24P125-P

Large diameter double-layer plasma source using permanent magnets and its characteristics
永久磁石利用ダブルレイヤープラズマ源の大口径化とその特性

Tatsuya Suzuki[1], Kazunori Takahashi[1,2] and Tamiya Fujiwara[1,2]
鈴木達也[1], 高橋和貴[1,2], 藤原民也[1,2]

[1]*Department of Electrical Engineering and Computer Science, Iwate University, 4-3-5 Ueda, Morioka, Iwate 020-8551, Japan*
岩手大学工学部 電気電子・情報システム工学科 〒020-8551 岩手県盛岡市上田4-3-5

[2]*Soft-Path Engineering Research Center (SPERC), Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka, Iwate 020-8551, Japan*
岩手大学ソフトパス工学総合研究センター 〒020-8551 岩手県盛岡市上田4-3-5

A diameter of a source tube of a permanent-magnets-expanded plasma source is enlarged from the previously reported 6.6 cm to 13 cm for a purpose of an increace in an electron-pressure-induced thrust for electric propulsion. A supersonic ion beam of about 13 cm in diameter is detected near the source exit simultaneously with a spontaneous formation of a potential drop. A plasma density, an electron temperature, and an rf power efficiency are experimentally investigated at various gas pressures and rf powers. The results are compared with particle balance and power balance equations.

1. Introduction

Formation of current-free electric double layers (DLs) and subsequent acceleration of ions in magnetically expanding radio-frequency (rf) plasmas have been observed in experiments, theoretical models, and PIC simulations. A new concept of electric propulsion device utilizing this phenomenon has been suggested [1]. In this type of plasmas, the accelerated ion beam is electrically neutralized by the energetic electrons overcoming the potential drop [2,3]. More recently, direct measurements of the thrust from the magnetically expanding DL plasma or simple rf plasma source have been demonstrated [4-6].

According to the balance equations between a volume ionization and a surface loss of the charged particles, and between a electric power and an energy loss, the thrust resulting from an electron pressure increases with an increase in a source diameter. The diameter of the previously reported DL plasma source using the permanent magnets was 6.6 cm [7]. Here a source diameter is enlarged up to 13.3 cm and its characteristics are presented.

2. Experimental setup

A schematic diagram of the *L*arge diameter *P*ermanent *M*agnets expanding *P*lasma machine of *I*wate University (*L-PMPI*) is shown in Fig. 1(a). A plasma source, consisting of a 60 cm long and 13.3 cm inner diameter glass tube, is contiguously connected to a 100 cm long and 76 cm diameter

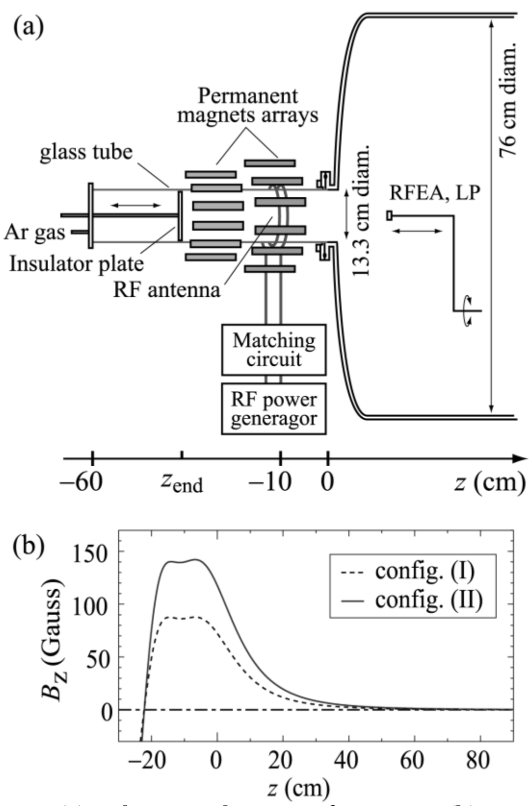

Fig.1. (a) Schematic diagram of *L-PMPI*. (b) Axial profile of the calculated axial component B_z of the magnetic field strength for the configuration (I) (dashed line) and (II) (solid line).

stainless steel vacuum chamber, which is evacuated to a base pressure of about 10^{-4} Pa. The source is

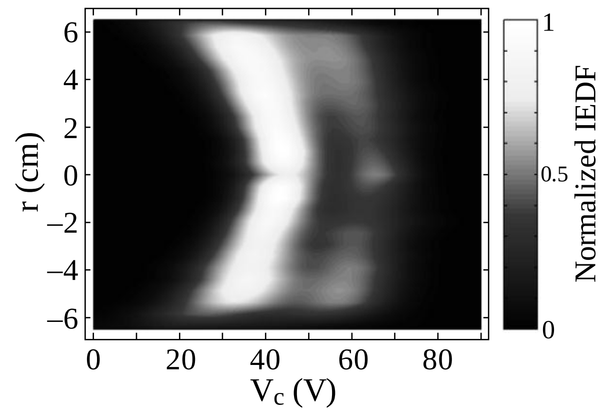

Fig.2. Contour image of the radial profile of the normalized IEDFs measured at 3 cm downstream of the source exit for the argon gas pressure of 40 mPa and the rf power of 300 W.

terminated upstream by an axially movable insulator plate at z = –28 cm, where z = 0 cm is defined as the source exit. In the present experiment, two types of magnetic field configurations provided by the permanent magnets are used as a shown in Fig. 1(b); all of the magnets has inward magnetization in the radial direction. For the configurations (I) and (II), the field strength in the source is about 80 and 140 Gauss, respectively. An argon gas is introduced from the upstream side of the source tube through a mass flow controller and the operating gas pressure in the diffusion chamber is maintained in the range 25-300 mPa, where an argon gas pressure is measured with an ionization gauge connected to the side wall of the diffusion chamber. A double-turn rf loop antenna winding the source tube at z = –10 cm is powered from a 13.56 MHz rf power generator through a matching circuit and an argon plasma is produced by an inductively-coupled discharge.

An axially and radially movable retarding field energy analyzer (RFEA) facing the source tube or a Langmuir probe (LP) is inserted from the downstream side of the diffusion chamber. Ion energy distribution function (IEDF) is measured by the RFEA using the pulsed probe technique [8], and the LP is used to estimate the local plasma density and the electron temperature.

3. Results

Fig. 2 shows the contour image of the radial profile of the IEDF, which is measured at z = 3 cm and normalized by the maximum of the IEDFs, for the argon gas pressure of 40 mPa, the rf power of 300 W, and the configuration (I). Around collector voltage of V_c ~ 30-45 V corresponding to the local plasma potential ϕ_p, the thermal ions exist within the radius of $|r| \leq 6.5$ cm. The accelerated group of ions is clearly detected within the radial range same as the thermal ions around V_c ~ 50-65 V, which corresponds to the beam potential ϕ_{beam}. The energy of the ion beam could be estimated as $\varepsilon_{beam} = e(\phi_{beam} - \phi_p)$ ~ 20 eV, where e is the elementary charge. The calculated ion beam velocity for the argon ion and an ion sound speed for the measured electron temperature of 7.5 eV are 10 km/s and 4.2 km/s, respectively. Therefore, the detected ion beam is supersonic [9].

In the configuration (II), the electron temperature and the plasma density are measured for various argon gas pressures and rf powers, and are compared with theoretical value derived from the balance equations between the volume ionization and the surface loss, and between the electric power and the energy loss in a global model. For the rf power of 300 W, the electron temperature decreases from about 8 eV to about 5 eV with an increase in the argon gas pressure from 25 mPa to 300 mPa. And the electron temperatures are about 6-7 eV for all of the rf power (50-800 W) and the gas pressure of 40 mPa. An rf power efficiency is about 80% for the gas pressure of 40 mPa and the rf power of 300 W; it increases with increase in the argon gas pressure and the rf power. The theoretical values of the electron temperature and the plasma density are in fair agreement with the measured ones.

References

[1] C. Charles: Plasma Sources Sci. Technol. **16** (2007) R1, and reference therein.

[2] K. Takahashi, C. Charles, R. W. Boswell, T. Kaneko, and R. Hatakeyama: Phys. Plasmas **14** (2007) 114503.

[3] K. Takahashi, C. Charles, R. W. Boswell, and T. Fujiwara: Phys. Rev. Lett. **107** (2011) 035002.

[4] K. Takahashi, T. Lafleur, C. Charles, P. Alexander, R. W. Boswell, M. Perren, R. Laine, S. Pottinger, V. Lappas, T. Harle, and D Lamprou: Appl. Phys. Lett. **98** (2011) 141503.

[5] S. Pottinger, V. Lappas, C. Charles, and R. Boswell: J. Phys. D: Appl. Phys. **44** (2011) 235201

[6] T. Lafleur, K. Takahashi, C. Charles, and R. W. Boswell: Phys. Plasmas **18** (2011) 080701.

[7] K. Takahashi, K. Oguni, H. Yamada, and T. Fujiwara: Phys. Plasmas **15** (2008) 084501.

[8] K. Takahashi, Y. Shida, and T. Fujiwara: Plasma Sources Sci. Technol. **19** (2010) 025004.

[9] Y. Itoh, K. Takahashi, and T. Fujiwara: IEEE Trans. Plasma Sci., *in press*.