Use Of Plasma Window For Enhanced Ion Beam Transmission From Vacuum To Air

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Abstract. Vacuum-high pressure (>1 Bar) interfaces have conventionally been implemented on accelerator systems by means of a thin foil barrier through which the ion beam passes or by spinning disc differential gas target technology. Both these techniques are relatively inefficient (energy loss and limited beam current in the foil system and the requirement for a pulsed beam and low duty cycle in the spinning disc system). The idea of using a plasma arc discharge as a barrier (plasma window), though not new, has been further developed through introduction of a venturi type gas flow system such that its potential for application in research and industry are vast.

1. Introduction

Vacuum-high pressure (>1 Bar) interfaces have conventionally been implemented on accelerator systems by means of a thin foil barrier through which the ion beam passes or by spinning disc differential gas target technology [1]. Both these techniques are relatively inefficient (energy loss and limited beam current in the foil system and the requirement for a pulsed beam and low duty cycle in the spinning disc system). Recent research in the development of a plasma arc discharge as a barrier has indicated great potential for accelerator applications [1,2,3].

Plasma arc discharges have the properties of high temperature and high viscosity, yet very low density. These properties hinder the passage of gas through the plasma itself while at the same time easily allowing a high-energy charged particle beam to pass through. Thus one can isolate the vacuum within an accelerator system from a high-pressure gas target or atmosphere. Furthermore, the magnetic field generated by the arc discharge actually helps to focus this beam, weakly for ions but strongly for electrons. More information regarding the theory behind the operation can be found in [4].

The plasma window concept has already been demonstrated at Necsa for an argon plasma holding off atmospheric pressure from a vacuum of $<10^{-7}$ Bar, while a 2 MeV proton beam passes through it from vacuum into air. It has also been demonstrated that a vacuum-atmosphere interface with helium or argon plasmas can be sustained whilst a 175 keV electron beam is transmitted through the plasma [4]. Previous work performed using plasma windows as a vacuum-pressure interface has demonstrated [3] that a deuterium gas target of 245 mBar can be held from a vacuum of $<10^{-7}$ Bar using a large diameter (5 mm) deuterium plasma window coupled to a differentially pumped vacuum system.

The aim of the work reported here has been to optimise the existing system and determine the limits of the technology. The primary gas used in the current experiments was argon with some brief experiments being performed in helium. Once the system has been optimised using argon and helium, investigations will be carried out into sustaining a deuterium gas target of up to 3 Bar separated from an accelerator beam tube at a pressure of $<10^{-7}$ Bar by a 5 mm diameter deuterium plasma arc discharge.

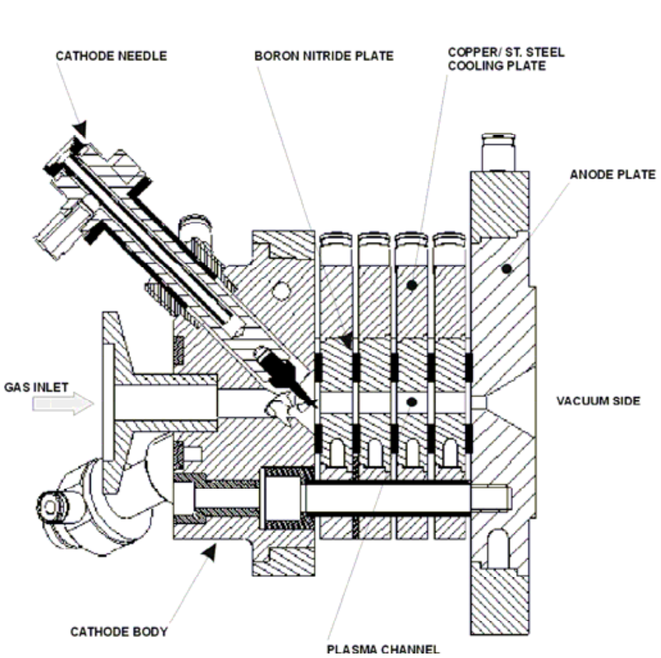

FIG. 1. Schematic of the plasma window (reproduced from [3])

2. Experimental Set-up

During the project, various experimental arrangements were put together in order to obtain the optimum performance. The basic components of the plasma window comprise the plasma arc assembly including cooling and power supply, and the layout of the overall vacuum and gas transport system.

2.1. Plasma Arc Assembly

The basic configuration of the plasma arc (shown in FIG. 1.) was based on that of Hershcovitch [4] and consisted of 3 cathodes (with thoriated tungsten tips) pointing into a 5 mm diameter, 45 mm long plasma channel (made up of copper cooling plates interspersed with boron nitride insulators) towards a copper anode plate. All the metal components were water-cooled. The cathodes were placed at a negative voltage and the anode plate was grounded. The power supply used was capable of delivering 100A at up to 500V DC and could operate in voltage and current limited mode. Some of the modifications to the original assembly design were: an increase in the aperture diameter from 2.36 mm in Hershcovitch's original design [4] to 5 mm in this one; a change in the orientation of the cathode tips (they were tilted at an angle pointing directly towards the anode); the original work performed at Necsa utilised cooling plates made of copper and stainless steel – this was changed to full copper plates, for better thermal conductivity, and with increased cooling channels; greater electrical insulation was also implemented for the cap screws used to hold the plates together.

2.2. Layout of the Vacuum System

A schematic of the vacuum system layout used is given in FIG. 2. The plasma arc assembly was attached to a standard 150 mm diameter vacuum tube "T-piece" which was evacuated on one side by a 2050 $m^3 \cdot h^{-1}$ roots blower. The other end of the tube was linked via a 5 mm flow

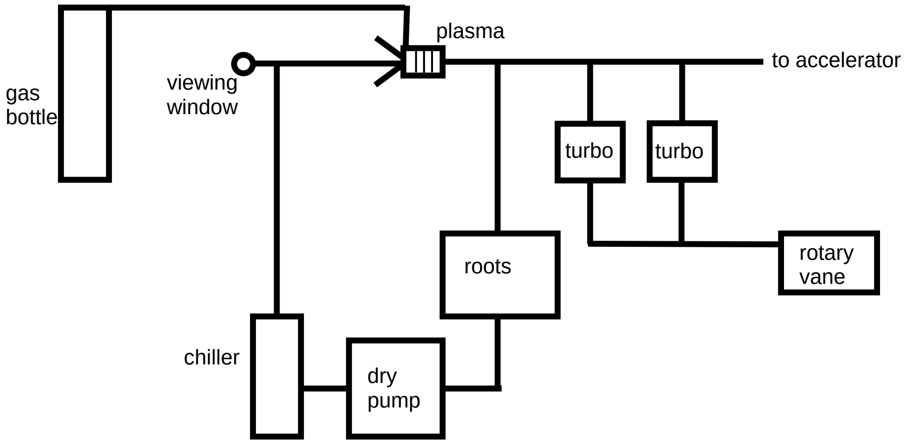

FIG. 2. Vacuum system layout

constrictor to two consecutive identical "T-pieces" which were each evacuated by 450 $l{\cdot}s^{-1}$ turbo molecular pumps and also separated from each other by 5 mm flow constrictors. The first T-piece after the plasma window contained a water-cooled deflector plate that helped cool and redirect the hot gas exiting the plasma towards the roots blower. Other cooling mechanisms were employed around this T-piece as it had to bear the bulk of the heat dissipation during operation. The roots blower was backed by a 300 $m^3{\cdot}h^{-1}$ dry pump which fed into a gas cooler and then back to the gas cell. Note that the only mechanical compression for the gas in the gas target cell was the outlet of this dry pump. The 2 turbo-molecular pumps were backed by a rotary vane pump which vented to atmosphere. The gas passing through the turbo-molecular pumps was not recycled due to the risk of oil contamination of the system and to allow greater pumping efficiency of the roots blower (although in future configurations this will also form part of the feedback loop). At the end of the gas target cell was a borosilicate glass observing window through which one had an optical path directly into the plasma window. This observing window could be removed when performing vacuum-atmosphere experiments. One of the significant differences between this system and the previous one operated at Necsa was the implementation of a venturi-type flow system feeding into the gas cell. Although the venturi pumping action was minimal, this component helped to redirect the flow of gas away from the plasma.

Operation of the plasma window was straightforward. First an initial gas flow was established in the system with a pressure of 10 mBar in the gas cell and a corresponding pressure of 4.5×10^{-2} mBar in the first chamber. A voltage of around 150V was applied and an arc struck by means of a Tesla gun aimed near to the middle of the cooling plate assembly. Once the arc was established an increased pressure differential was observed which could be increased by increasing the arc current, as well as increasing the gas pressure in the cell.

3. Results

The results presented here are a summary of two of the milestones achieved thus far: 1) the transmission of a proton beam from vacuum into atmosphere through the plasma window and, 2) the maximum pressure achieved thus far for an argon gas target.

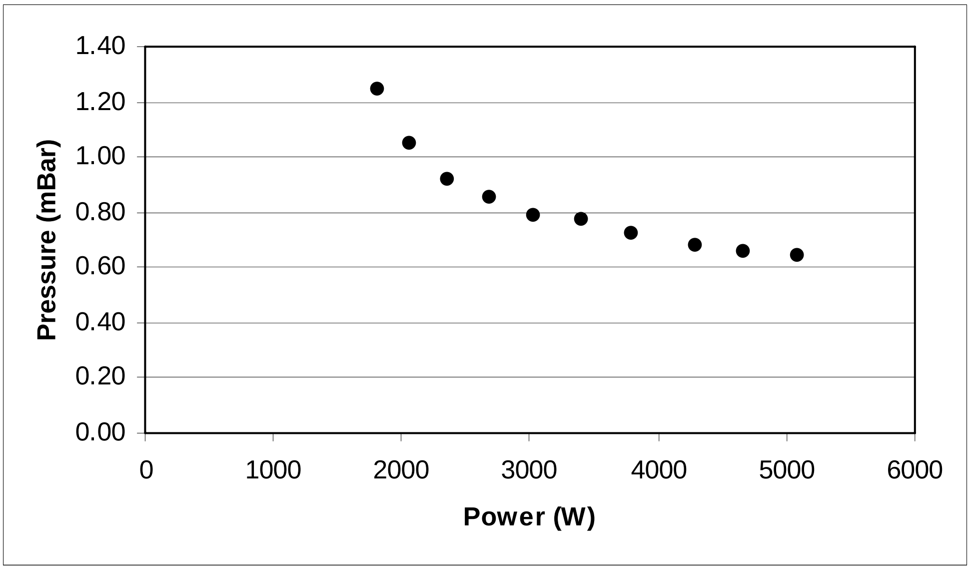

FIG. 3: Plot of electrical power supplied versus the pressure in the first vacuum chamber while the gas cell was open to atmosphere

3.1. Vacuum-Atmosphere Experiments

Our aim here was to send a particle beam from vacuum into atmosphere through an argon plasma window. The first step was to be able to open up the one side of the plasma window to atmosphere while still holding the other side under vacuum. With all pumps venting towards atmosphere and a separate gas feed to the argon plasma directly from the gas bottle, we could strike the plasma arc and then increase the pressure from the gas bottle until the end cap (held on by the pressure differential) fell free. Once the end cap was off, the pumps were redirected such that they vented out of the same orifice that the beam would pass through. This minimised the amount of fresh gas required to sustain the plasma. We were thus able to maintain the vacuum-atmosphere interface across the 5 mm orifice with just 1.8 kW of electrical power. This configuration ran stably for over an hour (before being intentionally switched off) with a corresponding pressure of approximately 1.2 mBar in the first of the differentially pumped vacuum chambers after the plasma window. FIG. 3 shows the dependence of the pressure in this chamber on electrical power supplied to the plasma window. The graph was generated by varying the power while the gas cell was open to atmosphere and recording the corresponding pressure readings in the first chamber. Error bars have been omitted since this was a relative comparison and errors were systematic.

Once we were confident that we could reliably hold off atmospheric pressure the system was aligned with one of the beam lines at the Necsa Van de Graaff accelerator facility, in order to direct an ion beam into atmosphere. We successfully transmitted a 2 MeV proton beam (current of 10nA) into atmosphere but have not yet quantified the characteristics of the beam.

3.2. Argon Gas Cell

In order to optimise the system for eventual use with a deuterium gas target (to produce fast neutrons), an argon gas target was used (argon being a much easier gas to ionise). This also served as a good way of measuring the effectiveness of the improvements made since the experiment was last conducted at Necsa [3]. The results were very favourable with an almost threefold improvement on the gas target pressure and a corresponding decrease of about a

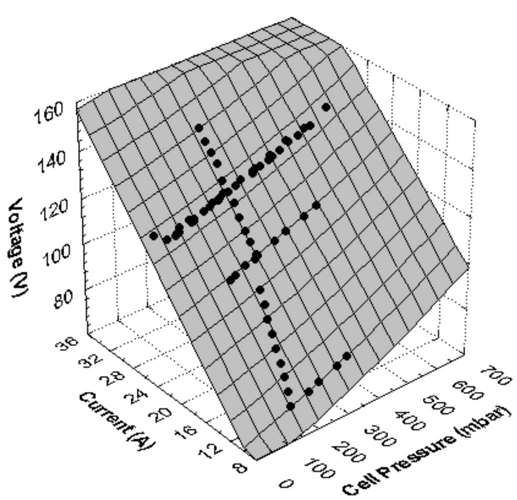

FIG. 4a. Surface plot of previous work [3]

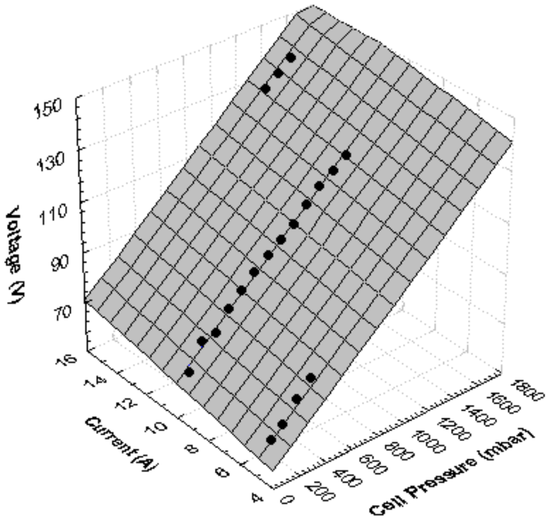

FIG. 4b. Surface plot of current work

third in power consumption. Previously [3], with a 5 mm aperture, a maximum argon target pressure of 585 mBar was obtained at a power consumption in excess of 10 kW (see FIG. 4a. reproduced from [3]). The new results (FIG. 4b.) show that we are able to maintain a target pressure of 1.5 Bar at a power consumption of only 6.3 kW. In both these experiments, the pressure in the first differentially pumped chamber was kept between 0.1 and 1 mBar. These favourable results serve as an important milestone towards implementing an efficient deuterium gas target.

A problem, which we hope to overcome with a new design (see section 4.5.), is that all the cathodes do not always fire together. With the 5 mm aperture, it seems that only one cathode (arbitrarily preferred) bears the entire load. At first it was suspected that an irregular flow was occurring but even changing the flow characteristics did not spread the load.

4. Discussion

It is very clear to us that this technology shows great potential in a variety of accelerator applications. However, a great deal of work is still envisioned for the near future and a few of the plans for further experiments and improvements are mentioned below.

4.1. Characterisation of Ion Beam in Atmosphere

Although we have succeeded in transmitting a 2 MeV proton beam into atmosphere, we have still to perform quantitative measurements in order to accurately characterise the emerging ion beam employing RBS (Rutherford back scatter) in terms of energy loss and spread.

4.2. Implementation of Venturi System

Although a device resembling a venturi has been implemented, it has not been used to produce the traditional venturi pumping action. Rather, it was used to redirect and stabilise the rapid flow of gas that supplies the plasma when in recycling mode. An actual venturi has still to be designed and built for the system, as first suggested by Hershcovitch et al [2]. This should result in a significant further improvement in the pressure differential obtained.

4.3. Improved Cooling

When dealing with such high electrical power confined to a relatively small area, the cooling of the metal components becomes a major limiting factor. Although we have implemented various novel cooling systems throughout the experimental arrangement, it was found that as one went up in power and gas cell pressure, the cooling became increasingly insufficient. More effective cooling techniques are currently under investigation.

4.4. Experiments with the Shape of the Plasma Channel

Thus far all experiments have been performed with a cylindrical, 5 mm diameter, 45 mm long plasma channel. Further investigations will examine the limits of the length and diameter of this channel. A larger diameter, shorter length plasma channel would be more conducive for some of the envisioned applications such as electron and ion beam irradiation. The current shape also allows for an undesirable flow of gas around the outside edge of the cylindrical plasma. Investigations need to be done into hampering this flow of gas. One suggestion is to vary the diameters of the apertures in alternative cooling plates such that one has a “wiggling” plasma rather than a cylindrical one, thus restricting gas flow in the space between the cooling plates and plasma.

4.5. Cathode Design

The traditional 3-cathode design has been used reliably for many years and will probably still be used for valuable experiments in the future. One of the problems that we have found, however, has been the reliability on having all cathodes firing at the same time. We have found that on most occasions, in the present configuration, current flows through only one cathode. With all cathodes evenly spaced, the choice of which cathode carries the load seemed to be totally unpredictable. One possible explanation is that the 5 mm separation is too great for the amount of power we are supplying. A new cathode design consisting of only one cathode in the shape of a cylinder with a circular knife-edge pointing in the direction of the anode will be tested soon. This configuration was developed to minimise the amount of un-ionised gas that finds its way to the outside of the plasma. With a cylindrical cathode, any gas that enters the plasma region would now be forced directly into the middle of the plasma.

5. Applications

There are many possible applications for this technology, many of which, we believe, are yet to be conceived. Various applications have also been mentioned in [2] such as fast neutron production, liquid targets, internal targets, and solid targets. Another major application is in the field of electron beam welding [4,5].

5.1. Fast Neutron Production

The $d(d,n)^3He$ nuclear reaction produces mono-energetic fast neutrons, which can be used for various applications. The plasma window technology, applied to an accelerator system with a deuterium gas target, will enable a continuous beam of deuterium ions to be delivered into the target with no foreseeable limit to the beam current. Achieving our aim of a 3 Bar gas target, with a 5 mm beam diameter, would mean a significant contribution to the field of gas target technology and would set new standards internationally, in the production of intense beams of mono-energetic neutrons. This technology would, however, have to be combined with appropriate flow technology within the gas cell in order to ensure maximum interaction with the target gas. An added characteristic of using plasma window systems is that by sandwiching the target gas between two plasma windows, one would be able to extract the incident ion beam on the other side and either use it for another purpose or redirect it back to the accelerator.

5.2. Ion Beam Experiments in Atmosphere

Now that one is able to bring a beam into atmosphere with no restriction on beam current and minimal energy loss [3], the possibilities are limited only by the imagination of accelerator users. For example, amongst the many projects under way at Necsa, the 4MV Van de Graaff accelerator is used for PIXE (particle induced x-ray emission) experiments. Currently all samples need to be placed within a vacuum chamber of limited size and shape. For larger samples, or samples not suited for a vacuum environment, we use a Be window to bring the beam into atmosphere without compromising the accelerator vacuum. This method, although useful, is limiting in terms of beam current and energy dispersion of the beam. Using plasma window technology we would be able to bring a purer beam into atmosphere and thus perform PIXE measurements on samples of any size, type or shape. Larger accelerators capable of delivering higher energy beams would find more applications for such technology, especially those machines capable of delivering very high beam currents.

5.3. Electron and Ion Beam Irradiation

Previous work regarding the implementation of the plasma window on electron beam lines has been developed mainly in the field of electron beam welding [4,5]. Irradiation of sewage and organic materials by an electron beam for treatment of bacteria can also be achieved using this technology. The upgrade suggested, however, is that the plasma window be placed at the focal point of a strongly focussed electron beam (or the pivot point of a swinging electron beam), which would thus irradiate a much larger surface area in a much shorter time. In order to implement this, the plasma window would either have to be somewhat conical in shape or considerably shorter than the current design.

6. Conclusion

It has been demonstrated that an argon plasma window with a 5 mm aperture supplied with only 1.8 kW of electrical power and coupled to a differentially pumped system can stably hold off atmospheric pressure from the vacuum within an accelerator beam tube while an ion beam passes through it into the atmosphere. Significant improvement has also been made in terms of holding off a gas target with the plasma window. An argon gas target of 1.5 Bar was held off from the accelerator vacuum by a 5 mm diameter plasma window using 6.3 kW of electrical power and also coupled to a differentially pumped system. Both these achievements represent important milestones in the development of plasma window technology at Necsa.

7. References

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