Coulomb crystal extraction from an ion trap for application to nano-beam source

K. Ito, K. Izawa, H. Higaki and H. Okamoto,
Advanced Sciences of Matter, Hiroshima University,
1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8530 Japan

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1. Introduction

Nano-ion beam

An ion beam with the radius of nano meter order

It allows extremely localized irradiation onto a target

Applications of nano-ion beam

Study of radiation damage in bio-molecules and semiconductor

New Material Creation (precise implantation)

Micro machining* (deposition & ablation)

- Radiation breeding
- Lithographic mask repair
- Secondary ion-microprobe mass spectorometry
- etc.

*)Provided by SII NanoTechnology Inc.
2. Conventional method of a nano & sub-micro ion beam production

- **Collimation** by micro apertures
- **Strongly focusing** by magnetic or electric lens

The tiny beam is obtained near the focal point, but the beam divergence is large.

The initial beam emittance is not sufficiently low.

- Liquid metal: ~keV, ~nA
- Accelerator: ~MeV, Single ion (Cyclotron, Tandem)
3. The ions are crystallized near zero Kelvin

Laser induced fluorescence (LIF) images of trapped ions

Ion cloud (~10^3 K)

laser cooling to ~mK

The emittance of a Coulomb crystal is close to the ultimate limit!!

small size & small divergence

Lo Line Density Hi
4. Concept of the nano-ion beam generator by Coulomb crystal

1. Trapping
2. Cooling
3. Extraction
4. Acceleration

1. The emittance is close to the ultimate limit.
   - The transverse size and the divergence are extremely small.
2. The time interval between any two ions is almost identical and controllable.
   - The ion train can be accelerated by rf field without major heating.
3. Individual ions can be observed by LIF imaging.
   - The precise number of ions can be counted.
4. Ions are not lost in acceleration process.
   - Radiation protection is not necessary.
5. etc.

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   - linear Paul trap
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5. Experimental setup

**Energy diagram of $^{40}$Ca$^+$**

- **Doppler limit** = 0.54 mK
- **Cooling laser** 397 nm
  - Intensity: 0.8 mW/mm$^2$
  - Radius: 1 mm
  - Line width: <9 MHz
- **LIF**
- **Re-pump laser** 866 nm
  - Excited state ($4p^2P_{3/2}$)
- **Re-pump laser**
  - Meta Stable ($4s^2S_{1/2}$)
- **Ground state** ($3d^2D_{3/2}$)

**Vacuum chamber**
- Base pressure: < 5x10$^{-7}$ Pa

**Optical bench**
- 1.5 m x 1.0 m

**Cooling Laser**
- Intensity: 2.9 mW/mm$^2$
- Radius: 0.4 mm
- Line width: <1 MHz

**Re-pump Laser**
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**Wavelength meter**

**ICCD Camera**

**Anamorphic Prism**

**Isolator**

**FPI**

**Brewster's window**

**Light shielding box**
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Radius: 0.4 mm
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Vacuum chamber
Base pressure: < 5x10⁻⁷ Pa

Optical bench
1.5 m x 1.0 m

Laser Source

Light shielding box
including the LIF imaging system

Doppler limit = 0.54 mK

Energy diagram of ⁴⁰Ca⁺

Ground state (3d²D₃/₂)
Meta Stable (4s²S₁/₂)
Excited state (4p²P₃/₂)
6. Linear Paul Trap

Parameters

Ion: \( ^{40}\text{Ca}^+ \)

Q-Rod
  - Radius: 3.45 mm
  - Length: 180 mm
End Plate
  - Distance: 6 mm
Trap region
  - Radius: 3 mm
  - Length: 6 mm

rf voltage on Q-rod
  \( \sim 30 \text{ V@2 MHz} \)
dc voltage on End-Plate
  0.5V@Trapping
7. Extraction of Coulomb crystal

Oscilloscope sampling time: 0.1 ns

7. Extraction of Coulomb crystal

- Oscilloscope sampling time: 0.1 ns

- Laser

- End plate B

- End plate A

- Pre-AMP

- Biased voltage on the end-plate $U_B$

- Axial potential on the trap axis

8. 3D simulation - Trapping -

Potential calculated by CST STUDIO* at a moment

3D multi-particle simulation code

- External potential is calculated by CST.
- Coulomb potential is calculated directly.

*)http://www.cst.com/

Ion distribution in the crystal state

*http://www.cst.com/
9. 3D simulation -Extraction-

Spatial distribution of extracted $^{40}\text{Ca}^+$ ions on MCP

Potential distribution

Ion distribution during the transport

Ions are kept a string!!
9. 3D simulation -Extraction-

Spatial distribution of extracted $^{40}\text{Ca}^+$ ions on MCP

Ion distribution during the transport

Ions are kept a string!!

Single shot
9. 3D simulation -Extraction-

Spatial distribution of extracted $^{40}\text{Ca}^+$ ions on MCP

Normalized rms emittance $10^{-16}$ m !! (ideal case)

Ion distribution during the transport

Ions are kept a string !!
10. We succeed in extracting string crystals!

The spatial structure of the Coulomb crystal
- number
- spatial position
- distance

Extracted ion (MCP signal)
- number
- TOF timing
- time interval

The temporal structure of the extracted ions

Ultracold ions are extracted without major heating!!
11. TOF can be controlled by the extraction voltage.

Controllability of TOF is important.

- TOF decreases with the increasing $U_B$.

We can control the TOF by $U_B$!!

- The experimental observations are in good agreement with 3D simulation results.

Other results:
- The average TOF is almost independent of the initial ion number.
- Possible errors in TOF measurements < 7ns.
12. Time interval between two ultracold ions is also controllable by the extraction voltage.

Another key factor is the controllability of time intervals between ions.

- $\Delta \tau$ decreases with the increasing $U_B$.

  We can control the time interval by $U_B$ !!

- The experimental observations agree well with 3D simulation results.
13. Conclusions

We have performed an experimental study of a novel ion source. The core of the system is a compact linear Paul trap where a small number of ions are manipulated with a laser before the extraction.

1. We have succeed in extracting a few ultracold ions from a linear Paul trap.

2. Detailed 3D numerical simulations are performed which indicate that the normalized rms emittance of the order of $10^{-16}$ m.

3. The TOF and the time interval between adjacent ions can be well controlled by adjusting extraction voltage. The experimental observations are in good agreement with corresponding 3D simulation results.

The present experimental facts suggest the feasibility of the ultralow-emittance beam generator that enables one to carry out extremely localized, deterministic irradiation of high-energy ions onto various targets.
A1. Doppler laser cooling

Deceleration of an ion by photons

\[ \omega_L \approx \omega_0 \left(1 - \frac{v_{\parallel}}{c}\right) \]

\(\omega_L, k_L\): angular frequency and wave number of photons

\(\omega_0\): resonant frequency of the ion

Cooling of trapped ions

\[ u_z = c \frac{\Delta f}{f_0} \]

\(\Delta f = f_L - f_0\): detune
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A2. Laser cooling and LIF measurement of $^{40}\text{Ca}^+$

The ion species that can be cooled directly by laser is limited.

Mg$^+$, Ba$^+$, Hg$^+$, Sr$^+$, Yb$^+$, Ca$^+$, Cd$^+$, etc

It is easy to handle.
It can be cooled by laser diode.

Energy diagram of $^{40}\text{Ca}^+$ about laser cooling & LIF

Cooling laser
397 nm

LIF

Re-pum laser
866 nm

attainable temperature
= 0.54 mK