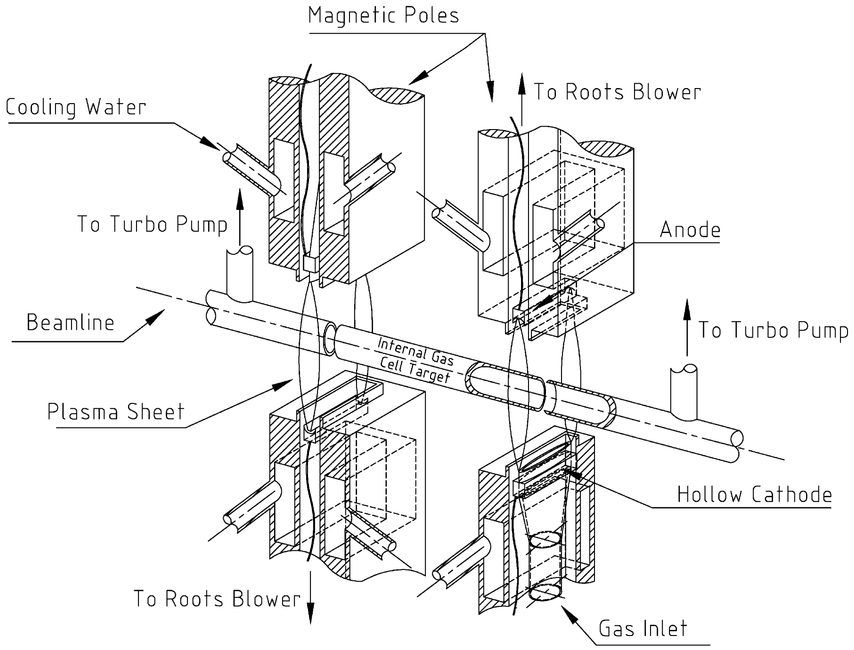

Fig. 5. Schematic diagram for an internal target set-up.

greatly reduces plasma window power and cooling requirements, gas consumption is two orders of magnitude larger. However, inexpensive commercially available compressors can easily handle this gas flow. For under $200 a small compressor can provide over 8 bar at 2.25 l/s (used for nail guns). Industrial compressors can handle a much larger gas flow (at a higher cost). With any plasma window configuration, the utilization of the plasma arc as the window for the gas target removes all of the limitations on beam current, energy, and energy focusing, that a solid window creates.

Present designs of the SNS and the muon collider are based on low current density, broad, primary proton beams passing through solid windows. Therefore, these protons either strike a large area on the targets, or have transverse energy components (if focused before impact) when striking the targets. In either case the result is lower brightness secondary beams (of SNS neutrons, or muon collider pions). Hence, solid windows limit performance in these applications. Alternatively, high current density ion beams can be used with windowless targets resulting in enhanced neutron and muon brightness.

Other applications like neutron generation for Boron Neutron Capture Therapy (BNCT), Accelerator-driven Transmutation of Waste (ATW), face extreme difficulties with solid windows. Some experiments like Daresbury Recoil Separator (DRS) compact gas cell can also benefit from plasma window based targets.

High-energy protons striking a lithium target is the most widely pursued scheme for generating neutrons for BNCT. BNCT based on recirculating proton beams can be realized with two plasma windows on either side of a lithium cell as in Fig. 5. Plasma windows offer a viable scheme for maintaining the needed (for BNCT) highly localized, 13 mbar lithium vapor cell inside a high-energy proton storage ring. Similarly, at ORNL the DRS compact gas cell needs a 13 mbar hydrogen target.

BNCT based on a solid lithium target can be realized with a setup similar to Fig. 4 with solid lithium in an inert gas environment.

The ATW project utilizes a spallation source to provide a flux of high density of neutrons needed to drive the transmutation of waste. Similar to all spallation targets, this project requires the use of a dense heavy atom target, and it has been hampered by the design of an interface between the accelerator and the target (liquid lead bismuth). No system previously developed has been able to withstand the high beam current and energy needed to drive the transmutation. The use of the Plasma Window and venturi nozzle removes these limitations.

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References

[1] A. Hershcovitch, J. Appl. Phys. 78 (9) (1995) 5283.
[2] A. Hershcovitch, Phys. Plasmas 5 (5) (1998) 2130.
[3] W. Gerber, R.C. Lanza, A. Hershcovitch, P. Stefan, C. Castle, E. Johnson, The plasma porthole: a windowless vacuum-pressure interface with various accelerator applications, 15th International Conference on Application of Accelerators in Research and Industry, CAARI'98, Denton, Texas, November 4–7, 1998, AIP Conference Proceedings, p. 475.
[4] B.T. Pinkoski, I. Zacharia, A. Hershcovitch, E. Johnson, P. Siddons, Rev. Sci. Instr., to be published.
[5] A. de Beer, A. Hershcovitch, C.B. Franklyn, S. van Straaten, J. Guzek, Nucl. Instr. and Meth. B 107 (2000) 259.
[6] J. Guzek, K. Richardson, C.B. Franklyn, A. Waites, W.R. McMurray, J.I.W. Watterson, U.A.S. Tapper, Nucl. Instr. and Meth. B 152 (1999) 515.
[7] E.B. Iverson, R.C. Lanza, L.M. Lidsky, A windowless gas target neutron source, in: Fifth International Conference on Applications of Nuclear Techniques, Crete, 1996, Proceedings of SPIE—the International Society for Optical Engineering, vol. 2867, 1997, pp. 513–516.
[8] A. Fisher, F. Mako, J. Shiloh, Rev. Sci. Instrum. 49 (1978) 872.
[9] J. Kriesel, R. Prohaska, A. Fisher, F. Rev. Sci. Instrum. 62 (1991) 872.
[10] SNS Design Manual, SNS_DM_98_00002, ORNL/M-6644, September 1998.
[11] A.I. Hershcovitch, V.J. Kovarik, K. Prelec, Rev. Sci. Instrum. 57 (1986) 827.