SPECTRAL DIAGNOSTICS OF ARGON PLASMA IN A 10mm APERTURE PLASMA WINDOW

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Abstract

A 10 mm diameter 60 mm long plasma window has been designed and managed to generate arc discharge with argon gas experimentally in Peking University. Based on the previous experiments and simulations, we have measured the electron temperature and density of the plasma via argon spectral diagnostics, and analysed the conditions to satisfy the criterion of local thermal equilibrium (L.T.E). The electron temperature is in the range of 12000 K to 16000 K. The electron density is in the range of $2.2 \times 10^{16}\ cm^{-3}$ to $3.2 \times 10^{16}\ cm^{-3}$, increasing with discharge current and gas flow rate. The results indicate that our argon plasma is in the L.T.E status. The sealing pressure characteristics of the plasma window is mentioned as well.

INTRODUCTION

Plasma window has been designed to use plasma discharge to separate vacuum from high pressure. As a windowless vacuum seal device, plasma window has many advantages over conventional solid windows which have bad effects on the beam qualities. It can provide lossless transmission of high purity and mono-energetic beams due to its lower equivalent thickness. Small aperture plasma windows have been experimentally realized to separate 2.85 bar from 0.6 mbar with a 2.36 mm diameter 40mm long arc [1], and up to 9 atm from 2 mbar with 2mm channel in diameter [2]. To exploring the application of plasma window on high current heavy ion beams, a 10 mm diameter plasma window has been built and studied in Peking University [3]. The structure of the plasma window is shown in Fig.1. It mainly consists of a cascade of 9 mm thick copper plates that are electrically insulated from each other. Electrical insulation and vacuum sealing are accomplished by 1mm thick boron-nitride (BN) spacer plates inside O-rings, mechanically stabilized by PEEK material washers outside the O-rings. Three cathodes, made of thoriated tungsten, are inserted at an angle of 45° into cathode chamber and axial symmetrically located. Cathodes and anode are connected to a constant-current power supply, which can deliver current up to 80 A. Argon gas is fed to Plasma window through gas inlet tube. At the end of Plasma window, the lower pressure is sustained by differential pumping system.

In this paper, the experimental data will be shown and the influence of the operating conditions (gas flow rate and discharge current) on the electron density, temperature and sealing pressure capability will be discussed.

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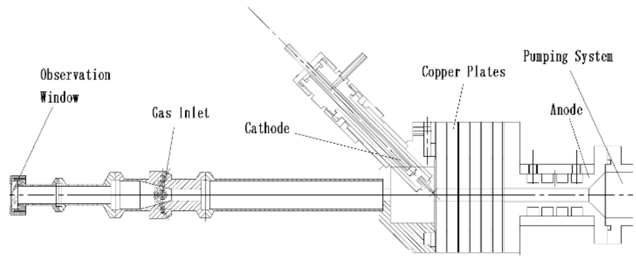

Figure 1: Diagram of Plasma window.

EXPERIMENT SETUP AND METHODOLOGY

Our spectroscopy setup (see Fig.2) consists of a spectrometer (Horiba IHR 550) along with a CCD camera (synapse) and a computer for running the spectroscopy program (SynerJY). Spectrum signal passing through quartz window is collected by spectrometer with optical fiber and the outcome data is stored by the computer. The spectrometer has three different gratings (300 gr/mm, 1200 gr/mm and 2400 gr/mm) to satisfy the requirements of different spectral coverage and resolution.

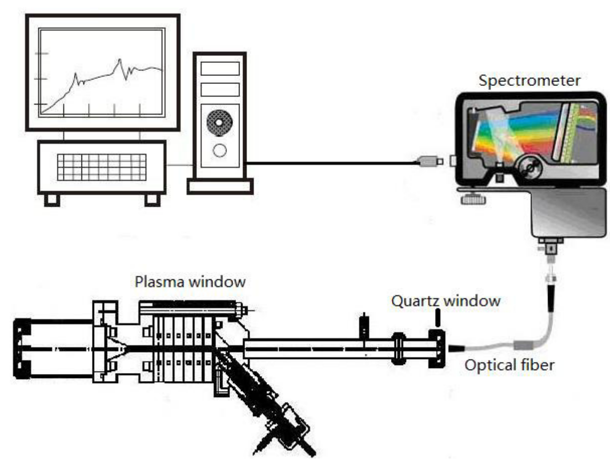

Figure 2: Diagram of spectroscopy setup.

The electron excitation temperature can be determined by atomic Boltzmann plot method [4] from the following equation:

$$ln(I\lambda / g_u A_u) = C - E_u / kT \tag{1}$$

where I is spectrum intensity, λ is the wavelength of the line and k is Boltzmann constant. A_u, E_u and g_u are transition probability, excitation energy and statistical weight of atomic state u, respectively. These values can be found in literatures. According to equation (1), we can get a straight line by linear fitting method. The inverse of line slop presents the electron temperature, assuming that the population of the emitting levels follows the Boltzmann's distribution.

Emission spectra of Ar II lines in the spectral range of 450-520 nm are shown in Fig.3. Seven resolved and distinct Ar II lines were chosen and corresponding A_u, E_u and g_u were taken from literature [5]. $ln(I\lambda/g_uA_u)$ vs E_u were plotted (see Fig.4), and the slope was obtained from the linear fitting. The correlation coefficient was more than 0.95 and the standard error of the slope was 9%. The electron temperature is about 11900 K at argon gas flow rate of 1.2 SLM and discharge current of 40 A.

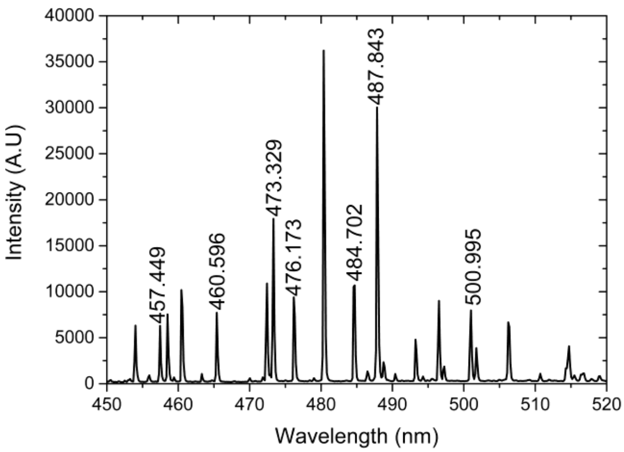

Figure 3: Emission spectra of Ar II lines in the spectral range of 450-520 nm.

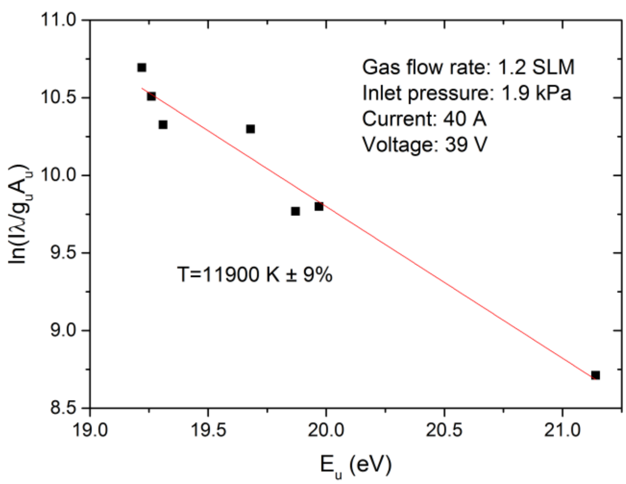

Figure 4: Typical Boltzmann plot for seven selected Ar II emission lines.

The Stark broadening of a certain spectral line emitted from plasma carries the electron density information. In our case, the Ar I line 430 nm is often used to calculate the electron density, as it is separated from other lines (see Figure 5), which guarantees a good resolution and accuracy. The empirical formula is given [6]:

$$logN_e(cm^{-3}) = 17.432 + 0.662\ log\Delta\lambda_{1/2} \qquad (2)$$

where $\Delta\lambda_{1/2}$ is the half width of Ar I line.

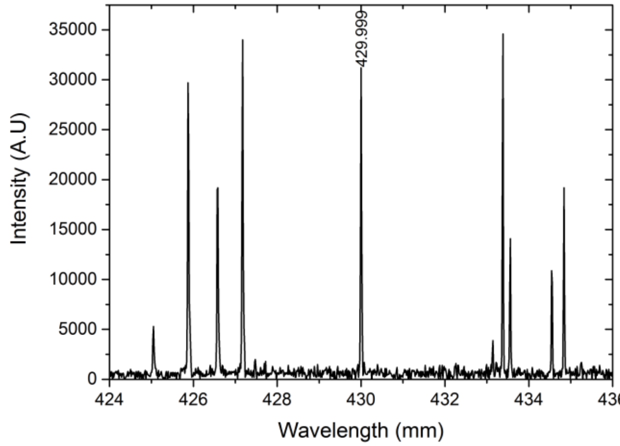

Figure 5: Emission spectra of Ar 430 nm line in the spectral range of 424-436 nm.

RESULTS AND DISCUSSION

The measured electron temperature as a function of gas flow rate is shown in Fig.6. We can see that the temperature decreases with the gas flow rate. It can be explained as that electron temperature decreases with increasing the pressure in the discharge channel [7] which can be caused by increasing gas flow rate. The simulated temperature distribution is shown in Fig.7. In simulation, the inlet pressure and outlet pressure are 6.8 kPa and 74 Pa, respectively. Electric potential of the cathode is -42 V, while the anode is 0 V.

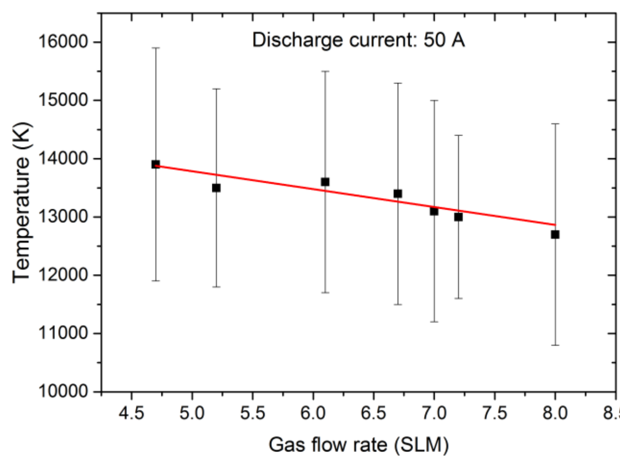

Figure 6: Temperature of argon plasma as a function of gas flow rate.

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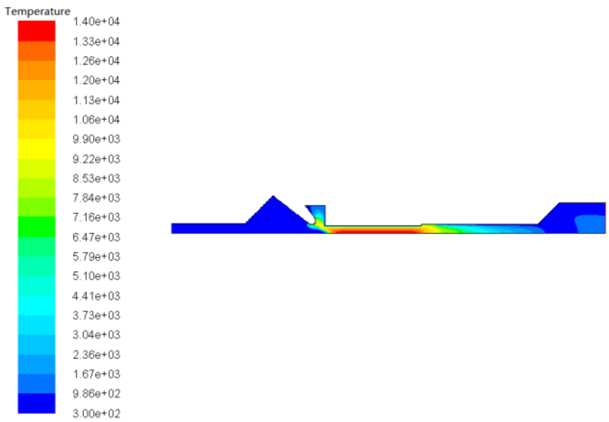

Figure 7: Simulated temperature distribution.

From poiseuille's equation, we can derive the equation (3) for argon plasma channel, under the condition that the outlet pressure is much smaller than the inlet pressure.

$$P_{in} = C\sqrt{\frac{\eta lkT\phi}{d^2}} \quad (3)$$

where C is a constant, η is the dynamic viscosity coefficent, d and l are the diameter and length of the channel, k is the Boltzmann constant, T is the temperature and ϕ is the gas flow rate. In our case, the diameter and length of plasma channel is fixed and the dynamic viscosity is nearly a constant at temperature between 12000 K and 16000 K. So the inlet pressure is proportional to the square root of temperature and gas low rate. Figure 8 shows the proportional relation between the inlet pressure and the square root of discharge current and gas low rate. For all the measurements, the gas flow rate and discharge current are in the range of 1.9 SLM to 9.8 SLM and 40 A to 80 A, respectively. Correlation coefficient is better than 0.99. Indirectly, we can see that the temperature of the plasma is proportional to the discharge current.

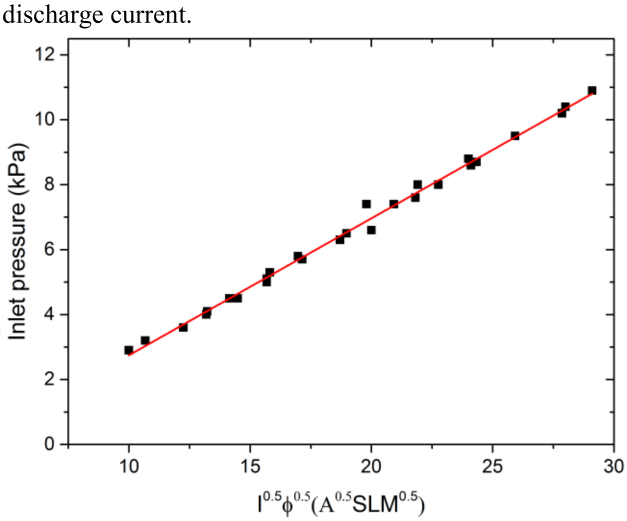

Figure 8: Inlet pressure as a function of square root of discharge current and gas flow rate. For all the measurements, the gas flow rate and discharge current are in the range of 1.9 SLM to 9.8 SLM and 40 A to 80 A, respectively. Correlation coefficient is better than 0.99.

The measured electron density at different discharge current and gas flow rate are shown in Fig.9 and 10. It can be seen that the electron density increases with the increasing discharge current or gas flow rate. According to Grime's theoretical criteria [8] for local thermal equilibrium (L.T.E) which has considered radiation absorption and resonance absorption, the critical electron density is about $1.44 \times 10^{16}\ cm^{-3}$ for argon plasma electron temperature of 14500 K. The measured electron densities are more than $2 \times 10^{16}\ cm^{-3}$. So the L.T.E has been established in the plasma window. But it is only in the axial region because of the high gradient temperature and velocity distribution from the plasma centre to water cooled wall.

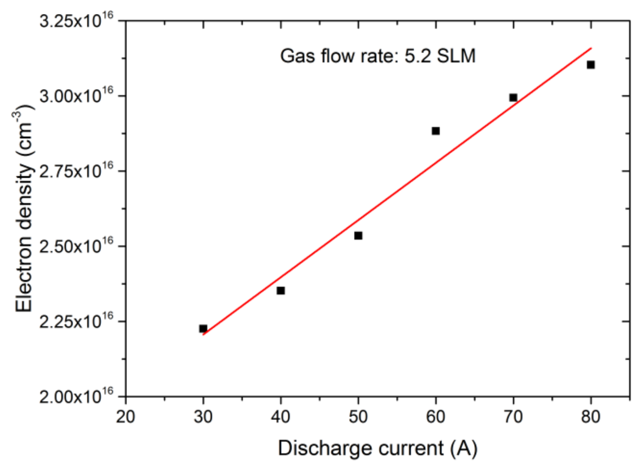

Figure 9: Electron density as a function of discharge current.

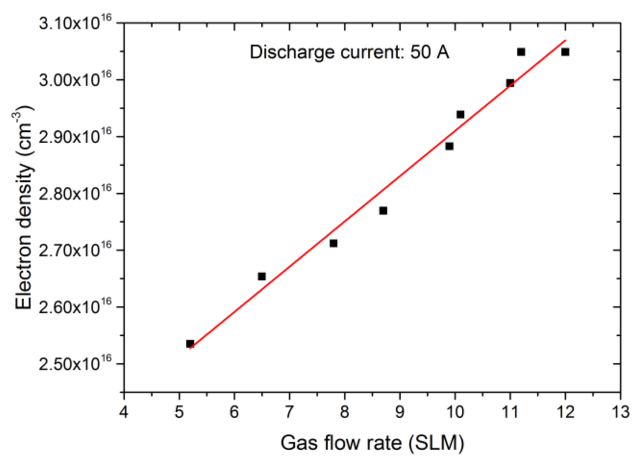

Figure 10: Electron density as a function of gas flow rate.

The sealing effect of the 10 mm plasma channel is not as good as 3 mm and 6 mm [3, 9]. The main reason can be seen from the equation (3) that inlet pressure is inversely proportional to square of diameter. In Fig.11, with the discharge current on, the inlet pressure is only several times larger than that of discharge current off at the same gas flow rate. While 3 or 6mm plasma channel can be several tens of times larger [9]. The application of 10 mm plasma window on high current heavy ion beams is not achievable for now.

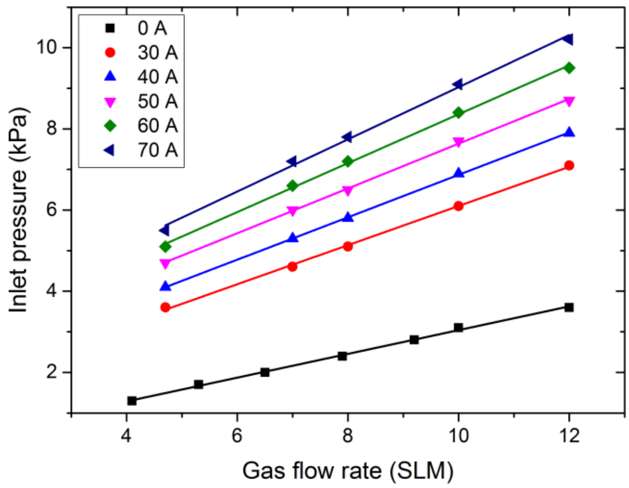

Figure 11:The inlet pressure of argon gas as a function of gas flow rate.

CONCLUSION

The electron temperature and electron density of the 10mm aperture argon plasma window is in the range of 12000 K to 16000 K and $2.2 \times 10^{16}\ cm^{-3}$ to $3.2 \times 10^{16}\ cm^{-3}$ respectively at our measurement conditions. The plasma at the axial region meets the requirement of local thermal equilibrium. The sealing property is not good enough to use on the high current heavy ion beams.

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