BNL-112492-2016-JA

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Submitted to Physics of Plasmas

July 2016

Collider-Accelerator Department

Brookhaven National Laboratory

**U.S. Department of Energy
Office of Science, Office of Nuclear Physics**

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Theoretical and experimental investigation on magneto-hydrodynamics of plasma window

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As a new device, plasma window has been designed to use plasma discharge to separate atmosphere from vacuum with high difference of pressure. It has many excellent properties, being able to be used as available passage for ion beam with negligible energy loss, also impervious to radiation damage and thermal damage. Normally beam focusing by accelerators is not that easy to achieve within channel of small cross section. 10 mm diameter plasma window's experimental realization could contribute to its further application in accelerator system. In this paper, 10 mm diameter 60 mm long plasma window has first been designed and managed to generate arc discharge with argon gas experimentally. The result proves that it has ability to separate at least 28.8 KPa (not the upper limit) from 360 Pa with 50 A direct current and 2.5 KW power supplied. Current increase leads to linear inlet pressure increase obviously, while it has less impact on outlet pressure and voltage, coming to the conclusion that the higher current of plasma discharge, the larger pressure difference it creates. Theoretical analysis of 10 mm diameter plasma window in axis symmetrical configuration using argon also has been provided, in which a numerical 2D FLUENT-based magneto-hydrodynamic simulation model is settled. It has a good agreement with experimental result on voltage and mass flow rate when inlet pressure is increased.

I. INTRODUCTION

The plasma window concept was first created by Ady Hershcovitch [1] in 1995, regarded as a device for windowless vacuum seal. It can sustain a huge pressure difference between two sides using plasma flow. There is great importance of it to be applied in many ways. For example in non-vacuum electron beam welding, plasma window has been realized by experiment, showing that it could provide a perfect effect on separating vacuum from atmosphere. It will bring energy efficiency and vacuum instruments savings [2]. In addition, plasma window could be used into composed gas target without solid window in small neutron source device. It enables a continuous beam of deuterium ions delivered into the target to produce mono-energetic fast neutrons [5]. Plasma window may also offer a possibility of enabling ion beam analysis in atmosphere. This will break the limitations in traditional experiments where samples have to be placed in vacuum environment. It could be utilized in internal targets, strippers, windows for lasers, lens in storage rings and windowless beamlines etc. [3] as well.

Previous research shows that the plasma arc could be used to separate high pressure at 2.85 bar [4] from vacuum (0.6 mbar) across a 2.36-mm diameter 40-mm long arc by three chamber differentially pumped system, and up to 9 atm [5] from 2 mbar with 2 mm channel in diameter. The diameter of plasma channel in record reaches from 2 mm to 6 mm [1-10]. As the

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result says, the electron beam with 175 KeV could successfully pass through from vacuum to atmosphere [7]. X-rays at any energy has been testified to be transmitted through plasma window with negligible energy losses [8]. And also proton beam with 2 MeV was successfully transmitted through the plasma window in argon, helium and deuterium, where the beam energy loss resulting from a slowing down through plasma was below the detection limit of RBS system employed (20 KeV) for all gases used [9]. Relevant diagnostics of plasma characteristics was recorded experimentally and computationally [14].

Research data shows that the pressure on the high vacuum can reach as low as 5×10^{-4} Pa with 2.36 mm diameter and 40 mm long using three-stage differential pumping system [4]. But the cross section of plasma channel is not large enough for ion beam to pass. It is relatively hard to focus ion beam within channel of 3 mm diameter. Thus enlarging the cross section of plasma window coupled with separation from atmosphere to high vacuum is necessary. If these requirements have been achieved, real function of plasma window can be of great use in many potential fields, in which inconvenience normal expected applications may encounter can be overcome.

In this paper, to study the characteristics of plasma window physically, experiment with 10 mm diameter was conducted and related analysis was given. Simulation model of plasma window with 10 mm diameter was also settled computing the plasma arc regime from gas inlet to outlet with Fluent. Comparison of theoretical and experimental results of 10 mm plasma window was also studied.

II. Experimental exploration

Experimental design of plasma window with 10mm diameter and 60 mm long channel is considered to meet the need for beam passing accessibility in the future, shown in Fig. 1. Three cathodes are 120° axial symmetrically located, providing negative voltage supplied by constant DC power source. Copper plates in the middle are cascade connected to help ignite the argon gas in the plasma passage. Anode is connected to the earth so that its electric potential is zero. Argon gas is fed from left to the right side using differential pumping system.

FIG. 1. Diagram of plasma window.

Experimental results in terms of characteristics of plasma window is showed as below. First, all plasma system was vacuumized to near 10 Pa. Then argon gas was fed in from inlet, making inlet pressure increase to several KPa. When constant DC power source provides voltage, argon gas flow could be ignited and stabilized at a constant electric current 50 A. Gradually increase of argon mass flow rate from 1.5 SLM to 48.4 SLM (not the upper limit) led to increase of inlet pressure from 1.7 KPa to 28.8 KPa and electric voltage from 33 V to 51 V. Voltage and power needed increased linearly at the same pace with inlet pressure increase showed in Fig. 2 (a). In addition, it could be inferred that when inlet pressure reaches 1 atm, the supplied power will be around affordable 5 KW. Meanwhile, from Fig. 2 (b) it can be seen that outlet pressure increased from 1.7 Pa to 360 Pa accompanied by the linear increase of pressure difference as inlet pressure increased. In case of linear correlation, it could be estimated that outlet pressure will reach about 1.44 KPa when inlet pressure approaches 100 KPa (1 atm). It seems necessary that another section could be added together as cascaded plasma window to lower the outlet pressure 1.44 KPa to high vacuum under such condition. All power needed will be around 7 KW. In such configuration, a controlling plate could be added in the middle to control the pressure distribution. First, all pumping system is activated and gas is fed into from left side. The pressure in the middle can be controlled to a proper value by the plate. Then voltage of two sections could be added to ionize argon gas separately. When pumping efficiency is improved, 10^{-5} Pa vacuum separation from atmosphere is believed to be achieved.

FIG. 2. Plots of cathode voltage and supplied power (a) as well as outlet pressure and the difference of inlet and outlet pressure (b) as functions of inlet pressure when gas flow rate is increased, with current being constant as 50A. Plots of voltage and current divided by voltage (c) as well as inlet and outlet pressure (d) as functions of discharge current, with mass flow rate being constant as 10.5 SLM, where residual sum of squares of I/U is 0.0089

In Fig. 2 (c), it shows I-V characteristics plot. It could be discussed by electrical conductivity variation due to temperature. From the experimental result of 3 mm plasma window discharge U-I plot in Reference of S. Huang [10], we can conclude that temperature has a linear correlation with current. As we know, electrical conductivity has such relation:

$$\sigma = \frac{I}{U} \frac{L}{S}. \quad (1)$$

In this situation, constant L represents length of plasma flow and S cross section area of plasma cylinder. So from Fig. 2 (c), electrical conductivity σ varies linearly with electric current, thus having linear correlation with temperature as well. The electrical conductivity's relation with temperature and pressure of argon has been fully discussed under LTE assumption in

Reference [11] showed in Fig. 3 (a). Normally deviation from LTE may occur in our experimental situation where the temperature is just slightly higher than that in LTE model [12] but it has little impact. From here we can know that before peak points 17000 K at 0.01 atm (1 KPa), 20000 K at 0.1 atm (10 KPa) and 22000 K at 1 atm (100 KPa) respectively, electrical conductivity increases almost linearly with temperature from 5000 K above in narrow temperature range. The simulation result shows that under the condition that inlet pressure ranges from 4 KPa to 8 KPa and current increases from 10 A to 60 A with mass flow rate around 10 SLM, the highest temperature is about 14000-15000 K, much less than 17000 K. The accuracy of temperature simulation compared with experimental result can be traced from the previous research in Reference [10]. So the temperature of plasma discharge under such condition must be located between 5000 K and 17000 K, meaning that electrical conductivity varies approximately linearly with current within narrow range. Consequently the trend of voltage with increased current could be explained by electrical conductivity's linear correlation with temperature in the consideration of linear correlation between temperature and current.

FIG. 3. Electrical conductivity (a) and viscosity (b) of argon as functions of temperature at different pressures 0.01 atm, 0.1 atm and 1 atm respectively.

When it comes to variation trend of outlet pressure showed in Fig. 2 (d), which has been studied more in Fig. S1 in supplementary materials [15], it could be clarified in consideration of viscosity's great variation [11]. The viscosity effect of plasma on argon gas flow can be described by Poiseuille's equation

$$P = \sqrt{P_0^2 - \frac{16}{\pi} \mu \frac{L}{r^4} \frac{m}{M_0} RT}, \quad (2)$$

where P and P_0 here represents low and high pressure at different side, μ is dynamic viscosity coefficient, r and L are tube radius and length, m is the mass flow rate, M_0 is the Moore molecular mass and T the temperature. Increased power supplied has the same pace with current increase, leading to higher temperature. Then from viscosity trend of argon as function of temperature and pressure showed in Fig. 3 (b), we can see that viscosity increases before a certain point, but there is a huge decrease when temperature approaches 8000 K at 0.01 atm, 9000 K at 0.1 atm and 10000 K at 1 atm respectively. We can infer that there will be a critical point of viscosity near 20 A in this situation, corresponding to viscosity's turning point between 8000 K and 9000 K. As is seen in formula (2), the lower pressure will decrease if increases of temperature and viscosity happen at the same time. However, when viscosity reaches maximum, it will decrease with high gradient. If this gradient of decrease is greater than that of temperature increase, then the outlet pressure will increase.

Fig. 4 (a) and Fig. 4 (b) give experimental results about inlet and outlet pressure variation trend due to mass flow rate concerning different current 5 A and 10 A and no discharge current. Obviously it shows sealing effect, keeping pressure difference between inlet and outlet side. Compared with 3 mm and 6 mm diameter plasma window [10], 10 mm sealing effect is relatively weak as the result of enlarged diameter of plasma channel. But it can be compensated by cascade plasma window configuration.

It can be concluded that increasing current will lead to obvious inlet pressure linear increase, but it has little impact on outlet pressure comparatively. Outlet pressure will drop near a critical point, but keeps increasing after that as a result of viscosity decrease. Voltage will increase nonlinearly with current because of electrical conductivity's linear increase with temperature. It is obvious that high current means high pressure difference, better sealing effect of plasma flow.

FIG. 4. Comparison among inlet pressure as function of mass flow rate when different discharge current are set zero, 5 A and 10 A, where residual sum of squares are 0.0556, 0.0351 and 0.0558 respectively (a). And comparison among outlet pressure as function of mass

flow rate when different discharge current are set zero, 5 A and 10 A, where residual sum of squares are 251.1097, 31.7449 and 23.4323 respectively (b).

III. Theoretical simulation

In the simulation, the axisymmetric plasma arc section has been designed with the same size as in experiment, mainly from cathode to anode. Its configuration, using denser mesh to be sure of stability and accuracy, more complicated than 3 mm model in terms of simulation, could easily cause divergence in computation. Targeted section is divided into lots of two dimensional quadrilateral cells calculated with finite volume method. Governing equations expressed in cylindrical coordinates are mass conservation, momentum conservation in axial direction, momentum conservation in radial direction and energy conservation. Thermodynamic and transport properties including thermal conductivity, viscosity, density, sound speed, specific heat and electrical conductivity are functions of plasma temperature and pressure, interpolated as user defined functions under Local Thermal Equilibrium (LTE) model [13].

All equations above coupled with Maxwell's equations under boundary conditions in Table. T1 listed in supplementary materials [15] can be calculated in MHD model using standard k-epsilon viscous model. As shown in boundary conditions, all temperatures of the wall are set 300 K except for cathode and anode (7000 K). Pressures of inlet and outlet are set 12.8 KPa and 200 Pa respectively. Electric potential of cathode is set 40 V, while the one of anode 0 V because of contact with the earth.

In simulation, energy and electric potential equations were calculated first, making sure arc discharge was stabilized. And it led to formation of electric current density vector field and temperature distribution which got higher around plasma flow regime between cathode and anode. Then flow and turbulence equations were computed independently to avoid divergence, in which pressure difference induces velocity field. Finally all these four parts were added together to give the simulation result showed in Fig. 5. As the arc discharge creates blocking effect, pressure gradually decreases from inlet to outlet. The temperature distribution can be easily understood because electric current flows between cathode and anode, producing and radiating heat mainly in this part. Some energy could be left along with rushing flow as well in the section after anode and some was turbulent energy left in the nozzle vacuum side. Fig. 6 (a) and Fig. 6 (b) give comparison of simulation and experimental result, with discharge current kept as constant 50 A. Fig. 6 (a) shows inlet pressure-voltage plot, indicating that simulation matches well to some extent with experimental result in terms of physical magneto-hydrodynamics. In addition, it can be seen that more power is needed to sustain arc discharge when inlet pressure is increased. Fig. 6 (b) gives mass flow

rate-inlet pressure plot, showing that there exists little deviation between simulation and experiment by means of calculating flow and turbulence equations in MHD model.

FIG. 5. Pressure and temperature distribution of plasma window.

FIG. 6. Comparison between simulation and experiment on electric voltage (a) and mass flow rate (b) as functions of inlet pressure, arc discharge current kept as constant 50A.

IV. Conclusion

In conclusion, 10 mm diameter plasma window was proposed and conducted both experimentally and was realized by computational simulation. Experimental properties of plasma discharge flow in plasma window were discussed and they have shown its effective sealing ability with DC arc discharge. Computational simulation performed with 2D axisymmetric MHD model reveals inner physical state of plasma flow and its simulated result has agreed well with experiment. Cascaded plasma window has been proposed and it is necessary to realize separation of atmosphere from high vacuum (10^{-5} Pa) based on 10 mm plasma window for the sake of further application to accelerator system.

This work is supported by the Major State Basic Research Development Program of China (973 program) (Grant No. 2014CB845503) and National Natural Science Foundation of China (Grant No. 91026012).

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- [15] See supplemental material at [] for detailed description. In supplemental Fig. S1 we show comparison of outlet pressure variation among different mass flow rate. In Fig. S2 we indicate modeled domain of plasma window. Table T1 shows boundary conditions for pressure, temperature and electric potential. Governing equations calculated in cylindrical coordinates are discussed here as well.