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# Characteristics of the plasma jet by applying a pseudo-spark discharge

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## Abstract

The PSD is a low-pressure gas discharge with an especially geometrical shape of a pair of parallel disk electrodes. In this paper, the pseudo-spark discharge (PSD) is applied to the source for a high current glow plasma jet. The mechanism of the plasma acceleration is an electromagnetic force,  $\vec{j} \times \vec{B}$ . To accelerate the plasma, the diameter of the anode hole is enlarged as compared with that of the cathode. The electron temperature and density of the plasma jet is measured by using an electric probe technique. In this experiment of the discharge current is 10 kA in hydrogen gas, the temperature reached approximately 4eV and the density was in the order of  $10^{14} \text{ cm}^{-3}$ . In addition, heat flux did not melt electrodes during a number of discharges, because PSD is glow mode. The geometrical shape of the electrodes plays an essential role in the characteristics of the PSD plasma jet. Thus, the high temperature and density plasma jet without the heat problem will become a useful tool for various technological applications.

## Instruction

Various technological applications demand a plasma jet because the plasma jet easily generates a high temperature and high-speed plasma flow. In particular, the powerful plasma jet has been applying to a propulsive system in outer space, a manufacturing of materials and so on. It is, therefore, well known a plasma-electrode interaction is a dominant disadvantage of the powerful plasma jet. Although the plasma temperature and jet speed increase with increasing the discharge current, the plasma-electrode interaction also increases. Electrodes are damaged by ion collisions, because the discharge changes from the glow to arc mode in the high current discharge. Consequently, the lifetime of electrodes device becomes short and impurities are generated from the melted electrode. These metallic impurities are mixed in the plasma flow. This is also disadvantage when the plasma jet is applied to a particle source for fusion plasmas. Thus, the discharge current density, which will decide the plasma temperature and jet speed, is limited by the heat load. The key for the development of a more powerful plasma jet with a long lifetime is to work out the solution to this heat problem.

This paper describes here the development of a new type of the plasma jet based on a high current glow discharge. In this study, a pseudo-spark discharge [1] (PSD) is applied to the plasma source for the plasma jet. The PSD is a low-pressure gas discharge with an especially geometrical shape of a pair of parallel disk electrodes. In a general gas discharge, a pair of single plane electrodes is widely used as shown in Fig.1 (a). Arrows show the direction of electrons along a line of electric force.  $\alpha$  and  $\gamma$  effects play an essential role in the discharge formation. The mode of the discharge, however, changes from the glow to arc mode, because of the increase in electrons necessary to sustain the high current discharge. In the PSD, electrodes with a small circular hole on the axis replace that of a pair of single plane. In addition, the cathode has a cylindrical cavity behind the circular hole as shown in Fig.1 (b). The PSD can be formed in a low-pressure region and by using this especially geometrical shape of electrodes. The property of the breakdown of the PSD obeys the Paschen law like relation

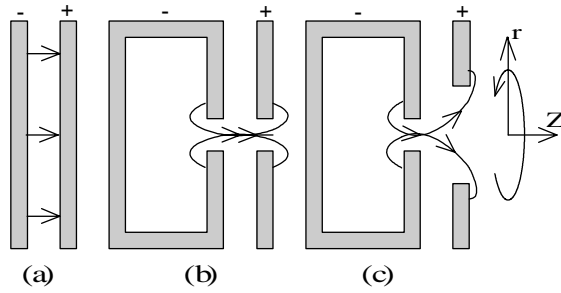


Fig.1 Schematic drawing of the geometrical shape of electrodes for (a) a general gas discharge, (b) a pseudo-spark discharge and (c) the plasma jet experiment. Arrows show the direction of electrons along the line of electric force.

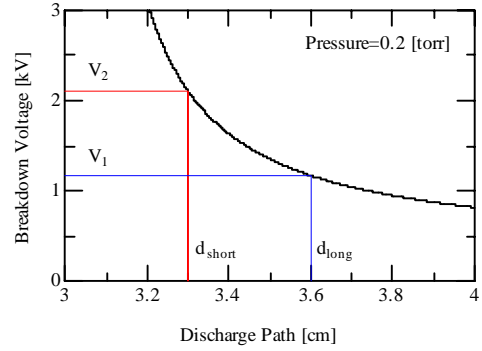


Fig.2 Numerical calculation of the discharge path dependence of the breakdown voltage for a hydrogen gas on the condition that the working pressure is constant of 0.2 Torr.

[2]. The breakdown voltage in the PSD will be also a function of a working pressure and a length of the discharge path. Figure 2 shows the numerical calculation of the discharge path dependence of the breakdown voltage for a hydrogen gas on the condition that the working pressure is constant of 0.2 Torr. On the left hand side of the minimum point of the Paschen curve, we can see that the breakdown voltage,  $V_1$  along the long discharge path,  $d_{long}$  is smaller than that,  $V_2$  along the short one,  $d_{short}$ . This result indicates that the discharge has a tendency to form along the long discharge path. In the PSD, the discharge does not form between the opposite surfaces of the electrode, because there is a hole of electrodes. The surfaces of the contact between the plasma and electrodes are the behind of opposite surfaces of the electrode as shown in Fig.1 (b). The length of the discharge path depends on the space distribution of the applied electric field. The penetration of the electric field through the electrode holes depends on the size of electrode holes, thickness and so on [3]. Consequently, the property of the breakdown in the PSD becomes very complex and the length of the discharge path becomes an uncertain parameter.

A high current discharge is built up easily in the PSD, because the breakdown voltage increases steeply on the left hand side of the minimum point of the Paschen curve. The hollow cathode effect plays an important role in the formation of the high current glow discharge. During the discharge, energetic electrons move around inside the cathode cavity. In this process, the ionization is enhanced by particle collisions and plenty of electrons are supplied from the cathode cavity to the bulk of the discharge. As a result, the discharge is kept the glow mode even if the discharge current exceeds several ten-kilo amperes high [4]. In our typical experiments of the PSD, the discharge current is more than 20 kA and the current density reaches  $10^{12} \text{A/m}^2$ . In general, a high current discharge makes a plasma high temperature and density.

Research and most developments regarding the PSD had concentrated on its applications as a fast high current switch [5,6,7], for electron and ion beam sources [8,9,10]. In this paper, a new application of the PSD for a powerful plasma jet has been proposed. The discharge property of the plasma jet experiment will be almost same that of the PSD experiment. The mechanism of the plasma acceleration is a Lorenz force. An electromagnetic force accelerates the plasma, which is similar to a magneto-plasma dynamics (MPD) arc jet. To spout out the plasma from the anode hole, the diameter of the anode hole is enlarged as compared with that of the cathode hole as shown in Fig.1(c). Since the discharge is formed through the electrode holes, the radial component of the discharge current,  $j_r$  is generated spontaneously. For the electromagnetic force due to the product of this radial discharge current by the azimuthal magnetic field,  $B_\theta$ , which is produced by the axial discharge current,  $j_z$ , the plasma is accelerated and spouted from the anode hole in the z-direction ( $f_z = j_r * B_\theta$ ) as shown in Fig.1(c).

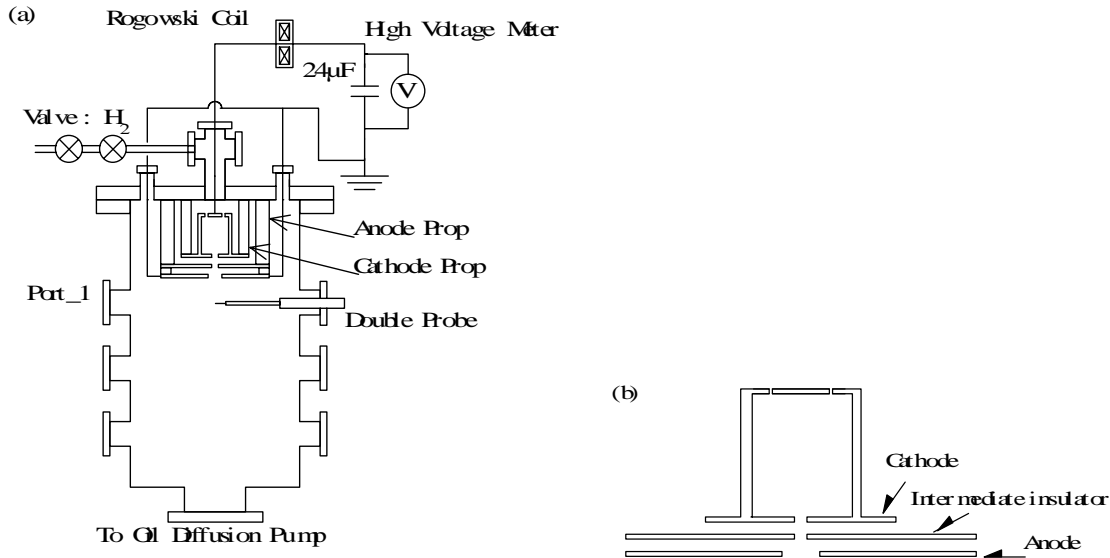


Fig. 3 The device for PSD and plasma jet experiments.

### Experimental Device and Set-up

The device for plasma jet experiment is shown in Fig.3 (a). Figure 3(b) shows the enlargement of the part of electrodes for the plasma jet experiment. The cathode and anode are made of a stainless steel. The cathode and its cavity becomes the same voltage because the cavity is also made of a stainless steel. The diameter of the cathode hole is 5mm. The diameter of the anode hole is 10mm and the anode-cathode distance is 12mm. To concentrate the discharge path into the electrode holes and to prevent the discharge between opposite surfaces of the electrodes, a intermediate insulator was inserted between the anode and cathode. The intermediate insulator is made of a ceramic and the diameter of the hole is 5mm. The occurrence of the surface flash over along the insulator at high voltage experiments are also prevented by using different props for the anode and cathode respectively as shown in Fig.3 (a).

The Rogowskii coil measured the discharge current and the high voltage meter measured the breakdown voltage as shown in Fig.3 (a). A double probe measured the local density and temperature of the plasma jet [11]. This probe has two cylindrical stainless steel tips. The length of tips is 5mm, the diameter is 0.5mm and the separated distance of two tips is 5mm. To obtain the  $I_d-V_d$  characteristic, a potential was applied between the tips, and the probe current was measured by a floating current probe circuit shot-by-shot.

The floating vacuum chamber with many ports for measurements is made of a stainless steel as shown in Fig.3(a). It created the vacuum by using the oil diffusion pump and the base pressure is in the order of  $10^{-6}$  Torr. After the evacuation, the vacuum valve to the oil diffusion pump was closed and the chamber was filled hydrogen at the given pressure by using needle and stop valves. The cathode is negative charged slowly through the condenser bank, and the discharge is formed spontaneously.

### Experimental Results and Discussion

Figure 4 shows the experimental plot of the breakdown voltage in hydrogen as a function of the initial gas pressure in the plasma jet experiments. The breakdown voltage increases steeply with decreasing the initial gas pressure. This result indicates that the discharge is formed on the left hand side of the minimum point of the Paschen curve, because the initial gas pressure is lower than that of minimum pressure, which is estimated by the Paschen's low in hydrogen on the condition of the anode-cathode distance of 12mm. The discharge will be glow mode because the property of the breakdown is almost similar to that of the PSD experiment [2,3]. The temperature of the electrode did not increase very much and heat flux did not melt electrodes and the intermediate insulator during a large number of the discharges.

Figure 5 shows the typical waveform of the plasma jet experiment. The time evolutions of the voltage of the

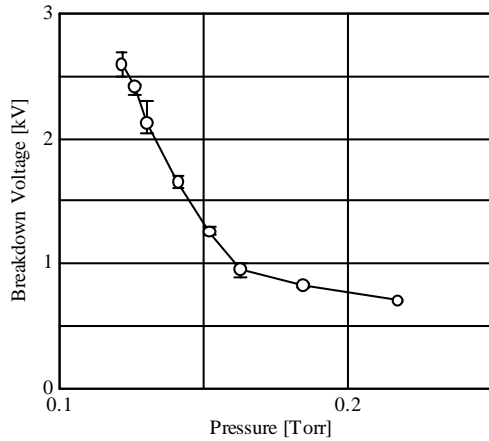


Fig.4 The experimental plot of the breakdown voltage as a function of the initial gas pressure in the plasma jet experiments. The breakdown voltage increases steeply with decreasing the initial gas pressure.

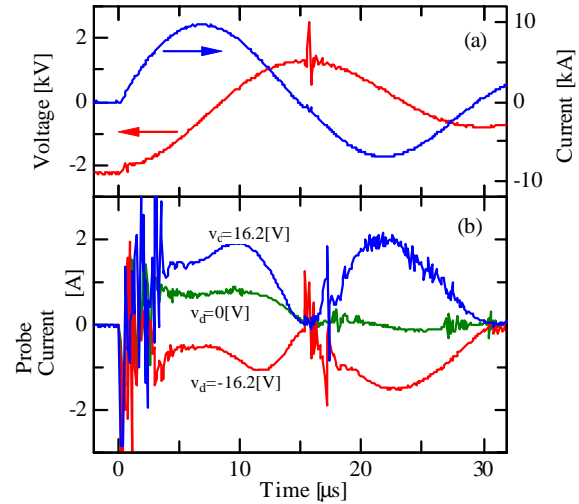


Fig.5 The time evolutions of (a) the voltage of the condenser bank, the discharge current and (b) the typical double probe currents at the applied potentials are shown.

condenser bank and the discharge current are shown in Fig. 5(a). The breakdown voltage was -2.1 kV and the maximum discharge current was approximately 10 kA. The pressure with the breakdown was approximately 0.13 Torr in hydrogen. The period of the discharge current was approximately 30  $\mu\text{s}$ . Although the polarity of electrodes is replaced periodically because the discharge current is damping oscillation, the direction of the flow of the plasma jet is the same.

Figure 6 shows the photograph during the discharge, which was taken a picture from the port-1 as shown in Fig.3 (a). The flow of the plasma jet is observed clearly. The radiant light in the core was reached to tips of the double probe and the flow of the luminous one around the core to the downstream was observed. The distance of the anode and the floating double probe is 22mm in this discharge.

Typical double probe currents  $I_d$  at the applied potentials  $V_d$  of +16.2, 0.0 and -16.2 V are shown in Fig.5 (b) respectively. The tips of the double probe were located on the z-axis and the distance of the anode and the probe is also 22mm. The period of the double probe current is almost synchronized with that of the discharge current. The electron temperature and density were estimated by using the characteristic of the  $I_d$ - $V_d$  curve. The fluctuation of the probe currents in the first phase will be due to the generation of electron beams, because the applied voltage between electrodes is still high. The temperature and density could not obtain in this phase. To obtain the  $I_d$ - $V_d$  curve after the first phase, an applied potential between the tips of the double probe was changed from -24 to +24 V. The probe currents were averaged at five discharges on the same experimental conditions. Figure 7 shows the time development of the discharge current, the electron temperature and the electron density of the plasma jet experiment. The maximum of the electron temperature was approximately 3.5 eV and its time is almost synchronized with that of the discharge current. The maximum of the electron density was approximately  $2.2 \times 10^{14} \text{ cm}^{-3}$ .

## Conclusion

In summary, a new type of the plasma jet by applying a high current glow discharge has been developed. In this research, we put a PSD to use for the formation of the high current glow discharge. The plasma is accelerated by an electromagnetic force due to the modification of the shape of electrodes. The breakdown voltage increases steeply with decreasing the initial gas pressure in the plasma jet experiment. This result indicates the discharge will be glow mode because the property of the breakdown is almost similar to that of the PSD experiment. In our experiment of the discharge current 10kA, the maximum of the electron temperature of

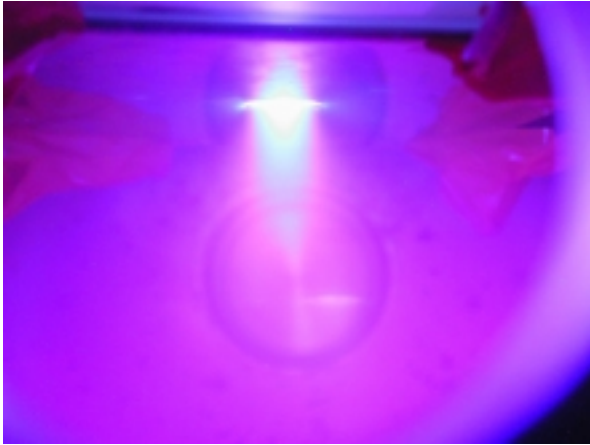


Fig.6 The photograph of the plasma jet experiment. The flow of the plasma jet from the anode hole is observed clearly.

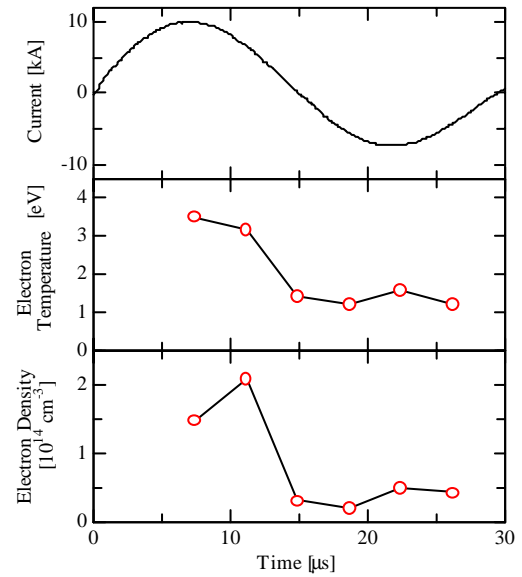


Fig.7 Time development of the discharge current, the electron temperature and the electron density of the plasma jet experiment.

the plasma jet was approximately 3.5eV and the electron density was in the order of  $10^{14} \text{ cm}^{-3}$ . These experimental results are not optimized for the discharge current, the geometrical shape of electrodes and so on. In addition, heat flux did not melt electrodes during a number of discharges. Thus, this high temperature and density plasma jet without the heat problem will become a useful tool for various technological applications.

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