Kinetic Analysis of Electron Transport in Hot Cathode Penning Ionization Gauge Sources

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1. Introduction

Penning Ionization Gauge (PIG) ion sources are one of the most commonly used ion sources due to their structural simplicity and ability to generate high-density plasma. The plasma generation mechanism in PIG source has been understood as the beam-plasma interaction, which can provide high energy electrons that can contribute to generation of highly charged ions in source [1].

PIG ion sources can be classified by their operational cathode temperature into cold cathode PIG and hot cathode PIG. Hot cathode PIG source features a heated cathode which provide electrons through thermionic emission. These electrons gain kinetic energy via cathode fall voltage, supplying beam-like energetic electrons inside the bulk plasma. Hot cathode PIGs can be categorized into directly heated cathode and indirectly heated cathode by cathode heating mechanism. Indirectly heated cathode PIG source separates the externally heated component from the cathode, offering maintenance advantages and an additional controllable parameter.

In the radial extraction from PIG sources, plasma is extracted in cross-field direction, traversing the external magnetic field which confines plasma. Since the cross-field transport is not strong in magnetized plasmas [2], significant reduction of plasma density in the extraction region is inevitable. To address this issue, Makov proposed a volume extraction ion source [3], introducing an additional electrode within the plasma volume to induce E×B drift of plasma into the extraction region.

In this work, we have investigated the enhancement of cross-field transport via E×B drift by measuring the electron energy probability functions (EEPFs) along radial direction in the transport-enhanced (or Makov-type) PIG ion source. The characteristics of the new ion source were also analyzed using EEPFs under various operating conditions and compared with the conventional PIG ion source.

2. Experimental Setup

Schematic diagram of the conventional PIG ion source is shown in Fig. 1(a). In the conventional source, the hot cathode is heated indirectly with a separately existing filament. The filament is driven by a filament power supply for thermionic emission of electrons. The bias power supply accelerates thermal electrons emitted from the filament into the cathode, resulting in the heating of the cathode. Schematic diagram of the transport-enhanced PIG ions source is shown in Fig. 1(b). The transport-enhanced PIG ion source is a PIG ion source that adapts the concept of the volume extraction PIG source by Makov [3]. Unlike the conventional PIG ion source, the transport-enhanced PIG ion source separates the anode electrode into two side electrodes and applies the electrostatic potential between them to generate E×B drift motion of plasma. Since the plasma potential is close to the anode potential (arc voltage), the strength of radial electric field become asymmetric so that the E×B drift would be more effective in the cathode side as depicted in Fig. 1(c). This asymmetric azimuthal E×B drift is expected to increase the plasma density at the extraction region.

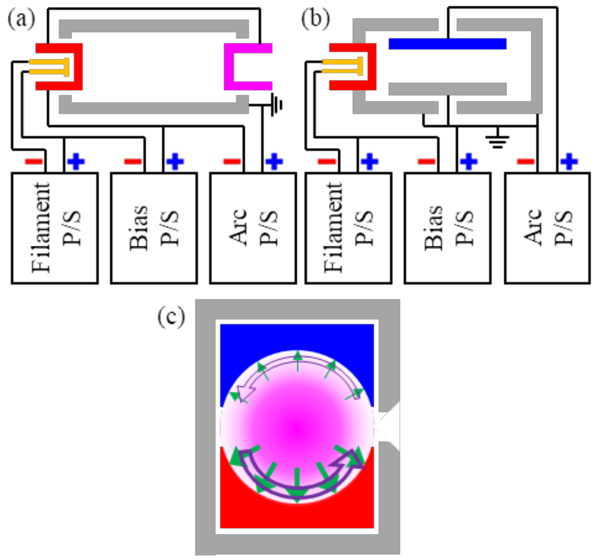

Fig. 1. Cross-sectional schematics and electrical connections of (a) conventional and (b) transport-enhanced PIG ion source. (c) Schematics of internal electrical field (green arrow) and E×B drift (purple arrow) inside the transport-enhanced PIG ion source.

Table I: Experimental conditions

Controlled Parameter	Source Type	Gas Flow Rate [sccm]	B-field Strength [G]	Arc Voltage [V]	Arc Current [A]	Bias Power [W]
Reference	Conventional	2.5	100	60.0	2.50	1400
B-field Direction	Transport-enhanced	2.5	**100**	60.0	2.49	1380
		2.5	**-100**	60.0	2.54	1400
Pressure		**1.5**	100	60.0	2.48	1440
		3.5	100	60.0	2.51	1360
B-field Strength		2.5	**50**	60.0	2.47	1420
		2.5	**150**	60.0	2.50	1370
Arc Voltage		2.5	100	**45.0**	2.55	1440
		2.5	100	**90.0**	2.55	1330

Measurements of EEPFs are performed with a single cylindrical Langmuir probe of 0.3 mm in diameter and 1 mm in length. Radial measurement has been conducted from –10 mm to +20 mm (end of the source) in 2 mm spatial resolution. Note that the radius of hot cathode is 10 mm and the extraction aperture is located at +15 mm away from the center with thickness of 5 mm. All experiments are conducted with Argon gas. Comparison between the conventional PIG ion source and the transport-enhanced PIG ion source has been done for the one reference case with two directions of magnetic field. Parametric analysis has been conducted for further understanding of the formation of EEPF by manipulating operating parameters such as gas pressure, magnetic field strength, and arc voltage. The experimental conditions are summarized in Table 1. Note that the positive values of B-field strength are designated as forward B-field direction which can induce the direction of the E×B drift to the extraction region.

3. Experimental Results and Discussion

In the PIG source, electrons can be classified into a few groups by their behavior, as shown in Fig. 2. A bulk electron group has the lowest kinetic energy with the Maxwellian distribution. This group occupies the largest number in the source in general. An energetic electron group consists of electrons with higher kinetic energy than bulk electrons, below the plasma potential. The energetic electron group is electrically confined in axial direction by the cathode fall potential and in radial direction by external magnetic field. This group is expected to contribute to the generation of the highly charged ions. An extra-energetic electron group includes the electrons with kinetic energy above the plasma potential. These electrons are believed to be generated by the energy spread of primary beam electrons through beam-plasma interaction mechanism [4,5].

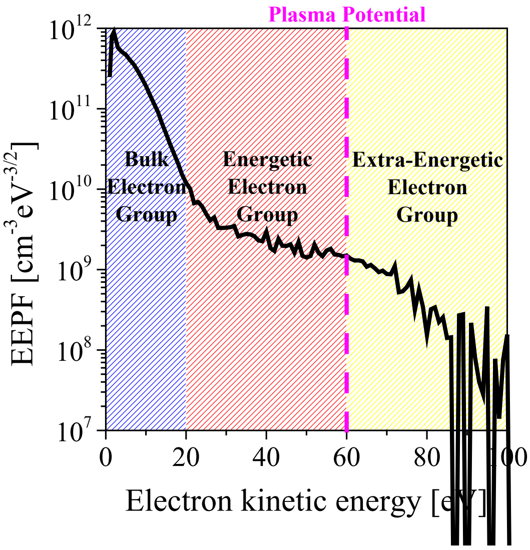

Fig. 2. Classification of electron groups on typical EEPF in hot cathode PIG ion source plasma.

As shown in Fig. 3(a), the evolution of EEPFs in the conventional PIG ion source has the characteristic of loss of thermal energy of bulk electrons [2,6] and dramatic decrease of a population of the energetic electrons. The same characteristic is also shown in the transport-enhanced PIG ion source with reverse B-field condition (Fig. 3(b)), because the direction of E×B drift is opposite to the extraction region.

However, the evolution of EEPFs for the transport-enhanced PIG ion source with forward B-field condition shows very different behavior compared to the above two cases, as shown in Fig. 3(c). It shows that the bulk electrons are transported radially while conserving its thermal energy and higher population of energetic electrons is observed at the extraction region. These differences could be the evidence of the enhancement of the transport by E×B drift in the forward B-field condition of the transport-enhanced PIG ion source.

Figure 4 shows the influences of gas pressure, magnetic field strength, and arc voltage on the formation of EEPFs at the central region of the

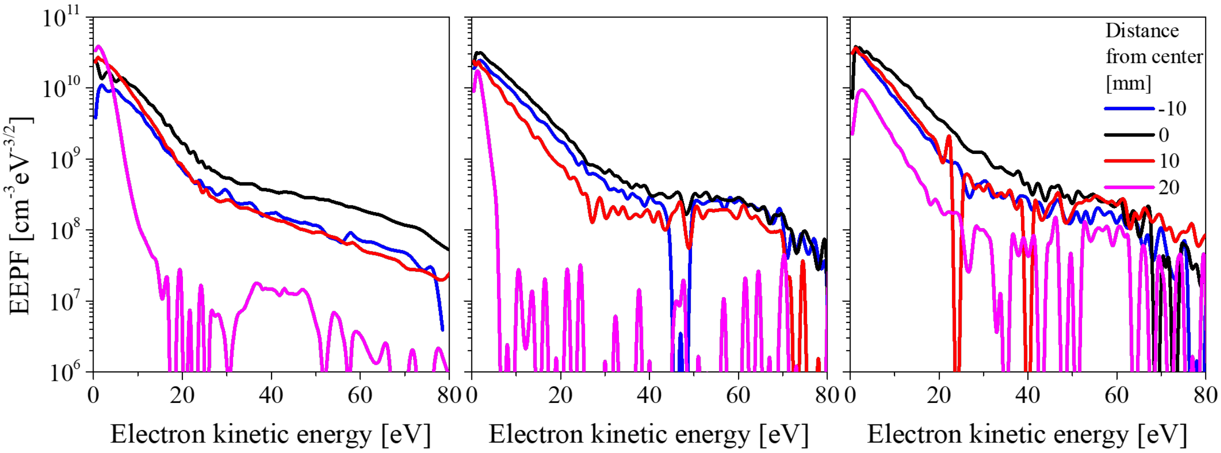

Figure 4. Evolution of EEPFs along radial positions in (a) conventional PIG ion source, (b) transport-enhanced PIG ion source with reverse B-field condition and (c) transport-enhanced PIG ion source with forward B-field condition.

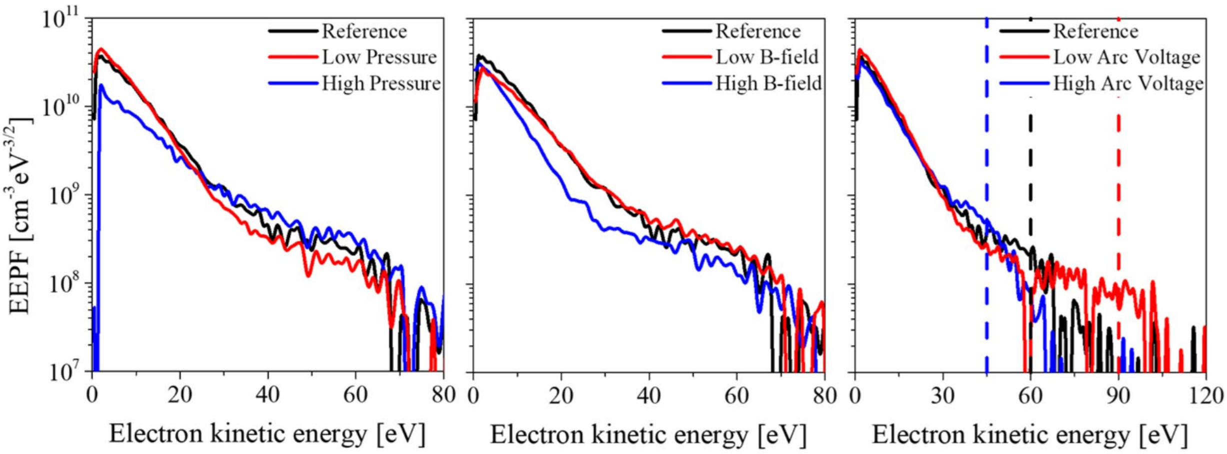

Figure 3. Parametric effects on EEPF formation of (a) gas pressure, (b) B-field strength and (c) arc voltage. In (c), the vertical dashed lines correspond to the respective arc voltage settings for each experimental condition.

transport-enhanced PIG ion source with forward B-field. Gas pressure affects the energy loss of energetic electrons. As the gas pressure increases, lesser energetic electrons are observed due to energy loss by frequent collisions with background neutral particles. A higher magnetic field improves the confinement of energetic electrons, allowing more energy transfer from energetic electrons to bulk electrons; temperature of electrons under ionization threshold energy is increased as shown in Fig. 4(b). The higher the arc voltage, the more energetic electrons are generated as shown in Fig. 4(c), because the energy of primary beam electrons is proportional to the plasma potential which is not much different from the arc voltage.

4. Conclusions

This paper confirms through a series of experiments that asymmetric E×B drift primarily enhances electron density at the aperture region in the new transport-enhanced PIG ion source in the radial boundary region between the plasma and side electrodes. The enhancement in plasma density at the aperture region has a great advantage in improving the ion source performance without a significant change in the source dimension and power level. In addition, we also recognize from the EEPF measurements that the fraction of charge state and ion species would be controlled by adjusting the operating parameters such as arc voltage and magnetic field strength. Therefore, the introduction of side electrodes in the transport-enhanced PIG ion source provides a new control knob to control the electron energy distribution at the aperture region of the ion source without a significant density degradation. This will be helpful for ion source operation in various kind of applications from highly-charged state sources to molecular abundant ion sources.

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REFERENCES

[1] J. R. J. Bennet, A Review of PIG Sources for Multiply Charged Heavy Ions, IEEE Transactions on Nuclear Science, Vol. 19(2), p. 48, 1972.
[2] J. Y. Kim, W.-H. Cho, J.-J. Dang, K.-J. Chung and Y. S. Hwang, Enhancement of negative hydrogen ion production at low pressure by controlling the electron kinetics property with transverse magnetic field, Plasma Sources Science and Technology, Vol. 25(6), p. 065019, 2016.
[3] B. N. Makov, A source with ion extraction from the plasma volume, Review of Scientific Instruments, Vol. 71, p. 4127, 2000.
[4] H. Schulte and B. H. Wolf, Ion and Electron Flow in Hot-Cathode PIG Sources for Multiply Charged Heavy Ions, IEEE Transactions on Nuclear Science, Vol. 23(2), p. 1053, 1976.
[5] Y. Sato, T. Yamada, H. Ogawa and S. Yamada, Ionization by electron impact in an indirectly heated Penning source, Journal of Applied Physics, Vol. 69(1), p. 151, 1991.
[6] J. Y. Kim, J. Y. Jang, W. I. Jeong, K. Choe, M. A. I. Elgarhy, K.-J. Chung and Y. S. Hwang, Characterization of the Penning ionization gauge source through electron energy distribution function analysis, in XXXIV ICPIG & ICRP-10 Conference Proceedings (PO18AM-038), Jul.14-19, 2019.