COULOMB CRYSTAL EXTRACTION FROM AN ION TRAP FOR APPLICATION TO NANO-BEAM SOURCE

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Abstract

An ion plasma confined in a compact trap system is Coulomb crystallized near the absolute zero temperature. The emittance of the crystallized ion plasma is close to the ultimate limit, far below those of any regular ion beams. This implies that, if we can somehow accelerate a crystal without serious heating, an ion beam of extremely low emittance becomes available. Such ultralow emittance beams, even if the current is low, can be used for diverse purposes including precise single ion implantation to various materials and for systematic studies of radiation damage effects on semiconductors and bio-molecules. We here performed proof-of-principle experiments on the extraction of Coulomb crystals from a linear Paul trap system developed at Hiroshima University. A string crystal of $^{40}Ca^{+}$ ions is produced with the Doppler laser cooling technique and then extracted by switching DC potentials on the trap electrodes. We demonstrate that it is possible to transport the ultralow temperature ion chain keeping its ordered configuration.

INTRODUCTION

In some applications of ion beams, it is crucial to know the precise information of beam properties in advance, such as the exact number and kinetic energies of the ions in the beam. It is also strongly required for the beam to have an extremely small transverse extent, so that we can define the exact spot at which a target is irradiated. Such low-intensity *microbeams* have typically been employed for the systematic study of radiation damages to various objects including living cells, semiconductor devices, and others [1-4].

In order to achieve extremely localized irradiation of ions onto a target, the beam emittance has to be as low as possible. If the ability of the ion source is insufficient, we will be forced to manipulate the beam after it comes out of the source; for instance, we collimate the beam with micro-apertures and, then, focus it before the target. This is actually what has happened in past microbeam experiments. In practice, however, it is clearly much more convenient to provide a sufficiently high-quality beam that needs no collimation and final focusing devices. For this purpose, we here consider the use of a compact non-neutral plasma trap instead of regular ion sources. A schematic view of the system is shown in Fig. 1. The key component is a linear Paul trap (LPT) that utilizes an rf quadrupole field to confine ions transversely [5]. The longitudinal ion confinement is achieved by applying DC voltages to the two end plates. The structure of our LPT is quite simple and conventional as sketched in Fig. 2. The four cylindrical electrodes of 180 mm long are 6.9 mm in

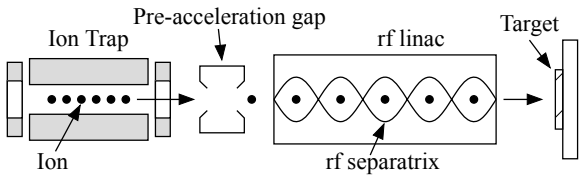

Figure 1: The ultralow-emittance beam generator.

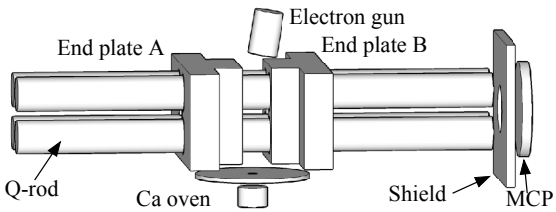

Figure 2: The linear Paul trap employed for the present experimental study.

diameter and placed 3 mm apart from the trap axis. Ion plasmas of a specific species are generated by ionizing neutral gases from an atomic oven with a low-energy electron beam. The system is equipped with a laser cooler. The Doppler limit of laser cooling is close to the absolute zero [6,7], which means that an extremely high-quality ion beam is available if we can extract the ultracold ions from the LPT without serious heating.

The concept of the ultralow-emittance beam generator was first considered theoretically in refs. [8] and [9]. Recently, Schnitzler et al. reported on experimental results of ultracold ion extraction from a unique, segmented LPT for nano-beam production [10]. In the present study, we demonstrate that it is possible, even with a simple conventional LPT, to extract laser-cooled ions maintaining the ultralow temperature state. We also show that some fundamental properties of the extracted beam can be controlled quite easily.

COULOMB CRYSTALS

A single-species plasma confined with a linear focusing force is Coulomb crystallized in an ultralow temperature range [11,12]. The structure of a Coulomb crystal depends on its line density [13]. At low density, a one-dimensional "string" crystal is formed where all ions are aligned along the trap axis at equal spatial intervals. The ultracold ions arrange themselves into the "zigzag" configuration when the line density exceeds a certain threshold. By adding more ions, we can transform the zigzag into a "shell" crystal. The emittance of an ideal Coulomb crystal is exactly zero except for quantum

noises [14]. To realize the nanobeam generator, we need the string configuration of ions.

We have applied the Doppler laser cooling technique to $^{40}Ca^{+}$ ions. Figure 3 shows examples of the three different types of Coulomb crystals obtained in our LPT. Each bright dot corresponds to a single $^{40}Ca^{+}$ ion. Since individual ions emit lots of photons (LIF: laser-induced fluorescence) during a cooling process, we can actually observe each of them at unltralow temperature by using a CCD camera. For the nano-beam generator, we first make a string crystal, count the number of ions, and then release them from the LPT by removing the longitudinal potential wall. If we can launch a string crystal from the LPT maintaining the linear ordered configuration, it is possible to put each individual ion onto the stable fixed point of an rf separatrix of the post-linac (see Fig. 1). The rf heating from the high accelerating field can then be considerably minimized because the ions execute almost no synchrotron oscillations.

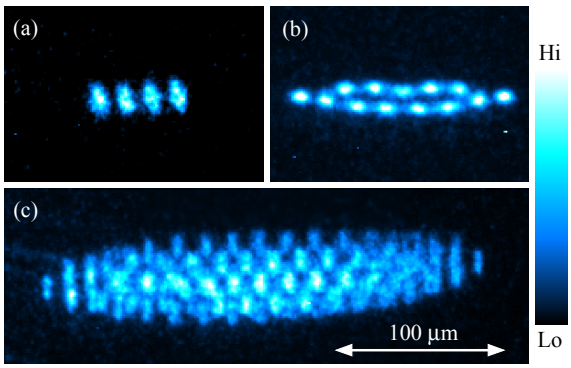

Figure 3: Laser-induced fluorescence images from ultralow-temperature Ca ions in the LPT. (a) string crystal, (b) zigzag crystal, (c) multi-shell crystal.

CRYSTAL EXTRACTION

To extract ultracold ions from the LPT, we have tried probably the most straightforward scheme as illustrated in Fig. 4. When confining and laser-cooling ions in the LPT, both end plates have an equal DC voltage (typically, 0.5 V) to form an axial potential well. After the linear crystalline state is established, we simultaneously switch the end-plate voltages to different values U_A (the detector side) and U_B (the other side). The end plate of the detector side is usually grounded (i.e. $U_A = 0$ V) at the ion extraction within 10 nsec. On the other hand, the DC potential U_B of the other side is increased to various non-zero values to obtain a sufficient electrostatic accelerating field gradient along the axis. The extracted ions go through the trap and are eventually detected by a micro-channel plate (MCP) sitting 5 mm away from the exit of the LPT. A thin metallic plate with a small hole is placed in-between the trap and MCP to minimize the switching and rf noises to the detector. Several samples of MCP measurements are displayed in Fig. 5. The left panels are

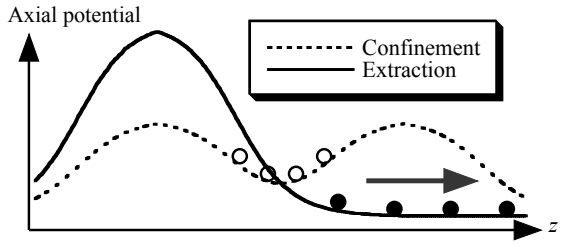

Figure 4: DC voltage switching for ion extraction.

LIF images before extraction, which clearly indicate the formations of string crystals. The corresponding MCP signals after the switch of the axial potential are shown in the right panels. It is evident that the crystals are extracted with no serious distortion of the string configuration. The average time-of-flight (TOF) is insensitive to the number of ultracold ions.

We have developed a three-dimensional (3D) multi-particle simulation code to analyze experimental results. The Maxwell equation solver "CST STUDIO" [14] is employed to obtain detailed 3D electric potential data that are imported into the code. According to systematic simulations in which actual experimental procedures as well as the LPT geometry are taken into account, the root-mean-squared (rms) spot size of the extracted beam on the MCP detector is about 5 μm and the normalized rms emittance reaches the order of 10^{-13} m or less.

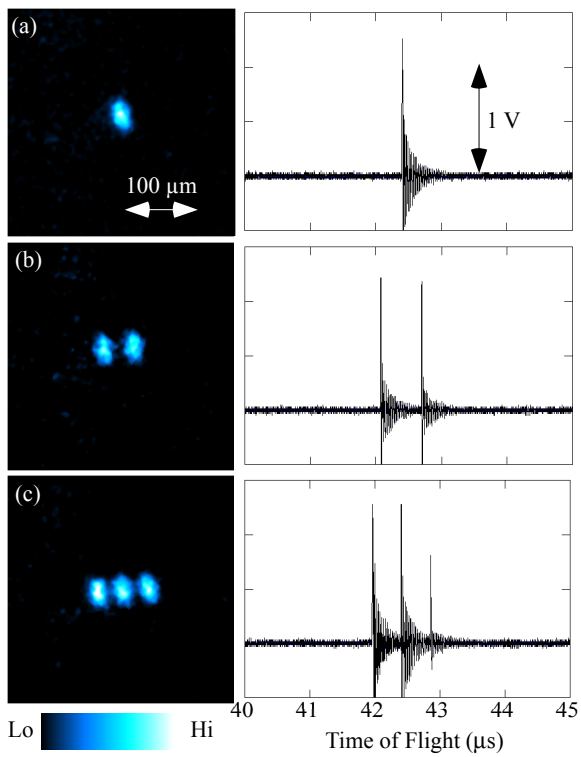

Figure 5: LIF images from string Coulomb crystals before extraction and corresponding MCP signals after the crystals are released from the LPT by switching the end-plate potentials.

Time-interval Control

A key issue that determines the practicability of the proposed novel beam-generator concept in Fig. 1 is whether we can control the time structure of the extracted ultracold ion chain. In fact, the time intervals between neighboring ions must approximately be an integer multiple of the operating rf period of the post-linac to avoid longitudinal heating of the beam. Note that the control of the *spatial* intervals is trivial; we can change the distance between adjacent ions simply by adjusting their kinetic energy with a DC accelerating field after the extraction [8].

Measured time intervals of two ultracold ions when they arrive at the MCP are plotted in Fig. 6 as a function of the extraction voltage U_B on the end plate. The possible measurement error here is ±7 nsec. The time interval becomes shorter as we increase U_B, because the second ion following the first one gains a bit more energy from the extraction potential. The broken line represents the corresponding 3D simulation results that agree fairly well with the experimental observations. We thus conclude that the time interval is controllable with the parameter U_B. We have also verified experimentally that the TOF of the ions to the detector can be varied with U_B. Naturally, the TOF is shortened at a higher value of U_B.

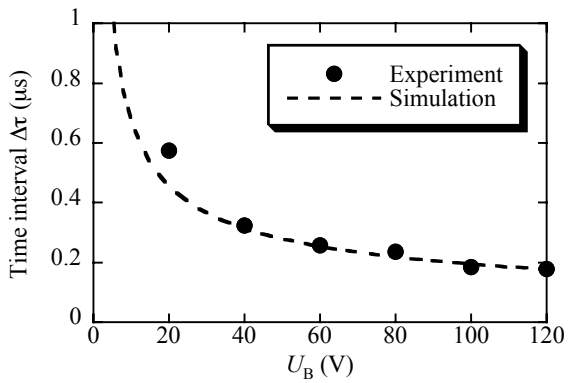

Figure 6: Time interval of two ultracold ions at the MCP detector versus the extraction voltage U_B.

SUMMARY

We have succeeded in extracting a few ultracold ions from a conventional LPT without major heating. Unlike the previous experiments of Coulomb crystal extraction [10], the LPT used here is the simplest four-rod type with two end plates. A few $^{40}Ca^{+}$ ions are laser-cooled in the LPT and, then, axially released toward the MCP by switching the DC voltages on the end plates within a short period. It is experimentally confirmed that the ultracold ions forming a string Coulomb crystal reaches the detector one after another at equal time intervals. Detailed 3D numerical simulations are performed which indicate that the normalized rms emittance of the order of 10^{-13} m is achievable with the current LPT. This number could be further improved by optimizing the design parameters of the system.

To control the time interval between adjacent ions travelling, we varied the switching voltages on the end plates at the ion extraction; the DC voltage of the detector side was dropped to zero while that of the other side was increased to accelerate the ultracold ions toward the MCP (see Fig. 4). It is shown that the time interval of the ions can be well controlled by adjusting the extraction voltage. The experimental observations are in good agreement with corresponding 3D simulation results. We have also confirmed experimentally that the extraction voltage on the end plates can be used to change the TOF of the ions to the detector. These experimental facts suggest the feasibility of the ultralow-emittance beam generator (Fig. 1) that enables one to carry out extremely localized, deterministic irradiation of high-energy ions onto various targets.

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