Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Investigation of Electronegativity in Negative Hydrogen Ion Source with Anode Spot

Jaeyoung Choi[1], June Young Kim[2], Y. S. Hwang[1], and Kyoung-Jae Chung[1*]
[1] *Department of Energy Systems Engineering, Seoul National University, Seoul 08826, Republic of Korea*
[2] *Department of AI Semiconductor Engineering, Korea University, Sejong 30019, Republic of Korea*
[*] *jkjlsh1@snu.ac.kr*

***Keywords : Negative Hydrogen Ion, Anode Spot Plasma, Electronegativity**

1. Introduction

Negative hydrogen ion (H^-) sources play a crucial role in various advanced technologies, including neutral beam injection systems for fusion reactors and ion sources for particle accelerators. The performance of these ion sources is often evaluated based on the density of negative hydrogen ions, which directly influences the effectiveness in each application. However, the concept of electronegativity, defined as the ratio of density of negative hydrogen ions to electrons ($\alpha \equiv n_{H-}/n_e$), is recognized as a critical parameter influencing both the efficiency and stability of the extracted ion beams [1]. Electronegativity not only affects the stability of the extracted ion beam but also mitigates challenges related to co-extracted electrons, which can degrade beam quality and reduce overall system efficiency.

Our recent research has focused on utilizing anode spot plasma to enhance the performance of negative hydrogen ion sources, specifically by increasing their density of negative hydrogen ions. Anode spot, characterized by a localized region of high electron density and high electron temperature, is known to have a boundary referred to as a double layer, a sharp potential gradient on the order of ionization energy levels [2]. It creates favorable conditions for confinement of negative ions, as the length of the anode spot plasma is typically shorter than the mean free path of electron detachment reaction of negative hydrogen ions by collision. This results in a significant increase in the density of negative hydrogen ions, by approximately 100 times compared to the level before the onset of anode spot plasma, with the addition of just 10 W of DC power. In this study, we experimentally investigate how the ratio of the area of the double layer (A_{DL}) to the volume of the anode spot plasma (V_{AS}) influences electronegativity.

2. Experimental Setup

The experiments were conducted using a custom-designed negative hydrogen ion source equipped with an adjustable anode electrode, as shown in Figure 1. This setup allowed for precise control over the formation of the anode spot by varying both the electrode size and the applied power level. The anode and measurement process were carried out in the diffusion region, where the plasma is diffused from the discharge region. A mixture of hydrogen and argon was used as the operating gas to initiate discharge and maintain a stable anode spot plasma, with the gas flow rate controlled individually by a mass flow controller. The ratio of partial pressure between hydrogen and argon was maintained at 3:1 throughout the experiments. The pressure in the diffusion region was monitored using a capacitive diaphragm gauge.

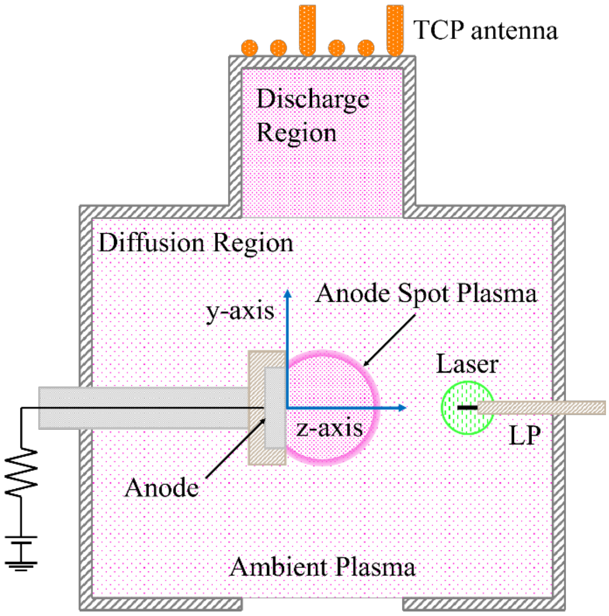

Figure 1. Schematic of experimental setup

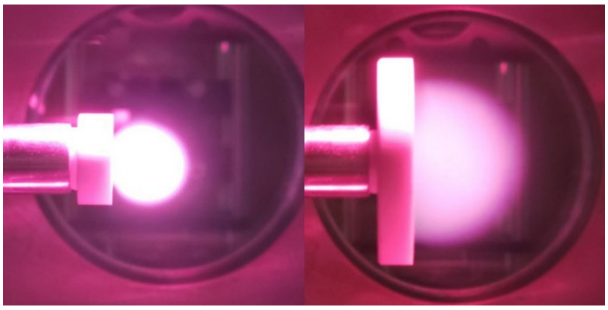

Figure 2. Images of the anode spot plasma with an anode diameter of 10 mm (Left) and 30 mm (Right)

The anode was constructed from a stainless-steel electrode, encased with a 3 mm width layer of alumina (Al_2O_3) ceramic. A DC power supply was connected to the anode through a 100 Ω current limiting resistor, with bias voltage and current continuously monitored. The bias voltage and current were varied between 30 and 51

V, and between 15 and 90 mA, respectively, falling within the stable operation range of the anode spot plasma [3].

For diagnostics, the area of the double layer and the volume of the anode spot plasma were calculated using side-view images, as shown in Figure 2, under the assumption that the anode spot plasma is ellipsoidal in shape. Electronegativity was measured using a laser photo-detachment method, in conjunction with a Langmuir probe and 1,064 nm Nd:YAG laser. The tip of the Langmuir probe had dimensions of 0.3 mm in diameter and 1.2 mm in length, ensuring that the collected current was less than 2% of the bias current for the anode spot plasma to minimize the perturbation. The probe tip was aligned in the negative x-direction, parallel to both the anode and the laser, with all centers consistently aligned. The ambient plasma near the anode was maintained at a density of 1 – 3 × 10^{14} m^{-3} and electron temperature of 0.6 – 1 eV.

3. Results and Discussion

The relationship between electronegativity and the ratio of the area of the double layer to the volume of the anode spot (A_{DL}/V_{AS}) is presented in Figure 3. It reveals a clear positive correlation between the A_{DL}/V_{AS} ratio and electronegativity across various anode diameters and operating pressures. As the A_{DL}/V_{AS} ratio increases, electronegativity consistently rises, indicating that a larger ratio effectively enhances the concentration of negative hydrogen ions, regardless of the pressure and anode diameter. This enhancement is likely due to the double layer's role in accumulating and confining negative ions within the anode spot, thereby preventing their escape and increasing their relative density.

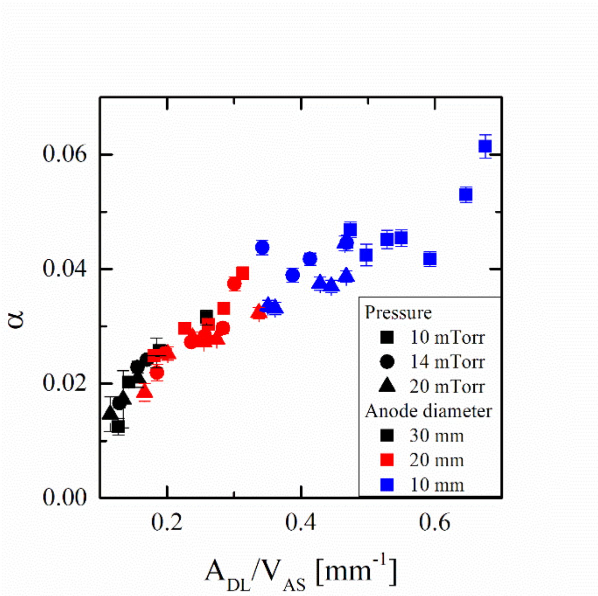

Figure 3. Correlation between A_{DL}/V_{AS} ratio and electronegativity for various electrode sizes and operating pressures.

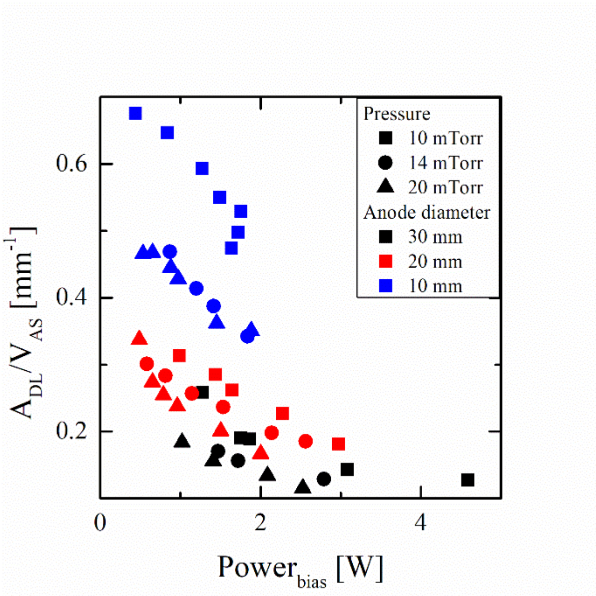

Figure 4. Effect of applied power level on A_{DL}/V_{AS} ratio for various electrode sizes and operating pressures.

Figure 4 shows the influence of operational parameters such as applied power, electrode size, and operating pressure on the variation of A_{DL}/V_{AS} ratio. It is clear that reducing applied power leads to an increase in the A_{DL}/V_{AS} ratio. This effect can be attributed to the reduction in current, which is proportional to the length scale of the anode spot plasma at a given anode area and pressure [4], thereby increasing the relative area of the double layer. Smaller electrode diameters also contribute to a higher A_{DL}/V_{AS} ratio, while lower pressure enhances this ratio, potentially due to more effective current collection at the same bias voltage. These trends suggest that optimizing operational parameters, specifically by reducing applied power at lower pressure and using smaller electrodes, can significantly increase the A_{DL}/V_{AS} ratio and, consequently, electronegativity. These findings provide a practical approach to enhancing the performance of negative hydrogen ion sources.

4. Conclusion

In this study, we found that the A_{DL}/V_{AS} ratio plays a critical role in enhancing electronegativity in negative hydrogen ion source with anode spot. We found that the A_{DL}/V_{AS} ratio could be effectively controlled by adjusting the operating parameters of anode spot, such as applied power level, electrode size, and operating pressure. Our finding provides a clear pathway for optimizing negative hydrogen ion source with implemented anode spot: operating at lower power levels and pressures, with the use of smaller electrodes, can substantially improve electronegativity. These insights are crucial for advancing the design and efficiency of ion sources.

Acknowledgements

This study was supported by the Materials/Parts Technology Development Program funded by Korean Government (MOTIE) (No. 20017354-K_G0120017354), National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (No. RS-2023-00208968), Korea University Grant.

REFERENCES

[1] U. Fantz, S. Briefi, A. Heiler, C. Wimmer and D. Wünderlich, "Negative Hydrogen Ion Sources for Fusion: From Plasma Generation to Beam Properties," *Frontiers in Physics,* vol. 9, p. 709651, 2021.

[2] S. D. Baalrud, B. Longmier and N. Hershkowitz, "Equilibrium states of anodic double layers," *Plasma Sources Science and Technology,* vol. 18, p. 035002, 2009.

[3] Y.-S. Park, Y. Lee, J.-J. Dang, K.-J. Chung and Y. S. Hwang, "Operating conditions for the generation of stable anode spot plasma in front of a positively biased electrode," *Review of Scientific Instruments,* vol. 85, no. 2, p. 02A508, 2014.

[4] Y. Lee, "Development of Anode Spot Plasma Ion Source for High Current Beam Extraction," Ph.D. Dissertation, Dept. of Energy System Engineering, Seoul National University, Seoul, 2017.