SIMULATION STUDY ON TRANSVERSE LASER COOLING AND ORDERING OF HEAVY-ION BEAMS IN A STORAGE RING

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Purpose of the Present Study

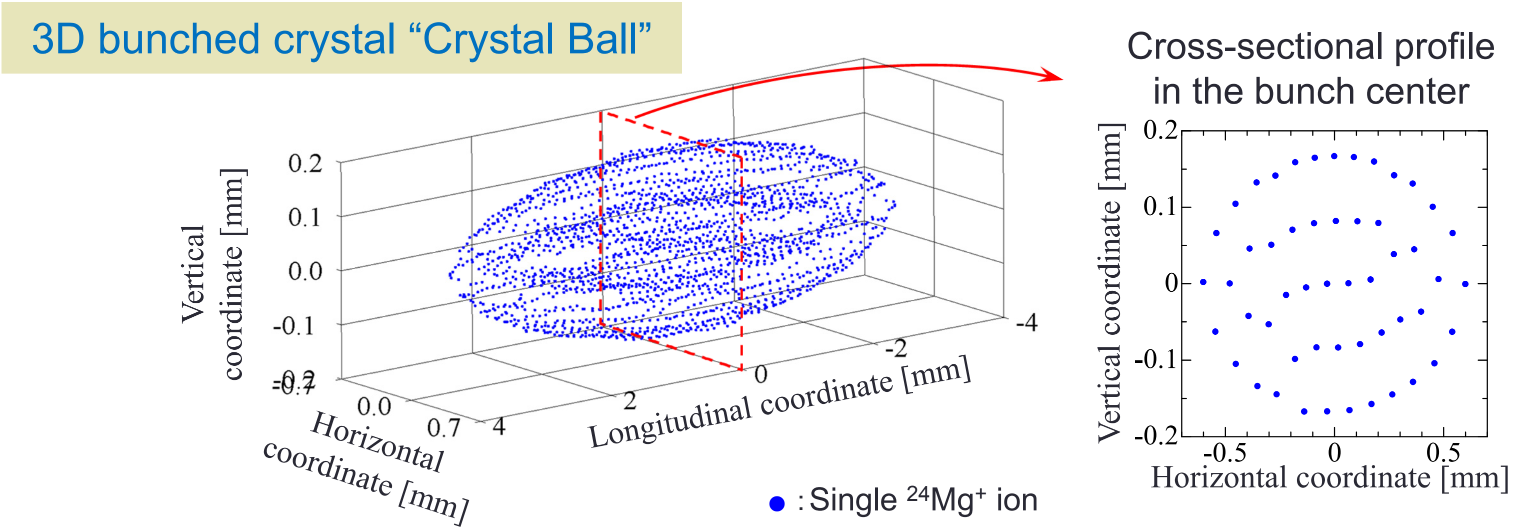
- Final goal:
  - Generation of ultralow-temperature ion beams
  - Realization of beam ordering and crystallization

  (in collaboration with H. Okamoto, A. Sessler, J. Wei, A. Noda, etc.)

- This work (Outline):
  - 3D laser cooling is investigated for generating ultralow-temperature beams with a molecular dynamics (MD) simulation.
  - A 3D ordered structure of the laser-cooled beam is formed in the ultralow-temperature state.
  - The characteristics of the ordered beam are discussed.

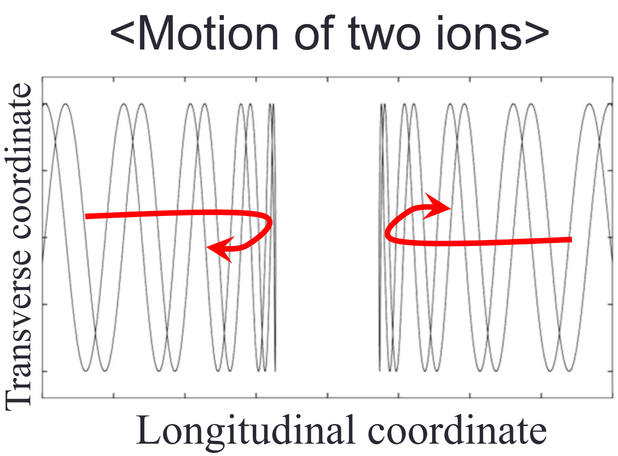
Crystalline Beam

- Coulomb crystalline state of a beam.
- No thermal motion.
- Periodic oscillation with the external focusing force.
- Coulomb coupling constant Γ > 170.
- Theoretically predicted, but not realized yet.



Beam Ordering

- Particle configuration is arranged in order.
- But, thermal motion remains.
- "1D (longitudinal) ordering" was observed experimentally in electron-cooled ultralow-intensity ion beams.
- The longitudinal relative positions of particles do not change.



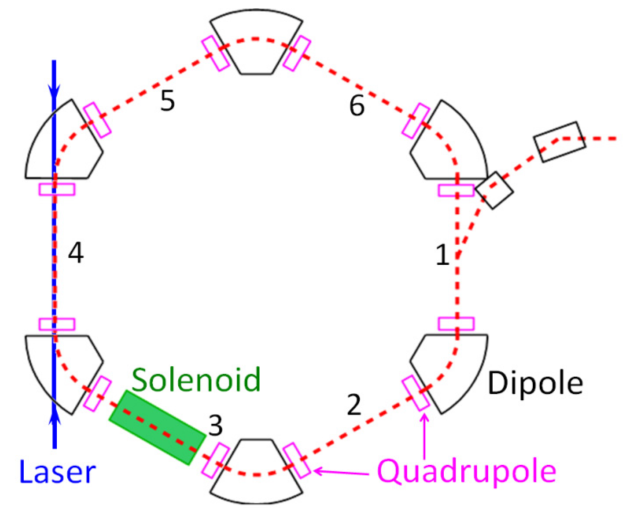
M. Steck et al., (PRL1996), H. Danared et al., (PRL2002), T. Shirai et al., (PRL2007)

Structure	Crystallization	Ordering
1D	Theoretically predicted (3D cooling needed)	Experimentally observed
3D	Theoretically predicted (special cooling force needed)	?

MD Simulation Conditions

- Machine (S-LSR at Kyoto Univ.)
  - Circumference 22.56 m
  - Superperiodicity N_{sp} 6
- Lattice
  - Betatron tunes $\nu_x = \nu_y (= \nu_0)$ 1.44
  - Maintenance condition ($\nu_0 < \frac{N_{sp}}{2\sqrt{2}}$) is fulfilled.

<Schematic view of S-LSR>

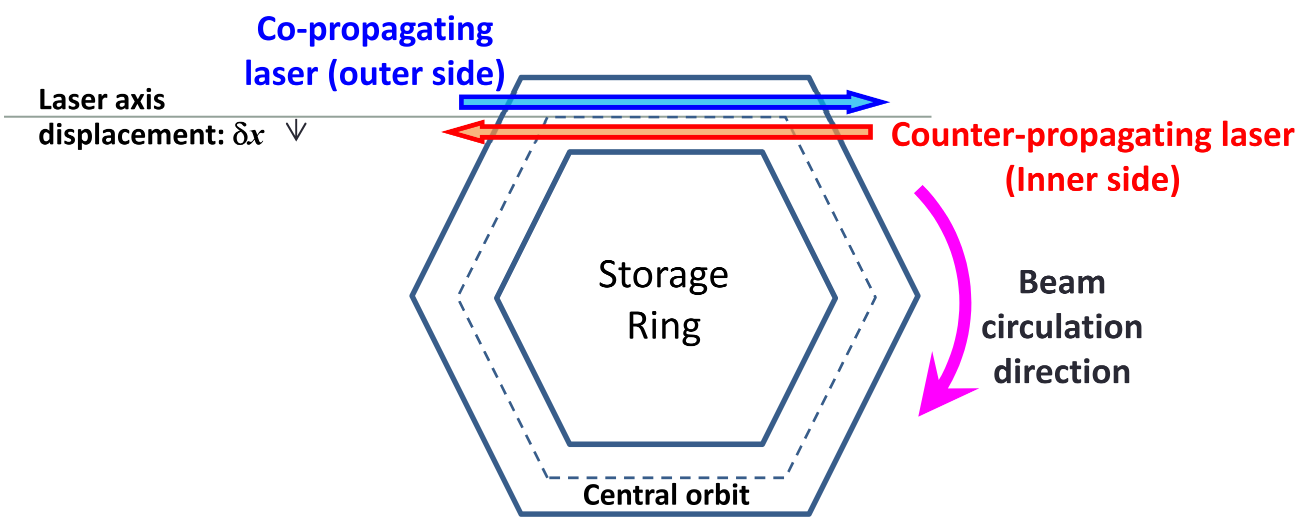


- Beam
  - Ion species 40-keV $^{24}Mg^{+}$
  - Lorentz factors β=1.89x10^{-3}, γ=1.00000179
  - Revolution frequency (period) 25 kHz (40 μsec)
  - Initial emittance (rms, $\varepsilon_x = \varepsilon_y$) 1x$10^{-9}$ π m.rad (Normalized)
    5x10^{-7} π m.rad (Un-normalized)
  - Initial dp/p (rms) 7x10^{-4}

From a typical experimental result

Transverse Laser Cooling (1)

- The axes of Gaussian lasers are displaced horizontally in a dispersive cooling section.
  - I. Lauer et al., (PRL1998), N. Kjærgaard and M. Drewsen, (PLA1999)



- The longitudinal cooling force is extended to the horizontal direction through momentum dispersion.
  - H. Okamoto and J. Wei, (PRE1998).

Transverse Laser Cooling (2)

- Resonant coupling method for vertical cooling.
  - H. Okamoto, D. Möhl, and A. M. Sessler, (PRL1993, PRE1994)

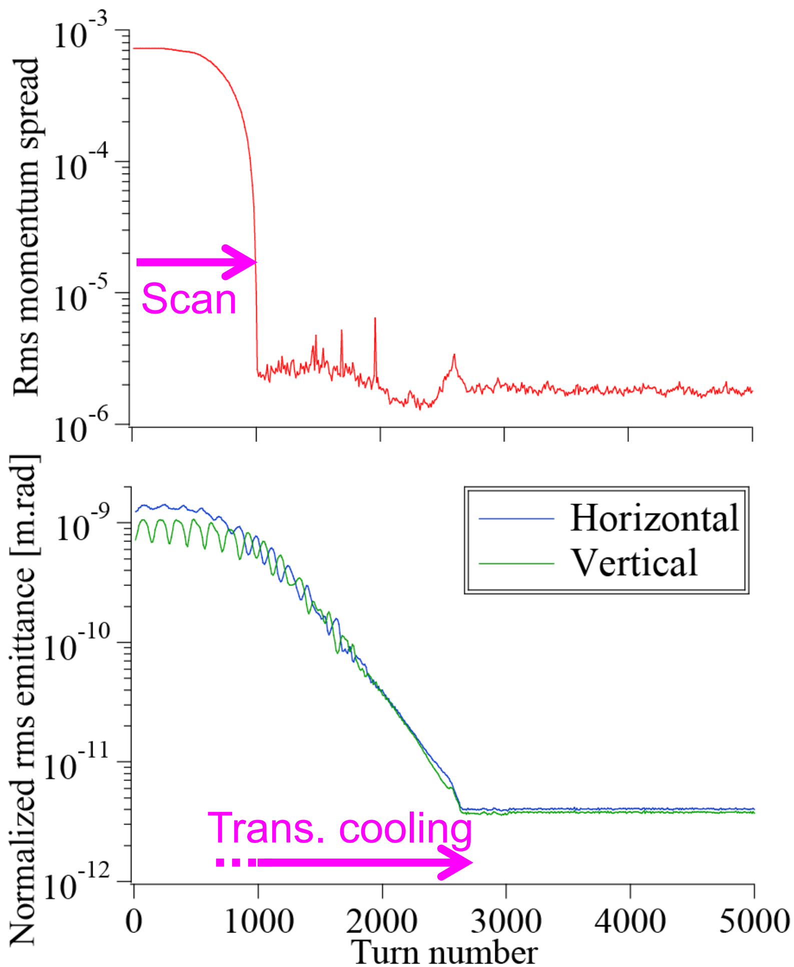
- First, introduce a coupling source in the ring:
  - Solenoid magnet for X-Y coupling

$$H = \underbrace{\frac{1}{2}(p_x^2 + \kappa_x^2 x^2)}_{\text{Horizontal}} + \underbrace{\frac{1}{2}(p_x^2 + \kappa_y^2 y^2)}_{\text{Vertical}} + g_{xy} xy$$

- Then, operate the ring at a difference resonant condition:

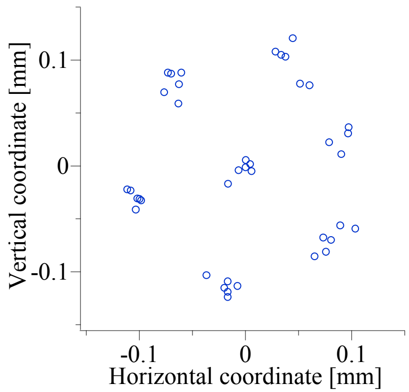
$$\nu_x - \nu_y \approx \text{integer}$$

MD Results (1: Time evolution)



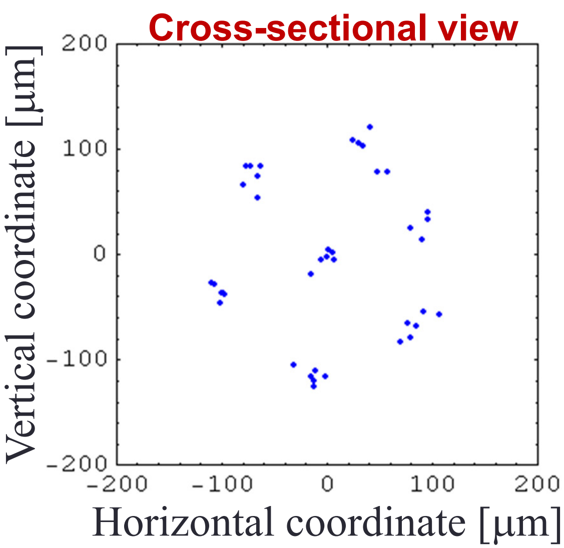
- Beam (40-keV $^{24}Mg^{+}$)
  - Line density: 4×10^4 m^{-1}
- Two Lasers
  - Power: 100 mW
  - Gaussian spot radius: 5 mm (2-sigma)
  - Axis displacement: 3 mm
  - Initial detuning: -4.3 GHz
  - Final detuning: -61 MHz
  - Frequency scanning: 1000 turns (40 ms)

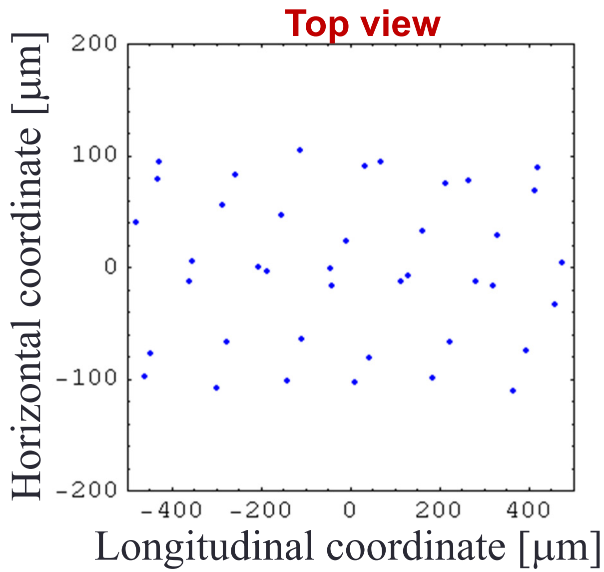
Cross-sectional view of the equilibrium state

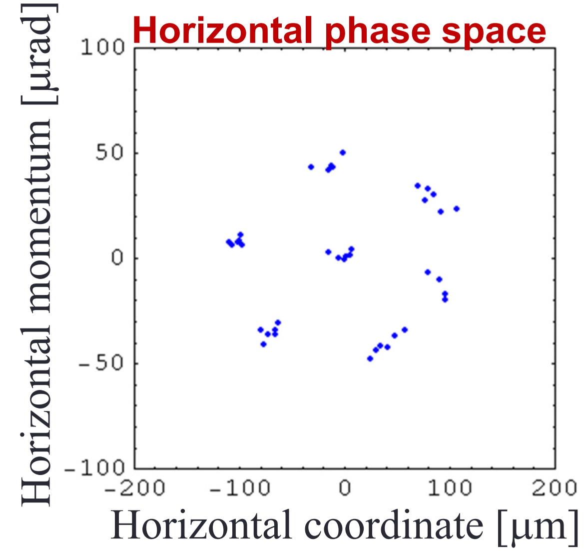


The transverse direction is cooled after the laser scan is ended because the transverse cooling rate is higher for smaller detuning.

MD Results (2: Equilibrium state)







Rotation of outer ions

- Depressed tunes:
  - $\nu_x = \nu_y$: 1.44 --> 1.20 (η~0.83)

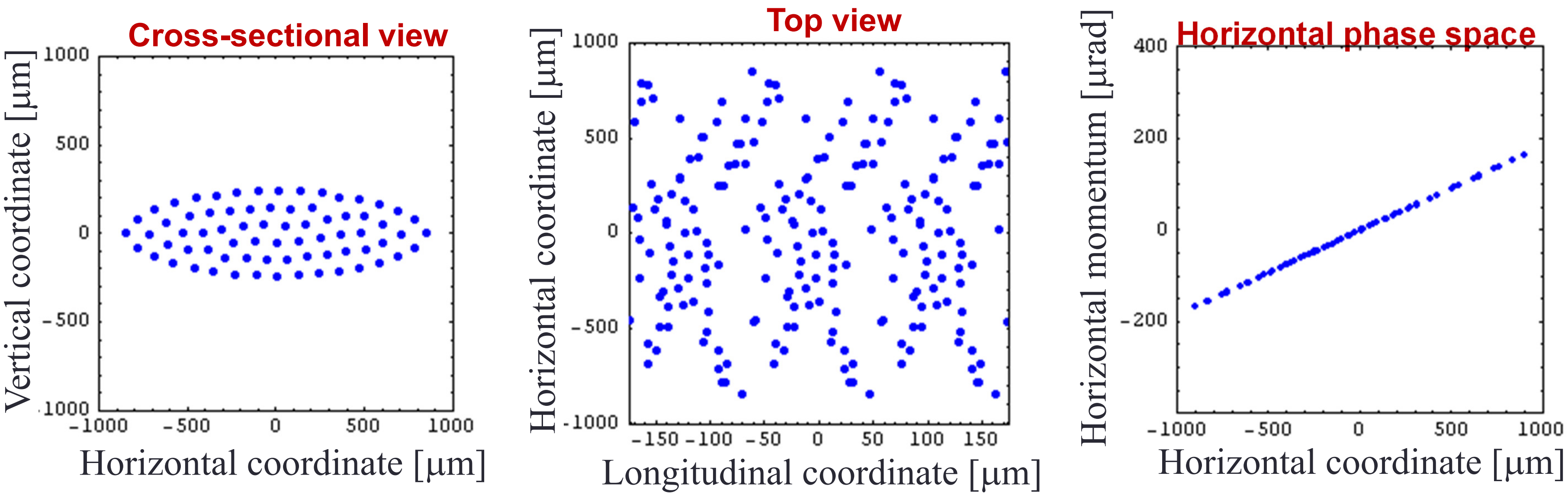
Still executes betatron oscillation!

Nonlinear phase-space configuration

- Equilibrium temperature:
  - $T_x \sim T_y \sim 0.3$ K, $T_z \sim 3$ mK
- Coulomb coupling constant
  - $\Gamma_x \sim \Gamma_y \sim 0.7$, $\Gamma_z \sim 70$

In the ultralow-temperature region,
the laser-cooled beam exhibits a 3D ordered structure.

Reference: Motion of a crystal



- Periodic oscillation with lattice superperiodicity. (No ordinary betatron oscillation)
- Linear phase-space configuration.

Summary

- 3D laser cooling and ordering of heavy-ion beams were studied using the MD simulation technique.
- A 3D ordered (but not crystallized) structure of the beam was formed by 3D laser cooling.
- The ordered beam exhibits unique characteristics such as the rotation of outer ions and phase-space distribution, unlike a crystalline beam.
  - Crystallization: Thermal oscillation fully suppressed
  - Ordering: Thermal oscillation remains, but ordered configuration
- Such an ordered beam can be generated in a cooler storage ring S-LSR, Kyoto University.