Controlling the Diameter of a Pure Electron Plasma to Produce an Exact Two-Fluid Plasma State in a Nested Trap

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Methods for controlling accurately the diameter d_e of a pure electron plasma in a nested trap of the BX-U machine are described. By controlling the acceleration voltages and the number of electron guns activated, we can successfully change d_e over the range between 0.28 and 2.27 cm. Therefore, d_e can be made almost exactly the same as the diameter of a lithium ion plasma enabling the investigation of a two-fluid plasma state by using non-neutral plasmas.

Keywords: two-fluid plasma, non-neutral plasma, nested trap

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A two-fluid plasma [1, 2] is an extended magnetohydrodynamic (MHD) model that is widely used for explaining microscopic plasma phenomena that cannot be explained by conventional one-fluid MHD. In a two-fluid plasma, the velocity fields of the ion and electron plasmas are determined by separate fluid equations of motion. Also, the densities of the ions and electrons may differ from each other. However, such a two-fluid plasma state—especially one in differentially rotating equilibrium [3]—has never been verified in laboratory experiments. To investigate the two-fluid plasma state experimentally, we have tested it by using pure lithium-ion (Li^+) [4] and electron (e^-) plasmas. These are so-called non-neutral plasmas [5]. They can be relaxed into separate rotating thermal equilibria, which rotate rigidly in opposite azimuthal directions, owing to the different signs of their charges. These properties provide definite initial conditions for the Li^+-ion and e^- plasmas before superimposing them to produce a two-fluid plasma state.

In our first series of superimposition experiments [6], two problems emerged to be solved. First, the densities of the ion n_i and electron n_e plasmas could not be controlled, an essential requirement for controlling the ratio of n_i to n_e precisely. Second, the diameter d_e of the e^- plasma was much smaller than that d_i of the Li^+-ion plasmas, which breaks the implicit assumption $d_e = d_i$ employed in theoretical studies of two-fluid plasmas. In the present paper, we describe methods for solving these two experimental problems.

Experiments to superimpose a Li^+-ion plasma on an e^- plasma have been conducted in the BX-U linear trap [7, 8] as shown in Fig. 1. Five guns are installed on the left-hand side of the tap. A sample of β-eucryptite is installed on the machine axis to emit Li^+-ions, while all four thermionic e^- emission cathodes are installed 2.3 cm away from the machine axis [7]. The number of cathodes used to produce the e^- plasma varies. However, in most cases, three cathodes are activated, because the three e^- beams merge quickly and form an e^- plasma in the short time of $\approx$ 200 µs [7]. The positions of these cathodes can be also varied; however, all are fixed in the presented research. From these guns, Li^+-ions and e^- beams launched toward the central part of the BX-U machine, where a set of multi-ring electrodes is installed. By applying an independent potential to each electrode, a nested trap [9, 10] can be formed there, as shown in Fig. 2. The BX-U trap contains a uniform axial magnetic field up to 0.13 T, which confines both the Li^+-ions and the e^- plasmas radially. The positive and negative potential wells trap [11] the Li^+-ion and the e^- plasmas separately but also simultaneously [12], as shown in Fig. 2 (a). We have not yet investigated experimentally the shape of the e^- plasma trapped in the negative harmonic potential well of the nested BX-U trap. However, the e^- plasma lasts for at least 5 s, which is much longer than the electron-electron binary collision time ($\approx$ 8 ms for $T_e \approx$ 15 eV and $n_e \approx 5.3 \times 10^{13}$ m^{-3}). We therefore expect the e^- plasma to be relaxed into rotational thermal equilibrium in the negative harmonic potential well, which strongly suggests that the shape of the e^- plasma is a spheroid. Subsequently, we translated the Li^+-ion plasma

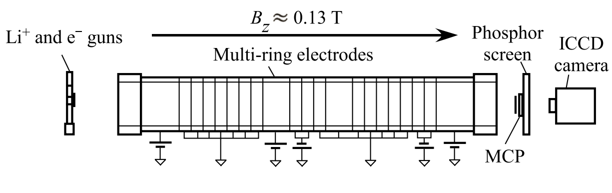

Fig. 1 Schematic of the BX-U linear trap.

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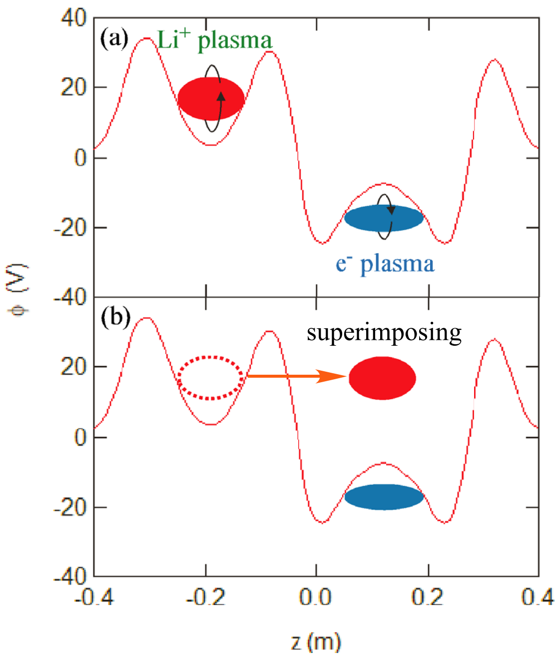

Fig. 2 The plasma-superpositioning sequence in the nested trap. (a) First, Li^+-ion and e^- plasmas are confined until each relaxes separately into thermal equilibrium in the respective positive and negative potential wells. (b) Second, the Li^+-ion plasma is superimposed onto the e^- plasma to create a two-fluid plasma state.

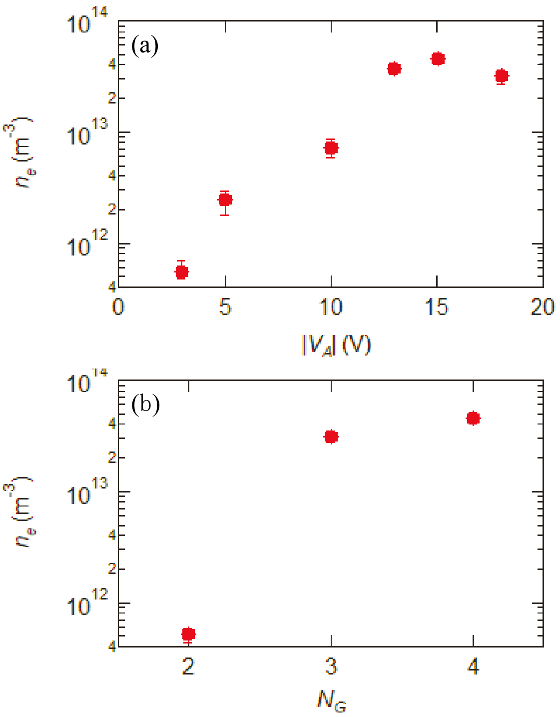

Fig. 3 Dependence of n_e on (a) V_A and (b) N_G. The error bars represent the maximum and minimum observed values.

into the nested trap where the e^- plasma is confined, as shown in Fig. 2 (b). For the duration of this superimposition, a two-fluid plasma state is thus generated experi-

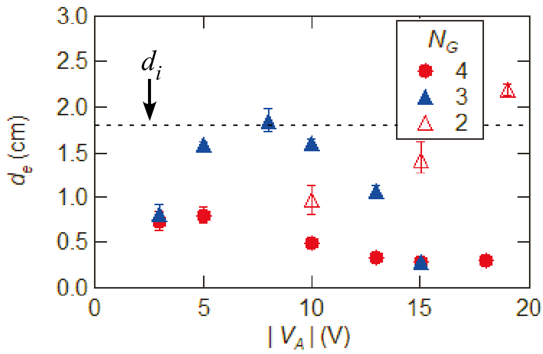

Fig. 4 Dependence of d_e on V_A and N_G. For the case where $N_G = 3$ and $V_A = -8$ V, we obtain $d_e = 1.84$ cm, which is approximately equal to the diameter $d_i = 1.77$ cm of Li^+-ion plasmas shown by the dashed line. The error bars represent the maximum and minimum observed values.

mentally. For diagnostics, we employ a microchannel plate (MCP) followed by a phosphor screen [13] . Images taken by a high-speed ICCD camera placed outside the vacuum vessel appear on the screen consecutively [14]. Using image analysis [13], we obtained the changes in the two-dimensional shapes of both the Li^+-ion and e^- plasmas after the formation of the two-fluid plasma state. We use the full width at half maximum of the one-dimensional luminosity profile along a horizontal line [4] passing through the center of the e^- plasma as the value of d_e. This is the same procedure as the method to determine the diameter d_i of pure Li^+-ion plasma confined in the BX-U [4].

The values of d_i and d_e are strongly correlated with the plasma frequency [15]. Since the plasma frequency depends on n_i (or n_e) [16], d_i (or d_e) can thus be controlled by controlling n_i (or n_e). Figure 3 shows the dependence of n_e on the accelerating voltage V_A and the number N_G of e^- guns activated. The density n_e is clearly changed by varying V_A and N_G. Figure 4 shows the dependence of d_e on V_A and N_G, demonstrating that d_e can be changed by controlling V_A and N_G. The holding time of e^- plasma is variable, but it is fixed at 5 s in these experiments.

The data on the left-hand side of Fig. 5 show two-dimensional integrated distributions for the e^- plasmas, while those on the right-hand side show one-dimensional distributions of particle numbers along dashed lines that pass through the corresponding center of the e^- plasmas. In fact, d_e increases from (a) 0.28 cm to (b) 1.84 cm as n_e decrease from $\approx 5\times10^{13}$ m^{-3} to $\approx 7\times10^{11}$ m^{-3}. For the case $N_G = 3$ and $V_A = -8$ V, we obtain $d_e = 1.84$ cm. On the other hand, by changing V_A applied to the Li^+ gun, n_i can be controlled from $\approx 2\times10^{11}$ m^{-3} to $\approx 2\times10^{12}$ m^{-3} without changing d_i (≈ 1.77 cm). In that case, the difference between d_i and d_e is only 4%. Currently, we are accumulating data on the two-fluid plasma state obtained by using the control methods described above. These data will be reported elsewhere.

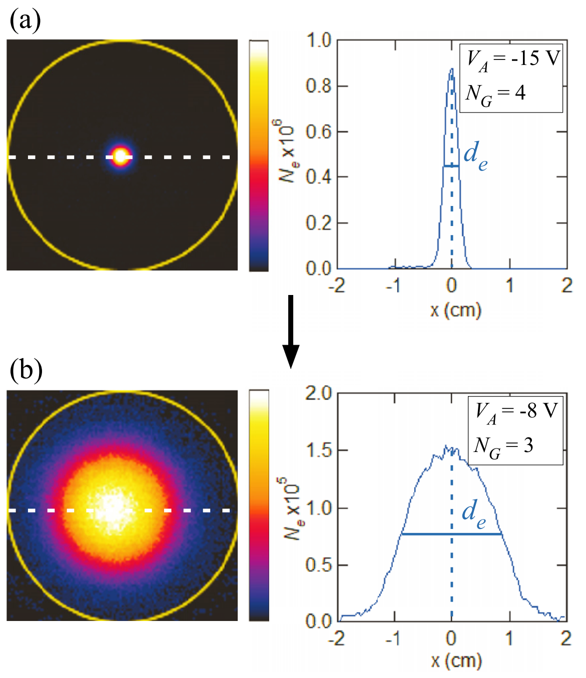

Fig. 5 Images and one-dimensional distributions of the particle number N_e for e$^-$ plasmas for cases where (a) $V_A = -15$ V and $N_G = 4$ and (b) $V_A = -8$ V and $N_G = 3$.

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