Measurement of the plasma density of tip gap discharge at atmospheric pressure by M-Z interferometry

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Abstract. In this paper, the plasma density in the lateral discharge of the tip gap at atmospheric pressure was measured by Mach-Zehnder interferometry. Based on the offset of the fringe picture, the maximum electron density of the plasma was calculated to be about $1.76 \times 10^{18}$ cm$^{-3}$. At the same time, the spatial distribution of plasma electron density and the change of the highest electron density with the applied voltage across the tip were obtained.

1. Introduction
In recent years, with the development of UHV transmission and compact transmission engineering, the gap structure of power transmission and transformation engineering needs to be optimized under the premise of ensuring safety1, 2. Therefore, studying the characteristics of atmospheric pressure gap discharge is of great significance for power transmission and transformation engineering. It is subjected to collisional ionization under the action of a strong electric field, thereby breaking through the air at the closest gap between the two electrodes to generate a plasma. As the initial stage of the breakdown of the space gap, the propagation of the flow column has an important influence on the gap breakdown. Therefore, the fingers discharge has received more and more attention, and it is also widely used in surface modification and pollutant control. Plasma diagnostic technology has always been a very important and key technology in plasma research, and it is the basis of other research and application of plasma3. In this paper, M-Z optical interference diagnostic technology is used to diagnose and measure the plasma density parameters of needle tip discharge under atmospheric pressure.

2. Theory of M-Z Optical Interference
The principle of the M-Z optical interference diagnostic system is shown in figure 1. The system adopts the principle of M-Z optical interference4, 5. The laser is divided into two light paths by a beam splitter: the reference light path and the detection light path. The two light paths pass through the beam-expanding mirror and the reflector, respectively, then merge at the second beam splitter. The receiving system is used to capture interference fringe pictures, such as D800, high-speed camera and so on. Due to the optical path difference between the two beams, the detection light path and the reference light path interfere at the second beam splitter, resulting in interference fringes between light and dark, that is, and the background stripes. After that, the detection light path passes through the plasma area to be detected. Due to the influence of the refractive index of the plasma, an additional optical path difference will occur between the two light paths, and the measured interference fringes will move. Compare the
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image of the interference fringe after the plasma with the previously obtained background fringe. The deformation state of the stripe can be used to calculate the refractive index of the plasma and related parameters such as density, temperature, pressure, etc., to realize the detection and diagnosis of the plasma state.

![Figure 1. Schematic of M-Z optical interference](image)

In the M-Z interference system, the interference fringe movement number $\delta(y, z)$ of a point $P(x, y)$ on the interferogram is closely related to the electron density $N_e$ of the plasma region through which the detection light corresponding to this point passes. The specific correspondence formula is shown below:

$$
\delta(x, y) = -\frac{e^2\lambda}{8\pi^2c^2\varepsilon_0m_e} \int_0^L N_e(x, y, z) \cdot dz
$$

Where $\delta$ is the stripe shift, $e$ and $m_e$ are the charge and mass of the electron, respectively, $\lambda$ is the laser wavelength, $N_e$ is the electron density of plasma, $c$ and $\varepsilon_0$ are the dielectric constant in the speed of light and vacuum, respectively, and $z$ is the direction of the detected laser beam, $L$ is the thickness of the disturbance zone. As can be seen from the above formula, the shorter the laser wavelength, the higher the number of electron densities that can be measured. In contrast, if you want to measure a lower density plasma, you need to choose a longer wavelength laser for interference diagnosis. Assuming that the electron density of the plasma region through which the probe light passes is constant, the average electron density on this path is:

$$
\overline{N}_e(x, y) = \delta(x, y) / (4.46 \times 10^{-14} \lambda)
$$

3. Experimental Setup

This experiment used a red visible laser with a wavelength of 635 nm. In order to diagnose a larger plasma range, on the basis of the conventional M-Z interference system, a beam expander is added to the two light paths to expand the beam. And the expanded laser beam has a diameter of 40 mm. This M-Z optical interference system expands the range of plasma diagnosis, and can obtain the spatial distribution of the plasma discharge state based on this. The measurement diameter is about 40mm. At the same time, the resulting interference fringes are photographed using a high-speed camera. The plasma region of this experiment was produced by two horizontally placed 4.5 cm stainless steel tip electrodes with a diameter of 4 mm, and the electrode pitch is 10mm. The alternating voltage is applied by the linkage excitation power source, and a relatively stable plasma discharge region is generated. The plasma discharge state is diagnosed by passing the expanded light path through the plasma generation region. The specific experimental system structure is shown in figure 2.
A picture of the adjusted interference fringes is shown in Figure 3. It can be seen that the stripes are parallel to each other. The image of the interference fringe before discharge is called the background stripe. With the influence of the plasma, the stripe will move up or down, generating an offset. And the plasma density can be calculated from the deformation of the stripe. Fine-tuning the offset angle of the beam splitter can change the optical path difference between the two light paths, thereby changing the thickness and spacing of the stripes. Debug the appropriate stripe width during the experiment.

Figure 3. Background stripe image

4. Experimental Results

Figure 4 shows the variation of the interference fringe picture as a function of the voltage applied across the tip electrode under the action of plasma. It can be found that near the discharge area of the tip electrode, the interference fringe will show an upward bend, and the fringe will move upward to produce deformation. Figure 4 (f) is the interference diagram when the tip gap discharge is extinguished due to the decrease in the voltage applied to both ends. It can be seen that there is no movement of any fringes on this interferogram, which means that the streak shift caused by the neutral gas density perturbation is negligible. Therefore, we can conclude that the offset of the fringes is mainly due to the contribution of the plasma.
Figure 4. Interference stripe image of tip gap discharge at different discharge voltages at atmospheric pressure, with a tip electrode spacing of 10 mm. (a) U = 4.6 kV, (b) U = 4.0 kV, (c) U = 3.4 kV, (d) U = 2.7 kV, (e) U = 2.0 kV, (f) U = 1.4 kV.

In figure 4, the shadow portions on the left and right sides are two opposite tip electrodes, and the plasma generated during the discharge causes the interference fringes to be significantly deformed. When the voltage at both ends reaches 4.6 kV, the air between the tips is broken down to generate plasma. The specific stripe shape variable is shown in Figure 4(a). The maximum stripe shape variable is 4.2 and the corresponding plasma density is $1.76 \times 10^{18} \text{cm}^{-3}$. As shown in figure 4(a)-4(f), as the voltage across the tip electrode decreases, the corresponding stripe shape variable is also decreasing, and the corresponding plasma density is continuously reduced. At the same time, the region where the stripe is deformed is continuously reduced as the discharge voltage is lowered, and the plasma region is continuously reduced. The discharge phenomenon is gradually gradual, and finally extinguished completely. Figure 5 shows the relationship between the maximum plasma density and the discharge voltage, and it can be seen that there is a positive correlation between the two.

Figure 5. Relationship between the plasma density and discharge voltage
From the above pictures of the interference fringes during discharge, it can be found that the discharge area of the tip gap is mainly concentrated between two parallel discharge electrodes, and has a tendency to expand upward. The stripe deformation at the central axis is most pronounced and the plasma density is also greatest. It can be found that the farther away from the central axis, the smaller the plasma density.

5. Conclusion
In summary, the plasma density of the tip gap discharge at atmospheric pressure is measured using the M-Z interference system. In the case where the electrode gap is just broken down, the plasma density is at most $1.76 \times 10^{18}$ cm$^{-3}$. As the voltage applied across the electrode decreases, the discharge phenomenon gradually flattens. The plasma region gradually decreases, and the plasma density decreases. At the same time, according to the interference fringe pictures under the discharge condition, the spatial distribution of the tip gap discharge plasma is obtained. The plasma discharge region is mainly concentrated between the two tip electrodes, and there is a tendency to expand upward. At the same time, the plasma density decreases radially on the central axis.

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