APPLICATION OF A PAUL TRAP TO THE STUDY OF SPACE-CHARGE-DOMINATED BEAMS II : EXPERIMENT

Ryota Takai, Masao Kanou, Yoshio Wada, Kiyokazu Ito,
Hiromi Okamoto, and Atsushi Ogata
Department of Quantum Matter, Graduate School of Advanced Sciences of Matter,
Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima 739-8526, Japan

Abstract

One-component plasmas confined in linear Paul traps are physically almost equivalent to beam observed in the rest frame. We can therefore study various behaviors of beams, such as the space-charge effects and the beam halo formation, by using a compact trap device instead of a large accelerator. In such cases, the density of confined ions serves as an important parameter. As the first step, we constructed a linear Paul trap, and succeeded in confinement of ions with the density of 1.4×10^5 cm^{-3}.

1 INTRODUCTION

The improvement of the beam quality (temperature, current, emittance) in accelerators used in science and in medical equipment has been increasingly demanded. It is necessary to understand behavior of the charged particles in accelerators for this purpose. However, it is difficult to study it experimentally with accelerators, because the actual accelerators have several restrictions for the experiments.

In recent paper, Okamoto and Tanaka has proved that the dynamics of one component plasmas (OCP) in quadrupole rf field correspond with that of the charged particle beams observed in the rest frame in an accelerator, and they indicate that the linear Paul trap can be applied to the experimental study of space-charge-dominated beams, such as the space-charge effects and the beam halo formation [1-2]. Following this study, Kjærgaard and Drewsen proposed numerical analysis about emulation of the stability of crystalline ion beams in storage rings by laser cooling ions, using a plasma stored in a pulse-excited linear Paul trap [3].

The experimental studies of beam physics using a linear Paul trap are planed in Hiroshima University. When we apply the ion trap systems as a simulator for beam physics, the density-to-temperature ratio of a plasma is important. In this paper, we report an experimental trial to examine the limit of the charge and the density which can be confined in the liner Paul trap system. The MAFIA code [4] is employed to analyze the confinement potential.

The organization of this paper is as follows. The experimental configuration is given in Sec.2, and the Experimental results are given in Sec.3. We conclude the paper in Sec.4.

2 EXPERIMENTAL CONFIGURATION

The experimental configuration is illustrated schematically in Fig. 1. In a linear Paul trap, ions are confined radially by an rf quadrupole electric field and axially by a static potential well. These potential fields were created by biasing the four cylindrical electrodes and the end-plate electrodes as shown in Fig. 2. We take the machine axis as z-axis with $z = 0$ at the mid-plane of the trap region.

The cylindrical electrodes with the radius of ρ = 4.75 mm and the length of L = 125 mm are arranged at R = 4.11 mm from z-axis. The end-plate electrodes are disks with the diameter of 30 mm and the thickness of 1 mm. The electrodes have holes with the diameter of 7 mm at the center to serve as the ion's path to the confinement region. They are placed at the both ends of the cylindrical electrodes. We can obtain an almost perfect quadrupole field in the radial direction and homogeneous potential field in the axial direction in the trap region using these electrodes configuration.

Ions are generated from residual gas, 2.6×10^{-8} Torr, using the electron impact ionizer, and injected into the confinement region through several focusing electrodes and the end-plate on the ionizer side. Therefore, we consider that the major species of the generated ions is N_2^+. We estimate the energy of the ions to be 3 eV from the experimental result.

The amount of trapped charge is measured by an electron multiplier on which the whole trapped ions are dumped

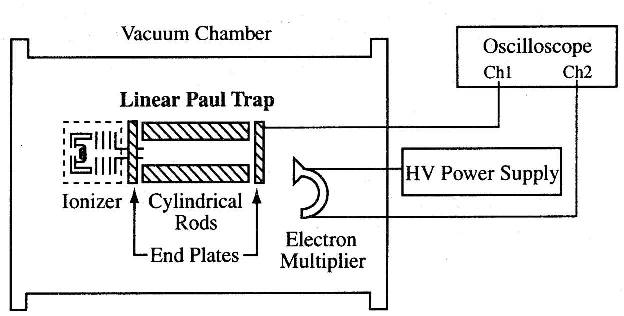

Figure 1: Schematic view of the experimental configuration. It consists of an electron impact ionizer, a linear Paul trap and an electron multiplier.

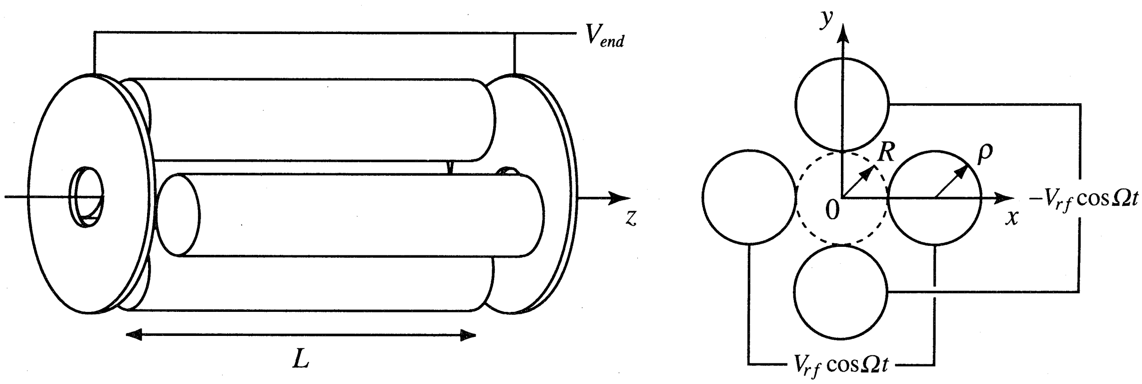

Figure 2: Schematic configuration of a linear Paul trap. An rf potential and a static potential V_{end} is applied to the four cylindrical electrodes and the two end-plate electrodes, respectively.

through the hole of the end-plate, as the bias voltage of the end-plate on the detector is turned off. The signals of the electron multiplier are recorded on the digital oscilloscope.

3 EXPERIMENTAL RESULTS

In this experiment, we chose an rf frequency $\Omega/2\pi = 2.25$ MHz and an amplitude $V_{rf} = 175$ V to create the transverse confinement field. This operating point is located within the stability region. A dc voltage biasing the end-plate electrodes to provide axial confinement potential is $V_{end} = 12$ V which is optimized experimentally.

Typical output signals of the electron multiplier are shown in Fig. 3. In each figure, the upper line represents the signal from the electron multiplier and lower line indicates the bias voltage of the end-plate on the detector side. Figure 3(a) shows the observed signal when the end-plates are biased positively. We do not observe any change of the signal level from the electron multiplier. On the other hand, after turning off the voltage of the end-plate, a decrease of signal level is observed for several ms as shown in Fig. 3(b). The decrease of the signal is caused by the ions which was confined in the trap region. The area of this component of the output signal is proportional to the amount of the trapped charge. By taking account of the amplification rate of the electron multiplier, we can calculate the absolute value of the charge.

We experimentally examine the upper limit of the charge amount which can be confined in this trap system. Figure 4 shows the charge amount as a function of the ion accumulation time. The charge amount increases with the increasing accumulation time until it reaches 180 seconds. However, the charge amount saturates at 6.8×10^{-15} C. We expect that it indicate the limit in this trap system. If we assume that the all ions are N_2^+, we can estimate the number of the ions as 4.3×10^4.

To examine the density of the trapped ions, we estimate the volume of the confined plasma. First, we estimate the axial length of the plasma. Figure 5 shows the potential distribution along z-axis generated by the applied voltages. This distribution is calculated by MAFIA code. The end-plates are placed at $z = \pm 64$ mm. The axial potential is homogeneous around the mid-plane, and it increase in the vicinity of the end-plates. We estimates that the axial length of a column of the confined plasma is typically 120 mm from this vacuum-field configuration and the ion energy of 3 eV.

Next, we estimate the transverse spread of the trapped ions. Here we introduce an assumption that the plasma is

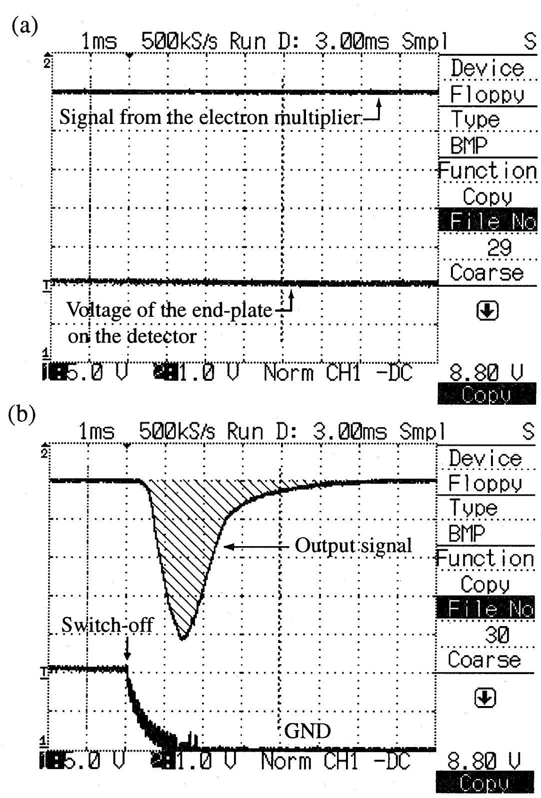

Figure 3: Typical signal from the electron multiplier. (a)Ions are not detected when the end-plates are biased. (b)Ions are detected immediately after turning off the voltage of the end-plate on the detector.

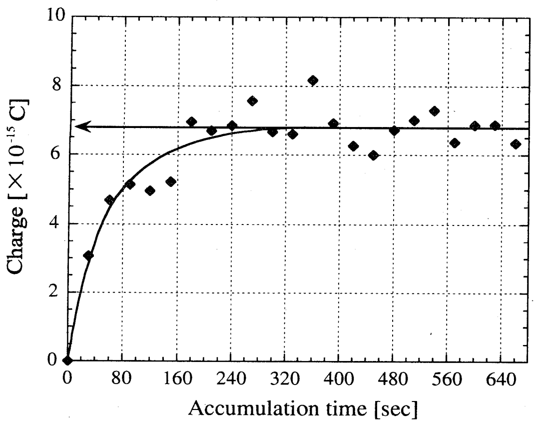

Figure 4: Total amount of trapped charge vary with the accumulation time of ions. The total charge is limited to 6.8×10^{-15} C.

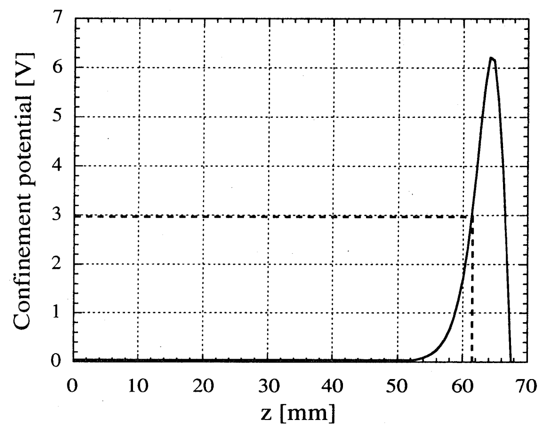

Figure 5: Axial profile of the confinement potential on z-axis calculated by MAFIA code.

stationary. Then, the relationship among the rms radius a_0, the line density n_l and the transverse temperature $T_\perp$ of the plasma is obtained as [5],

$$n_l = \frac{2}{r_p}\left[\sigma_p^2\left(\frac{a_0}{\lambda}\right)^2 - \frac{k_B T_\perp}{mc^2}\right], \tag{1}$$

where r_p is the classical particle radius, $\lambda = 2\pi c/\Omega$ is the wavelength of an rf field. k_B, c and m are the Boltzmann constant, the speed of light and the rest mass of ions, respectively. Here, σ_p is the betatron phase advance per unit cell,

$$\sigma_p = \frac{eV_{rf}}{\sqrt{2}\pi mc^2}\left(\frac{\lambda}{R}\right)^2, \tag{2}$$

where e is the charge state of ions.

Owing to the flat distribution of the vacuum-field potential in the trap region with axial length L_p, we can approximate that the actual line density is represented by $n_l = N/L_p$, where N is the observed maximum number of trapped ions. The line density of the plasma then becomes $n_l = 3.5 \times 10^2$ mm^{-1}. Moreover, we suppose that the plasma has reached the thermal equilibrium. We can obtain $T_\perp \simeq T_\parallel = 3$ eV from this assumption. Therefore, we obtain the $a_0 = 0.9$ mm by substituting these value into Eqs.(1) and (2).

Here, we assume that the plasma distribution is homogenous along the column with the radius of a_0 and the length of L_p. As a result, the number density of trapped ions are estimated as 1.4×10^5 cm^{-3} using the maximum ion number, 4.3×10^4.

This density is much smaller than the density required for the experimental study of beam physics, 10^{10} cm^{-3}. In order to improve this situation, it is required to decrease the temperature of the trapped plasma. Laser cooling must be the most effective means to accomplish this purpose.

We are planning to introduce an atomic oven ion source in order to inject a variety of ions, with lower initial temperature [6]. At the present, magnesium is planned in consideration of the previous result of laser cooling [7] and the melting point.

4 CONCLUSION

As the preliminary experiment to apply the ion trap systems as a simulator for beam physics, we examined the limit of the density which was able to be confined in the linear Paul trap. It turned out that the present density limit is 1.4×10^5 cm^{-3}. Because it is not high enough to simulate accelerator beams, we are planning to laser cool the ions in the trap.

5 REFERENCES

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