

ACCUMULATING LASER-COOLABLE IONS IN A LINEAR PAUL TRAP FOR ULTRAHIGH-DENSITY BEAM DYNAMICS EXPERIMENT*

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Abstract

An ion plasma confined in a linear Paul trap (LPT) exhibits the dynamic behavior physically equivalent to that of a charged-particle beam in an alternating-gradient (AG) transport channel. The Simulator of Particle Orbit Dynamics (S-POD) is a compact apparatus designed on the basis of this fact for diverse beam-physics experiments. We have so far employed Ar⁺ ions that can readily be produced from neutral Ar gas atoms through the electron bombardment process. A space-charge-induced tune shift of up to about 20% of the bare tune can be achieved in Ar⁺ plasmas.

We are now preparing for future S-POD experiment to explore even higher beam-density regions. For this purpose, a large number of Ca⁺ ions need to be stored in the LPT. Since S-POD is equipped with a powerful laser cooler for Ca⁺, the use of this ion species vastly expands the density range we can survey. The production of an intense bunch of Ca⁺ ions is, however, not so easy because of some technical reasons. By optimizing the operating condition of a multi-sectioned LPT, we succeeded in increasing the number of accumulated Ca⁺ ions to the level comparable to Ar⁺ ion plasmas. This paper reports on updated results of the experiment.

INTRODUCTION

S-POD is the unique experimental system developed at Hiroshima University for *Laboratory Accelerator Physics* [1,2]. It produces, within a very compact LPT, a bunch of charged particles that possesses approximately the same physical properties as a relativistic beam propagating through an AG focusing channel [3,4]. Experimental studies of various beam-dynamics issues can, therefore, be conducted in a local tabletop environment, without the use of large-scale machines. In most S-POD experiments so far [5,6], non-neutral plasmas of ⁴⁰Ar⁺ ions have been employed considering the simplicity of the plasma generation process. The initial plasma density is controlled by changing the number of stored ions, which limits the attainable tune depression to the range above around 0.8.

In S-POD experiment, the species of trapped ions does not play an essential role from the viewpoint of space-charge dynamics. The mass and charge state are nothing but scaling parameters in the basic equations of motion [3,4]. It is possible to expand the available range of tune depression η by using ⁴⁰Ca⁺ ions instead of ⁴⁰Ar⁺ because the Doppler laser cooling technique can be applied to the former ion species [7,8]. The Doppler limiting temperature is extremely low, typically in the milli-Kelvin range,

which means that even the ultimate low-emittance state corresponding to $\eta \approx 0$ can be reached with this advanced cooling technique. In addition, the laser-induced fluorescence (LIF) diagnostics is usable for high-precision profile measurement and even to probe the ion distribution in phase space. Note also that ⁴⁰Ca⁺ has the mass number identical to ⁴⁰Ar⁺. The whole system (the LPT, power sources, etc.) designed for ⁴⁰Ar⁺ ion confinement works for ⁴⁰Ca⁺ plasmas as well.

Ca is, however, solid at room temperature unlike Ar. We thus need an atomic oven to vaporize a piece of Ca. Vaporized atoms are ionized by a low-energy electron beam from an *e*-gun. It is preferable to separate the experiment section in the LPT from the section of ion production where a lot of neutral Ca gas atoms exist as a possible error source. (See the schematic drawing in Fig. 1.) The Ca-vapor jet from the oven may even contaminate the surfaces of the quadrupole electrodes, giving rise to weak distortion of the ion confinement potential in the LPT aperture. A relatively complex procedure is required to accumulate a large number of Ca⁺ ions sufficient for beam-dynamics experiments.

ION ACCUMULATION SCHEME

All LPTs designed and constructed for S-POD experiment are the “multi-sectioned” type; namely, they are axially divided into several quadrupole sections electrically isolated from each other, so that we can apply different DC bias voltages to those sections to form a variety of potential wells [1]. Figure 1 shows a typical potential-well profile and the side view of the LPT employed for the present study. This LPT consists of five sections referred to as the Ion Source (IS), the Gate (GT), the Experiment Region (ER), and two End Caps. We add a particularly large DC bias onto the End Caps to prevent ions from escaping axially. The bias on the Gate section is set suffi-

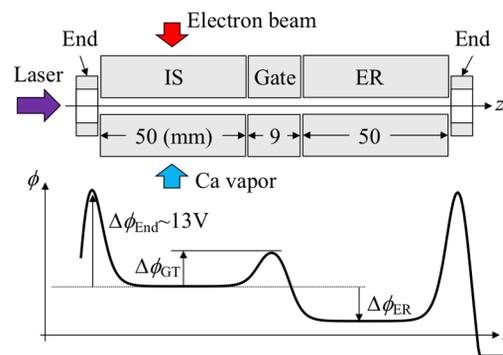


Figure 1: Schematic view of the linear Paul trap (side view) and a possible potential-well profile along the trap axis (*z*-axis) for the accumulation of Ca⁺ ions.

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This is a preprint — the final version is published with IOP

* Work supported in part by JSPS KAKENHI Grant Number 18H03472.
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ciently low so that ions produced in the IS section can flow into the ER section. Those ions go back and forth in-between the high potential barriers at both ends of the LPT, colliding with each other or with residual gas atoms. We expect them to be trapped, with a certain probability, by the deeper potential well in the ER. It may be possible to dramatically improve the accumulation efficiency by the help of the cooling laser that dissipates the kinetic energies of individual ions.

After a sufficient number of ions are accumulated in the ER, we quickly raise the Gate potential, wait for a certain short period if necessary to condition the ion bunch, and then start an intended experiment. The initial number of Ca^+ ions can be adjusted by changing the electron-beam current for ionization and the temperature of the atomic oven. The potential of the End Cap on the ER side is finally dropped to extract the bunch toward a calibrated microchannel plate (MCP). These components are placed in a compact vacuum vessel within which the base pressure is kept below 10^{-7} Pa.

RESULTS

Axial Potential Optimization

For the most efficient accumulation of ions in the ER, it is necessary to optimize the axial potential configuration, in other words, the combination of the bias voltages applied to the three quadrupole sections (IS, Gate, and ER). Ar^+ ions were employed for this purpose. The potential height in the ER relative to the base level in the IS are denoted here by $\Delta\phi_{\text{ER}}$. $\Delta\phi_{\text{ER}}$ is negative in the case illustrated in Fig. 1. $\Delta\phi_{\text{GT}}$ is the difference between the ER and IS potentials. These differences in the axial potential levels are defined on the LPT axis. They do not simply correspond to the differences of the bias voltages on the electrodes. We calculated $\Delta\phi_{\text{ER}}$ and $\Delta\phi_{\text{GT}}$ by solving the Maxwell equations numerically under proper boundary conditions.

Using the MCP detector, we first measured the number of Ar^+ ions (N_{ER}) accumulated in the ER with no potential bump at the Gate, i.e., $\Delta\phi_{\text{GT}} = 0$ V. After having kept the e -gun on for 1 s, we shut it down and simultaneously built up a high potential barrier at the Gate to separate the IS

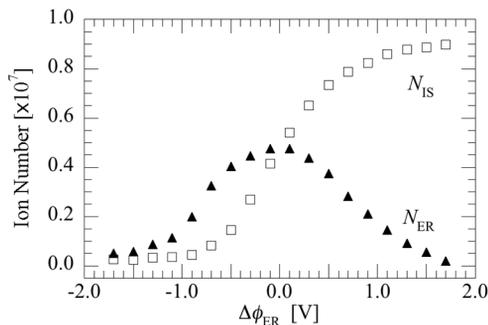


Figure 2: Number of $^{40}\text{Ar}^+$ ions trapped in the ER and IS sections when $\Delta\phi_{\text{GT}} = 0$ V. The ionization period has been fixed at 1 s.

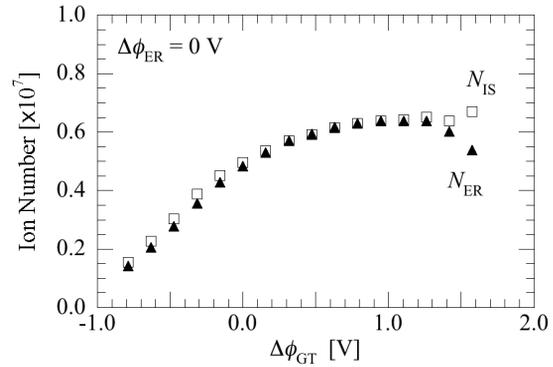


Figure 3: Dependence of trapped Ar^+ number on $\Delta\phi_{\text{GT}}$.

and ER sections. N_{ER} is plotted in Fig. 2 as a function of $\Delta\phi_{\text{ER}}$. The number of Ar^+ ions (N_{IS}) remaining the IS region is also shown. We see that N_{ER} is naturally equalized to N_{IS} at $\Delta\phi_{\text{ER}} = 0$ V. In the range $\Delta\phi_{\text{ER}} > 0$ V, there is no potential well in the ER section. N_{IS} then increases monotonically as $\Delta\phi_{\text{ER}}$ becomes higher. Interestingly, N_{ER} is still non-zero even when $\Delta\phi_{\text{ER}}$ exceeds 1 V. This is most likely due to the strong self-field potential that distorts the original potential profile on axis.

In the range $\Delta\phi_{\text{ER}} < 0$ V, both N_{ER} and N_{IS} decreases as $\Delta\phi_{\text{ER}}$ is lowered. We have confirmed, through three-dimensional tracking simulations, that considerable ion losses occur around the Gate and near the End Cap on the ER side. The loss rate becomes higher with increasing potential bump $|\Delta\phi_{\text{ER}}|$ that deteriorates the field uniformity in the axial direction. Since stored ions repeatedly traverse the Gate region, even weak degradation of the plasma confinement field can lead to serious ion losses. $\Delta\phi_{\text{ER}}$ should, therefore, be set to zero to accumulate as large a number of ions in the ER as possible.

We now consider the effect of $\Delta\phi_{\text{GT}}$, keeping $\Delta\phi_{\text{ER}}$ at the optimum value, i.e., $\Delta\phi_{\text{ER}} = 0$ V. Figure 3 shows how N_{ER} and N_{IS} vary depending on $\Delta\phi_{\text{GT}}$. The reduction of the ion numbers in the range $\Delta\phi_{\text{GT}} < 0$ V can be explained by the same loss mechanism as explained above. On the other hand, the exact reason for a slight increase of N_{ER} and N_{IS} is unknown. We currently suspect that there might be extra ion losses caused by mechanical errors, e.g., electrode misalignments around the Gate section. In fact, we have found that the lifetime of an ion bunch becomes longer when the bunch is localized either in the IS or ER

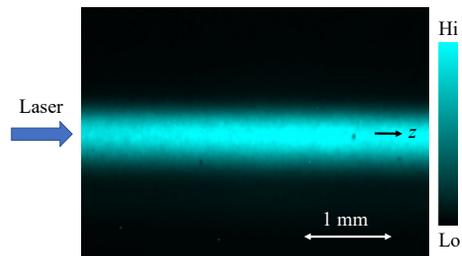


Figure 4: Laser-induced fluorescence image from $^{40}\text{Ca}^+$ ions in the LPT.

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by a high bias voltage onto the Gate electrodes. The effect from the imperfection field should be minimized then because the trapped ions no longer go across the central Gate region. The decrease of N_{ER} in the range $\Delta\phi_{GT} > 1.3$ V is due to too high a Gate potential blocking the ion flow from the IS into the ER.

Accumulation of $^{40}\text{Ca}^+$

The information gained through the preceding experiment with $^{40}\text{Ar}^+$ plasmas was utilized to generate a high-density bunch of $^{40}\text{Ca}^+$ ions. Figure 4 is a snapshot of a bunch of $^{40}\text{Ca}^+$ ions stored in the ER. We caught LIF photons from the bunch with a high sensitivity CCD camera. The temperature (T_{OV}) of the atomic oven sitting below the IS section is controlled carefully not to oversupply Ca atoms. The diameter of the laser used for this LIF measurement was smaller than the transverse extent of the ion bunch, so the LIF image in Fig. 4 does not reflect the actual bunch configuration. Since the strength of an LIF signal depends on the Doppler shifts of individual ions, we can probe the axial velocity space by scanning the laser frequency.

Figure 5 shows N_{ER} plotted as a function of $\Delta\phi_{GT}$. We adjusted the electron beam current in order to store roughly the same number of Ca^+ ions as the peak value ($\approx 0.6 \times 10^7$) in Fig. 3 while maintaining T_{OV} at 830 K. Similarly to the previous case with Ar^+ plasmas (Fig. 3), N_{ER} turns out to be maximized at $\Delta\phi_{GT} \approx 1$ V. $\Delta\phi_{ER}$ is, however, fixed at a negative value in this experiment. We found that, unlike in the Ar^+ case (Fig. 2), the peak of the N_{ER} curve slightly shifts to the low $\Delta\phi_{ER}$ side. We also realized that the optimum $\Delta\phi_{ER}$ at which N_{ER} of Ca^+ ions becomes maximum is not stable; it gradually changes in a long series of systematic experiments, which suggests that this unexpected phenomenon should be associated with the contamination developed on the electrode surfaces.

The use of $^{40}\text{Ca}^+$ plasmas makes it possible to come very close to the zero-temperature state where the betatron and synchrotron oscillations of individual particles are frozen out ($\eta \approx 0$). In the context of achievable tune depression, increasing the number of ions in the ER sec-

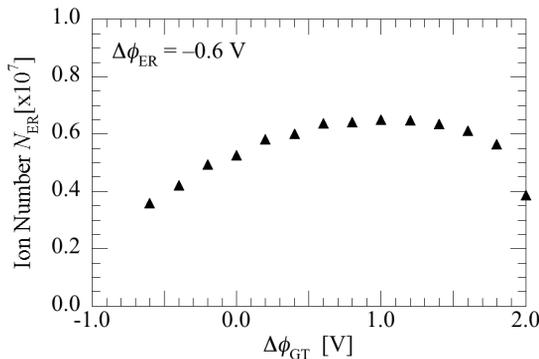


Figure 5: Number of $^{40}\text{Ca}^+$ ions accumulated in the ER with different value of $\Delta\phi_{GT}$. The potential level in the ER has been chosen slightly lower than that in the IS; namely, $\Delta\phi_{ER} = -0.6$ V.

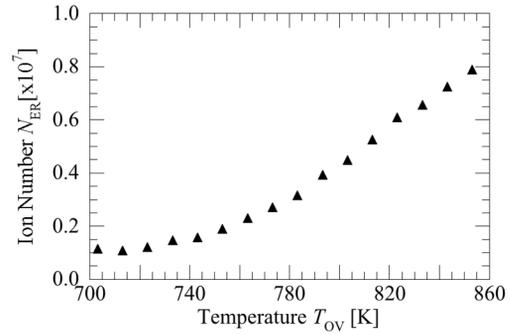


Figure 6: Number of $^{40}\text{Ca}^+$ in the ER vs. atomic-oven temperature T_{OV} . The bias voltages have been fixed such that $\Delta\phi_{GT} = 1.2$ V and $\Delta\phi_{ER} = -0.6$ V.

tion is not essential. The size of N_{ER} is, however, related to the issue of signal-to-noise ratio. Since the strength of an LIF signal is proportional to the ion number, it is certainly preferable to increase N_{ER} for better resolution. The result in Fig. 6 indicates that N_{ER} can be raised to near 10^7 , if necessary, by making T_{OV} higher.

SUMMARY

We have succeeded in accumulating a large number of $^{40}\text{Ca}^+$ ions in the multi-sectioned LPT by optimizing the axial potential well. The number of Ca^+ ions stored in the ER section has reached 0.8×10^7 at $T_{OV} = 853$ K, comparable to the maximum number of Ar^+ ions in past S-POD experiments. Recalling the melting point of Ca (1115 K), it should be possible to achieve a further increase of the stored Ca^+ number. The optimum differences of the base potentials between neighboring sections are $\Delta\phi_{ER} \approx 0$ V and $\Delta\phi_{GT} \approx 1$ V (at $N_{ER} \approx 0.6 \times 10^7$) for Ar^+ ions. A similar tendency was observed for Ca^+ ions, but we noticed a non-negligible effect probably from the electrode contamination caused during the ionization process. At present, we have not reached a definitive answer as to whether this unwanted effect keeps growing or comes to a sort of saturation. The impurity accumulation could be mitigated to some degree with an aperture for collimating a Ca vapor jet from the atomic oven.

An extremely wide range of ion density control is available for a bunch of $^{40}\text{Ca}^+$ ions by means of the Doppler cooling method. As the initial plasma conditioning with the cooling laser considerably extends the bunch lifetime, various issues of long-term beam stability can be explored systematically. The LIF diagnostics is also usable, which allows us to perform the real-time observation of the bunch-profile evolution as well as the high-precision emittance measurement. Furthermore, the vacuum condition is hardly worsened as opposed to the production of Ar^+ plasmas for which the vacuum vessel is filled with neutral Ar gas atoms. This is another favourable factor in using Ca^+ ions.

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