

# Monitoring of fluctuations in a direct current argon plasma jet at reduced pressure by double-electrostatic probe

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**Abstract:** Dynamic measurements of the ion saturation current in the plasma plume by a double-electrostatic probe system were carried out. Regular signals obtained by the electrostatic probe show good agreement with the stable plasma flow state. Dependence of the flow steadiness on the plasma generation parameters was discussed. As a fast response method, the double-electrostatic probe system is feasible to characterize the fluctuations in the plasma jet.

**Keywords:** double-electrostatic probe, plasma stability, reduced pressure.

## 1. Introduction

The use of thermal plasmas in industry has been continuously expanding in the past several decades. The special characteristics of thermal plasma have made it a widely accepted processing medium with one of the highest energy densities, which accordingly offers high processing rates, high fluxes of reactants and the potential for compact installations [1]. Direct current (dc) plasma is one of the most accessible thermal plasma sources, owing to its flexibility and cost-efficiency. It has been widely applied in a broad variety of industries [2], among which surface modification and coating is by far the most important application. In these applications, large and homogeneous treatment area is usually preferred. However, the high energy density of thermal plasma leads to strong gradients and to non-uniformities of the process. Also, instabilities are encountered reducing the process yield, and the large number of independent process parameters can make process controlling difficult. Particularly, for the case of dc plasma, because of the intrinsic discharge behavior, the plasma continuously fluctuates during the process. Such non-stationary features of the dc plasma handicap its application to specific tasks, where precise controllability is essential. To improve the controllability of the process requires a fundamental understanding and control of the plasma instabilities and the conditions in the plasma boundaries. Improved controls were achieved through various means such as controlling the arc-electrodes attachment and modifying the plasma/environment boundary conditions. To achieve a large plasma volume with moderate temperature and velocity gradient, attempts such as operating the process in a reduced pressure chamber were developed. In this research, a dc plasma torch with inter-electrode inserts and an abruptly-expanded anode was developed. With this torch, highly stable plasma with relatively large volume was obtained at reduced pressure of 0.1 – 10 kPa. In this research, a double electrostatic probe system was used to dynamically measure the ion saturation current (ISC) in the plasma plume. The obtained signal is closely related

to the electrical conductivity and was used to characterize the dynamic energy fluctuations of the plasma jet.

## 2. Experimental details

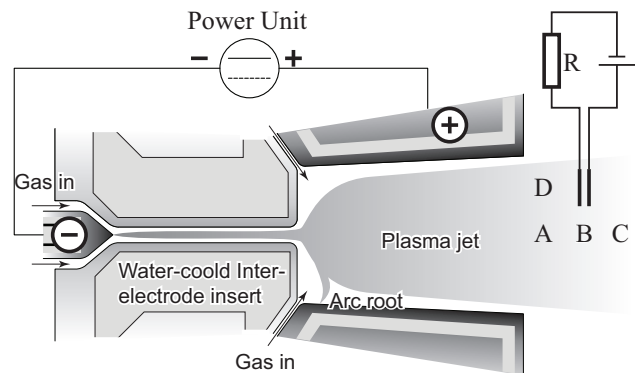


Fig. 1 Schematic diagram of the experimental system.

**Fig. 1** is the schematic diagram of the experimental system. Arc goes from the tip of the cathode, through the long channel of the inter-electrode insert and reaches the upper surface of an abruptly expanded anode. The size of the channel varies from 7-12 mm while that of the anode ranges from 50-80 mm in diameter. The inter-electrode insert has a floating potential without grounding. All the electrodes are water-cooled. A rectified power supply unit was used to generate plasma. A double-electrostatic probe system was adopted to monitor the ion saturation current in the plasma plume near the torch exit. Four positions were monitored in the present study. Positions A, B and C are along the torch axis, where A is at the torch exit, B is 15 mm and C is 30 mm off the torch exit. Position D is 20 mm away from position A radially. The double-electrostatic probe system consists of a 15 V bias voltage supply, a 500  $\Omega$  resistance and two molybdenum electrodes 0.3 mm in diameter. An oscilloscope with nano-second time resolution was used to monitor the dynamic voltage change on the ends of the resistance. Previous research showed that under the 15 V bias voltages,

the obtained signal represents the ion saturation current in the plasma plume under typical studied conditions. Another oscilloscope was used to monitor the arc voltage and current spectra simultaneously. Argon was used as the plasma gas and the gas flow rates varied from 8.4 to 21 slm. The chamber pressure was controlled to between 500 – 10 kPa and the arc current between 80 – 100 A.

### 3. Results and Discussion

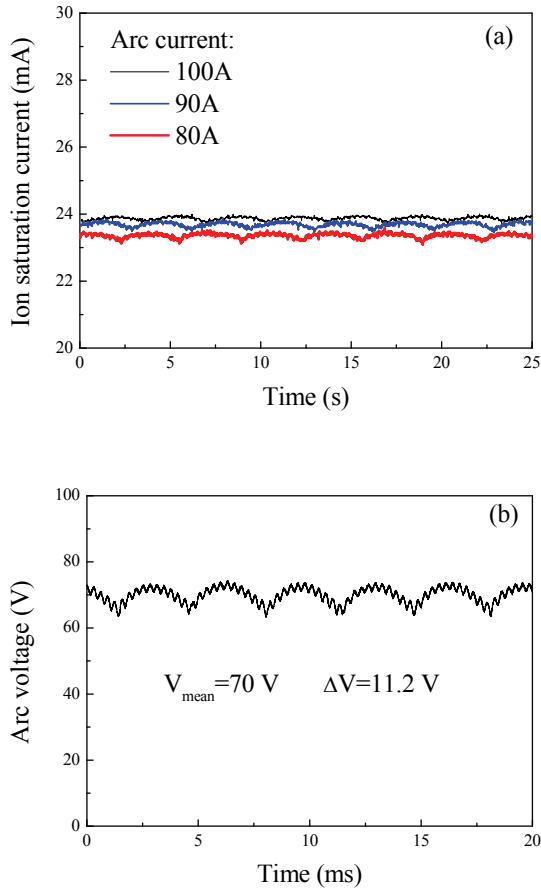


Fig. 2 (a) Dependence of ion saturation current at position A on the arc current; (b) Corresponding arc voltage spectrum. Chamber pressure is 0.5 kPa and the total gas flow rate of 16.8 slm.

**Fig. 2** (a) shows the dependence of the measured ion saturation current at position A on the arc current. Time dependent ion saturation current signals were recorded by the oscilloscope with a resolution of  $1 \times 10^{-5}$  s. Previous research showed that the rectified PSU used in the present study has a 300 Hz intrinsic fluctuation [3]. Such fluctuation was also detected by the probe system, which indicates that the fluctuation in the arc was transmitted to the downstream plasma jet. Besides the 300 Hz intrinsic fluctuation, the ion saturation current signal is rather smooth. This means that there are no significant fluctua-

tions caused by other factors in the plasma jet, while the chamber pressure being 0.5 kPa and the total argon gas flow rate being 16.8 slm. The average value of the ion saturation current does not change much with the increasing of the arc current. However, the fluctuation becomes smaller at elevated arc current. This indicates that the plasma jet is more stable at higher arc current of 100 A than those under lower arc current of 80 and 90 A. In previous research, similar dependence was observed when dc plasma was generated under atmospheric pressure using the same type of plasma torch [4]. Higher arc current was found to promote the laminar flow regime in the plasma jet.

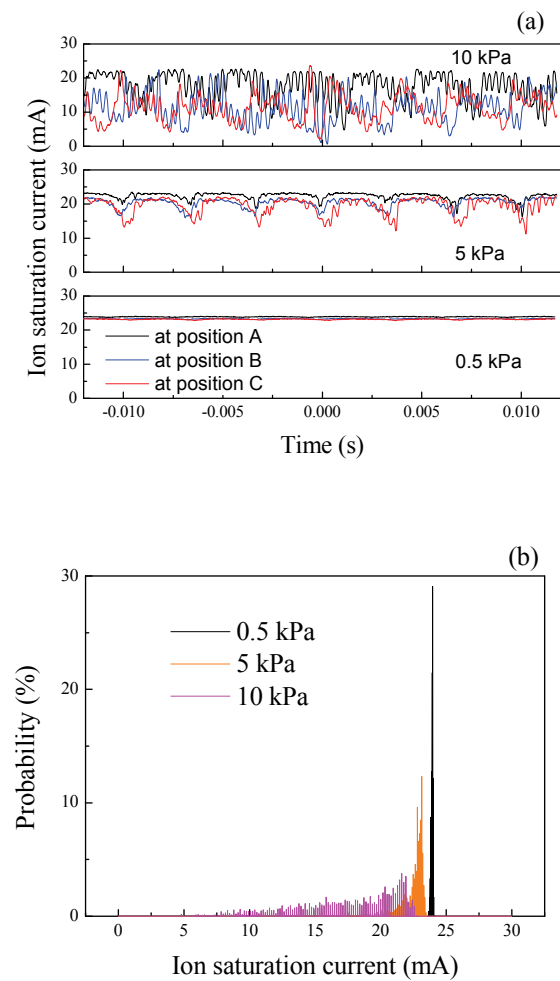
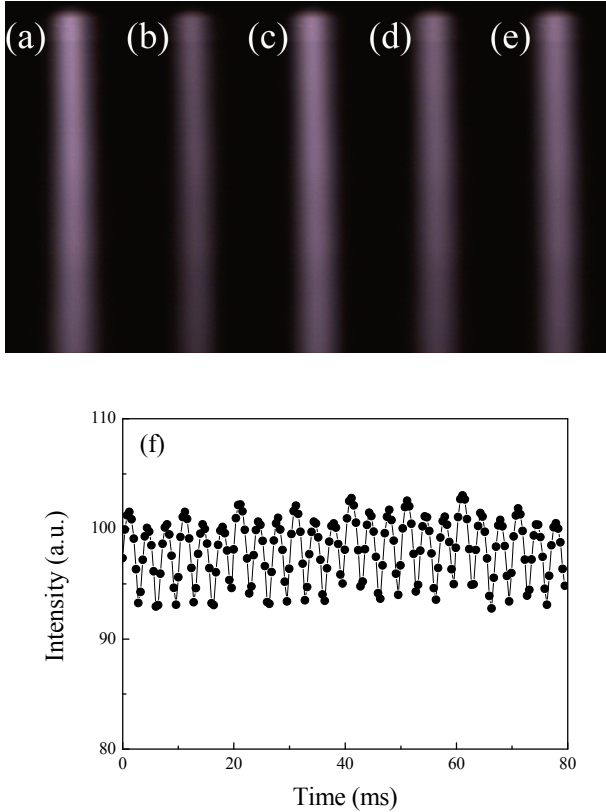


Fig.3 Effect of chamber pressure on the measured axial ion saturation current signals. (a): ion saturation current on position A, B and C for different chamber pressures; (b) Distribution of ion saturation current for position A at different chamber pressures.

Although the 300 Hz intrinsic fluctuation is much pronounced in the arc voltage spectrum (**Fig. 2** (b)), the in-

tensity of it is depressed at the torch exit. At a chamber pressure of 0.5 kPa, the detected ion saturation current is quite smooth, as shown in **Fig. 2** (a). The largest fluctuation is less than 2%, which is much smaller than the corresponding arc voltage fluctuation of 16% as shown in **Fig. 2** (b).

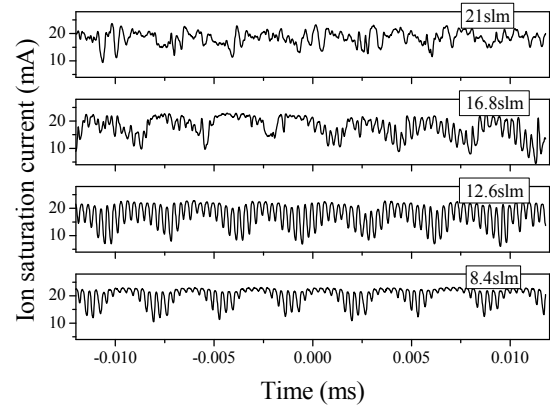


**Fig.4** Time dependence stability of the plasma jet generated at 80 A, 10 kPa. (a) – (e): high speed video camera photos of the plasma jets with time intervals of 2 ms and exposure time of 1  $\mu$ s; (f): Variation of plasma jet intensities with time.

With the increasing of the chamber pressure, the dynamic stability of the plasma jet becomes worse. **Fig. 3** compares the ion saturation current signals at different chamber pressures of 0.5, 5 and 10 kPa. The arc current is kept at 80 A and the total gas flow rate is 16.8 slm. From **Fig. 3** (a), it can be seen clearly that the detected ion saturation current signal becomes more disordered at higher chamber pressures. Larger perturbations with higher frequency superimpose on the 300 Hz intrinsic fluctuations when the chamber pressure is increased to 10 kPa. At the same chamber pressure, from position A to C, the ion saturation current becomes slightly smaller with pronounced fluctuations. **Fig. 3** (b) shows ion saturation current distributions for position A at different chamber pressures. It is seen that with the increasing of chamber pressure, wid-

er distribution of ion saturation current is observable, together with a lower average ion saturation current level. This result shows that at elevated pressure, the electric conductivity of the plasma decreases due to more intensive collisions between electrons and ions occur.

Although the detected dynamic ion saturation current signals shows unsteadiness of the plasma jet, the flow field of the plasma is still quite stable when the chamber pressure is up to 10 kPa. **Fig. 4** (a) shows the photo of the obtained plasma jet taken by a high speed video camera. The camera speed was set to be 2500 fps and the exposure time to be  $1 \times 10^{-6}$  s. Previous research shows that when the plasma jet is in a turbulent state, twisted plume can be clearly seen when the exposure time is as short as  $1 \times 10^{-5}$  s [5]. However, in the present study, even when the exposure time is 10 times shorter, no twist and distortion was observed, showing that the plasma jet is still in laminar flow state. However, there are observable changes in brightness and shape of the plasma jet if a series of images were compared. **Fig. 4** (b) to (e) shows a consequence series of photos with intervals of 5 frames (2 ms in time). A periodical change of the width and brightness of the plasma jet can be seen. By analyzing 200 images taken in 80 ms, the periodicity of the plasma jet intensity change is confirmed to be 300 Hz, which corresponds to the arc voltage fluctuations.



**Fig. 5** Dependence of ion saturation current on gas flow rate at position A with chamber pressure of 10 kPa and arc current of 80 A.

**Fig. 5** shows the effect of gas flow rate on the ion saturation current signals. In **Fig. 5**, the chamber pressure is 10 kPa, and the total gas flow rate of argon changes from 8.4 to 21 slm. It can be seen that when the gas flow rate is small in the case of 8.4 and 12.6 slm, the superimposition of higher frequency perturbations on the intrinsic 300 Hz fluctuation is clear. However, when the total gas flow rate is 21 slm, the ion saturation current signal is totally disordered, and no obvious periodicity can be seen. When

the gas flow rate is 16.8 slm, a transition of the two modes is observed.

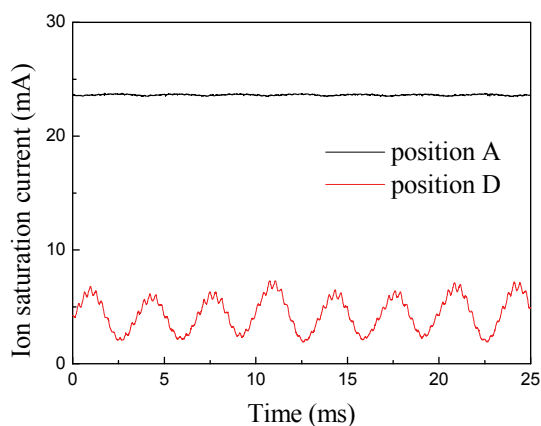


Fig. 6 Radial distributions of ion saturation current in the plasma jet.

The ion saturation current decreases rapidly in radial direction. Fig. 6 shows that when the probes moves from position A to position D, the detected ion saturation current decreases from 24 mA to 4 mA. The fluctuation also becomes more remarkable at position D. Compared with Fig. 4, it can be deduced that the large fluctuation on the edge is due to the displacement of the plasma jet. As Fig. 4 shows, the width of the plasma jet changes a lot with time, so when the probes are placed on the edge, the fluctuation of ion saturation current is larger than 100%, while in the center it is less than 2%.

Above results show that ion saturation current signal is very sensitive to plasma condition changes and is feasible to be used to characterize the steadiness of the plasma jet. It should be noted that, in most cases of thermal plasma processing, the fluctuation of electric conductivity is not the most crucial parameter that affect the process quality,

especially when the plasma is only used as a heat source, where temperature fluctuations dominates. However, in processes where active reactants are important such as in thermal plasma chemical vapor depositions, the change of ion saturation current may play an important role in improving the film/coating quality.

#### 4. Conclusion

Using a double-electrostatic probe system, time and space dependence of the steadiness of an argon plasma was characterized. Dynamic measurement of the ion saturation current is a fast response method to reveal the energy fluctuations in a plasma jet generated at reduced pressure of 0.5 – 10 kPa. With the increasing of chamber pressure and total gas flow rate, the dynamic stability of the plasma becomes worse with pronounced higher frequency perturbations in ion saturation current. Such fluctuation is mainly caused by the displacement of the plasma jet.

#### 5. Acknowledgement

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