A Method for Avoiding Following Ion Leakage from a Penning Trap*)

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Ion leakages from a Penning trap are studied in the BX-U linear trap [K. Akaike and H. Himura, Phys. Plasmas **25**, 122108 (2018).]. The following leakage stops as the rise time of the upstream potential barrier sets to be longer. In the case, the number of trapped ions increases with the ion plasma still oscillating in the potential well of the Penning trap.

Keywords: charged-particle trap, Penning trap, ion beam, pure ion plasma, non-neutral plasma

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1. Introduction

A Penning trap [1] has been widely used in many research fields such as quantum computing [2], two-fluid plasmas [3], antimatter particles [4], and nondestructive creation of high-quality beams [5,6]. The Penning trap employs a pair of end potential barriers and an axial uniform magnetic field to confine charged-particles. These can enter a potential well from the outside of the trap, when the one of the end potential barriers (hereafter, called the upstream potential barrier ϕ_{iu}) is opened [7]. Subsequently, ϕ_{iu} restores to its predifined voltage to trap the charged-particles. For the case where the charged-particles are positive lithium (Li^+) ions, some of those were observed to overcome the downstream potential barrier ϕ_{id} during the closure of ϕ_{iu} [8]. This ion leakage was called the initial leakage [8]. After this initial leakage, some ions were still intermittently pushed out from the potential well with synchronizing the axiall mode of the bulk of trapped Li^+ plasma [8, 9]. This phenomenon was called the following leakage [8], which was correlated with the self-electric potential ϕ^S of the Li^+ plasma. The detail of the leakage was clearly revealed recently [9]. However, we did not present any data that showed how the following intermittent ion leakage could be avoided in the paper [9]. This work addresses it.

2. Apparatus

Experiments were conducted on the BX-U linear trap [10]. A shematic of the BX-U linear trap is shown in Fig. 1 (a). In the BX-U, a set of multi-ring electrodes [10] is installed to form both positive and negative harmonic potential wells. Multi-ring electrodes comprise four long electrodes (L-electrode), 13 short electrodes (S-electrode), four segmented electrodes, and a pair of end-caps. The segmented electrodes are used for applying rotating electric fields [11], and each one is made by dividing an S-electrode into eight equal arc-shaped sectors. All the electrodes are made of gold-plated Al, and their inner and outer diameters are 100 mm and 119 mm, respectively. The roundness of the inner diameter is ±0.01 mm, and the assembling accuracy of the electrodes is approximately ±0.1 mm. The length of the S-electrodes is 23 mm, which is equal to the length of the segmented electrodes. On the other hand, the L-electrode is 70 mm, which is longer than the S-electrode. This length was determined from the fact that the harmonic potential wells of the trap domain fluctuate, even if the electric potential changes slightly outside the trap. This influence can be reduced by lengthening the L-electrodes at both ends of each potential well. Finally, the length of the two end-caps is 46 mm, which is double that of the S-electrode. Although twenty-three cylindrical electrodes are contained in the vacuum vessel along the machine axis, only the nine electrodes labeled A through I [see Fig. 1 (a)] are energized to form the positive potential well in which Li^+ ion plasmas are axially confined. To confine the ion plasmas in the radial direction, on the other hand, a uniform axial magnetic field B_z of 0.13 T is applied to the entire vacuum vessel. Figure 1 (b) shows an axial profile of the external potential along the machine axis, $\phi^E(0, z)$. The dotted curves show the change in ϕ_{iu} when the Li^+ ions enter the potential well.

Because the objective of the BX-U is to test two-fluid plasma states [3, 12], a light element similar in atomic weight to hydrogen is used for the positive charged particles constituting the ion fluid. As the source, a β-eucryptite (STD 600 Li6, HeatWave Labs Inc.) is employed to emit ions. The temperature T_w required for the filament to emit Li^+ ions is ∼ 1,000°C, which corresponds to ∼ 0.1 eV. The current flowing in the filament is typically set to ∼ 11 A. All the metal components, including a grounding

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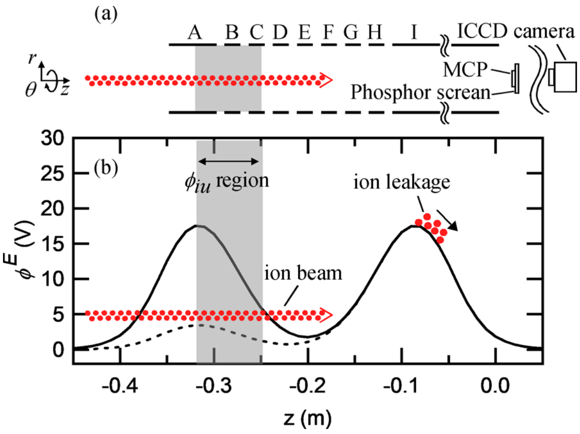

Fig. 1 (a) A schematic of the BX-U linear trap and (b) the axial potential profile of $\phi^E(0, z)$ on the machine axis. The dashed curve shows ϕ^E when Li^+ ions enter the potential well.

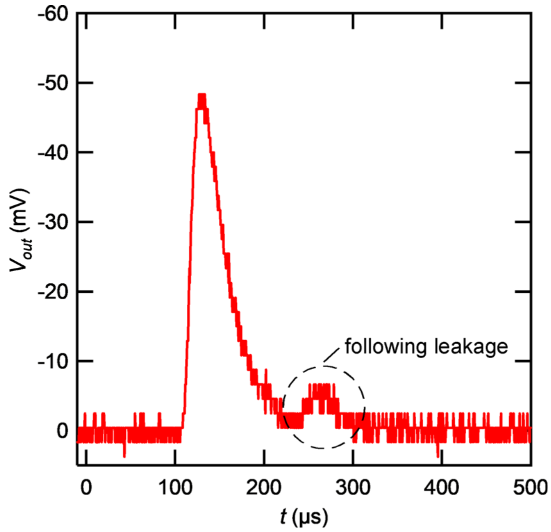

Fig. 2 Time dependence of V_{out} measured at the MCP attached to the phosphor screen for the case wherein $\phi^S \simeq 1.5$ V.

(COM) electrode near the discharging body, are made of molybdenum (Mo), because of its high melting point. For the extraction of Li^+ ions, the voltage supplied to the extractor of the ion gun is driven by a switching circuit [10]. As explained in Ref. [10], both the anode and the ion extractor are set to V_1 before the emission of Li^+ ions. Subsequently, by triggering TLP551 in the circuit, the drain voltage V_{ix} of K2478 is applied to the ion extractor, causing Li^+ ions to be launched from the anode. Because V_{ix} is as low as to the negative voltage of V_2 (< 0 V), a portion of the emitted Li^+ ions pass through the tungsten (W) mesh on the ion extractor and then the W mesh on the COM electrode that is grounded ($V = 0$ V). As a result, the acceleration voltage of the Li^+ ions becomes V_1. Typical values of V_1 and V_2 in experiments are 16 V and −10 V, respectively.

Since the acceleration voltage V_A of the Li^+ ions is set to be 5 V, they are able to overcome ϕ_{iu} when ϕ_{iu} is reduced to 4.5 V. Ions that overcome ϕ_{id} during closure of ϕ_{iu} finally reach a microchannel plate (MCP) with a phosphor screen attached to the back. The ions that reach the MCP may therein produce many secondary electrons. These produced secondary electrons hit the phosphor screen after being accelerated to 3 kV between the MCP and the phosphor screen. Thus, the phosphor screen emits visible light which is captured by an intensified charge-coupled device (ICCD) camera. Based on the total luminosity L of the visible light, the number of leaked Li^+ ions N_{leak} can be determined. N_{leak} can also be obtained directly from the output voltage V_{out} arising when the secondary electron current I_f passes through an integrating circuit.

Regarding the method for varying ϕ^S, the initial beam density of Li^+ ions n_b is changed by changing the filament current to heat up the β-eucryptite [10]. In the case, the trapped Li^+ ion density n_i changes in the range between $\approx 1 \times 10^{11}$ m^{-3} and $\approx 3 \times 10^{11}$ m^{-3}.

3. Experimental Results

3.1 The initial and following ion leakages

Figure 2 shows a typical time dependence of the voltage V_{out} across an integration circuit [13] with a resistance of $R = 10\,\text{k}\Omega$ and a capacitance of $C = 0.001\,\mu$F, which is outputted [13] by the secondary electron current of the MCP located in the most downstream part (at $z \sim 0.8$ m) of the vacuum vessel. In the case, ϕ^S is estimated to be ≈ 1.5 V/m from $\nabla^2\phi^S = en_i/\epsilon_0$, where $\nabla \simeq 1/l_p$ in experiments, e is the elementaly charge, ϵ_0 is the vacuum permittivity, and l_p is an axial semi-axis of the trapped Li^+ plasmas: $l_p \simeq 2.0$ cm [12]. At $t \sim 100\,\mu$s after the closure of the upstream potential barrier (at $t = 0\,\mu$s), V_{out} suddenly starts to appear (called the first leakage), which reaches a maximum value of $\simeq -50$ mV. Then, the level of V_{out} decreases gradually according to the time constant of the measurement circuit. At $t \simeq 250\,\mu$s after the initial leakage, the following leakage occurs clearly, despite ϕ_{iu} and ϕ_{id} have already restored their preset voltages to complete the positive potential well to trap the injected ions. By using the formula [9] for obtaining the number of incoming Li^+ ions to the MCP, we find $\simeq 1.0 \times 10^4$ leakage ions during the following leakage as shown in Fig. 3. Figure 3 shows dependence of the number of leaked Li^+ ions N_{leak} on ϕ^S for the following leakage. As expected, values of N_{leak} increase with increasing ϕ^S.

3.2 How to avoid the following ion leakage

As mentioned in past papers [9, 10], the following intermittent leakage occurs due to the axial oscillation of the trapped ions. The leakage frequency of ions f_{ml} does not depend directly on $\Delta\phi_{iu0}/\Delta t_{rs}$, where $\Delta\phi_{iu}$ and Δt_{rs} are the incremental change in ϕ_{iu} and the rise time of ϕ_{iu}, respectively. As recognized from Fig. 8 in Ref. [9], despite keep-

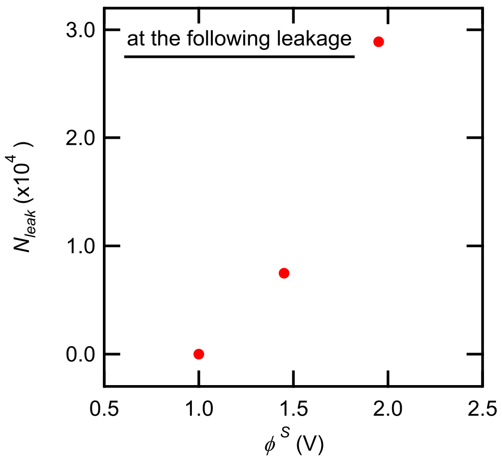

Fig. 3 Dependence of N_{leak} on ϕ^S measured at the following leakage.

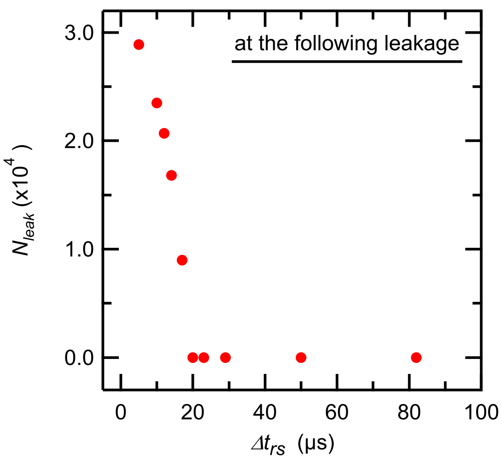

Fig. 4 Dependence of N_{leak} on Δt_{rs} at the following leakage for the case where $\phi^S \simeq 2.0$ V.

ing $\Delta\phi_{iu0}/\Delta t_{rs}$ at a constant rate ($\simeq 3.0$ V/μs), $\Delta_{ml}(\equiv 1/f_{ml})$ changes significantly. In addition, the observed results agrees with those of Dubin's (1, 0) mode [14], where the axial semi-axis l_p used to determine the aspect ratio A that is the ratio of the axial length to the diameter of a spheroidal plasma was inferred from ϕ_{i0} and n_i was calculated with the assumption that the Li^+ ion plasma was spheroidal. Detailed information on these can be found in Refs. [9, 10].

In those papers, we also mentioned that the initial and the following intermittent leakages are prevented in the case where Δt_{rs} is longer than a threshold time. However, we did not present any data. Figure 4 shows it measured at the follwoing intermittent leakage. As recognized, values of N_{leak} descreases significantly with increasing Δt_{rs}. It becomes 0 when $\Delta t_{rs} > 20$ μs with still trapping the Li^+ plasma in the positive potential well. This result can be explained by the fact that Δt_{rs} of 20 μs is almost the same as the staying time Δt_{st} of each ion in the ϕ_{iu} region during the closure of ϕ_{iu} in the BX-U linear trap: $\Delta t_{st} \simeq 35$ μs as presented in Ref. [8]. In the case, the axial oscillation is too weak to cause the following intermittent ion leakage. This is because the injected ions have almost passed through the ϕ_{iu} region during the potential barrier closure [8]. Thus, only a few energy from ϕ_{iu} is deposited to the flowing ions in the ϕ_{iu} region. In the case, the number of trapped Li^+ ions increases resultantly, since no following ion leakage occurs at all. A typical increment observed in the BX-U is from $\simeq 7.1 \times 10^6$ to $\simeq 9.4 \times 10^6$, which is approximately 30%. The threshold time of Δt_{rs} is concluded to be approximately $\sim$ 20 μs to avoid the following ion leakage from the Penning trap produced in the BX-U linear trap. Similar relationships between Δt_{st} and Δt_{rs} could be found out in other Penning traps for trapping charged-particles efficiently.

4. Summary

The intermittent ion leakage from a Penning trap is experimentally studied in the BX-U linear trap. To present overall dependence of the intermittent leakages on the slew rate of the upstream potential barrier, we show the dependence of the number of leaked ions N_{leak} on the rise time of the upstream potential barrier Δt_{rs}. Although N_{leak} is certainly observed unless the self-electric potential ϕ^S of the Li^+ plasma is decreased to be approximately 1 V, owing to the Dubin's (1, 0) mode. However, by setting Δt_{rs} to almost the same time as the staying time $\Delta t_{st}$of each ion which just passes through the ϕ_{iu} region during the closure of ϕ_{iu}, N_{leak} can decrease to 0 even if ϕ^S exists. Similar relationships between Δt_{st} and Δt_{rs} could be considered for efficiently trapping charged-particles in other Penning traps.

Acknowledgments

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