

Axial Distribution of Plasma Properties in a Hollow Cathode Plasma Discharge

Hikaru NAKAMURA and Masayuki WATANABE¹⁾

*Graduate School of Quantum Science and Technology, Nihon University,
Kanda-surugadai, Tokyo 101-8308, Japan*

¹⁾*Institute of Quantum Science, Nihon University, Kanda-surugadai, Tokyo 101-8308, Japan*

(Received 4 October 2021 / Accepted 15 October 2021)

Hollow cathode plasma discharge technology has several engineering and industrial applications. To further enhance these applications, information on plasma characteristics (such as its axial distribution inside the hollow cathode cavity) is essential. This work determines the axial distributions of electron temperature and density inside said cavity by inserting a triple probe. The temperature and density inside the hollow cathode cavity were approximately 4 eV and -10^{17} m^{-3} , respectively. It was also confirmed that the plasma existed over almost the inside the cathode cavity and the electron temperature increased and the electron density decreased rapidly in the region near the anode.

© 2021 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: hollow cathode, glow discharge, plasma measurement, triple probe, axial distribution

DOI: 10.1585/pfr.16.1206101

Hollow cathode plasma discharge (HCPD) is a variant of glow discharge technology. In HCPD, several secondary electrons are generated in a widely spread cathode sheath placed inside the hollow cathode cavity. The reciprocating motion of these electrons, when surrounded by a negative potential, lead to a dramatic rise in plasma ionization. As a result, the density and brightness of the plasma in glow discharge can be very high [1–3].

For these reasons, HCPD technology has been applied not only to various plasma and charged particle sources [4–7], but also to high-brightness plasma light sources [8–10] and high-speed plasma switches [11, 12]. Recently, it has also been incorporated into electric propulsion sources [13, 14]. Considering the application to new fields, it is thought that it may be possible to apply it to the plasma window [15, 16], which is an atmosphere-vacuum interface. To further develop its applications, it is important to know more about its discharge characteristics — such as the distribution of its parameters inside the hollow cathode cavity — which have not been well-understood. This paper bridges this gap in knowledge by determining the axial distribution of plasma parameters within the hollow cathode in a typical HCPD.

In this experiment, the mesh is applied to the anode in consideration of the application of the HCPD to a charged particle source or plasma source. Figure 1 shows the schematic diagram of the hollow cathode and the mesh anode in our experiment. The hollow cathode is made of molybdenum, with an inner diameter and length of 10 and

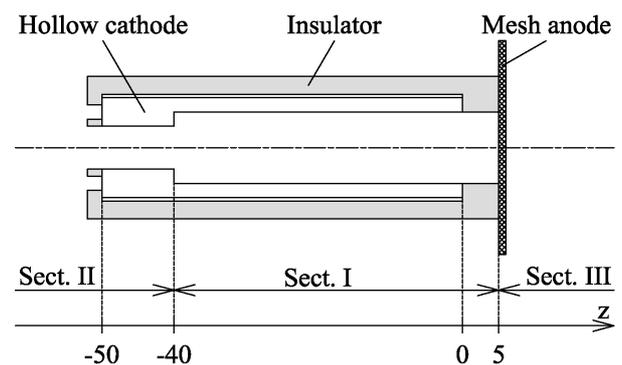


Fig. 1 Position of the experimental device.

40 mm, respectively (Section I). Built into the end of the hollow cathode and on the opposite side of the anode is a narrow space with an inner diameter and length of 6 and 10 mm, respectively (Section II). An insulator is inserted between the hollow cathode and the mesh anode. The mesh anode is constructed from stainless steel, with a wire diameter of 0.1 mm and a porosity of 36.76%. The distance between the mesh anode and the hollow cathode is 5 mm.

In the experiment, the HCPD is formed by applying a high voltage between the cathode and anode via a stationary power supply. The gas used for the experiment is air. The discharge current and interelectrode voltage are measured and a triple probe is used to measure the temperature and density in and around the hollow cathode cavity. The reason for choosing a triple probe is that it must be able to be used in suspension to prevent damage to the electrodes due to the discharge between the hollow cath-

authors' e-mail: cshk19002@g.nihon-u.ac.jp,
watanabe.masayuki66@nihon-u.ac.jp

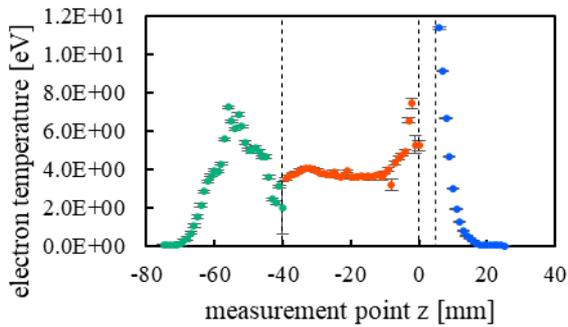


Fig. 2 Axial distribution of electron temperature.

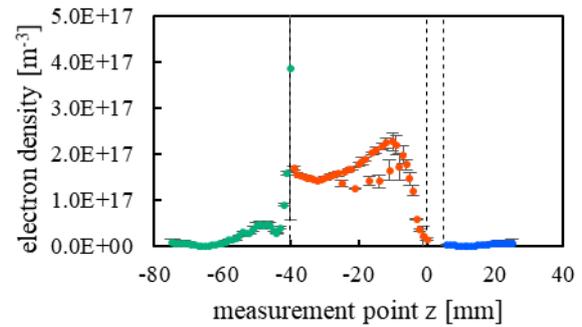


Fig. 3 Axial distribution of electron density.

ode and the probe, and also to measure the electron temperature and electron density quickly. When measuring plasma parameters with a triple probe, the electron velocity distribution function must be Maxwellian. It is known that some plasmas, such as weakly ionized plasmas and RF plasmas, do not have Maxwellian velocity distribution functions [17, 18]. Since the HCPD is a DC discharge, and the plasma produced is considered to have no strong oscillations or waves and no low density, we assumed that the velocity distribution of electrons is Maxwellian.

The triple probe was cylindrical, with all parts (except the tip) covered with a ceramic tube with a diameter 4 mm. The probe was made of tungsten, with a tip diameter of 0.8 mm, a length of 2 mm, and a distance of 1.4 mm. Measurements with the triple probe were taken on the central axis of the hollow cathode (dash-dotted line in Fig. 1). The position of the cathode was taken as the origin of the z -axis, while the cathode facing the anode was taken as the positive z -direction as shown in Fig. 1. Measurements were taken at points ranging from 0 to -80 mm in the side of the hollow cathode (Sections I and II) and from 5 to 25 mm in the side of the mesh anode (Section III). Electron temperature and density were measured at each point for 200 ms, with a sampling time of 5 μ s.

The conditions of the HCPD in this experiment are described as follows: for a discharge current of 50 mA and an anode-to-cathode voltage of approximately 430 V, the power input to the hollow cathode plasma was estimated to be 21.2 W. The experimental device itself was at a pressure of 250 Pa. The ion mass required for the calculation of the electron density was set to 14, which is the value of the dissociated nitrogen ion.

Figures 2 and 3 show the axial distributions of electron temperature and density in and around the hollow cathode plasma, with the horizontal axes indicating position along the z direction and standard deviations at each measurement point shown by error bars. From both results, the existence of plasma was confirmed throughout the hollow cathode (Section I). The electron temperature of plasma, at its most stable state, was approximately 4 eV, while the electron density was roughly 10^{17} m^{-3} .

Electron density inside the hollow cathode cavity

peaked at around $z = -10$ mm (Section I); the phenomena of cathode glow and Faraday dark space can be observed around this peak. Because of the short distance between the hollow cathode and mesh anode, a positive column is hardly formed in this discharge. Therefore, the electron density decreases rapidly on moving towards the anode and reaches zero at the anode; this decrease in electron density was accompanied by an increase in electron temperature.

The hollow cathode used in this experiment had a hole opposite to the anode, as shown in Fig. 1 (Section II); plasma leakage was observed from this hole. Between positions of -40 to -50 mm in the z direction, electron density decreased sharply, while electron temperature increased more gradually. Low-density plasma was also found to exist outside the hollow cathode cavity.

Plasma of very low density alone was found to exist outside the mesh anode (Section III). This can be explained by the absence of an electric field in this space, due to which charged particles cannot gain energy to ionize the neutral gas molecules.

In this study, the distribution of plasma parameters (namely temperature and density) inside a hollow cathode cavity in an HCPD device was investigated. Plasma was confirmed to exist in the entire space inside the cavity and its parameters, when stabilized were 4 eV and around 10^{17} m^{-3} , respectively. It was also confirmed that the plasma existed over almost the inside the cathode cavity and the electron temperature increased and the electron density decreased rapidly in the region near the anode. Low-density plasma also existed outside the hollow cathode cavity opposite to the anode. In addition, plasma of very low density alone was found to exist outside the mesh anode opposite to the hollow cathode. A limitation of this study, however, is that the influences of probe-insertion on plasma characteristics has not been accounted for; future works in this field could include this in their scope.

- [1] A. Guntherschulze, *Z. Tech. Phys.* **19**, 49 (1923).
- [2] R.R. Arslanbekov, A.A. Kudryavtsev and R.C. Tobin, *Plasma Sources Sci. Technol.* **7**, 310 (1998).
- [3] J. Chen, S.J. Park, Z. Fan, J.G. Eden and C. Liu, *J. Microelectromech. Syst.* **11**, 536 (2002).

- [4] V.I. Gushenets, A.S. Bugaev, E.M. Oks, P.M. Schanin and A.A. Goncharov, *Rev. Sci. Instrum.* **81**, 02B305 (2010).
- [5] Y. Ohtsu and Y. Kawasaki, *J. Appl. Phys.* **113**, 033302 (2013).
- [6] J. Hu and J.L. Rovey, *J. Appl. Phys.* **114**, 073301 (2013).
- [7] N. Kumar, R.P. Lamba, A.M. Hossain, U.N. Pal, A.D.R. Phelps and R. Prakash, *Appl. Phys. Lett.* **111**, 213502 (2017).
- [8] Y. Shimada, Y. Chida, N. Ohtsubo, T. Aoki, M. Takeuchi, T. Kuga and Y. Torii, *Rev. Sci. Instrum.* **84**, 063101 (2013).
- [9] V.K. Saini, P. Kumar, K.K. Sarangpani, S.K. Dixit and S.V. Nakhe, *Rev. Sci. Instrum.* **88**, 093101 (2017).
- [10] S. Karatodorov and V. Mihailov, *AIP Conf. Proc.* **2075**, 060006 (2019).
- [11] C. Jiang, A. Kuthi and M.A. Gundersena, *Appl. Phys. Lett.* **86**, 024105 (2005).
- [12] Y.D. Korolev, N.V. Landl, V.G. Geyman, O.B. Frants and G.A. Argunov, *Phys. Plasmas* **25**, 113510 (2018).
- [13] D. Leva, G. Alon and L. Appel, *Rev. Sci. Instrum.* **90**, 113303 (2019).
- [14] D.M. Goebe, G. Becatti, I.G. Mikellides and A.L. Ortega, *J. Appl. Phys.* **130**, 050902 (2021).
- [15] A. Hershcovitch, *J. Appl. Phys.* **78**, 5283 (1995).
- [16] A. Islam, T. Yamaguchi, K. Fukuyama, H. Kawazome, N. Tamura and S. Namba, *IEEE Trans. Plasma Sci.* **46**, 20286987 (2021).
- [17] B.P. Wood, M.A. Lieberman and A.J. Lichtenberg, *IEEE Trans. Plasma Sci.* **23**, 4964242 (1995).
- [18] I.D. Kaganovich, D. Sydorenko, A.V. Khrabrov, Y. Raitses, V.I. Demidov, I. Schweigert and A.S. Mustafaev, *IEEE Int. Conf. Plasma Sci. and Int. Conf. High-Power Particle Beams*, Washington, DC, United States (2014).