

# First Observation of Independent Ion and Electron Plasmas after Elapse of Two-Fluid Plasma State

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We produce independent lithium-ion and electron plasmas that exhibit completely different fluid motions to experimentally explore the physics of two-fluid plasmas; further, we simultaneously confine those plasmas in a nested trap. Despite that, the time elapse for the plasma mixing is much longer than any characteristic time related to fluid dynamics. Thus far, no disruptive phenomena have been observed, and this can possibly be attributed to a two-fluid plasma effect.

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Recently, the extended magnetohydrodynamics (MHD) model, in particular, a two-fluid plasma state, has been extensively used for theoretical and computational studies in the field of plasma physics. Unlike the standard MHD model, two-fluid plasmas allow ion and electron plasmas, which together constitute the entire plasma, to move independently. This property provides many degrees of freedom to the constituent plasma. Thus, some distinctive effects that never appear in the MHD can emerge in two-fluid plasmas. These effects, collectively called the two-fluid effect, are cited as the possible reasons for those observations such as high- $\beta$  plasma equilibria [1] and fast magnetic reconnection [2] that cannot be explained via MHD. However, no experiment that clearly demonstrates the evolution of ion and electron fluid dynamics in the two-fluid plasma state has been reported yet.

Contrary to the MHD, scale lengths exist in two-fluid plasmas and the two-fluid effect is considered to be of the order of the ion skin depth  $\lambda_i$ . In magnetically confined plasmas having ion density  $n_i \sim 10^{19} \text{ m}^{-3}$ ,  $\lambda_i$  is  $\sim 1 \text{ mm}$ , which is too short for precise observation of their dynamics. However,  $\lambda_i$  can be considerably extended in a pure-ion plasma [3] which is a non-neutral plasma. Other merits of applying non-neutral plasmas to test the two-fluid effect are that they relax in thermal equilibria and that the plasma temperature is very low, which reduces the uncertainty arising from thermal motion in experiments. Also, non-neutral plasmas are rigid-rotating about their axes owing to the  $\mathbf{E} \times \mathbf{B}$  drift; therefore pure ion and electron plasmas rotate in mutually-reversed perpendicular (azimuthal) directions. Thus, by mixing these plasmas, we can effectively add the independent ion and electron fluid motions obtained from experiments to each other as if the values were obtained mathematically from the equations of fluid

motion so as to derive the MHD equation of motion. In this study, we present the first set of observations of the macroscopic shape of each plasma after the plasma mixing in actual experiments.

Experiments were conducted in the BX-U linear trap [4] where both positive and negative harmonic potential wells could be formed. In the corresponding wells, lithium ion ( $\text{Li}^+$ ) and electron ( $\text{e}^-$ ) plasmas were confined simultaneously. While the value of  $n_i$  was fixed to be  $\sim 10^{11} \text{ m}^{-3}$ , the electron density  $n_e$  was varied between  $\sim 10^{11}$  and  $\sim 10^{12} \text{ m}^{-3}$ . Rotation frequencies of the  $\text{Li}^+$  and  $\text{e}^-$  plasmas are  $\sim 3.9 \times 10^3$  and  $\sim 1.2 \times 10^4 \text{ Hz}$ , respectively. The value of  $\lambda_i$  is approximately  $10^4$  times the plasma radii [3]. Other parameters related to the plasma can be found in Ref. [4]. The plasma mixing is performed in a nested trap that contains a potential well (an inner well) within another potential well (an outer well), as depicted in Fig. 1 (a). The solid curves in the figure show the axial profiles of the external potential  $\phi^E$  along the machine axis at  $r = 0$ . The nested trap is formed in the range between  $z \sim -0.05 \text{ m}$  and  $0.3 \text{ m}$ .

After completing the production of  $\text{Li}^+$  and  $\text{e}^-$  plasmas (see also Fig. 1 (a)), the downstream negative potential barrier is quickly reduced to 0 V, as shown in Fig. 1 (b) causing the  $\text{e}^-$  plasma to move to the right-hand side where the  $\text{Li}^+$  plasma is confined. Then, the negative potential barrier is restored to its predefined voltage level. Further, both the  $\text{Li}^+$  and  $\text{e}^-$  plasmas are simultaneously confined in the nested trap for 0.1 s, as depicted in Fig. 1 (c). The duration of this plasma mixing is an experimental parameter. Subsequently, the  $\text{Li}^+$  plasma is solely extracted from the nested trap via reducing the downstream positive potential barrier to 0 V, as shown in Fig. 1 (d). Approximately 8 ms later, the remaining  $\text{e}^-$  plasma is streamed out by reducing both the extreme downstream negative potential barrier

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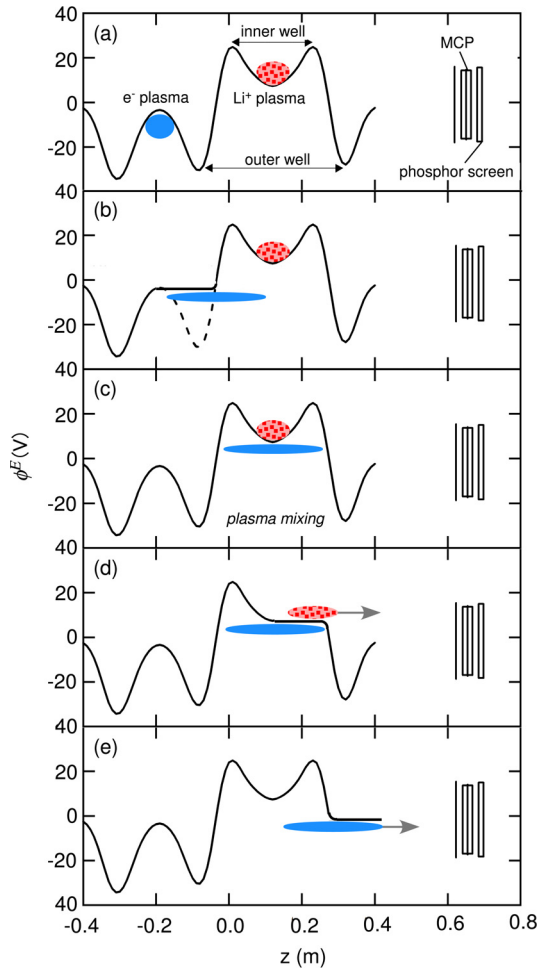


Fig. 1 A sequence of the plasma mixing performed in a nested trap of the BX-U linear trap.

and the upstream positive potential barrier of the nested trap to 0 V, as shown in Fig. 1 (e).

Both the  $\text{Li}^+$  and  $e^-$  plasmas enter a micro-channel plate installed at the extreme downstream position of the vacuum vessel and the resulting secondary electrons impinge a phosphor screen, emitting two-dimensional luminescence. This emission of light is captured using an ICCD camera through an end-on port and recorded as an image of each plasma. Both images of the  $\text{Li}^+$  and  $e^-$  plasmas are captured in a single attempt [5]. Figures 2 (a) and (b) show the images of  $\text{Li}^+$  and  $e^-$  plasmas before the plasma mixing. In contrast, Figs. 2 (c) and (d) show the plasmas after the mixing. Horizontal profiles of the line-integrated density  $n_{i,e}\ell_z(x)$  along the white lines passing through each plasma center are also presented. The duration of the plasma mixing is set to be 0.1 s for this shot, which is much longer than any characteristic times of plasma rotation perpendicular to  $\mathbf{B}$  or the growth time of diocotron instabilities<sup>1</sup>. Nonetheless, both  $\text{Li}^+$  and  $e^-$  plasmas still lasted, though both plasmas seemed to shift slightly.

<sup>1</sup>The growth time is approximately 10 times longer than the time of one plasma revolution around the plasma axis.

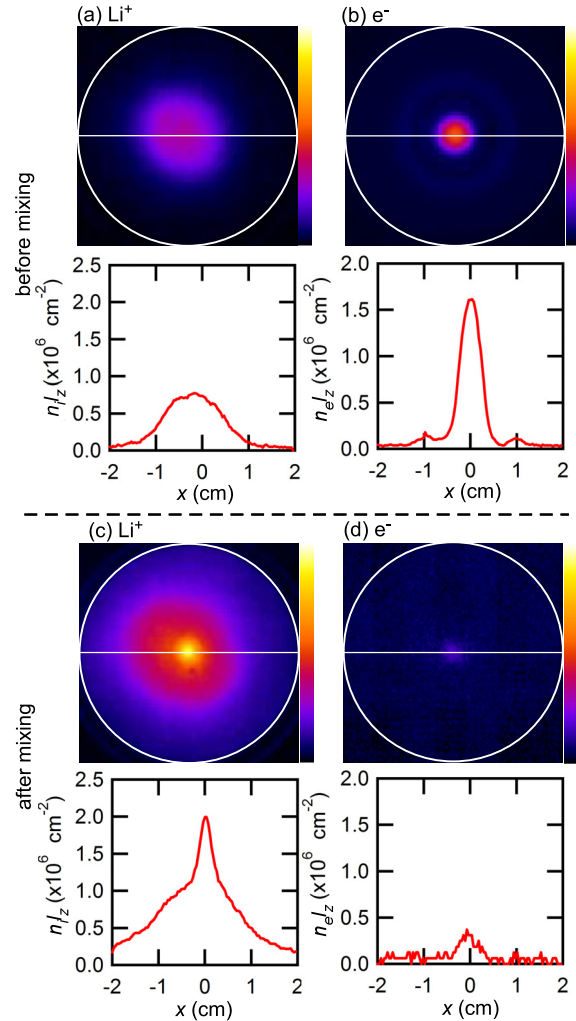


Fig. 2 A set of end-on images of  $\text{Li}^+$  and  $e^-$  plasmas before and after the plasma mixing for the case where the duration of the mixing is 0.1 s. Values of  $n_i$  and  $n_e$  are the same as the order of  $\sim 10^{11} \text{ m}^{-3}$ .

Another notable fact is that  $n_i\ell_z(x)$  changes to show a peaked profile after the plasma mixing. Because the plasma mixing continued for a relatively long time ( $\sim 0.1$  s), an electron-impact ionization of the residual gas or the hydrogen contained in the vacuum vessel would affect the measured luminosity to a certain extent. In fact, the integrated value of  $n_i\ell_z$  along the  $x$ -axis in Fig. 2 (a) is smaller than that in Fig. 2 (c). Although the change in the plasma length during plasma mixing has not been measured yet, this result strongly suggests that the total number of ions increases during the plasma mixing. However, Fig. 2 (c) indicates the possibility that the ion diffusion coefficient around the plasma core is not enhanced via the plasma mixing. If the peaked  $n_i\ell_z(x)$  after the plasma mixing is caused by the electron impact ionization, a similar peaked profile would be expected in  $n_e\ell_z(x)$  also. However, no such apparent peak is observed in  $n_e\ell_z(x)$ ; in fact, it seems to be rather flattened. Currently, we have accu-

mulated many images of both the  $\text{Li}^+$  and  $\text{e}^-$  plasmas for different durations of plasma mixing and  $n_e$  for a detailed investigation on the evolution of the dynamics of both plasmas during plasma mixing. Some of the results may reflect the fact that the canonical angular momentum of the  $\text{Li}^+$  plasma is rigidly conserved even during plasma mixing and some of the others may be caused by the two-fluid effect, which will be dealt with in subsequent works.

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