Supersonic Ion Beam Driven by Permanent-Magnets-Induced Double Layer in an Expanding Plasma

Kazunori Takahashi, Yutaka Shida, Tamiya Fujiwara, and Kaoru Oguni

***Abstract*—Plasma potential structures and ion-energy distribution functions are measured in a magnetically expanding radio-frequency plasma using permanent magnets (PMs) and in a geometrically expanding one, where the radio-frequency power and the argon-gas pressure are maintained at 250 W and 1 mtorr, respectively. In the magnetically expanding plasma, a rapid potential drop like a double-layer structure and a subsequent supersonic ion beam are detected by retarding field energy analyzers. On the other hand, a plasma potential structure following Boltzmann relation accelerates the ions in the geometrically expanding plasma. The comparison between the results in both cases indicates that the existence of the PMs is effective for the generation of the high-speed ion beam, where the mach number of the ion beam is increased to about 3.5 by using the PMs compared with the mach number of 2.3 in the operation mode of the geometrically expanding plasma.**

***Index Terms*—Double layer (DL), expanding plasma, ion acceleration, permanent magnets (PMs), plasma potential structures.**

I. INTRODUCTION

EXPANDING RF plasmas containing electric double layers (DLs) or Boltzmann electric fields have recently been vigorous research subjects in connection with the development of electrodeless electric propulsion devices. In magnetically expanding plasmas, supersonic ion beams accelerated by current-free DLs are detected at the downstream side of the DLs, where a rapid potential drop with thickness of about several tens to several hundreds of Debye length is formed near the open end of the plasma sources [1]–[6]. On the other hand, the DL has not been observed in the series of experiments on a geometrically expanding plasma, but an ion beam accelerated by the Boltzmann electric field is detected [7], [8].

In association with the aforementioned topics, the authors have already reported the new type of the magnetically expanding plasma source with a diverging magnetic-field configuration provided by permanent magnets (PMs) only instead of the electromagnets, where a formation of the DL structure and a supersonic ion beam with energy corresponding to the DL potential drop are observed [9], [10]. The use of the PMs would lead to a reduction of the electric power consumption and the weight of the propulsion device utilizing the ion acceleration in the magnetically expanding plasmas. However, the effects of the magnetic fields provided by the PMs have not been discussed in the series of studies on the expanding plasma source using the PMs, although the magnetic-field configuration would be one of the important parameters. Therefore, it is very important to investigate the effects of the existence of the magnetic field provided by the PMs on the plasma potential structure and the ion-energy distribution function (IEDF).

In this paper, we provide experimental data on the plasma density, the plasma potential, and the IEDF for the cases with and without the PMs, i.e., in the magnetically and geometrically expanding plasmas; the effects of the expanding fields provided by the PMs are discussed based on the difference in the results between these two modes of machine operation.

II. EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig. 1(a), which was previously described by Takahashi *et al.* [9]. Briefly, a plasma source, consisting of a 20-cm-long and 6.5-cm-diameter glass tube surrounded by a double-turn loop antenna situated at $z = -9$ cm and powered from an RF generator of 13.56 MHz and 250 W, is contiguously connected to a 30-cm-long and 26-cm-diameter stainless-steel vacuum chamber (the diffusion chamber), where $z = 0$ is defined as the exit of the source tube. The chamber is evacuated to a base pressure of 10^{-6} torr by a diffusion/rotary pumping system. The argon gas is introduced from the source side, and the pressure is maintained at 1 mtorr in the present experiments. The side and axial views of the double concentric arrays of neodymium iron boron (NdFeB) magnets surrounding the source tube are shown in Fig. 1(a) and (b). The inner and outer arrays consist of eight sets of three and four PMs (10 cm in length, 1.5 cm in width, and 0.5 cm in thickness), respectively. The calculated magnetic-field strength B_z is plotted in Fig. 1(c); it is found that the expanding magnetic field of about 270 G in the source ($z \sim -12$ to -5 cm) and about 10 G in the middle of the diffusion chamber ($z = 15$ cm) is provided by the PMs, where the field strength is increased by adding the magnet bars, compared with our previous works [9], [10]. The condition that the PMs are set

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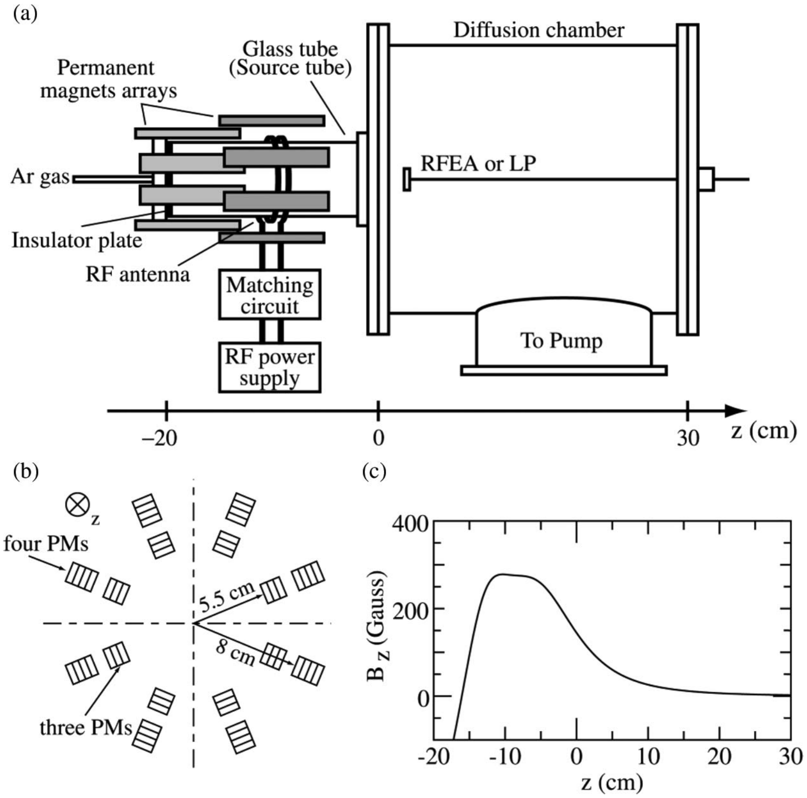

Fig. 1. (a) Schematic of the experimental setup. (b) Axial view of the PMs. (c) Axial profile of the calculated axial component B_z of the magnetic-field strength produced by the PMs.

around the source tube is labeled as "with PMs." When the PMs are not set, the source simply acts as an inductively coupled plasma (ICP) device, labeled as "without PMs," and basically the same as the geometrically expanding plasma machine [7].

The plasma potential structures and the IEDFs downstream of the source tube are measured by the axially movable retarding field energy analyzers (RFEAs) [9] with an orifice facing radially and with an orifice facing axially to the source tube, respectively. The IEDF is well known to be proportional to the first derivative of the current I_c–voltage V_c characteristic of the collector electrode of the RFEA. The first derivative is directly obtained by a pulsed probe technique [11]–[13], where the current signal is differentiated through an analog active circuit during a linear sweep of the collector voltage V_c. An axially movable planar Langmuir probe (LP) is also inserted from the downstream side of the diffusion chamber for measurements of the electron temperature and the ion saturation current.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig. 2 shows the axial profiles of the plasma density (open squares) estimated from the ion saturation current of the LP and the measured electron temperature of 5 eV for the cases (a) with and (b) without the PMs. With the PMs, the rapid density drop around $z \sim 0$ cm and the uniform density profile in the downstream side $(z > 3$ cm) are observed, as shown in Fig. 2(a). Between these two regions, the slight density dip appears to be present around $z \sim 3$ cm and to separate the upstream and downstream plasmas, which has been often observed in the experiments on the DL [14], [15]. On the other hand, the density without the PMs is found to gradually decrease along the z-axis as previously reported in some experiments on the plasma expansion into a vacuum [7], [16]–[19].

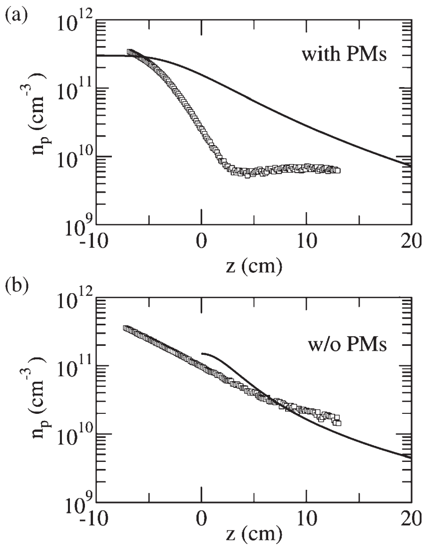

Fig. 2. (Open squares) Axial profiles of the plasma density estimated from the ion saturation current of the LP (a) with PMs and (b) without PMs. The solid line in (a) and (b) shows the results obtained from (1) and (2), respectively.

We consider the simple model assuming the plasma diffusion along the magnetic-field lines in the magnetically expanding plasma. For a plasma with density n_0 in a constant magnetic-field (B_0) area, the density $n(z)$ in the diverging field area

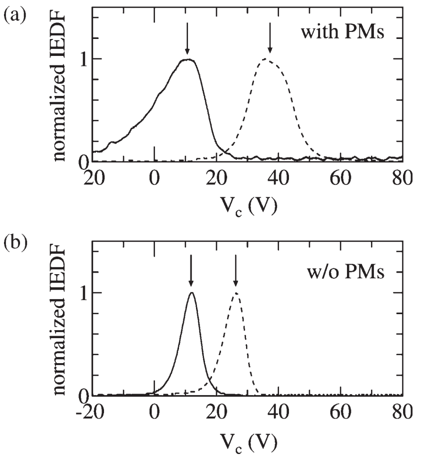

Fig. 3. Typical normalized IEDFs measured by the radially facing RFEA located at (dashed lines) $z = -3$ cm and (solid lines) $z = 5$ cm (a) with PMs and (b) without PMs, together with the arrows indicating the local plasma potentials.

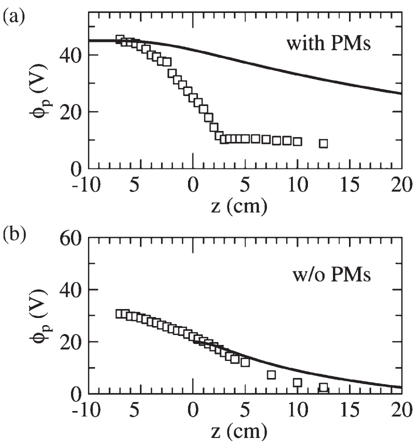

Fig. 4. Axial profiles of the local plasma potential ϕ_p (a) with PMs and (b) without PMs, together with the (solid lines) potential derived from the Boltzmann relation and the modeled density profile in Fig. 2.

is basically related to the local magnetic-field strength $B(z)$ by [20]

$$\frac{n(z)}{n_0} = \frac{B(z)}{B_0}. \tag{1}$$

The above relation yields the density profile shown in Fig. 2(a) as a solid line; it is found to be not in agreement with the experimentally observed density at all. Thus, it is considered that the observed structure with the PMs is not the result of the simple modification of the plasma structure by the diverging magnetic-field configuration. Although the details are described later, the existence of the DL near the source exit is implied in this paper. On the other hand, the density profile from the source into the diffusion chamber in the case without the PMs is modeled according to the previously reported geometrically expanding plasma [7], [21] as

$$\frac{n(z)}{n_0} = \frac{R_0^2}{R_0^2 + z^2} \tag{2}$$

where R_0 is the source-tube radius. The modeled density profile shown in Fig. 2(b) as a solid line is modestly in agreement with the experimental one.

Fig. 3(a) and (b) shows the typical normalized IEDFs measured by the radially facing RFEA at $z = -3$ cm (dashed lines) and $z = 5$ cm (solid lines) with and without the PMs. The IEDFs with the PMs shown in Fig. 3(a) appear to broaden in comparison with those without the PMs in Fig. 3(b). It might be because strong RF electric fields would make the IEDF broad or separated into two peaks [22], although we need to investigate the details of the RF fields hereafter. However, V_c yielding the peaks of the IEDFs can give us the local plasma potentials ϕ_p, as indicated by the arrows. The estimated plasma potentials ϕ_p at $z = -3$ cm and $z = 5$ cm are 38 and 10 V for the case with the PMs, and 26 and 12 V for the case without the PMs, respectively. Hence, there are potential differences between the source tube and the diffusion chamber for both cases.

Detailed axial measurements of the plasma potential are carried out by the axially movable RFEA facing radially. The results of the axial profiles for the cases with and without the PMs are plotted in Fig. 4(a) and (b), respectively, as open squares. A potential drop of about 30 V within 3–4 cm is observed near the source exit at $z \sim -2$ cm to $z \sim 2$ cm for the case with PMs, where the potential gradient is about 6–8 V/cm and is much larger than that measured in the source tube (e.g., about 2 V/cm). The recent DL experiments in the magnetically expanding plasma have reported that the thickness of the DL is about 50 Debye lengths [3], whereas a result by a laser-induced fluorescence technique in the different magnetically expanding plasma [4] and the past experiments on the DL [23], [24] have shown the DL with thickness of a few hundreds of Debye lengths. The currently observed potential structure appears to be very close to the latter DL. Furthermore, a slight dip of the plasma density as shown in Fig. 2(a) near the potential drop has also been observed in other DL experiments [14], [15]. Here, we compare the observed potential structure with a simply modeled potential structure derived from (1) and the Boltzmann relation given by

$$\phi_p(z) = \phi_p(z_0) + T_e \ln\left[\frac{n(z)}{n_0}\right]. \tag{3}$$

Equations (1) and (3) give an axial variation of the plasma potential shown in Fig. 4(a) as a solid line. It is found that the observed potential cannot be explained by the simple modification by the expanding magnetic fields at all, where we expect that the DL near the source exit would cause the structure modifications of the plasma density in Fig. 2(a) and the plasma potential in Fig. 4(a). Based on the aforementioned considerations on the observed profiles of the plasma density and potential, we suggest the DL formation near the source exit in the present experiment under the condition that the PMs providing the expanding magnetic field are set around the source tube.

For the case without the PMs, i.e., the simple ICP device, a gradual decrease in the plasma potential along the axis is observed as plotted in Fig. 4(b). It appears that the potential gradient in the diffusion chamber is larger than that in the upstream source tube. In the present experiment, the vacuum-chamber diameter is spatially changed at the interface between the source tube and the diffusion chamber; then the plasma geometrically

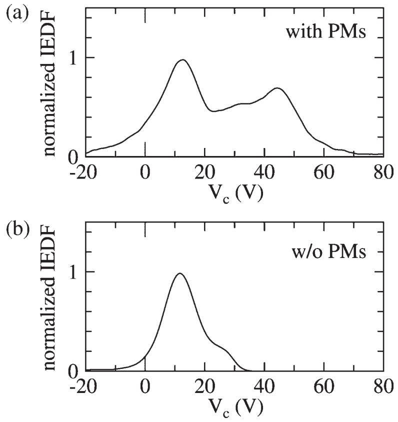

Fig. 5. Normalized IEDFs measured by the axially facing RFEA for the cases (a) with PMs and (b) without PMs, where the results in (a) and (b) are measured at $z = 3$ cm and $z = 5$ cm, respectively.

expands as reported in [7]. Equations (2) and (3) also give an axial variation of the plasma potential modeled by the plasma expansion into the vacuum, which is shown in Fig. 4(b) as a solid line. The result fairly agrees with the experimentally observed one. Therefore, for the case without the PMs, the potential structure following the Boltzmann relation is formed due to the geometric expansion of the plasma and the resultant density decrease along the axis.

Under the conditions that the plasma potential structures shown in Fig. 4(a) and (b) are formed, the axial IEDFs are measured in the downstream diffusion chamber by the RFEA facing the source tube. Fig. 5(a) and (b) shows the normalized IEDFs measured by the axially facing RFEA for the cases with and without the PMs, respectively, where these data are obtained at $z = 3$ cm and $z = 5$ cm.

The IEDF with the PMs shown in Fig. 5(a) clearly shows the accelerated group of ions, i.e., the ion beam, at the collector bias voltage of $V_c \sim 44$ V, being in good agreement with the plasma potential in the upstream source tube. The energy $\varepsilon_{\mathrm{beam}}$ of the accelerated ion beam is estimated as about 32 eV because the left-hand peak at $V_c \sim 12$ V in Fig. 5(a) shows the local plasma potential at this point and corresponds to the zero energy of the ions. Since the ion-beam energy agrees with the potential drop observed in Fig. 4(a), the DL structure induced by using the PMs electrostatically accelerates the ions. The background population of the ions at $V_c \sim 12$ V would be generated through the charge-exchange process between the accelerated argon ions and the background neutral argon atoms [10], [25]. In addition, the IEDF shown in Fig. 5(a) indicates another peak at $V_c \sim 31$ V, which would be created through an elastic scattering.

The IEDF without the PMs in Fig. 5(b) also shows the accelerated group of the beam ions at $V_c \sim 25$ V corresponding to the upstream plasma potential in Fig. 4(b), in addition to the background ions at $V_c \sim 12$ V. The ion acceleration by the Boltzmann electric field has been observed in many experiments on simple ICP devices; these showed two types of the IEDF having the beam ions and the hot-tail ions [7], [8], [16]–[19]. The shape of the IEDF is relevant to the charge-exchange process, which is discussed here qualitatively because we have now no information on the spatial variation of the neutral pressure. When the mean free path for charge exchange is shorter than the distance of the potential drop, the IEDF would show the hot tail because the bulk ions thermalized halfway down the potential drop are accelerated again. In our experimental condition, the effective mean free path for charge exchange is about 4–5 cm, which is very close to the distance from the start of the plasma expansion to the measurement point. Then, almost all ions are thermalized near the measurement point, which would be detected as bulk ions. Thus, it is considered that the energetic group of the ions is observed as the beam ions.

The velocity v_{beam} of the beam ions with energy $\varepsilon_{\mathrm{beam}}$ is derived as

$$v_{\mathrm{beam}} = \sqrt{\frac{2e\varepsilon_{\mathrm{beam}}}{M_i}} \tag{4}$$

where M_i and e are the ion mass and the elementary charge, respectively. The velocity v_{beam} of the ions with energy of 32 and 13 eV observed in Fig. 5(a) and (b) are estimated as about 12.4 and 7.9 km/s, respectively. The electron temperature measured by the LP located in the diffusion chamber is $T_e \sim 5$ eV, giving an ion sound speed of $C_s \sim 3.5$ km/s. These values give us the mach numbers M of the ion beams as $M \sim 3.5$ with the PMs and $M \sim 2.3$ without the PMs; the observed ion beams are found to be supersonic. Here, it is noted that the beam velocity with the PMs is much faster than that without the PMs. Hence, the existence of the PMs providing the expanding magnetic-field configuration induces the enhancement of the ion-beam energy due to the formation of the DL structure.

IV. CONCLUSION

The plasma density, the plasma potential, and the IEDFs have been investigated by the radially and axially facing RFEA and the LP in the magnetically expanding plasma using PMs and in the geometrically expanding plasma using the same machine. The supersonic ion accelerations have been observed in both operations (with and without PMs) of the machine. Our results and discussions have implied that the DL structure electrostatically accelerates the ions for the case with the PMs, whereas the Boltzmann electric field does it for the case without the PMs. It has been evidenced that the existence of the PMs is effective in the generation of the high-speed ion beam due to the DL acceleration. Our result has shown that the mach number of the ion beam is increased to 3.5 by using the PMs. The optimization of the solenoid-free expanding plasma source using the PMs is our next challenge in the development of a long-lifetime electrodeless electric thruster.

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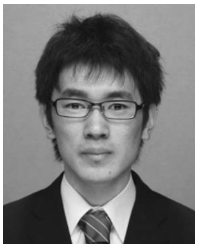

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