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

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Contents

1. Introduction

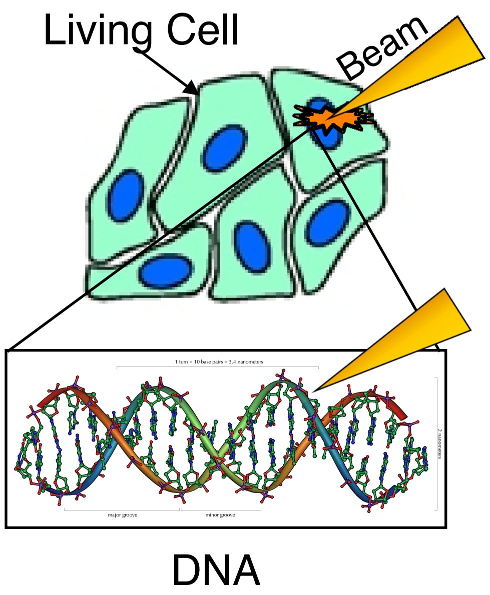
Nano-ion beam

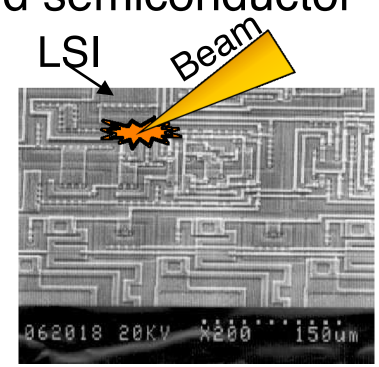
An ion beam with the radius of nano meter order

⇨ It allows extremely localized irradiation onto a target

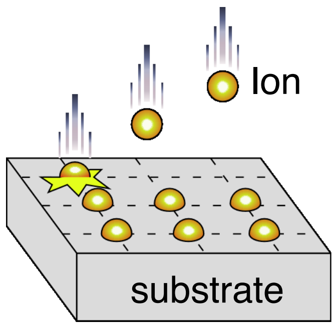
Applications of nano-ion beam

Study of radiation damage
in bio-molecules and semiconductor

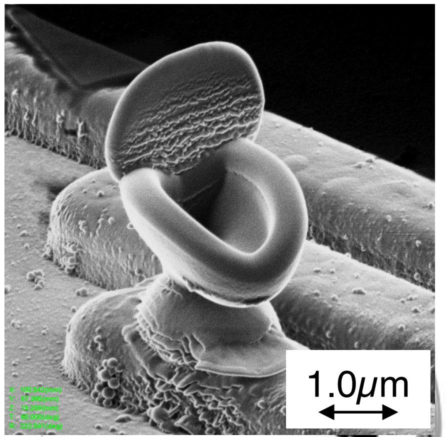




New Material Creation
(precise implantation)



Micro machining*
(deposition & ablation)



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

*)Provided by SII NanoTechnology Inc.

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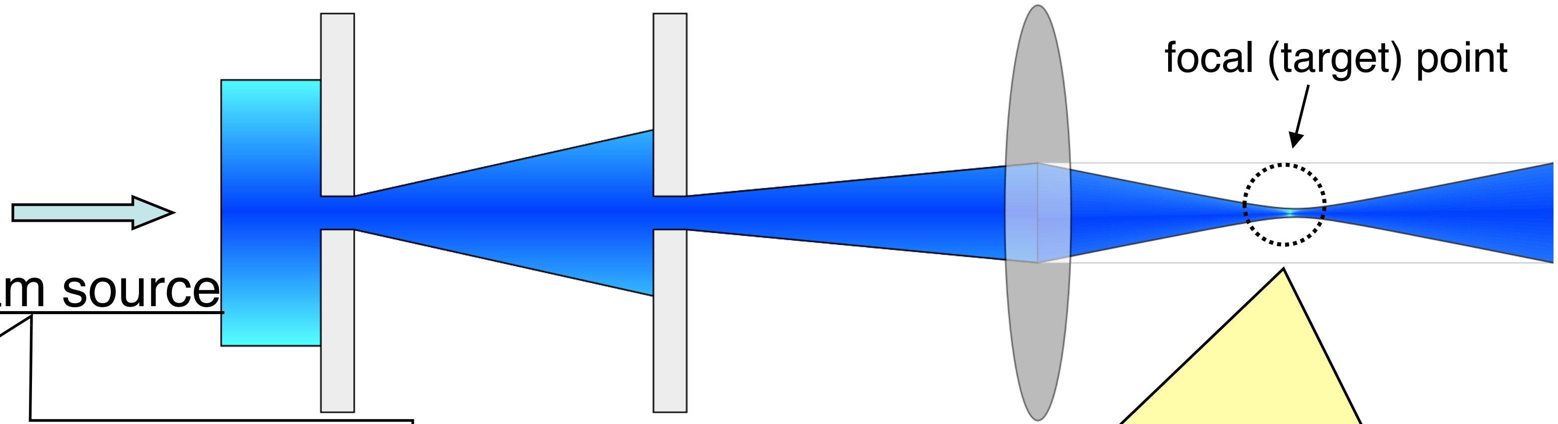
2. Conventional method of a nano & sub-micro ion beam production

collimation by micro apertures

strongly focusing by magnetic or electric lens

from a beam source



- Liqiuid metal: ~keV, ~nA
- Accelerator: ~MeV, Single ion (Cyclotron, Tandem)

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

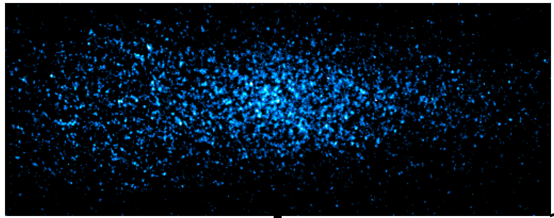
⇧

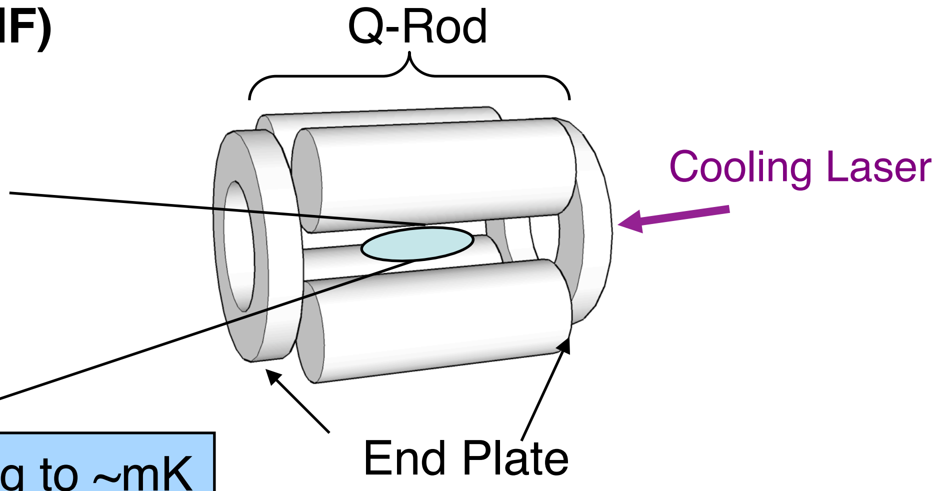
The initial beam emittance is not sufficiently low.

3. The ions are crystallized near zero Kelvin

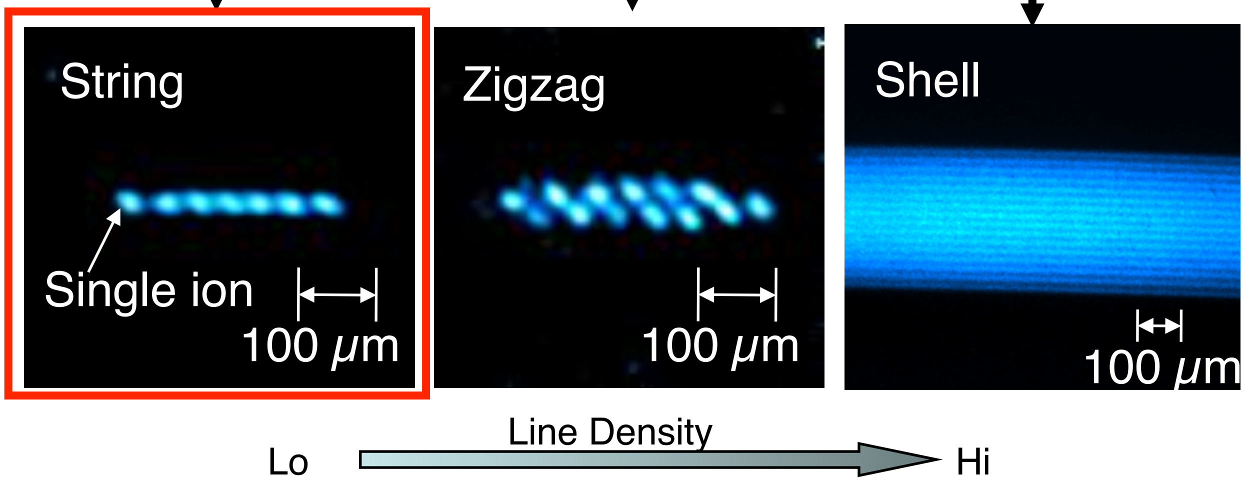
Laser induced fluorescence (LIF) images of trapped ions

Ion cloud (~10^3 K)





laser cooling to ~mK



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

⇩

<u>small size</u>

&

<u>small divergence</u>

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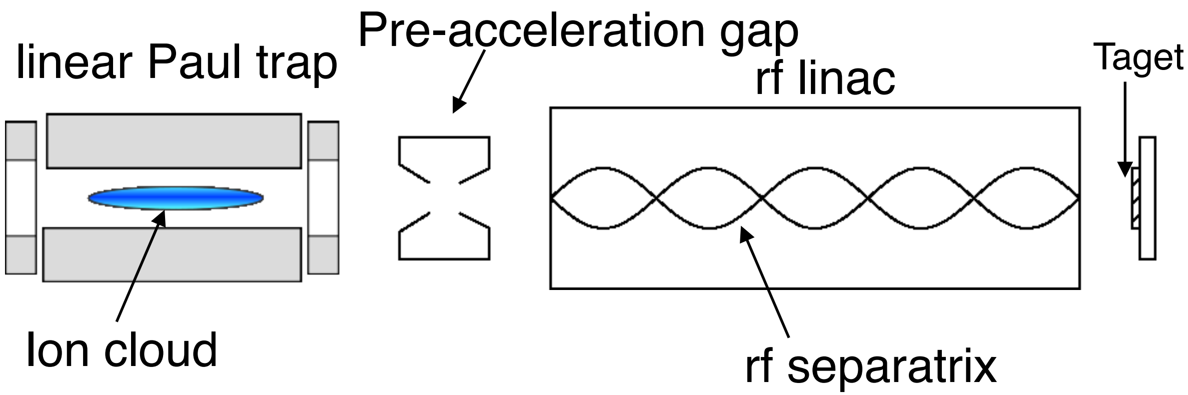
4. Concept of the nano-ion beam generator by Coulomb crystal

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.

M. Kano et al., J. Phys. Soc. Jpn. **73** (2004) 760.
K. Ito, A. Ogata and H. Okamoto, Int. J. Appl. Electromagnetics and Mechanics **14** (2000) 23.

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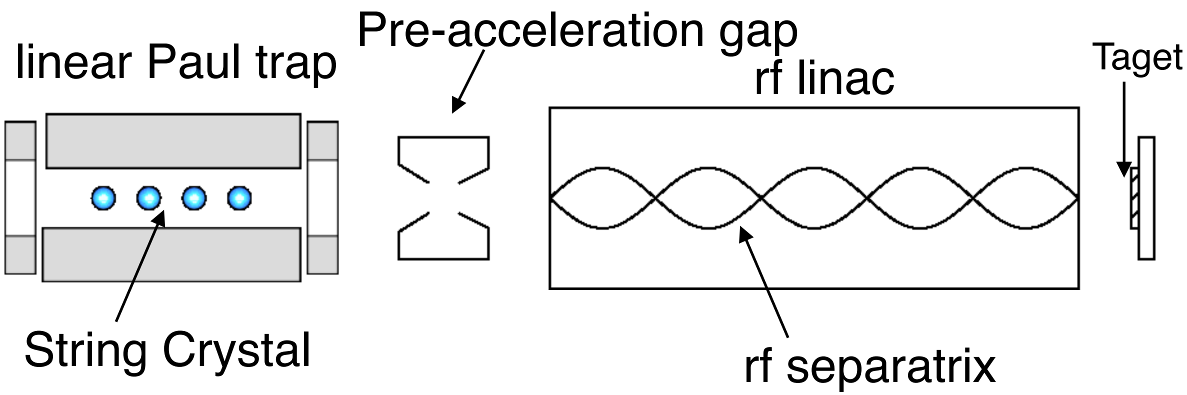

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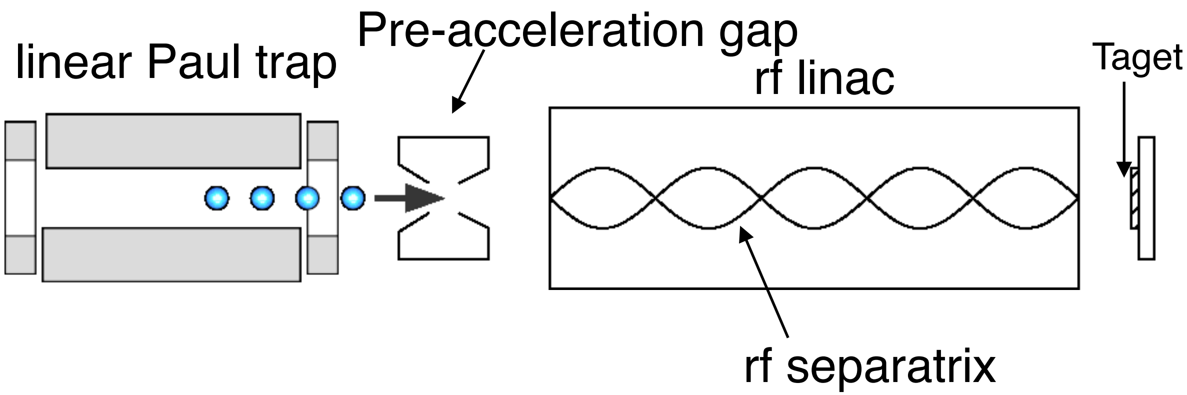

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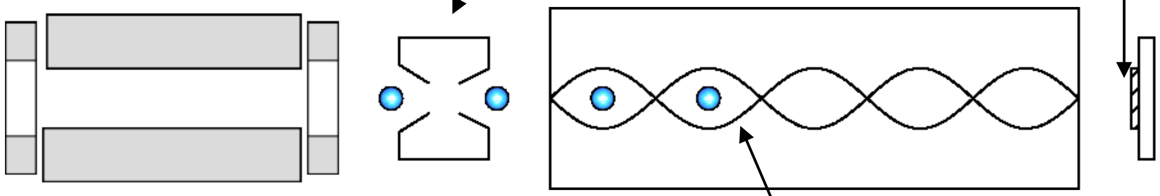

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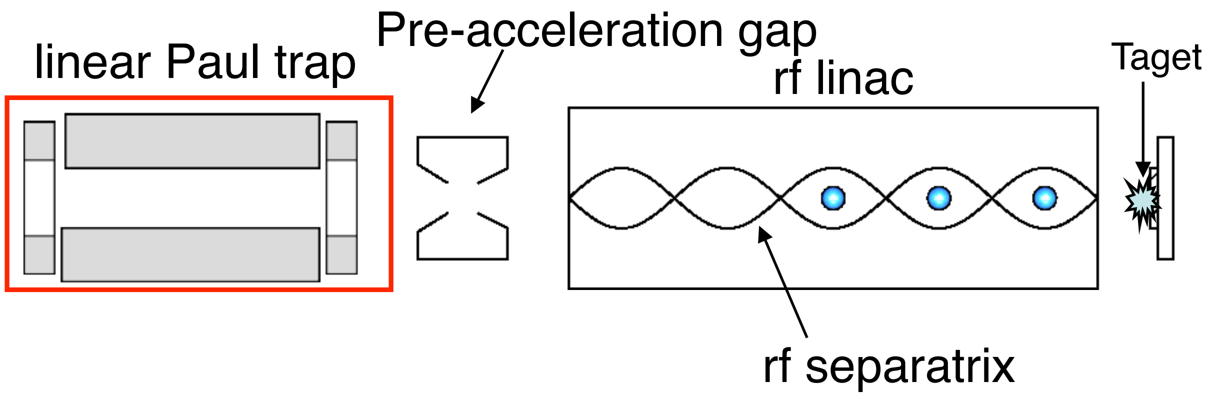

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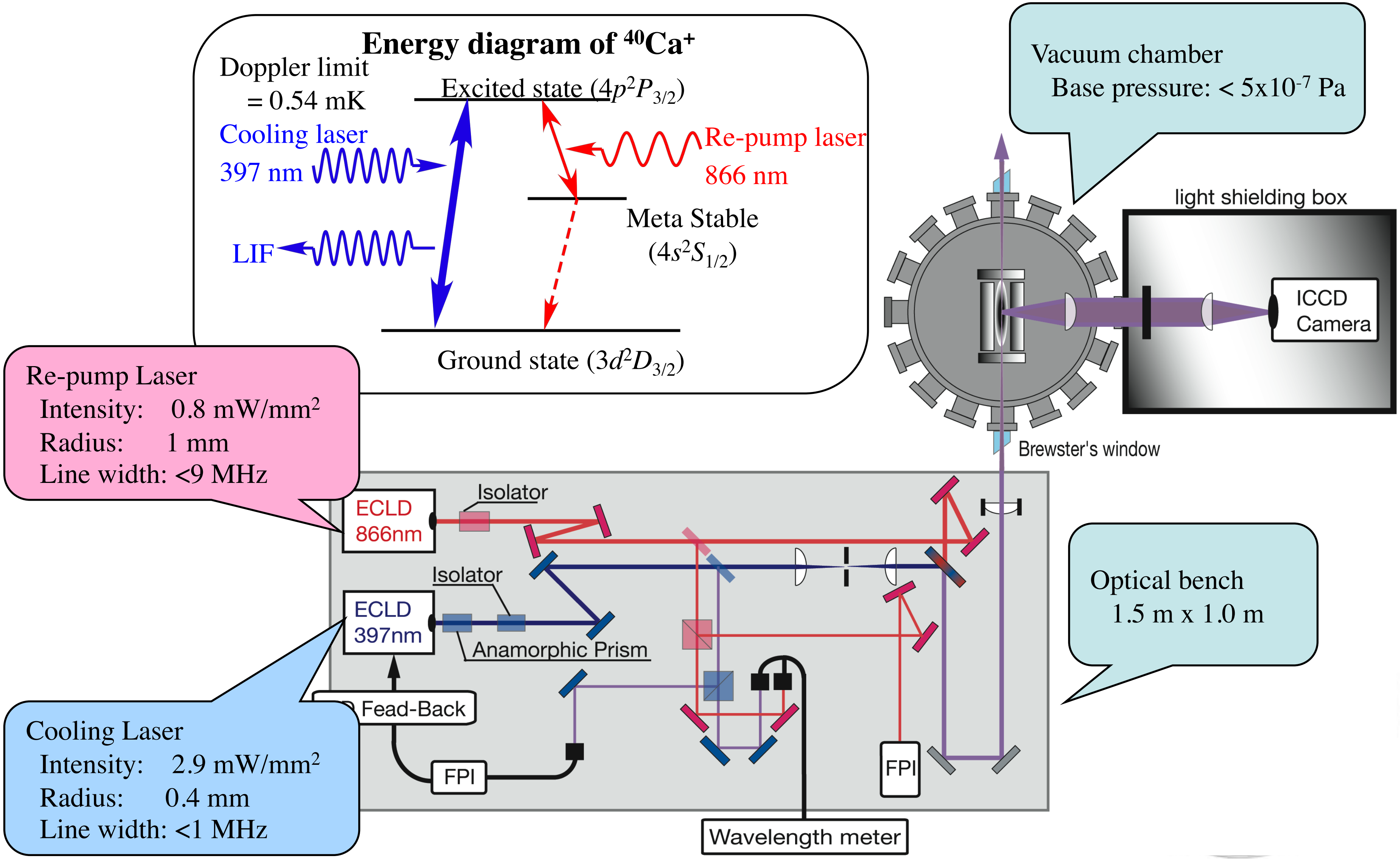
5. Experimental setup



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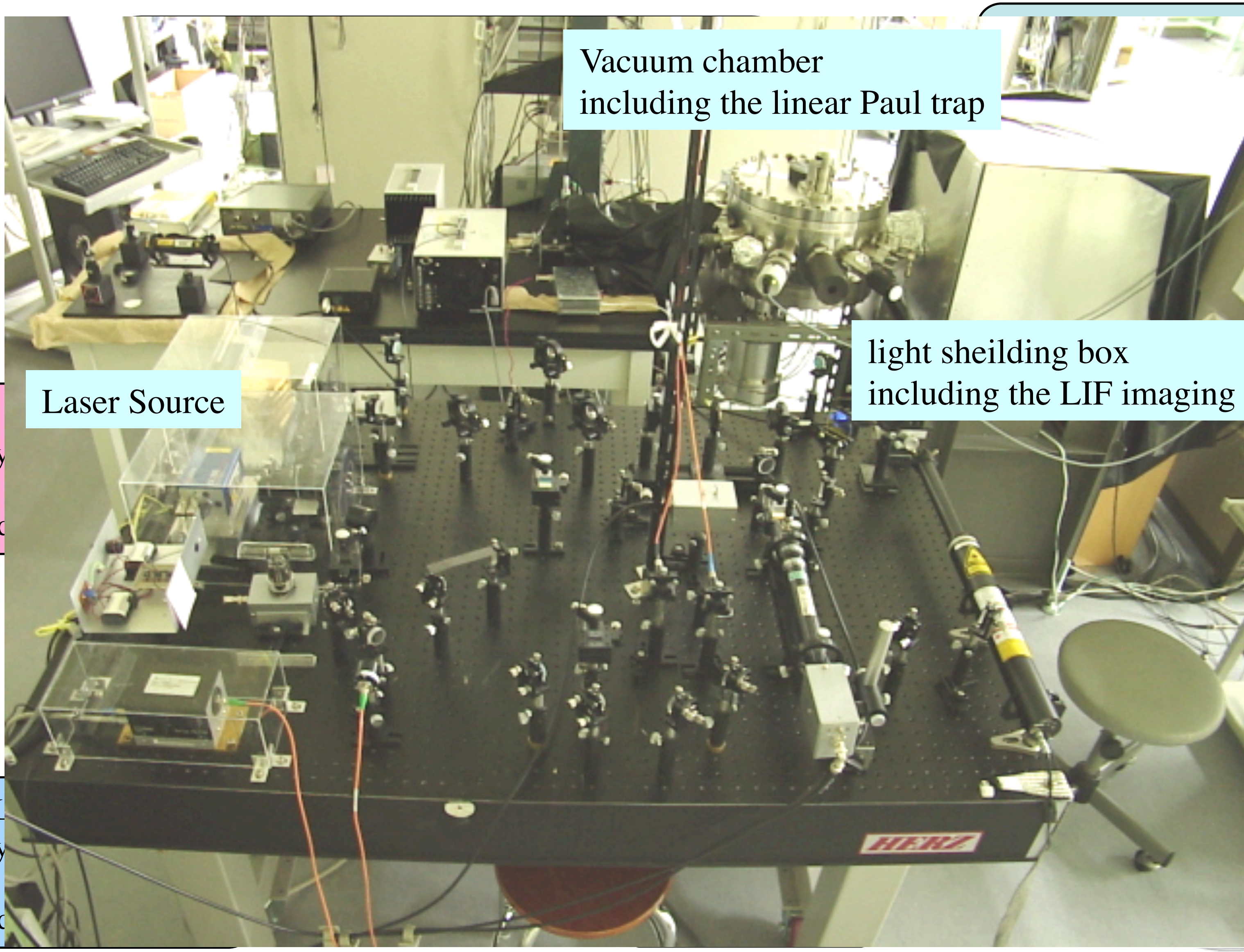


$x10^{-7}$ Pa

elding box

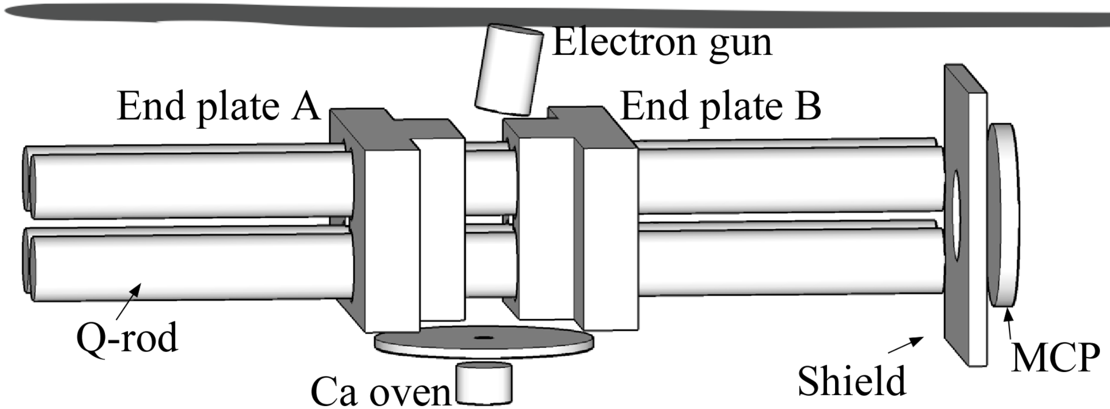
ra

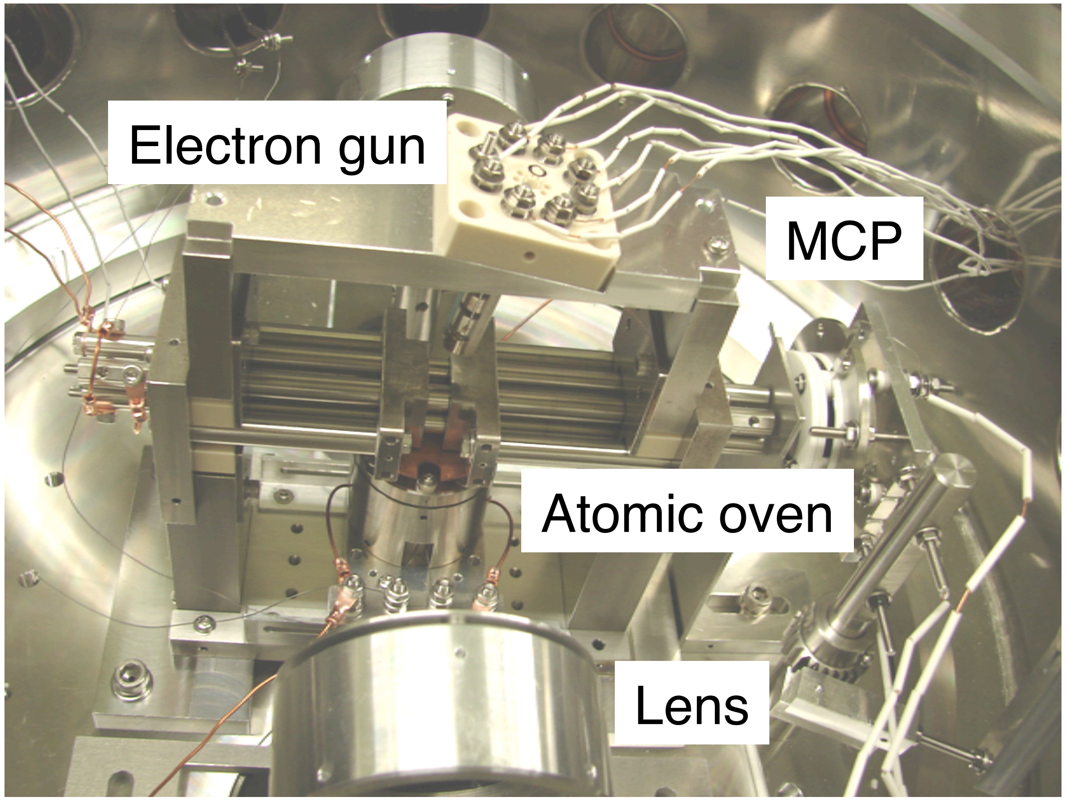
n

Re-pump
Intensity
Radius:
Line wic

Cooling L
Intensity
Radius:
Line wic

6. Linear Paul Trap





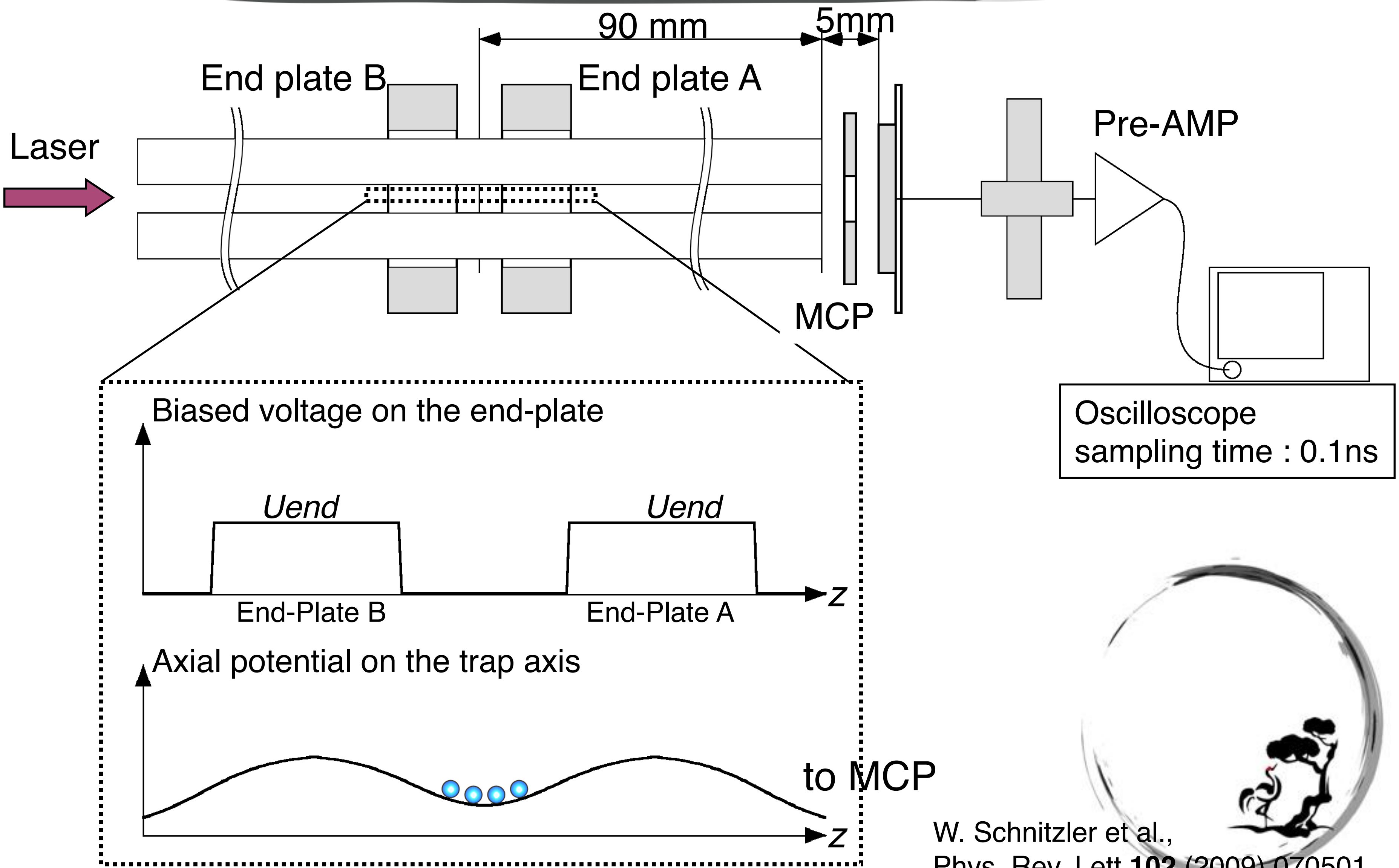
Parameters

Ion: $^{40}Ca^{+}$

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

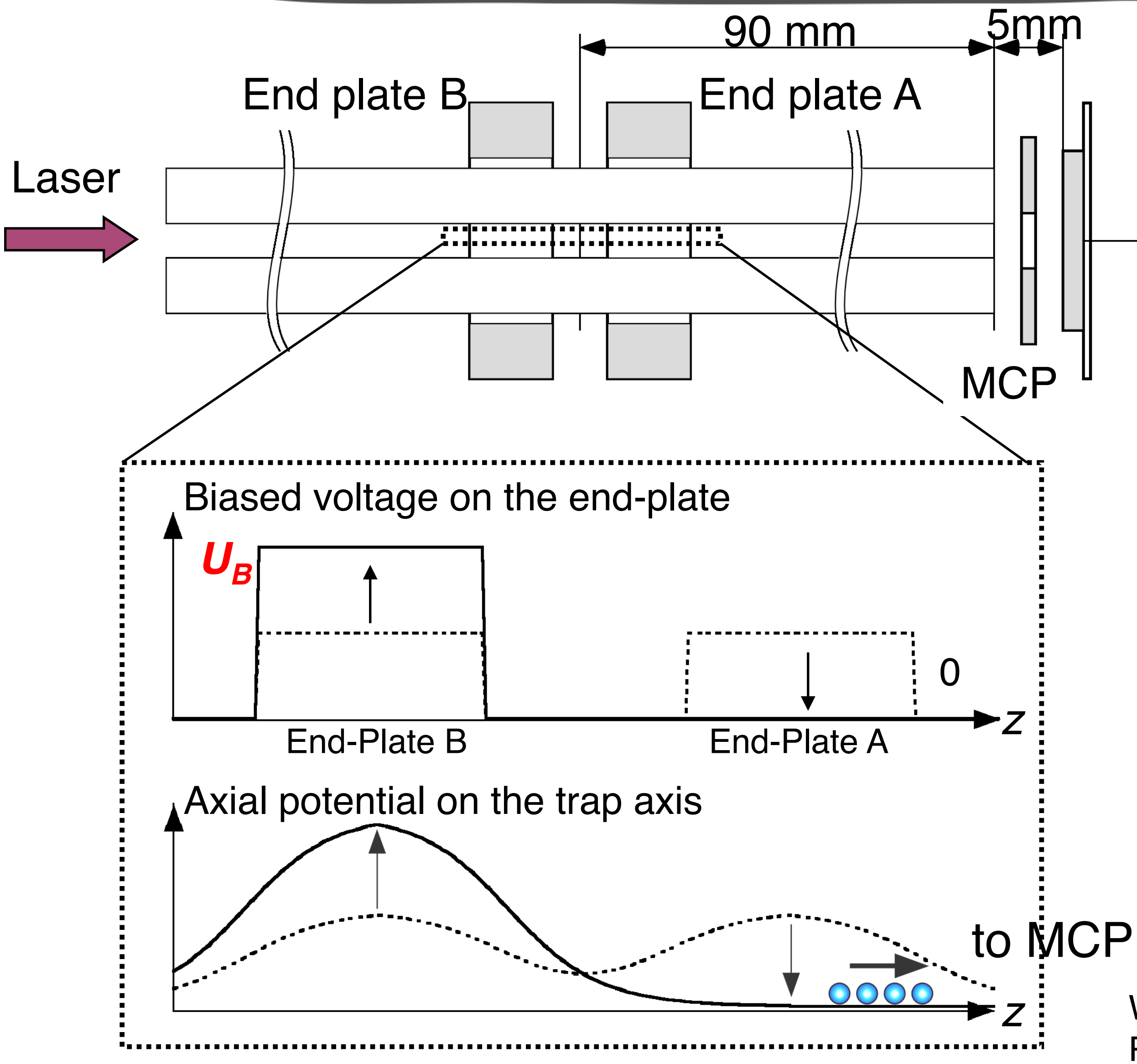
rf voltage on Q-rod
  ~30 V@2 MHz
dc voltage on End-Plate
  0.5V@Trapping

7. Extraction of Coulomb crystal



W. Schnitzler et al.,
Phys. Rev. Lett **102** (2009) 070501.

7. Extraction of Coulomb crystal

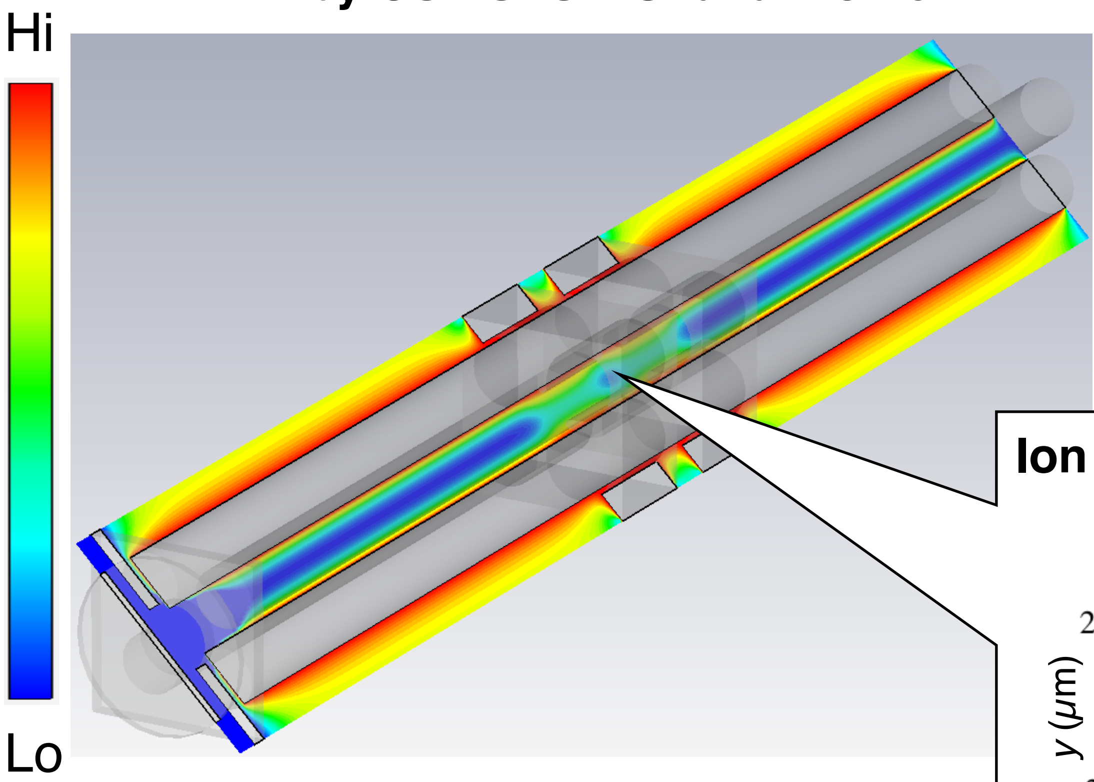


Oscilloscope
sampling time : 0.1ns

W. Schnitzler et al.,
Phys. Rev. Lett **102** (2009) 070501.

8. 3D simulation -Trapping-

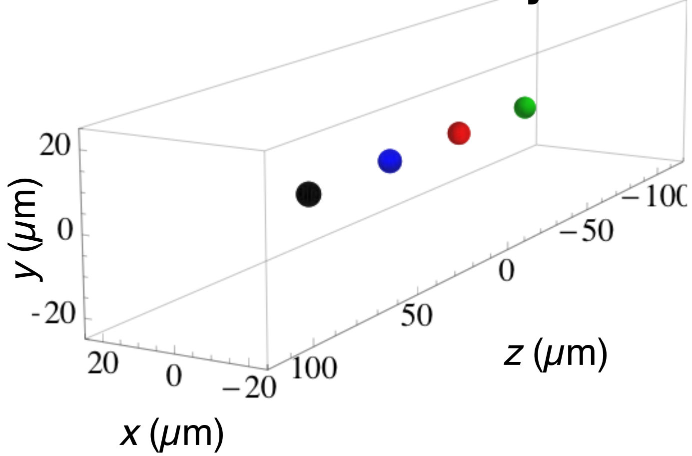
Potential calculated by CST STUDIO* at a moment



3D multi-particle simulation code

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

Ion distribution in the crystal state

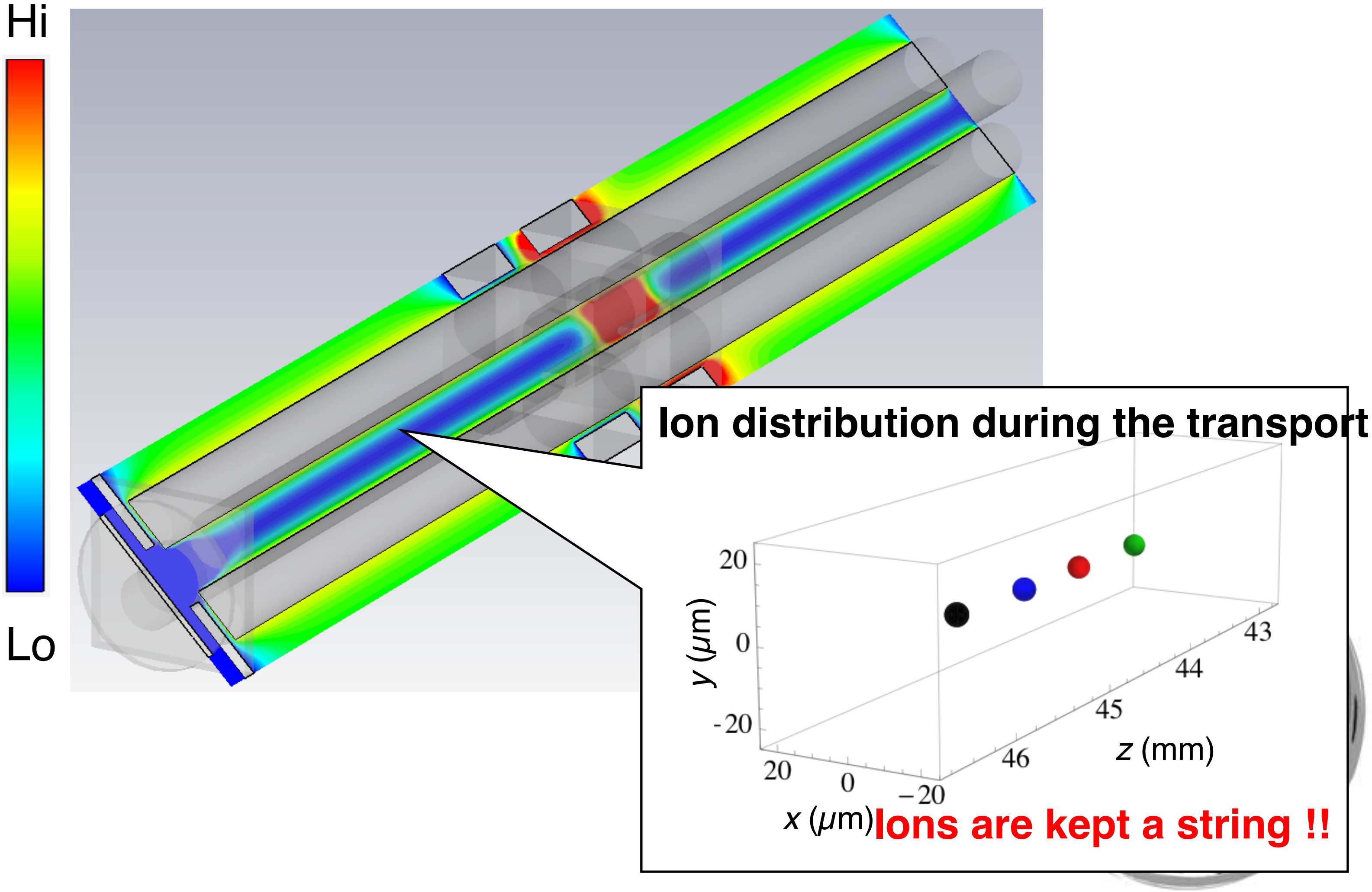


*)http://www.cst.com/

9. 3D simulation -Extraction-

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

Potential distribution



9. 3D simulation -Extraction-

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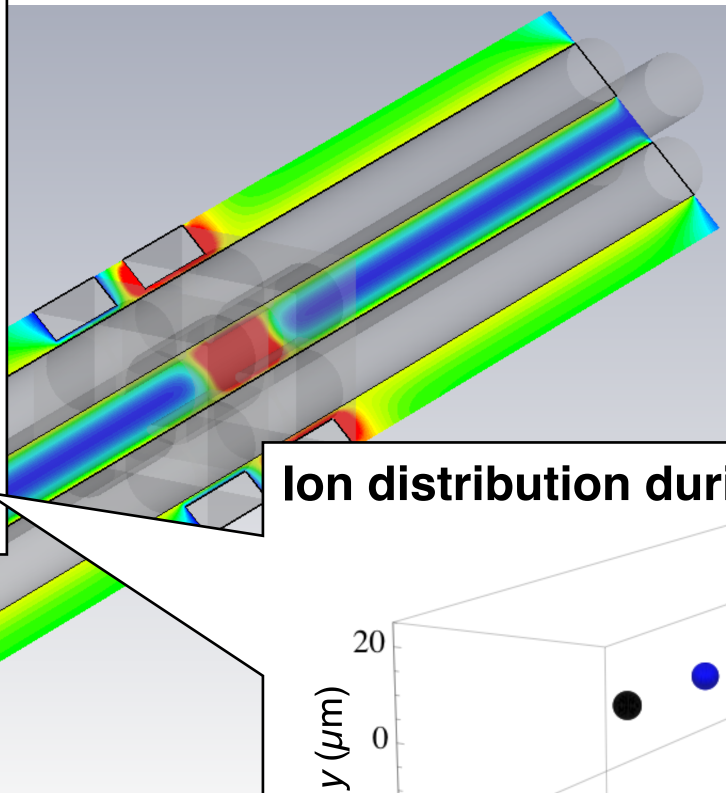
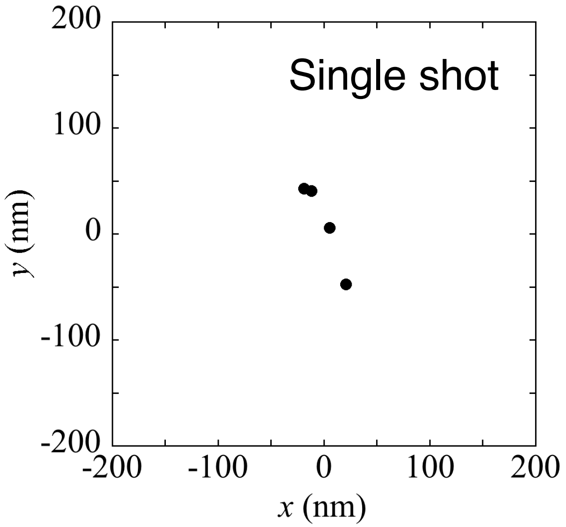
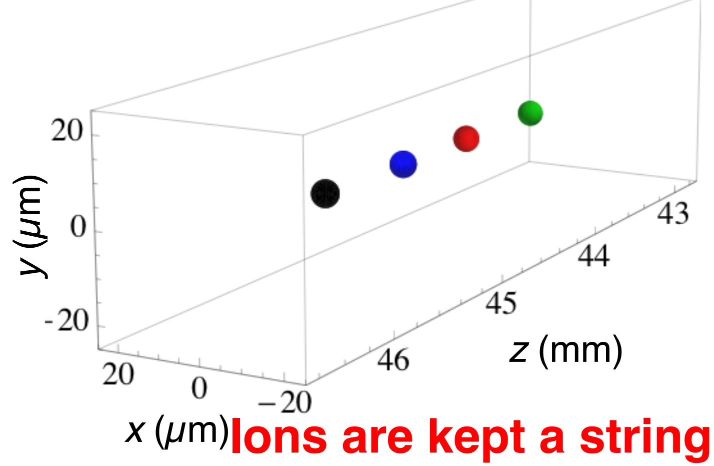


Spatial distribution of extracted $^{40}Ca^{+}$ ions on MCP

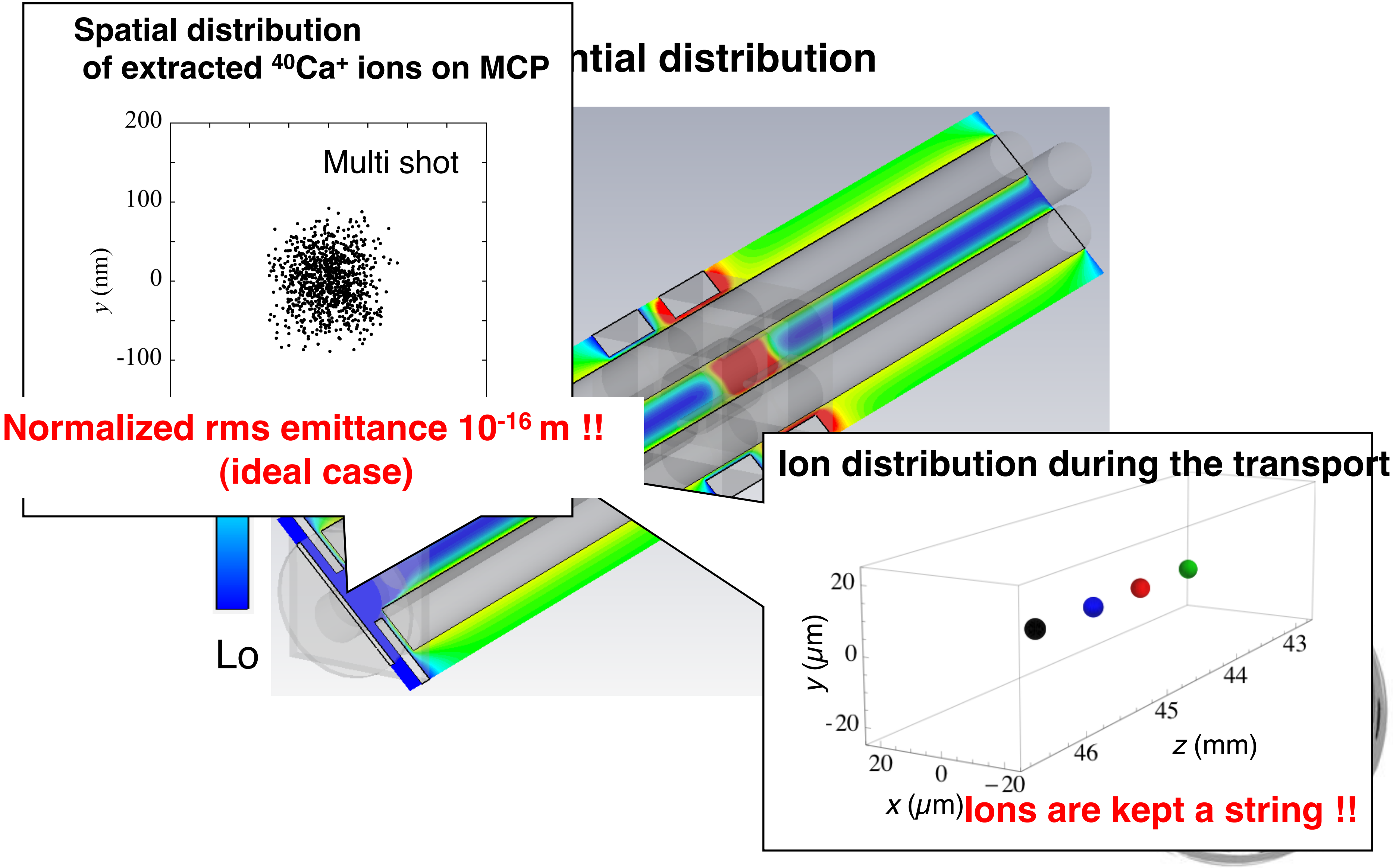


Ion distribution during the transport

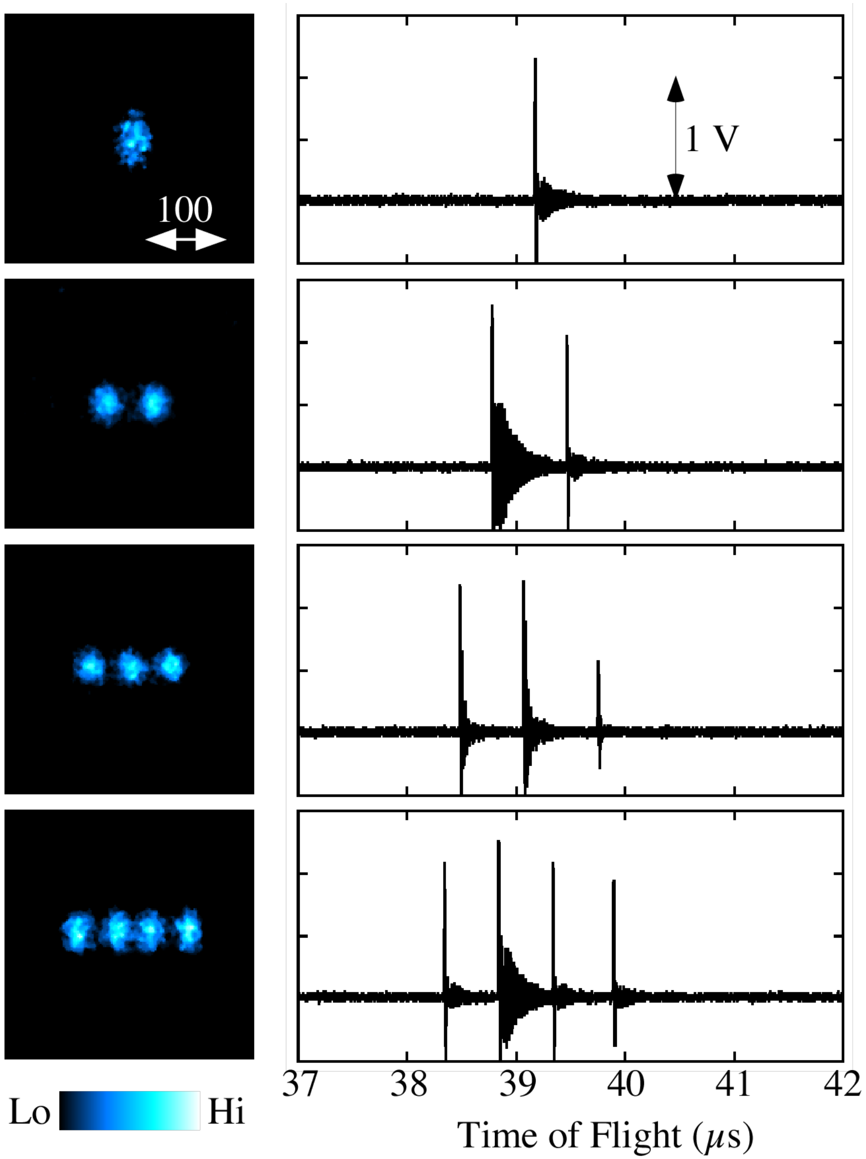


Ions are kept a string !!

9. 3D simulation -Extraction-



10. We succeed in extracting string crystals !



Coulomb crystal (LIF signal)

- number
- spatial position
- distance

Extracted ion (MCP signal)

- number
- TOF timing
- time interval

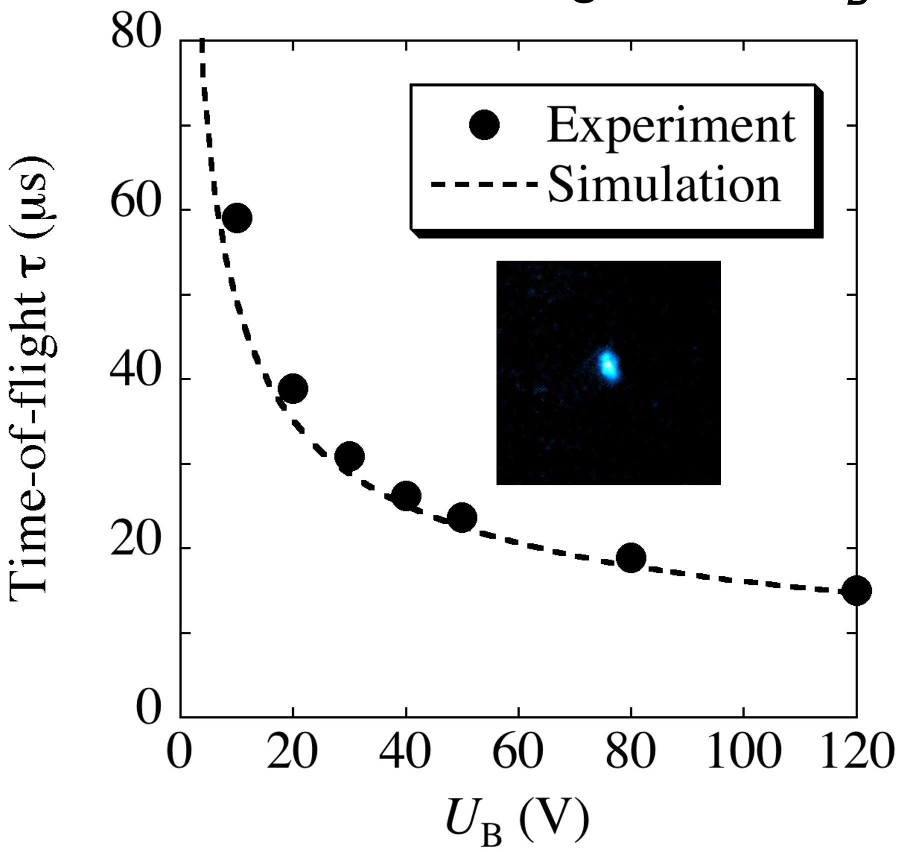
The spatial structure of the Coulomb crystal

The temporal structure of the extracted ions

Ultracold ions are extracted without major heating !!

11. TOF can be controlled by the extraction voltage.

Dependence of the TOF of an ultracold single ion on U_B



Controllability of TOF is important.

- TOF decreases with the increasing U_B.

⇩

We can control the TOF by U_B !!

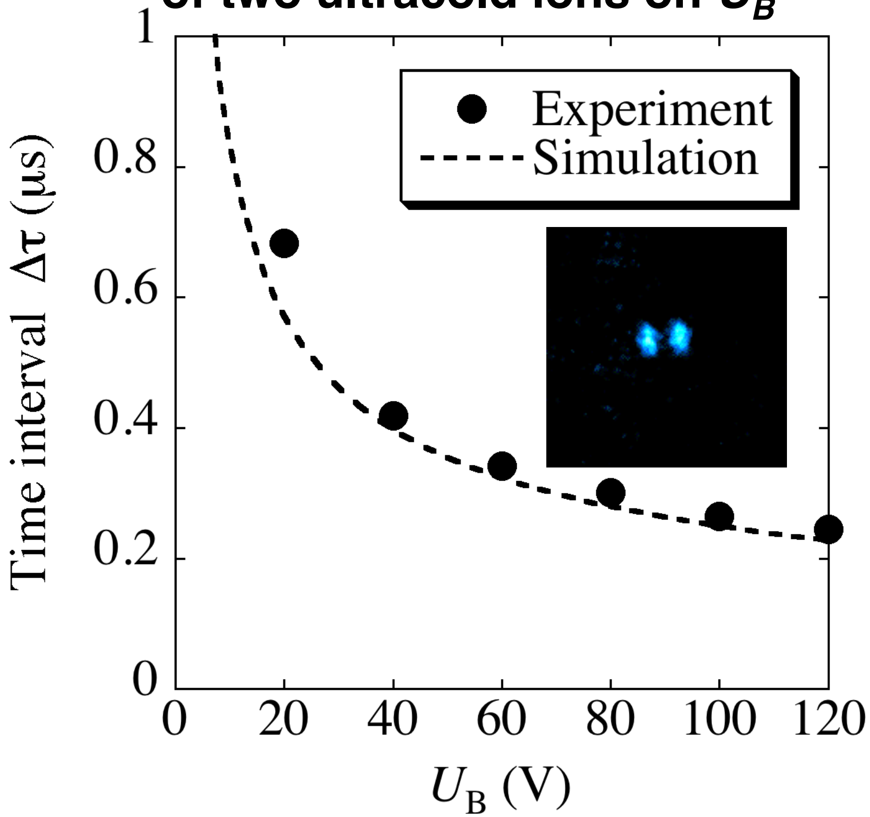
- The experimental observations are in good agreement with 3D simulation results.

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.

Dependence of the time interval of two ultracold ions on U_B



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

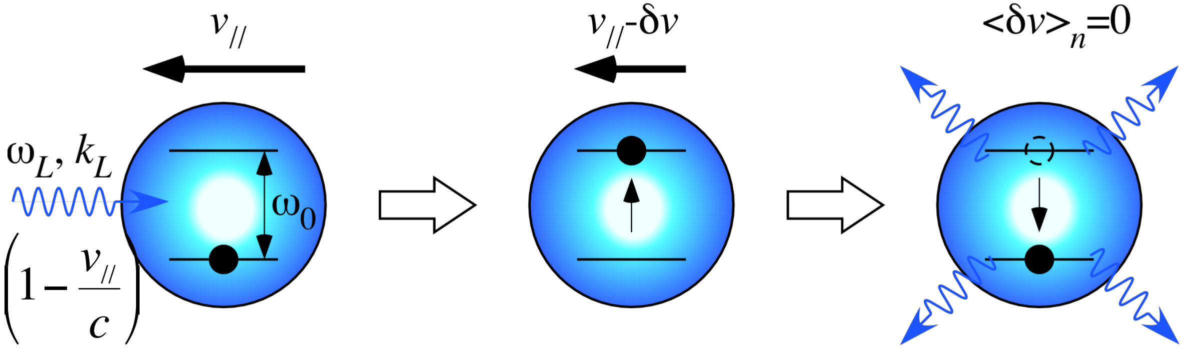
We have performed an experimental study of a novel ion source. The core of the system is a compact linear Paul trap where a small number of ions are manipulated with a laser before the extraction.

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

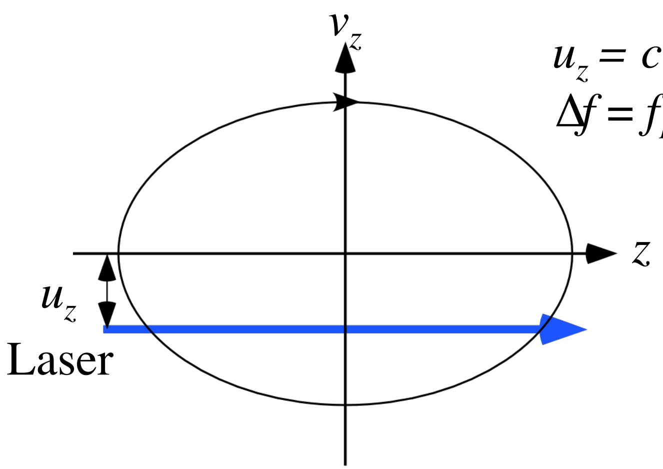


$$\omega_L \approx \omega_0\left(1-\frac{v_{//}}{c}\right)$$

ω_L, k_L: angular frequency and wave number of photons

ω_0: resonant frequency of the ion

Cooling of trapped ions

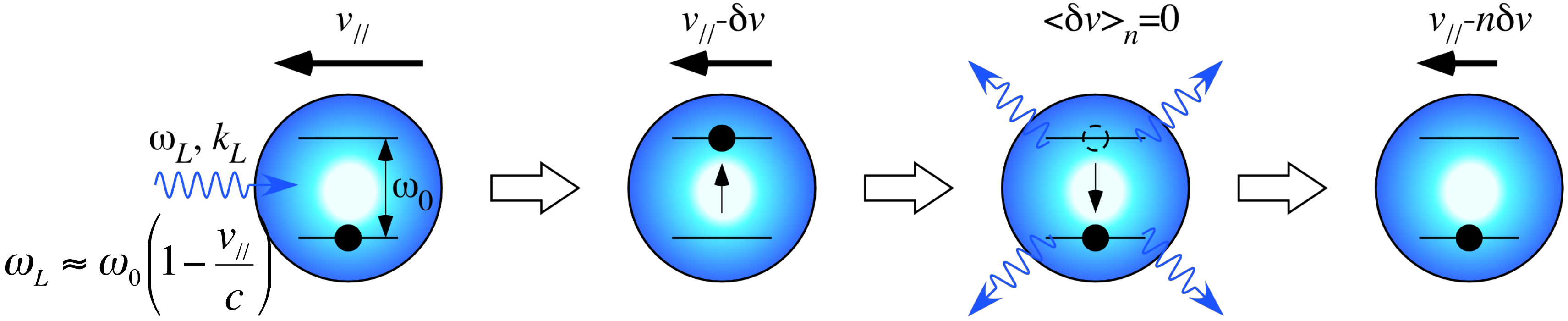


$u_z = c\Delta f / f_0$

$\Delta f = f_L - f_0$: detune

A1. Doppler laser cooling

Deceleration of an ion by photons



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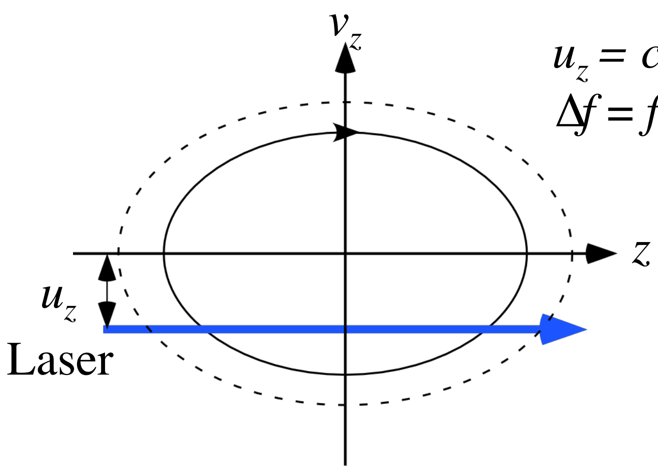

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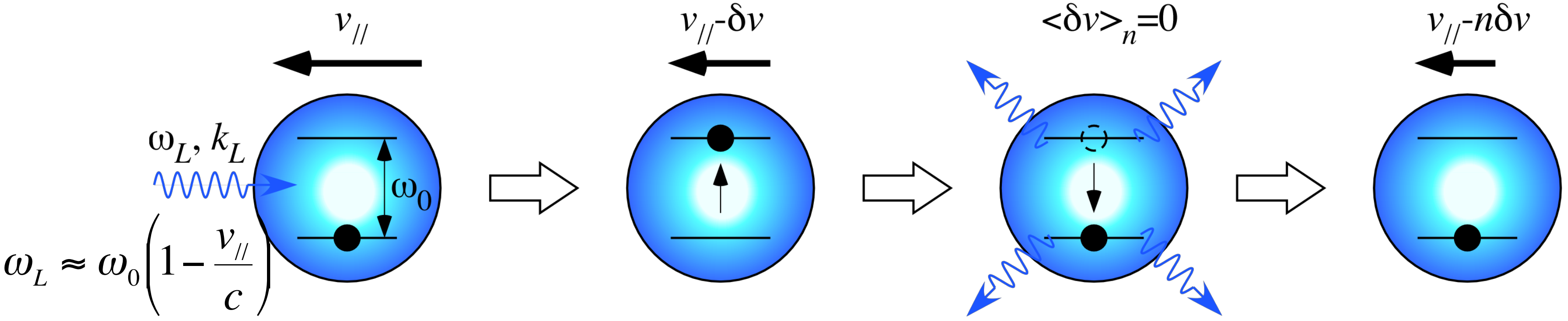

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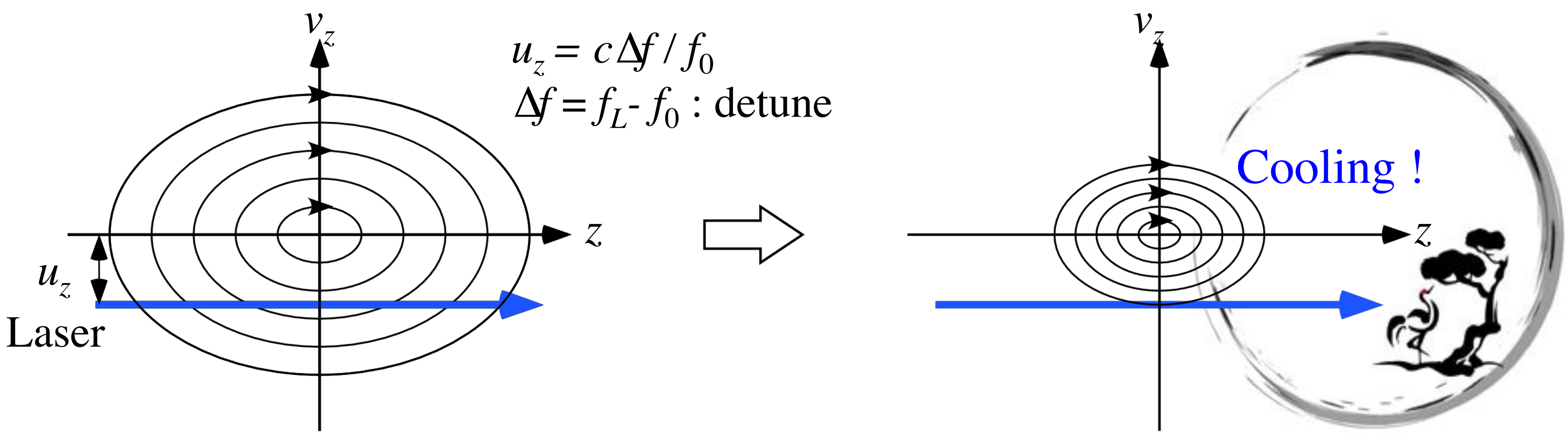


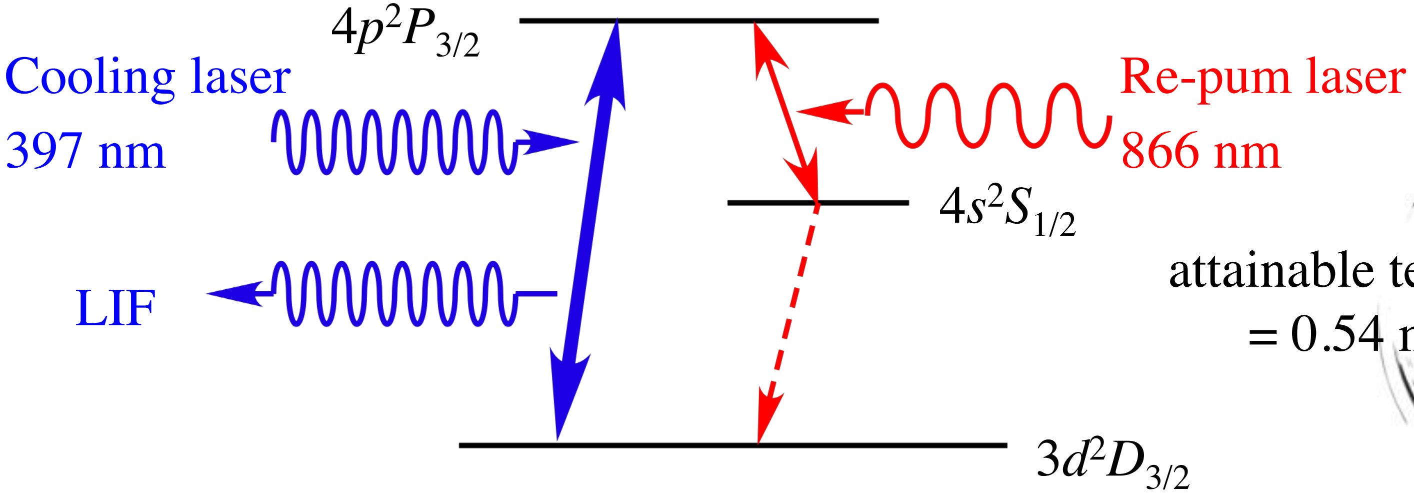
A2. Laser cooling and LIF measurement of $^{40}Ca^+$

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 $^{40}Ca^+$ about laser cooling & LIF



attainable temperature
= 0.54 mK