Efficiency Improvement of an E×B Penning Discharge Source by Enhanced Cross-field Transport of Electrons

June Young Kim, Jaeyoung Choi, Y. S. Hwang, and Kyoung-Jae Chung
Department of Nuclear Engineering, Seoul National University, Seoul, Republic of Korea
e-mail (speaker): ptcbcg@gmail.com

Precise control of the particle motion is essential to effectively generate plasma and deliver a stable ion beam current in several applications, such as the semiconductor process to electric propulsion. In line with this engineering necessity, academia has designated low-temperature plasma sources with the characteristics of partially magnetized plasma as a new classification system called E×B discharge sources. In the operation of these sources, the particle motion is coupled with externally applied electric and magnetic fields, and many physical phenomena have been reported in E×B devices such as transport and magnetic confinement[1], instability[2], and thermodynamics[3].

Various E×B sources have a common property where only electrons are strongly magnetized (i.e., partially magnetized plasma), but the method of particle confinement is different depending on the types of sources. Generally, electrons are azimuthally rotated with closed E×B drift loops that contribute to an efficient gas discharge in the case of Hall thrusters and magnetron sputtering devices. In contrast, electrons are confined along the magnetic field line in the E×B Penning discharge source. The heating and energy relaxation of the beam electrons in the E×B Penning device is concentrated in the central plasma column along the magnetic field line, and the electrons bounce back and forth when they encounter an axial cathode sheath.

The electron confinement method should be effective for the extraction of high-current of ion beam. For classical E×B sources (Hall thruster and magnetron sputtering device), the direction of the ion beam is perpendicular to the plane of E×B drift of electrons; therefore, a closed drift current of electrons in azimuthal direction contributes to supplying uniform- and high-current ion beam. In contrast, in the case of the E×B Penning source, the ion beam extraction slit is located at the radial edge of a cylindrical source. Therefore, current methods of radially centered electron confinement do not guarantee efficient ion beam extraction.

The aforementioned state of affairs provides the motivation for this study. We introduce an E×B plasma with a unique plasma transport mechanism unlike the conventional E×B Penning sources described in the literature thus far. We demonstrate that the spatially asymmetric sheath structure in the E×B Penning system can improve the overall source efficiency and increase the plasma density at the extraction region by overcoming the limitation of a conventional source where the strong magnetic confinement disconnects the plasma column and its surroundings[4].

We concentrate on the method to enhance the cross-field transport of electrons toward the extraction region. The generation of a spatially asymmetric sheath structure allows the beam and energetic electrons to be transported to the extraction region via the E×B drift of the electrons. The transported electrons contribute to the expansion of the electron heating and ionization regions to the extraction region by breaking of axial symmetry of the sheath, thereby increasing the temperature and density of the electrons in the extraction region as the magnetic field strength increases. The enhanced discharge efficiency defined as the ratio of the electron density to the discharge current is noticeable, recording approximately twice the improved efficiency compared to the conventional mode with symmetric sheath structure.

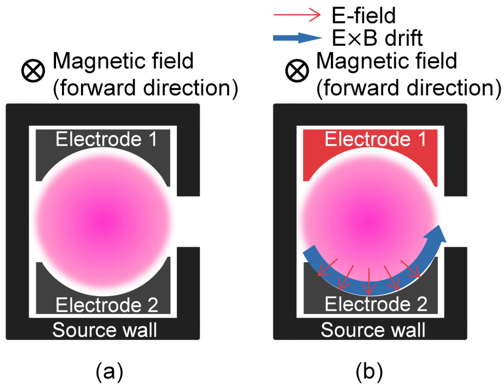

Figure 1. Schematics of the three different modes of the E×B Penning source: (a) conventional mode, and (b) enhanced (forward). Assuming that the equipotential line around electrode 2 resembles the curvature of the electrode 2, the red and blue arrows indicate the expected direction of the electric field and E×B drift, respectively. Electrode 1 is marked red to indicate the positive voltage application in the enhanced modes.

References

[1]J. Y. Kim, J. Y. Jang, J. Choi, J. Wang, W. I. Jeong, M. A. I. Elgarhy, G. Go, K.-J. Chung, and Y. S. Hwang, “Magnetic confinement and instability in partially magnetized plasma” Plasma Sources Sci. Technol. 30, 025011 (2021).
[2]A. Powis, J. Carlsson, I. Kaganovich, Y. Raitses, and A. Smolyakov, “Scaling of spoke rotation frequency within a Penning discharge” Phys. Plasmas 25, 072110 (2018).
[3]J. Y. Kim, H. C. Lee, G. Go, Y. H. Choi, Y. S. Hwang, and K. J. Chung, "Exploring the nonextensive thermodynamics of partially ionized gas in magnetic field" Phys. Rev. E 104, 045202 (2021).
[4]J. Y. Kim, J. Choi, J. Choi, Y. S. Hwang, and K.-J. Chung, and Y. S. Hwang, “Efficiency improvement of an ExB Penning discharge source by enhanced cross-field transport of electrons” Plasma Sources Sci. Technol. 31, 05LT02 (2022).