Experimental study of the plasma window *

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Abstract: The plasma window is an advanced apparatus that can work as the interface between a vacuum and a high pressure region. It can be used in many applications that need atmosphere-vacuum interface, such as a gas target, electron beam welding, synchrotron radiation and a spallation neutron source. A test bench of the plasma window is constructed in Peking University. A series of experiments and the corresponding parameter measurements have been presented in this article. The experiment result indicates the feasibility of such a facility acting as an interface between a vacuum and a high pressure region.

Key words: plasma window, cascaded arc, windowless target

PACS: 52.80.Mg, 29.25.-t **DOI:** 10.1088/1674-1137/38/1/018201

1 Introduction

In 1995, the concept of the plasma window was originally proposed by Ady Hershcovitch from BNL [1]. The following experiments showed that the plasma window can separate a vacuum of 7.6×10^{-6} torr from the atmosphere for argon [1]. Transmission of electrons, x-ray and ions has been proven successfully by some experiments [2]. High-quality electron beam welding with plasma shielding was achieved [3]. The basic characteristics of the plasma window have been described in some papers [1, 4].

The conventional metallic foil window used in gas target, such as the aluminium window, molybdenum window and Havar window (a kind of colt-based non-magnetic alloy), cannot be very thin because of the strength requirements for the pressure differential. Therefore, a foil window can cause beam energy loss, especially in the case of low-energy ion beams. Besides, the beam intensity is limited under the consideration of the cooling problem and the lifetime of the window. Compared with the foil window, the plasma window can sustain a high-current ion beam almost without energy loss. In addition, the invulnerable feature of the plasma window can enable the whole system to work stably in the long run. For further application, a deuterium gas target with a plasma window has been built to generate the mono-energetic fast neutron [5]. A plasma window can also work as an interface which separates the lead-bismuth eutectic target from the vacuum of a particle accelerator in ADS (Accelerator-driven Subcritical Nuclear Energy System). The high pressure region generated by a plasma window is useful for controlling the free surface of liquid metal[6].

2 Plasma window device

The plasma window is a channel filled with plasma generated by a stable DC discharge arc. It consists of three cathodes, an anode and a stack of six cooling copper plates. The thickness of the plates is 9 mm; the thin plate design makes it easy to ignite because of the improved electric field. The six plates are insulated from each other by boron nitride spacers, which have remarkable thermal stability and conductivity among available insulating materials. The cylindrical apertures in the center of each copper plate and BN spacers form a DC discharge space. In this experiment, copper plates with different diameters are used: one is 3 mm and the other is 6 mm. Water cooling is critical for the stable operation of the arc, so all components that are close to the arc have well-designed water cooling channels. Compared with the common free-burning arc, such wall-stabilized arc can guarantee a higher voltage with a smaller current. Therefore, arc power can be increased while the life span of cathodes can be expanded largely [7]. The schematic is shown in Fig. 1. A similar design was also used in the research on the physical properties of plasma [8].

Received 25 March 2013

* Supported by National Natural Science Foundation of China (10805003, 91026012)

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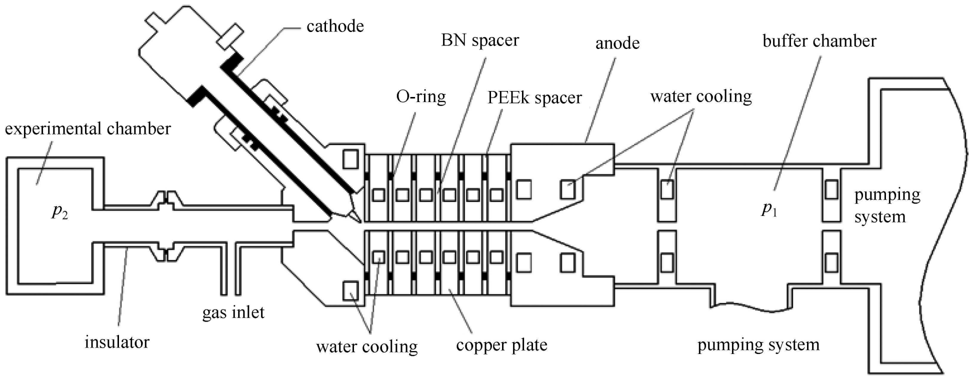

Fig. 1. Schematic diagram of plasma window.

The separation function of the plasma window mainly depends on the pressure equalization effect [1]. According to the equation of state for ideal gas:

$$p = nkT,$$

considering the average temperature is 12000 K within the arc and 300 K in the experimental chamber, the density in the arc is 1/40 of the gas density of the experimental chamber [1]. The dynamic viscosity effect is another contributive factor. It is known that the pressure will drop while a laminar gas flows through the tube, which can be roughly described by the Poiseulle's equation for compressible ideal gas:

$$p_2^2 - p_1^2 = \frac{16}{\pi}\eta\frac{l}{r^4}NRT,$$

where r and l are the tube's radius and length, N represents the mole number of the gas flow rate and η is the dynamic viscosity coefficient. The viscosity of plasma gas depends highly on temperature, but varies little with pressure. According to the data of Ref. [9], the viscosity of argon plasma is 2.42×10^{-4}, ten times higher than that of argon at room temperature. These properties make the plasma window form a pressure differential between two sides. If pumping system is arranged properly, the pressure differential can be very high.

3 Experiment results of plasma window

The experiment system comprises a stabilized current power supply, a differential pump system with a combination of roots pump and claw-type pump, measurement instruments and plasma window. A photograph of the plasma window is shown in Fig. 2. The stabilized current supply provides a direct current output from 10 A to 80 A, a DC voltage output from 40 V to 400 V and an ultimate power output up to 30 kW. A pressure sensor is mounted on the side of the experiment chamber with high pressure. On the other side of the plasma window is a buffer chamber connected with a pump and a vacuum gauge. Integrated with a high frequency triggering system, the power supply provides an alternating output voltage of more than 6000 V for ignition. In all previous designs, many additional devices are used, including the Tesla coil or other setups for ignition, LC filters to reduce the electromagnetic noise and high-power resistors with a low Ohm value to further stabilize the current.

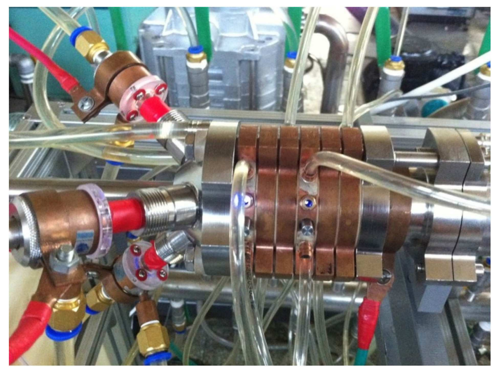

Fig. 2. Photograph of plasma window.

A series of measurements have been done to test the performance of the entire system. The plasma window operates under various powers and gas flow rates with argon. In the experiment, only the gas flow rate and the discharge current can be adjusted. The power consumed by the arc discharge is related to the pressure p_2, which can influence the function of the mass flow controller. By adjusting the gas flow rate and current simultaneously, p_1 can be set at a constant value 60 Pa. In this way, the data of p_2 have comparability, so too does the pressure reduction factor (the pressure reduction factor is defined as p_2/p_1).

At first, different pressure data without discharge are measured by adjusting the flow rate. The relationship of p_1 and p_2 is shown in Fig. 3. For the 6 mm aperture, the pressure of p_1=60 Pa in the buffer chamber corresponds to p_2=2.6 kPa in the experimental chamber. The pressure reduction factor is 43. For the 3 mm aperture, the factor is about 100 and p_2=5.3 kPa. The relationship between p_1 and p_2 is shown in Fig. 3. The pressure sensor is used for the measurement of p_2, the error is less than 10% around 0.1 atm. For the measurement of p_1, the error of the quartz vacuum gauge is less than 30% in the range of 10 Pa to 100 Pa. All of the pressure data are an average of 20 records.

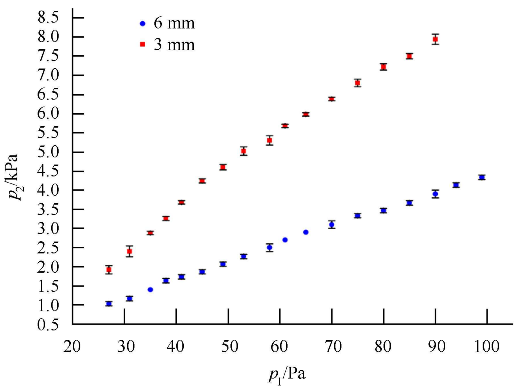

Fig. 3. p_1 and p_2 with different gas flow rate.

The pressure p_2 under different power is shown in Fig. 4. A factor up to 200 has been achieved for the 6 mm aperture with stable arc discharge, and 800 for the 3 mm aperture. Although the reduction factor decreases three times from 6 mm to 3 mm at the same power supply, it increases with power. A further improvement space for a larger diameter can be speculated if the higher power supply is used.

A typical potential distribution of copper plates with 50 A discharge current is shown in Table 1. It is reasonable to assume that the plasma in the middle of the discharge column is fully developed, so the average electric field intensity is calculated based on the voltage drop between the second and fifth cooling plates. For the voltage drop between the copper plate and the anode, there is a fluctuation of 0.1 or 0.2 V. For the voltage drop between anode and the cathode, the fluctuation is less than 0.4 V. The average plasma conductivity can be calculated by: $\sigma = I/\pi r^2\overline{E}$ [4]. It is 30.6 $\Omega^{-1}\text{cm}^{-1}$ for a 3 mm aperture, and 21.2 $\Omega^{-1}\text{cm}^{-1}$ for 6 mm. In Ref. [4], $\overline{E}$ is the average electric field between the cathodes and the first copper plate, which is inappropriate because of the existence of a steep potential fall near the cathodes. According to the data of Ref. [9], the average temperature is estimated to be 10100 K for 3 mm and 8900 K for 6 mm.

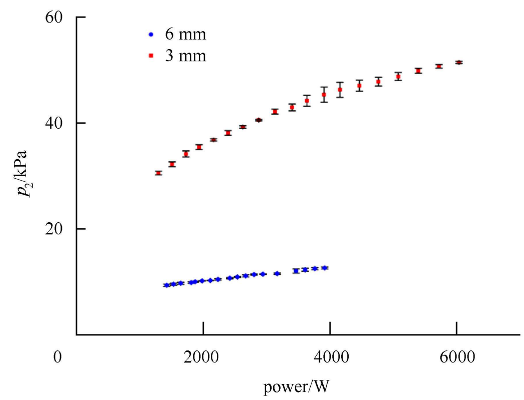

Fig. 4. p_2 under different power.

Table 1. The copper plate potential distribution of different aperture diameters: 3 mm & 6 mm.

	1st	2nd	3rd	4th	5th	6th	anode	p_1/Pa	p_2/kPa
3 mm	14.2	36.1	52.2	68.3	84.6	100.2	114.4	60	46.3
6 mm	11.6	20.8	26.5	32.2	38.3	43.8	53.4	60	11

4 Conclusions

In summary, a 6 mm diameter discharge channel and a 6.1 cm total length are the largest dimensions used, compared with similar experiments. In the experiments, water cooling is found to be a very crucial factor, especially for the buffer chamber due to the contact with the anode jet. The experimental data presented in this paper demonstrate the feasibility of the plasma window with a large bore diameter. However, a larger diameter requires a higher power supply and a more powerful pump system. In this experiment, only one pump system is used. Its effective pumping rate under 100 Pa is less than 1 L/s. We are planning to utilize a new vacuum system with a higher pumping rate to secure a better pressure differential. The following experiments will focus on the optimization of the operating parameters and larger diameter. Besides, further structure modifications are proposed.

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