

Operation of a permanent-magnets-expanding plasma source connected to a large volume diffusion chamber

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Abstract

A 6.6-cm-inner-diameter permanent-magnets-expanding plasma source is connected to a large volume diffusion chamber of about 76 cm in diameter and 100 cm in length, and is operated over a range of 20 – 300 mPa argon gas pressure. An rf power of 13.56 MHz for plasma production is maintained at 200 W and the expanding magnetic field of about 200 Gauss in the source is provided by permanent magnets arrays. A potential drop of a few tens volts are observed; the supersonic ion beam with energy corresponding to the potential drop is detected in the diffusion chamber. Radial investigation of the ion beam in the diffusion chamber indicates a detachment of the ion beam from the expanding magnetic field lines provided by the permanent magnets, at about several centimeters downstream of the source exit.

Introduction

Formation of plasma potential structures has been an attractive research topic as it is associated with the particle acceleration in space plasmas [1-3] and with the confinement of fusion plasmas [4]. Especially, the detailed studies on electric double layers (DLs) in laboratory plasmas, which has a narrow region of potential change and a localized electric field, were vigorously carried out in double and triple plasma systems in a few decades ago [5-8]. The DL structure was also observed in the single plasma source system, where the two-electron-population plasma expands into the vacuum. In the single plasma system containing the DL, the ion acceleration by the potential drop of the DL was demonstrated by spatiotemporal measurements of the plasma potential structure and the ion energy distribution [9]. On the other hand, the ion reflections due to the DL formations were reported when the high speed ion beam is injected along a convergent magnetic field [10] or when the electrons are heated by cyclotron resonance heating under the convergent field [11-13].

In recent years, studies on magnetically expanding, low-pressure radiofrequency plasmas in laboratory experiments, theoretical analyses, and simulations have shown spontaneous formation of the DL and subsequent generation of the supersonic ion beam accelerated by the potential drop of the DL [14-17]. It has also been reported that the accelerated ion beam is electrically neutralized by electrons which are depleted energetic tail of an electron energy distribution in the upstream source and can overcome the potential drop of the DL [18]. These one-dimensional behaviors of the positive ions and the negative electrons are very similar to that in a grid-type ion engine [19], where the ion beam is generated by the grid acceleration and a neutralizer supplies electrons into the downstream side of the acceleration grid. The spontaneous ion acceleration mechanism due to the DL formation in the magnetically expanding plasmas is being used in a development of an innovative, electrodeless, long-lived plasma thruster [20].

For the development of the electrodeless thruster, the experiments in laboratory plasmas

have recently been extended into two- or three-dimensional measurements [21-23]. One of the key issues for the application to the thruster is an ion detachment phenomenon from the magnetic nozzle downstream of the DL. The previously reported simulation and two-dimensional experimental results have already shown that the accelerated ions are detached from the field lines at about ten centimeters downstream of the DL [22, 24].

For further development of the thruster, the reduction of the consumed electric power for the solenoid coils forming the expanding magnetic field has also been important subject; a permanent-magnets-expanding plasma source has recently been developed, where expanding magnetic fields are provided by some types of the permanent-magnets (PMs) configurations [25-28]. In one of these sources connected to compact diffusion chambers, a rapid potential drop of a few tens volts with a thickness over a few centimeters, corresponding to a few hundreds Debye length, forms near the source exit and the supersonic ion beams are generated in the diffusion chamber [25]. However, the ion detachment from the magnetic field lines provided by the PMs has not been verified so far.

In the present paper, the PMs-expanding plasma source is connected to a large volume diffusion chamber and is tested over the range of 20-200 mPa argon gas pressure, where a potential drop of a few tens volts and a supersonic ion beam accelerated by the potential drop are observed. The radial investigations on the ion beam profile in wide spatial range, which are allowed by the large diameter diffusion chamber, imply a detachment of the ion beam from the magnetic field lines at several centimeters downstream of the source exit.

Experimental Setup

The Large diameter Permanent Magnets expanding Plasma machine of Iwate University (L-PMPI) is constructed as shown in Fig. 1(a). The machine has a 76-cm-diameter and 100-cm-long

stainless steel cylindrical large volume vacuum chamber (diffusion chamber). A diffusion/rotary pumping system is connected to the bottom side of the diffusion chamber and is controlled by the electronic circuit. The chamber is evacuated to a base pressure below 10^{-4} Pa. A schematic diagram of the experimental setup is presented in Fig. 1(b). A 6.6-cm-inner-diameter and 20-cm-long pyrex glass tube (source tube) with upstream flange is contiguously connected to the diffusion chamber. Argon gas is introduced from the upstream side of the source and the operating gas pressure in the diffusion chamber is maintained in the range of 20-300 mPa, where the argon gas pressure is measured by an ionization gauge connected to the side wall of the diffusion chamber. The double concentric arrays of the Neodymium Iron Boron (NdFeB) magnets similar to the previously reported PMPI machine [25, 28] surrounds the source tube, and provides an expanding magnetic field of about 200 Gauss in the source tube and of a few Gauss in the diffusion chamber as plotted in Fig. 1(c). The double turn rf loop antenna wound around the source tube at $z = -10$ cm is continuously powered from an rf generator of 13.56 MHz and 200 W through the π -type impedance matching circuit, where $z = 0$ is defined as the open exit of the source tube. The forwarded and reflected rf powers are monitored by a power meter and a VSWR (voltage standing wave ratio) meter, where variable capacitors in the matching circuit are tuned as the VSWR becomes precisely one, i.e., the reflected power becomes zero. Under these conditions, an argon plasma is produced by an inductively couple mode discharge in the source tube. The plasma is terminated by an insulator plate at the upstream side of the source tube.

An axially movable retarding field energy analyzer (RFEA) with an orifice facing to the source tube or facing radially, or a Langmuir probe (LP) is inserted from the downstream vacuum port of the diffusion chamber. These probes have a bent shaft and its rotation allow the approximate radial measurements. Ion energy distribution function (IEDF) and the local plasma potential are measured by the RFEAs facing to the source and facing radially, respectively, where the IEDF can

be obtained by the pulsed probe technique [28]. The LP is used for the estimation of the local plasma density.

Experimental Results and Discussions

Figure 2 shows the IEDFs measured by the RFEAs facing to the source tube (solid line) and facing radially (dotted line) at $z = 0$ cm for the gas pressure of 40 mPa. The IEDF measured by the RFEA facing radially exhibits a single peak at about 37 V corresponding to the local plasma potential, while the IEDF measured by the RFEA facing to the source tube clearly indicates the additional peak at about 63 V in addition to the low energy peak at 37 V. Although it is reported that the IEDF measured by the RFEA often shows two peaks due to an rf modulation of ions in the RFEA sheath for both the RFEAs facing radially and axially [29], the present results evidence the presence of the axially accelerated ion beam. The local plasma potential ϕ_p and beam potential ϕ_{beam} are estimated as about $\phi_p = 37$ V and $\phi_{\text{beam}} = 63$ V, respectively, where the error of the estimations of these potentials are below ± 1 V. In the RFEA measurement, zero energy of the ions corresponds to the local plasma potential. Thus, the energy $\varepsilon_{\text{beam}}$ of the ion beam at $z = 0$ cm can be estimated as $\varepsilon_{\text{beam}} \equiv e (\phi_{\text{beam}} - \phi_p) \sim 26$ eV, where e is the elementary charge.

Detailed axial measurements are performed by the movable RFEAs and the LP for 40 mPa. Figure 3(a) shows the axial profiles of the local plasma potential measured by the RFEAs with orifice facing radially (open squares) and with orifice facing to the source tube (crosses). It is found that the data obtained by two different RFEAs agree well; the results show the potential drop near the source exit from about 60 V to 25 V over several centimeters. The result is very similar to the previously reported DL structures in the PMs-expanding plasma source [25], and the ion acceleration phenomenon observed by optical diagnosis in other experiments [30, 31]. The local beam potential observed by the axial RFEA is also plotted in Fig. 3(a) as open triangles. It is found that the beam

potential corresponds to the upstream local plasma potential; hence the observed accelerated group of ions comes from the upstream plasma source with being accelerated by the potential drop near the source exit. Here, it is noted that the rapid potential drop near the source exit has not been observed when the PMs are not set in the present machine. Without the PMs arrays, the gradual potential decrease similar to the previous results [32, 33] is observed, which is considered to be not the DL but the Boltzmann electric field due to the geometrical plasma expansion. Therefore, the PMs-expanding plasma source can generate the DL structure and the subsequent ion beam even if it is connected to a large volume space. It is found in Fig. 3(a) that the maximum energy of the ion beam, i.e., the difference between the beam and plasma potentials, reaches over 30 eV in the diffusion chamber. The plasma density estimated from the ion saturation current of the LP and the electron temperature of 8 eV is also shown in Fig. 3(b), where the temperature is measured at $z = 10$ cm and assumed to be constant in the system. The density drop from 10^{11} cm⁻³ to 10^9 cm⁻³ is observed across the potential drop of the DL.

In previously reported experiments [28, 34], the operating gas pressure is a key factor of the strength of the DL. Figure 4(a) shows the local plasma potential and the beam potential measured at $z = 0$ cm for various gas pressure in the range of 20-300 mPa. Both the plasma and beam potentials decrease with the increase in the argon gas pressure. Above the pressure of 200 mPa, the accelerated group of ions suddenly disappears as well as the previous experiments on the PMs-expanding plasma source [25]. The energy of the ion beam is also estimated from Fig. 4(a) and plotted in Fig. 4(b). As the local plasma potential and the beam potential have the error below ± 1 V, the error of the estimated beam energy is below ± 2 eV. The energy of the ion beam flowing in the downstream plasma is found to be increased up to about 35 eV.

In L-PMPI, the large volume diffusion chamber allows us to measure the ion beam in the wide spatial range. The radial investigation of the ion beam current is performed at various axial

positions. The measurement of the ion beam current is carried out by the RFEA, where the discriminator voltage is chosen as it can detect only the beam ions coming from the upstream high potential plasma. The operating gas pressure is selected as 25 mPa here, because the increased energy of the ion beam allows us to detect only the accelerated ions by selecting the discriminator voltage, where the discriminator voltage is chosen as 80 V corresponding to the beam potential observed in Fig. 4(a). Figure 5(a) shows the radial profile of the ion saturation current of the LP located at $z = -5$ cm, where the dashed lines shows the radial positions of the glass source wall. It is found the plasma in the source tube has a bi-modal density profile, which indicates the plasma production by the inductively coupled mode [35]. Figure 5(b) shows the radial profiles of the normalized ion beam currents at various axial positions, measured by the RFEA facing axially. The profiles of the ion beam current are also found to have a bi-modal profile mirroring the upstream plasma density. The radius of the ion beam profile is an important parameter for discussing the ion beam divergence and the ion detachment from the magnetic nozzle. The results imply that only the radius of the beam profile at $z = 3$ cm is found to be smaller than the results at other axial positions.

In the present paper, the radius r_{beam} of the ion beam is estimated by a half width at half maximum (HWHM). As the beam profiles are asymmetrical to some extent, the mean of the HWHM for positive and negative radii is defined as the beam radius r_{beam} . The resultant error of the estimation is below ± 0.5 cm. The beam radius r_{beam} estimated from the results in Fig. 5(b) is plotted as open squares in Fig. 6. It is found that r_{beam} increases along the axis for $z < 7$ cm, and becomes constant for the downstream region at $z > 7$ cm. In order to discuss the ion detachment phenomenon, the radius of the ion beam is calculated assuming that the ion beam is frozen to the magnetic field lines. For the ion beam frozen to the field lines, the calculated radius $r_{\text{cal}}(z)$ of the ion beam is related to the local magnetic field strength $B(z)$ by

$$\frac{B}{B_0} = \left(\frac{r_0}{r_{cal}} \right)^2, \quad \dots(1)$$

where B_0 and r_0 are chosen as the field strength (80 Gauss) at the source exit and the radius (3.3 cm) of the source tube for the calculation. Substituting the calculated axial profile of the magnetic field strength in Fig. 1(c) for $B(z)$, we can obtain the calculated radius r_{cal} of the ion beam as drawn by a solid line in Fig. 6. The observed beam radius r_{beam} agrees with the calculated r_{cal} for $z < 7$ cm, which indicates that the ion beam generated by the potential drop diverges along the field lines there. On the other hand, r_{beam} is found to deviate from r_{cal} for $z > 7$ cm and shows the constant value. The deviation shown in Fig. 6 indicates that the ion detachment from the magnetic field lines occurs at $z \sim 7$ cm and the spatially collimated ion beam is propagating into the axial downstream side. The identification of the condition of the ion detachment will be progressed hereafter.

Conclusion

In summary, the detailed investigations of the ion energy distribution in the large volume diffusion chamber evidence the generation of the ion beam from the low-pressure, PMs-expanding, rf plasma source due to the spontaneous formation of the DL. The comparison between the observed ion beam profiles and the magnetic field structures shows that the ions accelerated from the upstream high potential plasma are detached from the expanding magnetic field lines provided by the PMs at several centimeters downstream of the source exit.

Acknowledgements

The authors are indebted to Prof. Kashiwaba from Iwate University for his assistance for constructing the large diameter diffusion chamber. We also thank Prof. K. Takaki, Y. Shida, and H. Chiba from Iwate University for helpful discussions and technical assistance. This work is partially

supported by a Grant-in-Aid for Young Scientists (B 20740317 and A 22684031) from the Ministry of Education, Culture, Sports, Science and Technology, Japan. A part of this work is also supported by TEPCO Research Foundation.

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Figure 1: (a) Photograph of the Large diameter Permanent Magnets expanding Plasma machine of Iwate University (L-PMPI). (b) Schematic diagram of the experimental setup. (c) The calculated magnetic field along the axis.

(This figure is in color only in the electronic version)

Figure 2: Normalized IEDFs measured by the RFEAs facing to the source tube (solid line) and facing radially (dashed line) at $z = 0$ cm for the gas pressure of 40 mPa.

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Figure 3: (a) Axial profiles of the local plasma potential measured by the RFEAs facing to the source tube (crosses) and facing radially (open squares), together with the beam potential (open triangles) for the gas pressure of 40 mPa. (b) Axial profile of the plasma density.

(This figure is in color only in the electronic version)

Figure 4: (a) Local plasma potential (open circles) and beam potential (filled triangles) as a function of the gas pressure. (b) Ion beam energy estimated from Fig. 4(a).

Figure 5: (a) Radial profile of the normalized ion saturation current of the LP in the source tube. The dashed lines shows the position of the glass source wall. (b) Radial profiles of the normalized ion beam current at various axial positions. Here the gas pressure is maintained at 25 mPa.

(This figure is in color only in the electronic version)

Figure 6: Axial profiles of the observed ion beam radius r_{beam} (open squares) for 25 mPa, and the calculated radius r_{cal} assuming that the ion beam is frozen to the magnetic field lines.











