Initial Results on Simultaneous Confinement of Pure Lithium Ion and Electron Plasmas[*)]

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Pure lithium ion (Li^+) and electron (e^-) plasmas are not only produced separately but also trapped simultaneously in a Malmberg-penning trap called BX-U. No extreme degradation of confinement times or disruptive instabilities are so far observed even for the case of simultaneous confinement of both Li^+ and e^- plasmas.

Keywords: non-neutral plasma, lithium ion plasma, pure electron plasma, extended MHD model, two-fluid plasma

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1. Introduction

The extended MHD model, especially the two-fluid plasma state [1] is one of puzzling questions in experimental plasma physics. Usually both ion and electron fluids are considered to move together in plasmas, which is in fact one of conventional plasma conditions in basic textbooks. Contrary to that, in the two-fluid plasma, the ion and electron fluids are expected to move independently each other. This kind of novel plasmas have been proposed in both theoretical and computational works of plasma physics to explain recent experimental observations such as high-β equilibrium [2] and magnetic reconnections [3]. In fact, those phenomena can be never understood by the conventional MHD model where both ion and electron fluids move completely together. However, no experimental tests for the extended MHD models have ever been conducted yet.

One of reasons why no experiment has been carried out is probably due to the scale length of ion skin depth λ_i ($\equiv c/\omega_{pi}$) in which the extended MHD plasma state is expected to appear. In usual plasmas, the ion density n_i is in the range between 10^{16} and 10^{19} m^{-3} so that λ_i is calculated to be $0.5 \sim 17$ mm, which is too short to be measured clearly. This means we need to expand the scale length of λ_i.

Such scale expansion of λ_i is possible by using non-neutral plasmas (NNP) trapped electro-magnetically in the Penning trap, because of the relatively lower density of NNP. This actually would alleviate experimental difficulties to measure motions of ion and electron fluids in an expanded length of λ_i. Moreover, there is one more merit to use NNP in the Penning trap. In the trap, NNP exhibits $\boldsymbol{E}\times\boldsymbol{B}$ rigid-rotation around the machine axis, because of its uniform self-electric field $\boldsymbol{E}$ and the uniform bias magnetic field $\boldsymbol{B}$. Therefore, pure ion and electron (e^-) plasmas, both of which are NNP, rotate in the opposite direction perpendicular to $\boldsymbol{B}$. In other words, they exhibit completely different fluid motions each other. Thus, using these NNP as initial states of a two-fluid plasma, we may experimentally test whether the two-fluid plasma exists or not. To do that, we proposed a new experiment [4] in which positive and negative non-neutral plasmas (NNP) [5] were used to test the extended MHD plasmas. For the proposed experiment, there are two technical issues to be solved. Firstly, pure ion and e^- plasmas must be produced separately, and moreover, have been confined simultaneously until the two plasmas relax in thermal equilibrium. Secondly, both ion and e^- guns to produce NNP must be installed together in the one side of the machine. This actually makes it possible to place plasma measuring instruments on the other side of the machine.

To answer these, we have developed a Malmberg-penning trap called BX-U in which both positive and negative potential wells are externally created in order to trap both ion and e^- plasmas [6]. To make those potential wells, two sets of ring electrodes are installed into the chamber. Regarding the ion species, we determine to use lithium ions (Li^+), because the mass number is relatively small and those can be easily extracted from a thermionic cathode called β−eucryptite. On the other hand, as for the electron source, four micro filaments are employed in this research. And, through a self-organization process [7], a pure e^- plasma is formed axisymmetry. Using these sources for Li^+ and electrons, successful production and simultaneous confinement of Li^+ and e^- plasmas have been observed at the first series of experiments. In this paper, we report the initial results on those.

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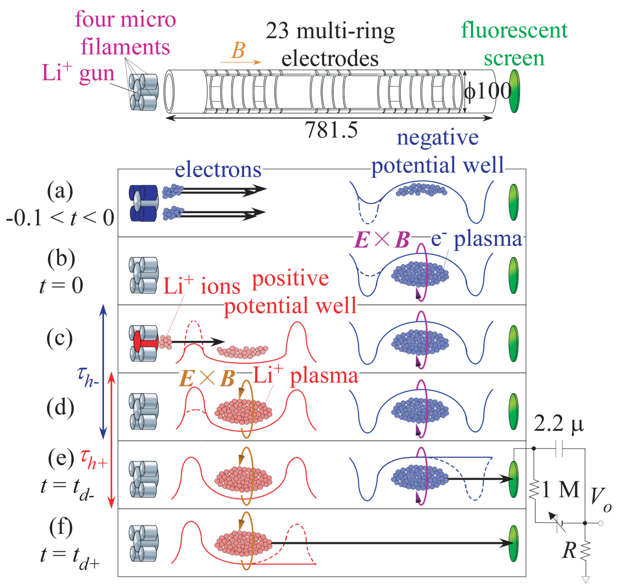

Fig. 1 A schematic diagram of the experiment producing and confining both lithium ion (Li^+) and electron (e^-) plasmas simultaneously.

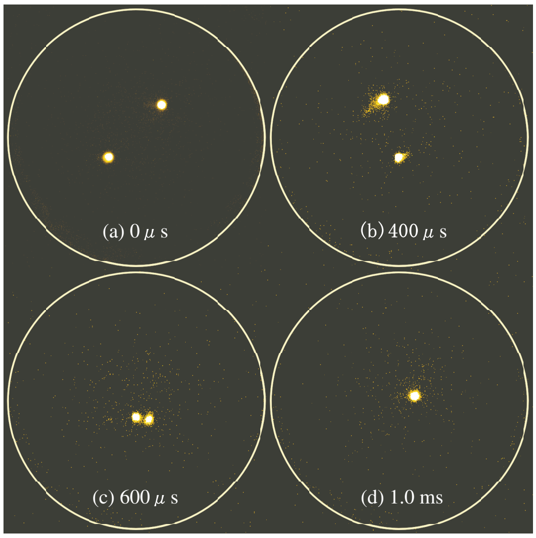

Fig. 2 A typical set of pictures that shows how a single e^- plasma is formed from several e^- beams on BX-U. Through a self-organization process, those beams are merged together completely.

2. Apparatus

Figure 1 shows a schematic diagram of the experiment on BX-U. Both Li^+ and e^- guns are mounted on a metallic holder that is located on the most left-hand side of the chamber. The axis of the Li^+ gun is adjusted to fit to the machine axis of BX-U. On the other hand, four micro filaments, which consist of the e^- gun, are equally placed 22 mm apart from the machine axis. Typical vacuum pressure p_0 is $\sim 2 \times 10^{-8}$ Torr in this first experiment. The detail of the BX-U machine is now prepared, and will be reported in elsewhere.

As mentioned briefly, Li^+ ions and electrons are produced by thermionic emission and injected by applying negative and positive potentials to the extractors, respectively. In experiments, first of all, four e^- beams are continuously emitted for 0.1 s from the four e^- filaments. At this moment, the negative potential gate on the left-hand side is intermittently opened for storing more electrons. The number of the multiple injection is changeable, which is in fact useful to control the value of electron density n_e. The least number of the multiple injection is unity, in other words, it is called a single injection. Also, the number of e^- filaments is variable in experiments.

Figure 2 shows a typical series of pictures of the end-on fluorescent screen [8] when two of e^- filaments are energized. Those pictures have been taken for the case of the single injection by changing the time when the downstream potential barrier is pulsed to ground. At that time when this potential barrier becomes 0 V, the rest of the injected e^- filaments in the potential well can thus stream out there, and then hit the end-on fluorescent screen. As seen from the data, until $\sim 600\,\mu$s after the e^- filaments are fired, the two filaments keep their revolutions around the machine axis (see also Figs. 2 (a)-(c)). However, those are gradually gathered each other. And at last about 1 ms later, those are merged together through a self-organization process (see also Fig. 2 (d)). Consequently, a single pure e^- plasma is then produced and confined in the bottom of the negative potential well. The shape of the potential well is parabolic, which is formed by applying independent potentials to the 23 multi-ring electrodes [9] (see also shown in Fig. 1). By the potential well, the axial confinement of the plasma is accomplished. On the other hand, regarding the radial constraint, it is attained by a homogeneous magnetic field of $B_0 = 0.1$ T.

During the confinement of the e^- plasma, the Li^+ gun is subsequently fired to produce a Li^+ plasma in the bottom of the positive potential well on the left-hand side. Unlike the e^- plasma, no self-organization process is used to form the pure Li^+ plasma, because the single Li^+ gun is exactly located on the machine axis, as mentioned.

3. Experimental Results

3.1 Independent confinement

At the first series of experiments, we have tested if each non-neutral plasma can be confined independently. Figure 3 shows a typical set of time histories of the collector current I_f ($= V_o/R$, where $R = 51$ k) that flows out from the end-on collector. Those are taken for both e^- and Li^+ plasmas independently by changing the holding time that shows how long the plasma is trapped after the multiple injection is completed. The holding time is defined as τ_h in Fig. 3.

For the case of e^- plasmas (see also Fig. 3 (a)), 0.5 s after the multiple injection of electrons is completed, the negative potential gate (-120 V) on the most right-hand side is pulsed to 0 V. This dump allows the remaining elec-

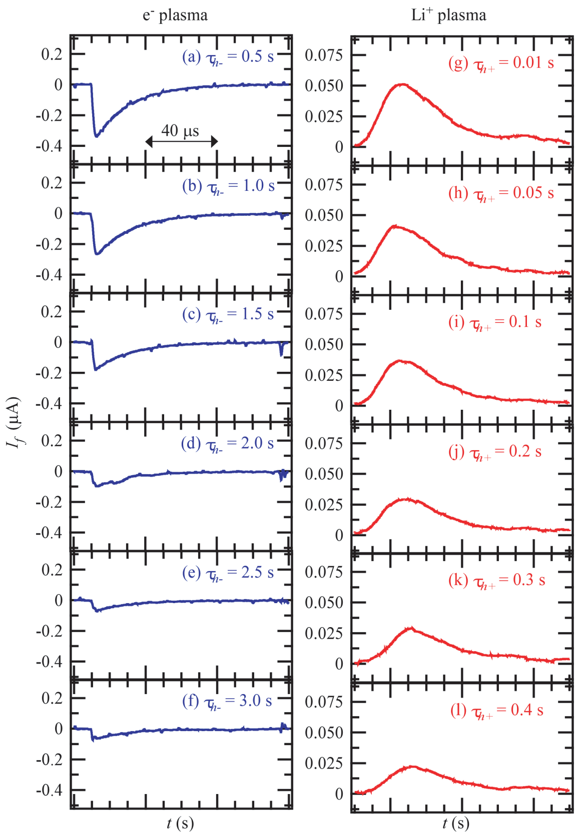

Fig. 3 A typical set of time histories of I_f measured by the end-on collector for cases where either (a) - (f) an e^- or (g) - (l) a Li^+ plasma is confined independently. As recognized, successful confinements of both non-neutral plasmas are certainly realized.

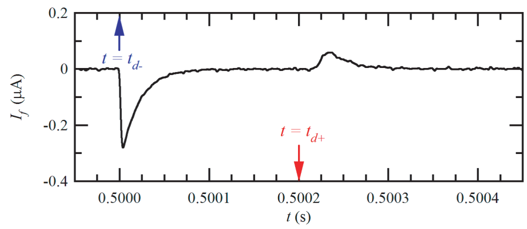

Fig. 4 A typical waveform of I_f. The data is smoothed. At $t = t_{d-}$, the e^- plasma is flowing out, while the Li^+ plasma is extracted at $t = t_{d+}$.

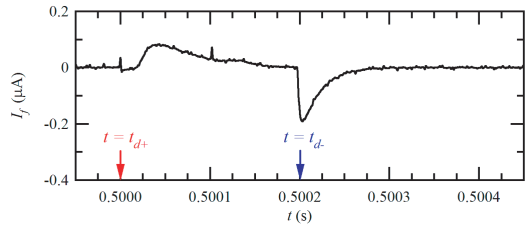

Fig. 5 A typical waveform of I_f. The data is smoothed. Contrary to the case in Fig. 4, the Li^+ plasma is firstly extracted at $t = t_{d+}$, and subsequently, the e^- plasma is flowing out at $t = t_{d-}$.

trons to stream out axially along the magnetic field lines for collection and analysis. Because of the negative charge of electrons, the measured I_f results in negative. When τ_h is longer, the absolute value of I_f becomes smaller, as expected (see also Fig. 3). These data clearly show the successful confinement of e^- plasmas.

Similarly, as recognized from Figs. 3 (g) - (l), Li^+ plasmas are successfully confined on BX-U, as well. Contrary to the case of electrons, the sign of charge is positive for Li^+ ions. Thus, the measured I_f turns to be positive in case of the extraction of the Li^+ plasma, as seen in Fig. 3.

3.2 Simultaneous confinement

The plasma confinement described in the above is still realized even when both e^- and Li^+ plasmas are trapped at the same time. Figure 4 shows a typical time history of I_f for the simultaneous confinement. For this case, the e^- plasma is firstly trapped on the right-hand side as shown in Fig. 1, and secondly the Li^+ plasma on the left-hand one. Therefore, the e^- plasma is drawn out of the potential well at an earlier time, and the resultant signal of I_f is negative, as seen at $t = 0.5$ s in Fig. 4. Subsequent to the electron extraction, the right-hand positive potential gate (+120 V) is then pulled down to 0 V in order to take out the remaining Li^+ ions, which can be recognized as the positive output of I_f at $t = 0.5002$ s in Fig. 4. Thus, from such data as Fig. 4, it is clearly recognized that the simultaneous confinement of Li^+ and e^- plasmas is certainly attained on BX-U.

The above simultaneous confinement is realized even for the case where the polarities of the potential wells are completely flipped each other. In this case, the Li^+ plasma is firstly produced on the right-hand side near the end-on collector in Fig. 1, while the e^- plasma is secondly confined on the left-hand one. Figure 5 shows the time history of I_f measured for the case. As seen from the data, the resulting first signal of I_f is positive and the second one negative. From these experimental results, we conclude that both pure Li^+ and e^- plasmas are successfully confined in separate both positive and negative potential wells simultaneously.

3.3 Preliminary data on confinement times

Since the two non-neutral plasmas need to be in thermal equilibrium for the forthcoming extended MHD experiments, the question would be asked on what the confinement time τ_N is so far attained. Figure 6 shows preliminary data on time evolutions of total particle numbers of Li^+ (N_i) and e^- (N_e), when both Li^+ and e^- plasmas are confined simultaneously. These data are obtained with changing the time when the downstream potential gate is dumped to 0 V systematically. The number of remaining particles $N_{i,e}$ have been obtained as $N_{i,e} = (1/q) \int I_f \, dt$ at each time, where q is the elementary charge. Using the obtained N, τ_N can be determined as the 1/e decay time of N.

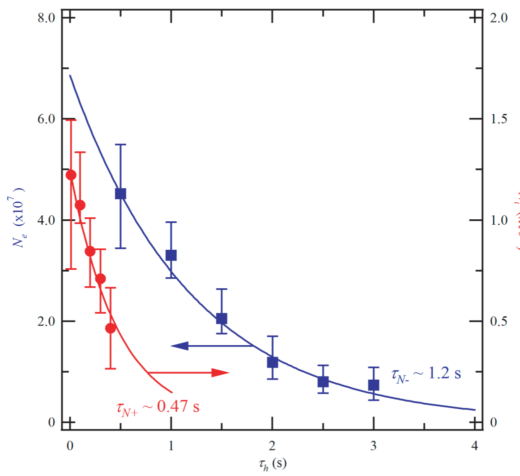

Fig. 6 Preliminary data on time evolutions of total particle numbers of Li^+ (N_i) and e^- (N_e) plasmas when both Li^+ and e^- plasmas are confined simultaneously.

From these calculations, as shown in Fig. 6, values of τ_N of e^- and Li^+ plasmas are so far $\tau_{N-} \sim 1.2$ s and $\tau_{N+} \sim 0.47$ s, respectively. Although no data on plasma temperature has measured yet, these values of $\tau_{N\pm}$ seem to be hardly short to become equilibria.

It should be mentioned here that the observed $\tau_{N\pm}$ seems to be shorter than those expected for experiments of non-neutral plasmas. Two possible reasons can be considered; First of all, in the presented experiments, p_0 has been $\sim 10^{-8}$ Torr, which is higher than the past non-neutral plasma experiments. For the case of $p_0 \sim 10^{-8}$ Torr, the electron-neutral collision time is the order 1 s. This is actually comparable to the observed τ_{N-}. In fact, our most recent data obtained with lower p_0 ($\sim 10^{-9}$ Torr) has shown a longer value of τ_{N-}. Secondly, the DC power supply we have used may be inadequate for non-neutral plasma experiments. This is because the ripple level of the DC power supply to energize a set of solenoidal coils seems not to be low enough to effectively conserve values of canonical angular momentum of non-neutral plasmas. Indeed, this would not be examined until a new stabilized DC power supply is employed to experiments.

3.4 The size parameter S^* and others

Let us consider the value of the size parameter S^* that is the most important index for distinguishing if the extended MHD state appears. Regarding the plasma density, the typical value of N_e is calculated to be 4.5×10^7. From the end-on collector measurements, we assume here that the e^- plasma is spheroidal and that its minor and major axes are 0.7 and 24 cm, respectively. Then, the electron density n_e is calculated to be 7.3×10^{12} m^{-3}, which is much smaller than its Brillouin density n_{B-}: $n_{B-} = 4.9\times10^{16}$ m^{-3} for $B = 0.1$ T. On the other hand, regarding the ion density n_i, it is calculated to be about 4.1×10^{11} m^{-3} on the following assumptions; the radius of the Li^+ plasma is equal to the emission surface of the ion source. And, the plasma shape is spheroidal with the major axis of 24 cm as well as the e^- plasma. The value of n_i is an order of magnitude smaller than n_{B+}: $n_{B+} = 3.8 \times 10^{12}$ m^{-3}. Therefore, as for the dependence of the size parameter $S^* \equiv L/\lambda_i$ where L is a typical scale length of a plasma and $\lambda_i = \sqrt{m_i/\mu_0 e^2 n}$ is the ion skin depth, the value of S^* is calculated to be about 8×10^{-6}, which is enough small to move on the next experiment for testing the extended MHD models, especially the two-fluid plasma state predicted by theoretical works [10].

The density difference results in the existence of either positive or negative electrostatic potential, depending on which plasma density is larger. Thus, the flow velocity field as well as the self-electric field is determined by what densities of Li^+ and e^- plasmas are merged. This would probably affect the characteristic of the merged plasmas, which strongly suggests that the density difference would become one of important experimental parameters.

As for the validity of treating lots of ions and electrons as plasma fluids, those could be regarded as non-neutral plasmas. This is because those exhibit typical collective phenomena such as the diocotron instability. In fact, even if we assume that the temperature of e^- and Li^+ plasmas are room temperature ($T = 300$ K), the Debye lengths λ_D of those are $\lambda_{De} \sim 4.4 \times 10^{-4}$ m and $\lambda_{Di} \sim 1.9 \times 10^{-3}$ m, respectively. Thus, numbers of charged particles in each Debye sphere are much larger than unity: $N_{De} \sim 2.6 \times 10^3$ and $N_{Di} \sim 1.1 \times 10^4$, respectively.

Regarding other fluid parameters, the Knudsen and the magnetic Reynolds numbers are calculated to be $\sim 10^5$ and $\sim 10^3$ in presented experiments, respectively. Therefore, the viscous force caused by interactions with background neutrals is negligible. Both Li^+ and e^- plasmas are basically governed by only electromagnetic forces.

4. Summary

Recently, extended MHD plasmas have been discussed, especially in both theoretical and computational works of plasma physics. In order to test those experimentally, we have proposed a new experiment using two non-neutral plasmas, and almost completed constructing a machine to perform it. At the first series of experiments, pure e^- and Li^+ plasmas are not only produced independently but also confined simultaneously on the BX-U machine. No destructive instabilities occur in experiments. After optimizing experimental parameters to precisely control plasma densities, we could apply those two non-neutral plasmas to produce an extended MHD plasma state in laboratory experiments, for the first time.

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