

Demonstration of Plasma Window with 20 mm Diameter and Pressure Separation for Accelerator Applications

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A large diameter plasma window was developed for accelerator applications. In this study, a pressure separation using the plasma window was demonstrated, and the maximum diameter of the plasma window reached up to 20 mm. The prediction formula based on the viscous flow for confinement pressure cannot be applied in the case of large diameters due to low input power density to the plasma.

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Beam windows are often used in particle accelerator systems to separate vacuum from an atmosphere in regions where the beam can propagate. Solid materials are generally used as beam windows; however, such materials cannot be used for high-intensity beams because of their low durability against heat load and radiation damage.

The plasma window (PW) [1] separates vacuum from an atmosphere using an arc plasma filling the discharge channel; it is a novel technology for beam window. Many applications of the PW are expected in accelerator systems, such as gas charge stripper [2, 3] for heavy ion accelerator and beam window for accelerator-driven subcritical reactor [4]. However, PW's small diameter is a critical problem for its use in various applications. The first PW, invented by Hershcovitch [1], primarily focused on electron beam welding in an atmosphere, and its aperture was only 2.36 mm. However, beam spot sizes in our intended cases are several tens of millimeters. Therefore, for applications of PW in accelerator systems, it is essential to enlarge its diameter. Furthermore, an investigation to study the relation between confinement pressure and diameter is also important for the prediction of PW performance for various applications. Conventional PW design has a geometrical limitation that restricts the enlargement of the diameter. Therefore, we selected a different type of PW designed by Namba *et al.* [5] for our study. Several modifications were made to enable a variable diameter of up to 20 mm. The purpose of this study is to develop a PW with a large diameter and demonstrate the improvement of confinement pressure by generating the plasma.

The structure of developed PW is shown in Fig. 1. It comprised a cathode, eight isolated intermediate elec-

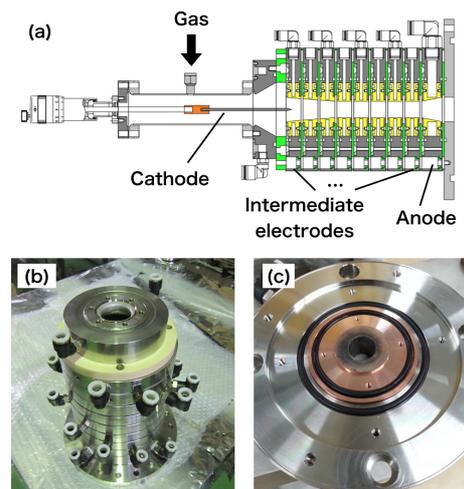


Fig. 1 Developed PW: (a) schematic of the PW; (b) overall view of the PW; (c) internal structure of the intermediate electrode.

trodes, and an anode. A CeW welding rod sharpened to a pencil point was used for the cathode. The intermediate electrode was comprised of two parts: the inner part was made of CuW that has a high melting point and thermal conductivity and the outer part was made of stainless steel. The anode had the same structure as the intermediate electrode; however, the anode was thicker and tapered to moderate the thermal load. These electrodes were cooled by flowing water between the inner and outer parts. The channel diameters in the PW were 6, 10, 15, and 20 mm, and they were varied by replacing the inner parts.

The experimental setup is shown in Fig. 2. Ar gas was introduced from the high pressure side of the PW. The PW was attached to a chamber that was exhausted using two mechanical booster pumps (~200 L/s) with a rotary

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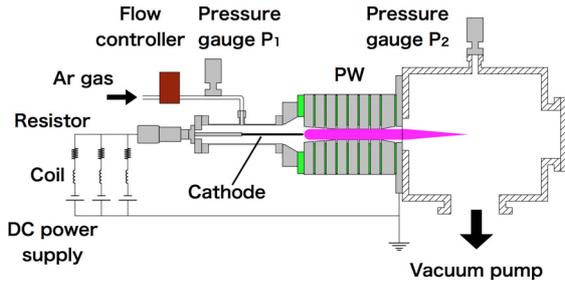
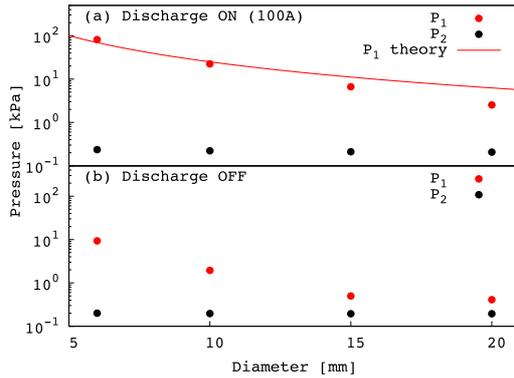


Fig. 2 Experimental setup.


 Fig. 3 Measured P_1 , P_2 , and theoretical P_1 as a function of diameter.

pump. Three DC power sources supplied a total arc current of 100 A and the discharge voltage was monitored. A mass flow controller was used to maintain the gas flow rate at 20 L/min. Both the pressures at upstream P_1 and downstream P_2 were measured.

The results of the measurements are summarized in Fig. 3. P_1 increased up to 10 times after filling with arc plasma. However, P_2 demonstrated only a small difference with and without the plasma conditions because P_2 is almost determined by gas flow rate and pumping speed. Therefore, pressure separation using the PW with a 20 mm diameter was successfully demonstrated to reduce the conductance by a factor of 10.

Pressure separation using the PW is explained by the following two effects [1]: first, the arc plasma with high temperature compensates the high density on the high-pressure side. Pressure p is given by the equation of state: $p = \rho kT/m$. Here, ρ , k , T , and m are the mass density, Boltzmann constant, temperature, and mass of gas particle, respectively. The second effect is viscosity, i.e., viscous flow through a circular tube is described using Hagen-Poiseuille law.

$$Q = \frac{\pi r^4 \rho}{8\eta L} \Delta p. \quad (1)$$

Here, Q , r , L , η , and Δp denote the mass flow rate, channel radius, channel length, viscosity, and pressure difference ($\Delta p = P_1 - P_2$), respectively. Since the viscosity of Ar plasma is proportional to temperatures up to 12,000 K [8], the high temperature plasma causes large pressure differ-

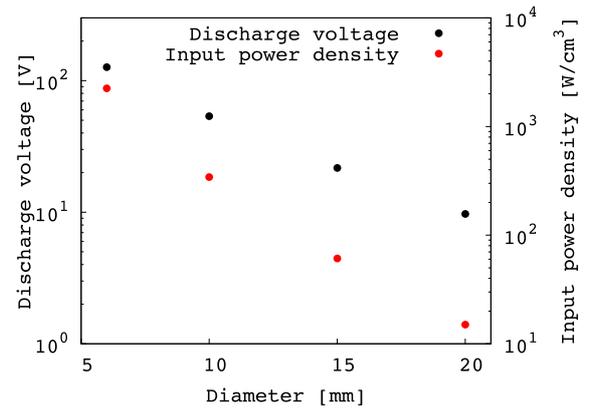


Fig. 4 Discharge voltage and average input power density as a function of diameter.

ence. These equations give a prediction of the upstream pressure (i.e., the confinement pressure) P_1 [6, 7].

$$P_1 \approx \sqrt{\frac{16\eta kT}{\pi m}} \frac{\sqrt{QL}}{r^2}. \quad (2)$$

We calculated the theoretical value of P_1 using Eq. (2), assuming a temperature of 1 eV according to a spectroscopy measurement conducted in Ref. [5]. The corresponding viscosity η was obtained from Ref. [8]. Figure 3 compares the measured and calculated P_1 values. In the case of ϕ 6 and 10 mm diameters, the measured value agreed with the predicted value. However, the measured P_1 became less than the predicted P_1 at large diameters. This discrepancy between the experimental and theoretical values was observed at low input power density with large diameters. As shown in Fig. 4, the average input power density estimated from the discharge current (fixed at 100 A), voltage, and the geometry of the PW, showed a drastic reduction in the region of large diameters. As a consequence, the plasma conditions need to be significantly changed.

In conclusion, we have successfully demonstrated conductance reduction using a PW with a diameter of up to 20 mm. The well-known prediction formula for confinement pressure cannot be applied in the case of large diameters due to low power density.

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