Double Layer Formation in a Low-Pressure Argon Plasma Expanded by Permanent Magnets

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A plasma-potential structure is experimentally investigated in a low-pressure inductively coupled argon plasma expanded by permanent magnet arrays, where the rf power and frequency are maintained at 250 W and 13.56 MHz, respectively. The diverging magnetic field without cusp field near the outlet of the source is generated by employing double concentric permanent magnet arrays, where the field strength decreases from about 100 G in the source to a few G in the middle of the diffusion chamber. A rapid potential drop at the diverging-field area is observed for low pressure below about 2 mTorr. The potential structure in the low-pressure case is not in agreement with Boltzmann's law; consequently, we deduce the structure is an electric double layer. For the case of high pressure above 2 mTorr, on the other hand, it is found that the plasma potential tracks Boltzmann's law.

Keywords: expanding plasmas, permanent magnets, double layer, low pressure plasma, ion acceleration, electric propulsion

1. Introduction

Plasma expansion has attracted a great deal of attention because it self-consistently forms nonlinear plasma-potential structures causing electrostatic ion acceleration. The process has been investigated for a long time in connection with space plasmas [1] and electric propulsion devices [2]. The plasma-potential structures are divided broadly into two types: one is an electric double layer (DL) due to charge separation phenomena, another is a potential gradient determined by a pressure gradient, i.e., following the Boltzmann's relation. Recent experiments and theories have shown the DL formation and/or the ion acceleration in expanding plasmas [3–10]. Charles and Boswell have suggested that the new type of electric thruster, named the helicon double layer thruster, can yield a long-lifetime because it does not require ion extraction electrodes. Recent measurements of the electron energy distribution function upstream of the helicon double layer showed that only a single upstream plasma source is required to maintain the formation of the double layer [10–12], hence the above-mentioned ion accelerator is considered to be applicable to the thruster.

Helicon wave discharges, i.e., rf-driven plasmas under steady-state magnetic field, are well known to be efficient plasma sources for high-density plasma production. In conventional helicon sources, electromagnets are used for generating the steady-state magnetic fields, which consume much electricity, and make the devices large and costly. From the viewpoint of the industrial applications, compact helicon sources using permanent magnets were developed [13–15]. More recently, Shamrai *et al.* developed the compact helicon source introducing the permanent magnets for electric propulsion [16]. The magnetic fields produced by the permanent magnets are normally strongly nonuniform with reverse-fields, i.e. cusps. They demonstrated that the cusps prevent plasma diffusion and the ion beam formation. In order to eliminate the cusps near the outlet of the source tube, the magnetic fields produced by electromagnets (solenoidal coils) are superimposed in their experiments, where the ion beam is detected as a result of optimizing the magnetic field. After that, by employing the double concentric magnets arrays, authors have achieved the ion acceleration in a solenoid-free plasma expanded by only permanent magnets [17].

In the present paper, we demonstrate the formations of the rapid potential drop in the solenoid-free expanding plasmas using only permanent magnets and the behavior of the structure for various gas pressure.

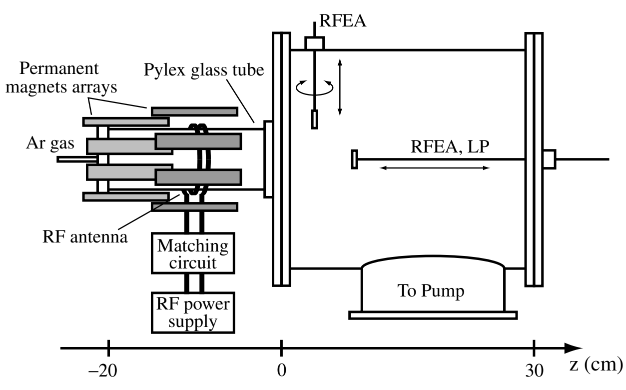

Fig. 1 Schematic diagram of expanding plasma reactor using permanent magnets.

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It is clearly observed that the rapid potential drop decreases with an increase in the gas pressure and disappears at the gas pressure of about 2 mTorr.

2. Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 1. A cylindrical glass tube of 20 cm in length and 6.6 cm in inner diameter (source tube) is attached contiguously to a 26-cm-diam and 30-cm-long grounded diffusion chamber. The chamber is evacuated to a base pressure of 2×10^{-6} Torr by a diffusion/rotary pumping system, and the argon gas is introduced from the source side through a mass flow controller. An argon plasma is excited by a double-turn loop antenna located at $z = -9$ cm and powered from an rf generator of 13.56 MHz and 250 W, where $z = 0$ is the interface between the source tube and the diffusion chamber.

Double concentric arrays of NdFeB magnets (10 cm in length, 1.5 cm in width, and 0.5 cm in thickness) arranged as shown in Fig. 2(a) are set around the source tube, where all of the magnets have radially inward magnetization. Although the single magnet-array consisting of eight magnet bars forms the cusp at the axial center of the bar without a constant field area, the double arrays with different radii of 5.5 cm and 7 cm located at different axial positions can produce the constant field area for plasma production and the diverging field area in the downstream side. The calculated and experimentally measured axial component B_z of the local magnetic-field strength are shown

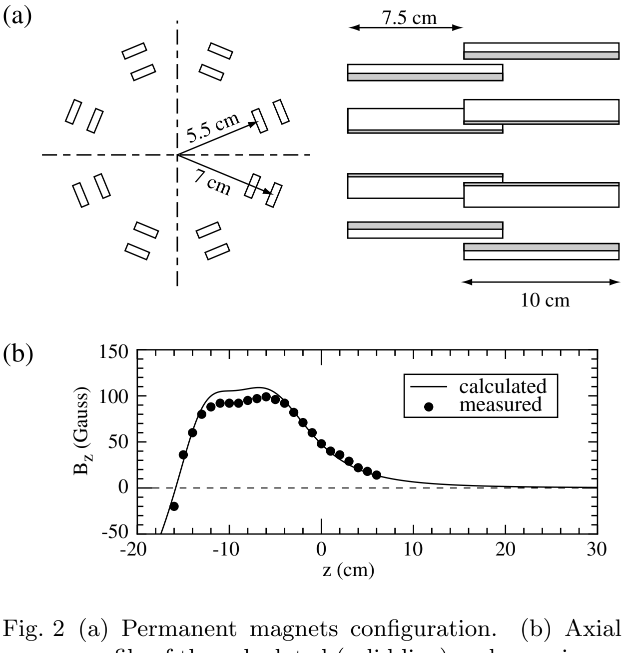

Fig. 2 (a) Permanent magnets configuration. (b) Axial profile of the calculated (solid line) and experimentally measured (closed circle) axial component B_z of the magnetic-field strength produced by the permanent magnets arrays shown in Fig. 2(a).

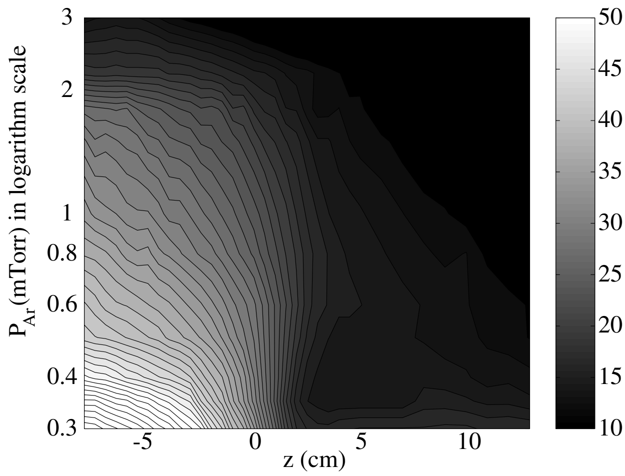

Fig. 3 Contour plot of axial profile of the plasma potential ϕ_p as a function of the gas pressure P_{Ar}.

in Fig. 2(b) as solid line and closed circle, respectively, these are fairly in good agreement with each other. Near the outlet of the source tube, it is found that there is no cusp showing the null point of the B_z profile.

A planar Langmuir probe (LP) and two retarding field energy analyzers (RFEAs) are inserted from the downstream side and the side wall of the diffusion chamber for characterizing the plasma density, the plasma potential, and the ion energy distribution function (IEDF). The IEDF, i.e. the first derivative of the I-V curve, is directly obtained by a pulsed probe technique using active analogue circuits [11, 12].

3. Experimental Results

Figure 3 shows a contour plot of the axial profile of the plasma potential ϕ_p as a function of the working gas pressure P_{Ar}, measured by the RFEA with a radially facing entrance orifice, where the P_{Ar} is in logarithm scale. We need to mention the IEDF obtained by the RFEA with the radially facing orifice has a single peak giving the local plasma potential ϕ_p. The results clearly shows high plasma potential inside the source tube and the rapid potential drop near the outlet of the source tube for low pressure conditions. It appears that the potential difference between the inside of the source tube and the diffusion chamber becomes reduced with an increase in the gas pressure, and subsequently disappears at about 2 mTorr. This result is similar to the behavior of the current-free helicon double layer in experiments and theory reported previously [18,19]. When the gas pressure is increased, the effect of the expanding magnetic fields would be lost and the diffusion process would be dominant. In order to have a confidence on the above consideration, the experiment under stronger magnetic-field strength is required.

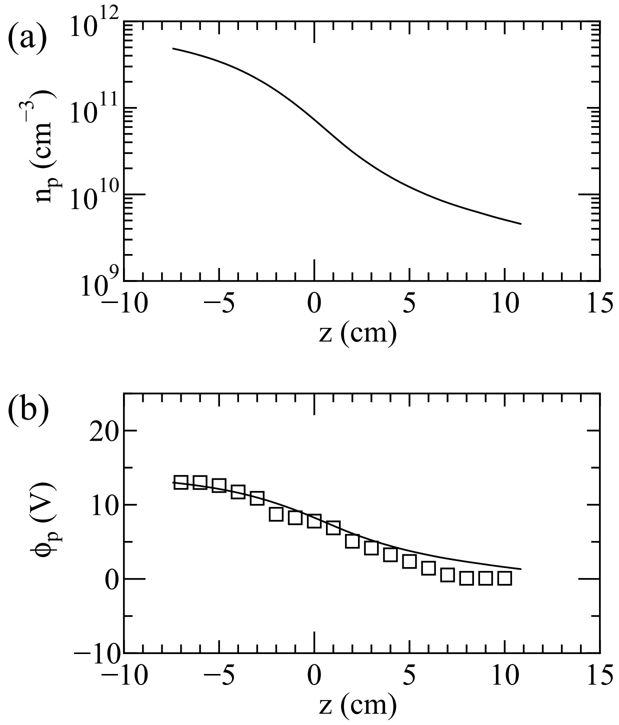

Fig. 4 Axial profile of (a) the plasma density n_p, and (b) the plasma potentials ϕ_p measured by the RFEA with radially facing orifice (open square) and estimated from the Boltzmann's law (solid line) for higher gas pressure $P_{Ar} = 3$ mTorr.

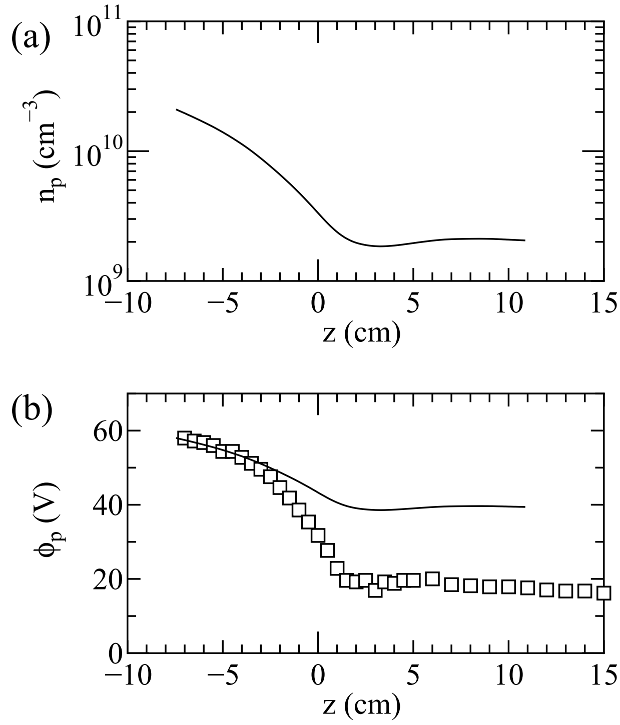

Fig. 5 Axial profile of (a) the plasma density n_p, and (b) the plasma potentials ϕ_p measured by the RFEA with radially facing orifice (open square) and estimated from the Boltzmann's law (solid line) for lower gas pressure $P_{Ar} = 0.35$ mTorr.

Figure 4(a) shows the axial profile of the plasma density estimated from the ion saturation current of the LP for $P_{Ar} = 3$ mTorr, where the LP is transferred by a servomotor and the spatial profile of the ion current can be contiguously obtained as shown in Fig. 4(a). The density profile and the electron temperature T_e would give the plasma-potential structure following the Boltzmann's law as

$$\phi_p(z) \quad = \quad \phi_p(z_0) + T_e \ln\left(\frac{n_p(z)}{n_p(z_0)}\right), \qquad (1)$$

where $\phi_p(z_0)$ and $n_p(z_0)$ are the plasma potential and the plasma density at $z = -7$ cm, respectively. We assume the axially constant electron temperature for the time being, although it is expected that the electron energy distribution in the source tube is different from that in the diffusion chamber. For 3 mTorr, we used $T_e = 2.5$ eV, measured in the diffusion chamber by the LP. The plasma potential following Eq. (1) for $P_{Ar} = 3$ mTorr is plotted in Fig. 4(b) as solid line, together with the experimentally measured one. The plasma-potential structure for 3 mTorr, in the condition that there is no rapid potential drop, is found to follow the Boltzmann's law.

The same data set measured for $P_{Ar} = 0.35$ mTorr as Fig. 4 is presented in Fig. 5, where the electron temperature of 8 eV is used for deriving the potential structure from Eq. (1). The result in Fig. 5(a) shows the slight density dip near $z = 2$ cm. It is found in Fig. 5(b) that a rapid potential drop from 50 V to 20 V at $z = -3$ - 1 cm, where the potential gradient is 7 - 8 V/cm and is much larger than the other area (e.g., about 2 V/cm at $z < -3$ cm), is generated near the outlet of the source tube. The measurement of the plasma-potential profile for the case that no magnets are set was carried out (not shown here). The result does not show the rapid potential drop but shows a gradual decrease of the plasma potential, which would follow Boltzmannfs law. Hence, the potential drop in the present experiments is due to the magnetic-field configuration produced by the permanent magnets. Moreover, the axial profile of the plasma potential measured by the RFEA with radially facing orifice cannot be reproduced by the Boltzmann's law as shown in Fig. 5(b).

The thickness of the potential drop for the low pressure case needs to be addressed here. The recently observed DL in the magnetically expanding plasma has a discontinuous change of the plasma potential and its thickness has been reported to be about $50\lambda_{De}$ [4], where λ_{De} is Debye length. On the other hand, there are reports on the formation of the DL with thickness of several centimeters [1] (several hundreds λ_{De}) and on the observation of the ion acceleration through 5-cm-thick DL by a laser-induced fluorescence technique [6]. Our result in Fig. 5(b) shows the potential drop within 3 - 4 cm (100 - 200λ_{De}) from 50 V to 20 V; its characteristic length is close to the latter DLs. Furthermore, the density dip, being often observed correlating with the DL formations [20, 21], is also formed near the transition area of the plasma potential as indicated in Fig. 5(a). Once again, the rapid potential is not in agreement with the Boltzmann's law. Based on these facts, we suggest the formation of a DL in the plasma expanded by the PMs under the low pressure conditions.

4. Conclusion

A plasma-potential structure is experimentally investigated in a low-pressure inductively coupled argon plasma expanded by permanent magnet arrays. The constant magnetic-field and the diverging magnetic field, without a cusp field near the outlet of the source, is generated by employing the double concentric permanent magnet arrays, where the maximum field strength is about 100 G. For the case of high pressure above 2 mTorr, on the other hand, it is found that the plasma potential tracks the Boltzmann's law. A rapid potential drop at the diverging-field area is observed for low pressure below about 2 mTorr. The potential structure in low-pressure case is not in agreement with Boltzmann's law; consequently we deduce the structure is an electric double layer. The thickness of the DL is found to be 100 - 200λ_{De}. It is observed that the potential drop of the DL increases with a decrease in the gas pressure.

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