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AN ULTIMATE SINGLE-ION SOURCE USING A COULOMB CRYSTAL IN A PAUL TRAP

K. Muroo*, K. Ito, and H. Okamoto,
AdSE, Hiroshima University, Higashihiroshima, Japan

Abstract

As an ion cloud confined in a Paul trap reaches a Coulomb crystalline state when cooled near absolute zero, the normalized emittance of a Coulomb crystal can be in the sub-femtometer range. This trap is usable for a unique ion source for nanobeam creation, though the available beam intensity is limited. In this paper, we report the results of recent experiments where an attempt was made to extract calcium or nitrogen ions one by one from a compact linear Paul trap. In particular, we consider in detail the possibility of a new extraction scheme using multi-shell crystalline structure.

INTRODUCTION

The quality of a charged-particle beam is characterized by the emittance that represents the volume occupied by the particles in six-dimensional (6D) phase space. The more the emittance is reduced, the narrower beam we can produce. The 6D emittance is an approximate invariant in a regular particle accelerator, which means that some dissipative interaction must be introduced to improve the beam quality. Reducing the emittance with a dissipative force is called *cooling* because it results in the reduction of the beam temperature. It is known that, near absolute zero, the beam reaches a crystalline state where the natural Coulomb repulsion among individual particles is in equilibrium with the external beam focusing potential. The structure of a *Coulomb crystal* changes depending on the number of particles in the bunch (and on the focusing strength). At very low line density, all particles are aligned along the design orbit at almost equal intervals. If we keep increasing the number of particles, the linear *string* is converted into a *zigzag* and eventually into a *multi-shell* configuration.

Among several well-established cooling methods applicable to ion beams, the Doppler *laser cooling* technique is the only way to achieve Coulomb crystallization or, in other words, to obtain an ultimate high-quality beam of ions. Crystallizing a fast circulating beam in a storage-ring accelerator is, however, extremely difficult because laser cooling is not very effective in the transverse dimensions of an ordinary hot beam. It is also necessary to compensate the strong dispersive heating effect brought by bending magnets.

In contrast, we have no problem forming a Coulomb crystal in a compact ion trap, though the number of cold ions available may be limited. The trap can, therefore, be considered as a unique ion source if the beam intensity is not an issue. Low-intensity microbeams are actually quite useful and have been employed for a variety of purposes. Even the irradiation of a single ion suffices to explore the single event effect, possible biological response to radiation in cells, etc. Consecutive extraction of a few ultracold ions from a linear Paul trap (LPT) has been demonstrated experimentally by some research groups making use of string Coulomb crystals [1, 2].

Laser cooling is applicable only to limited species of ions, but in principle, we can sympathetically cool any ion species through Coulomb interaction with laser-coolable ions. Groot-Berning et al. recently succeeded in extracting a single nitrogen ion ($^{14}N_2^+$) sympathetically cooled with ultracold calcium ions ($^{40}Ca^+$) in a LPT [3]. A similar experimental study is now in progress at Hiroshima University, using a conventional LPT of the simple four-rod configuration. We are considering the use of multi-shell crystalline structures instead of the string. In the following, a brief description is given of our LPT system and new extraction scheme. We also report on results of some preliminary experiments.

PAUL-TRAP ION SOURCE

The experimental system consists of a vacuum chamber, an LPT, a channel electron multiplier (CEM) for detection of extracted ions, a laser cooler, an intensified charge coupled device (ICCD) camera for observation of laser-induced fluorescence (LIF) from $^{40}Ca^+$ ions, and a vacuum pump. Figure 1 (a) and (b) show the layout of the LPT. It consists of four rods and three end-plate electrodes. Each rod electrode has a diameter of 6.88 mm and a length of 88 mm, and the distance from the trap axis is 3 mm. The LPT uses an rf quadrupole field to confine charged particles transversely. The rf frequency is 2 MHz, and the rf amplitude V_{rf} is 30 V or lower. Three end-plate electrodes (End-A, Gate, and End-B) with a uniform thickness of 12 mm are biased at a few volts DC voltage (V_{A},V_{Gate} and V_{B}) to form two axial potential wells. The ion confinement region where ions are crystallized (between Gate and End-B) is separated from the ion production region (between End-A and Gate) to avoid contamination. The gap between Gate and End-B is 7.1 mm, which can generate an almost parabolic potential.

The ion species for the experiment are $^{40}Ca^+$ ions and $^{14}N_2^+$ ions. $^{40}Ca^+$ ions are coolable through the use of two lasers: a cooling laser (397 nm) for transition of $4s^2S_{1/2}$–$4p^2P_{1/2}$, and a repumping laser (866 nm) for excitation from the metastable state $3d^2D_{3/2}$. The lower temperature limit, known as the Doppler cooling limit T_{D}, is defined as $T_{\mathrm{D}} = \hbar\Gamma/2k_{\mathrm{B}}$ where Γ, $\hbar$ and k_{B} represent the natural width of the excited state, the reduced Plank constant and Boltzmann constant, respectively. In the case of $^{40}Ca^+$ ions, Γ is 22.5 MHz, and thus T_{D} is estimated as 0.54 mK.

* muroo-kento@hiroshima-u.ac.jp

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The nitrogen ($^{14}N_2^+$) ion is chosen as the sympathetically cooled ion due to its ease of introduction. In addition, it is especially interesting to use ultracold nitrogen ions to create nitrogen-vacancy centers in diamond [3]. When an experiment with nitrogen ions is conducted, pure nitrogen gas is introduced into the vacuum chamber through a variable leak valve.

Figure 1 (c) shows the scheme of single ion extraction. After being confined in the LPT, ions are cooled and crystallized. As the voltages applied to the LPT are controlled, a single ion is directed toward the CEM detector.

The vacuum chamber is evacuated by a turbomolecular pump, and the base pressure is kept under 5×10^{-8} Pa. The LIF images detected by the ICCD camera in past experiments at Hiroshima University are shown in Figure 2. One bright dot represents a LIF emitted from a $^{40}Ca^+$ ion. Figure 2(a) shows a multi-shell Coulomb crystal. Figure 2(b) is an image of a string crystal consisting of three $^{40}Ca^+$ ions and one different ion species accidentally confined in the trap. Since there is an especially wide gap between the first and second dots from the right side of the figure, it is thought that an ion that does not emit the LIF is captured in the gap.

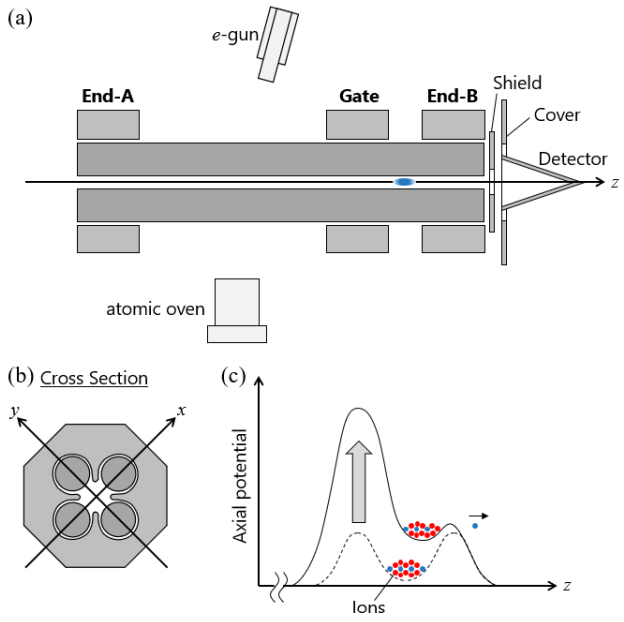

Figure 1: (a) Schematic view of the LPT in this study and (b) its cross section. The structure of the LPT follows the past configuration adopted in nanobeam experiments at Hiroshima University. (c) Scheme of a single ion extraction. Ions are trapped in the potential well generated by DC voltage applied to Gate and End-B electrodes (dashed line), and they are crystallized by lasers. While keeping the voltage applied to End-B, the voltage of Gate is adiabatically raised (solid line). Since the potential well becomes shallow, a single ion is extracted from the LPT.

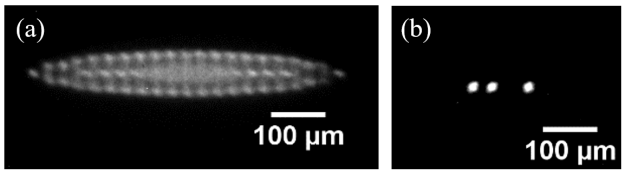

Figure 2: LIF images of (a) a shell Coulomb crystal and (b) a two-component string Coulomb crystal.

SIMULATION

We conduct numerical simulations using a 3D molecular dynamics (MD) code independently developed in our laboratory. The LPT potential is calculated by CST Studio Suite [4] under the boundary conditions that reproduce the actual structure of the LPT. The details of this MD code are described in [5]. Figure 3 shows a two-component shell crystal generated in a simulation, which comprises twenty-four $^{40}Ca^+$ ions and six $^{14}N_2^+$ ions. Here $V_{rf} = 20$ V and $V_{Gate} = V_B = 5$ V. In the LPT potential, the lighter (strictly speaking, the less charge-to-mass ratio m/q) a particle is, the stronger force directed to the trap axis a particle feels. Hence, the lighter $^{14}N_2^+$ ions form a line on the trap axis, and the heavier $^{40}Ca^+$ ions surround them.

The time evolution of the ions when V_{Gate} increases from 5 V to 237.55 V in 25.16 ms is shown in Figure 4. When Δt, which is the time measured from the start of raising V_{Gate}, is 25.3 ms, though the whole crystal has been transported to the detector side, all ions are still trapped in the potential well. At $\Delta t \approx 25.4$ ms, the top $^{14}N_2^+$ ion gets over the potential wall of End-B and flies to the detector, while other ions that composed the crystal remain in the LPT even at $\Delta t = 30$ ms. We conducted this simulation independently 100 times and confirm that only a single $^{14}N_2^+$ ion at the top is extracted onto the detector in all 100 simulations. The normalized root-mean-square emittances, which are calculated from the distribution in front of the CEM, are 4.6×10^{-16} m·rad and 4.3×10^{-16} m·rad in the directions of x and y, respectively.

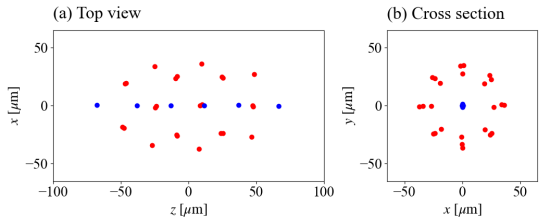

Figure 3: Two-component shell Coulomb crystal composed of six $^{14}N_2^+$ ions (blue) and twenty-four $^{40}Ca^+$ ions (red) in the simulation.

ION EXTRACTION EXPERIMENT

Generation of a Two-component Coulomb Crystal

We confirm the generation of a two-component Coulomb crystal. Nitrogen gas is introduced to the chamber under

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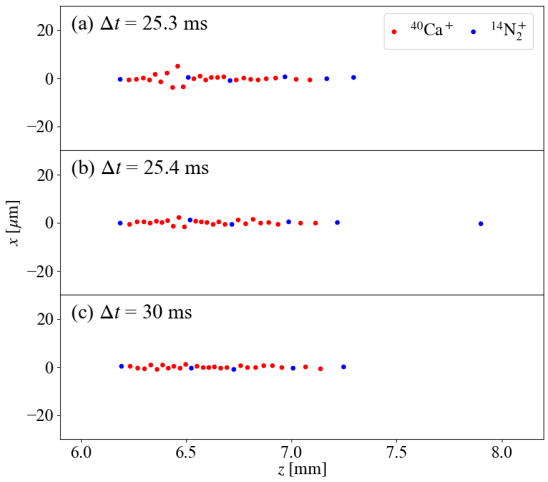

Figure 4: Time evolution of the two-component crystal. (a) Δt = 25.3 ms, (b) Δt = 25.4 ms, and (c) Δt = 30 ms. The origin of the horizontal axis is the center of the ion confinement region.

the pressure of 5×10^{-7} Pa, and a heated oven releases calcium atoms in the chamber. These atoms are ionized by collision with electrons emitted from an electron gun, and they are confined in the LPT. By sweeping the frequency of the cooling laser to the proper value, calcium ions are cooled, and nitrogen ions are cooled by Coulomb interaction with other cooled ions. The cooled ions eventually form a Coulomb crystal. The image of a two-component Coulomb crystal taken by the ICCD camera is shown in Figure 5, where V_{rf} = 20 V and V_{Gate} = V_{B} = 1.5 V. The bright area of the outer part of the crystal is the LIF from calcium ions. The dark area of the inner part is considered to include nitrogen ions that do not emit light.

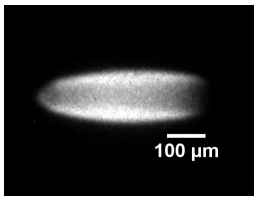

Figure 5: Image of two-component shell Coulomb crystal.

Extraction of Ca^+ ions from a Single-component Crystal

Here we describe a proof-of-principal experiment for the ion extraction method mentioned above. Note that at this time, we attempt to extract a whole crystal composed of only $^{40}Ca^+$ ions to confirm the operation parameters. Figure 6 shows the crystal images before extraction and the graphs that indicate the time interval for ion detection. The transverse axes are the number of detected ions, and the horizontal axes represent the elapsed time from the previous ion detected by the CEM. The applied voltages V_{rf}, V_{Gate} and V_{B} before the extraction are 30 V, 0.5 V and 0.5 V, respectively. For extraction, V_{Gate} is raised from 0.5 V to 30 V in (a) 10 ms or (b) 50 ms. In each case, about 50 ions are detected. Some parts of time intervals are twice as long or longer than most intervals because the previously extracted ions are not detected by the CEM. Hence, the actual number of $^{40}Ca^+$ ions that compose the crystals is considered greater than the number of detected ions. The mean time intervals in (a) and (b) are 7.0 μs and 32.8 μs, respectively. This result implies that the time interval is controllable by varying the speed of the end-plate voltage change.

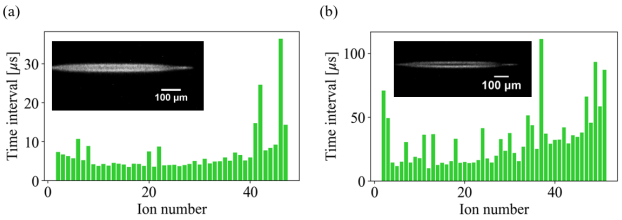

Figure 6: Time interval of signals detected by the CEM. The voltage of Gate is raised from 0.5 V to 30 V in (a) 10 ms, and (b) 50 ms. The LIF images in the frame are taken by the ICCD camera just before the voltage change.

SUMMARY AND FUTURE PLANS

We have conducted a preparatory study for ultra-high precision extraction of a single nitrogen ion using the LPT. Numerical simulation shows that it is possible to extract a single nitrogen ion with rms emittance on the order of 10^{-16} m·rad from a two-component Coulomb crystal. In the experiments, we succeed in generating a Coulomb crystal, which consists of calcium ions and nitrogen ions. Furthermore, the extraction of a $^{40}Ca^+$ Coulomb crystal by raising the end-plate voltage gradually is confirmed.

Currently, we are investigating the matching between the results of simulation and experiment and attempting to demonstrate the extraction of ions from a two-component Coulomb crystal experimentally. In addition, we are planning another experiment in which trapped ions are cooled in all directions, providing greater cooling efficiency than the current unidirectional experimental setup.

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[4] CST Studio Suite is a commercially available software. For more detail, see https://www.3ds.com/products/simulia/cst-studio-suite

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