SIMULATION STUDY ON TRANSVERSE LASER COOLING AND CRYSTALLIZATION OF HEAVY-ION BEAMS AT THE COOLER STORAGE RING S-LSR

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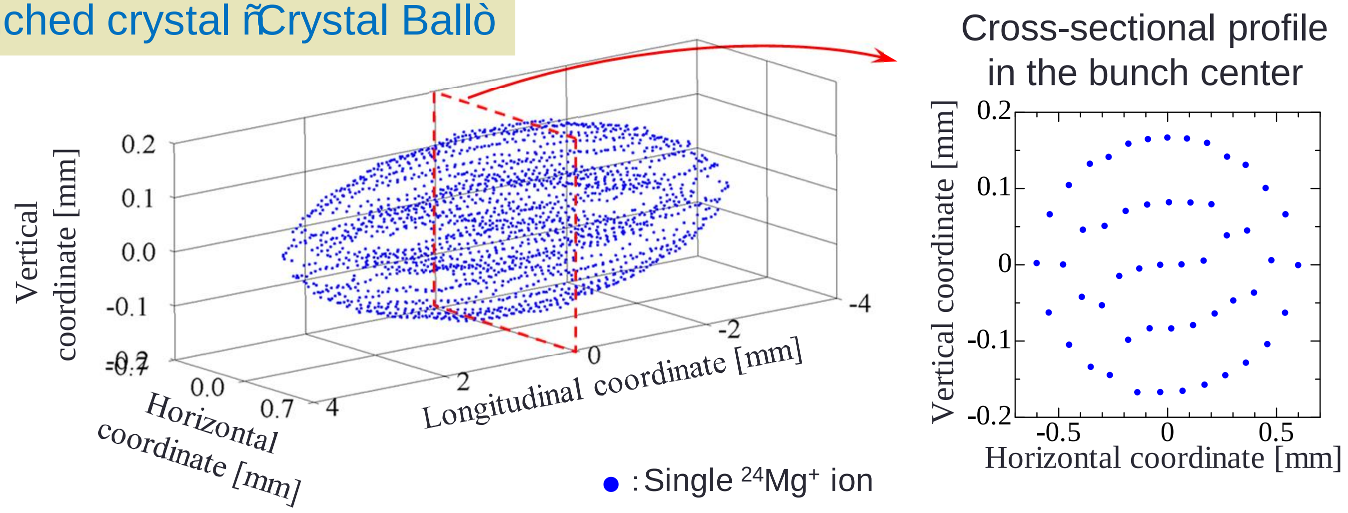
Outline

- Intro: Purpose of the present study
- Molecular dynamics (MD) simulation
- Simulation conditions
- MD results
  - Three-dimensional laser cooing
  - Crystallization
- Summary

Beam Crystallization

3D bunched crystal ñCrystal Ballò



- Coulomb crystalline state of an ion beam strongly cooled in a storage ring
- Characteristics:
  - Ultralow emittance
  - Coulomb coupling constant > 170
  - Periodic oscillation with the external focusing force
  - Stable after removing the cooling force

Purpose of the Present Study

- Feasibility of beam crystallization was already predicted if the ring and laser conditions were sufficient. (PRL2004, PRSTAB2005)
- However, laser-cooling conditions have been limited in the recent experiments at S-LSR.
    - Single laser beam, low power, and fixed detuning.

- To show numerically how to attain a low-emittance beam using Resonant Coupling and Laser Cooling by assuming actual parameters at S-LSR.
    - Optimization of a cooling laser for high cooling efficiency (To be presented at NA-PAC13)
    - Fast 3D cooling of low-current beams
    - Feasibility of beam crystallization

- Numerical study using a Molecular Dynamics (MD) simulation technique.

Molecular Dynamics (MD) Simulation

- The most reliable simulation technique for the study of beam cooling and crystallization.
- Hamiltonian

$$H = \frac{p_x^2 + p_y^2 + p_z^2}{2} - \frac{\gamma}{\rho} x p_z + \frac{x^2}{2\rho^2} - \frac{K(s)}{2}\left(x^2 - y^2\right) + \frac{r_p}{\beta^2\gamma^2}\phi.$$

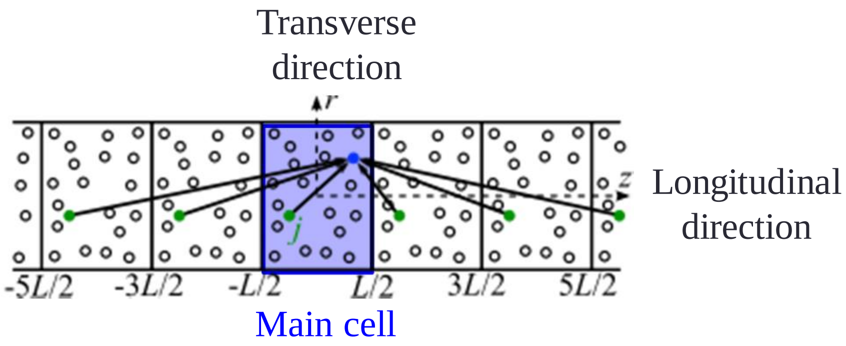
  - Motion of real particles is integrated in a symplectic manner.
- Coulomb potential --- Periodic boundary condition imposed

$$\phi = \sum_j (\phi_{short}^{(j)} + \phi_{long}^{(j)}).$$

$$\phi_{short}^{(j)} = \frac{1}{\sqrt{(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2}}$$

$$\phi_{long}^{(j)} = \frac{2}{L}\int_0^\infty \frac{\cosh(kz^{(j)}/L) J_0(kr^{(j)}/L) - 1}{e^k - 1} dk$$

where $z^{(j)} = |z - z_j|$ and $r^{(j)} = \sqrt{(x - x_j)^2 + (y - y_j)^2}$.



For a bunched beam, *L* can be set as a bucket length (*C*/*h*).

Resonant Coupling for 3D Cooling

- A possible scheme for efficient transverse cooling
  - H. Okamoto, D. Mohl, and A. M. Sessler, (PRL1993, PRE1994)

- First, introduce a coupling source in the ring.
  - RF cavity placed where the dispersion is finite for X-Z coupling
  - Solenoid magnet for X-Y coupling

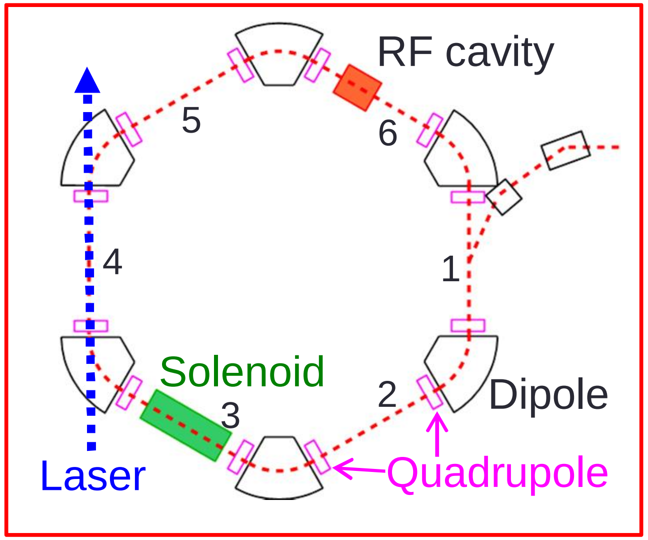
- Then, operate the ring at a difference resonant condition;

$\nu_x - \nu_z \approx \text{integer}$ for X-Z coupling

$\nu_x - \nu_y \approx \text{integer}$ for X-Y coupling

MD Simulation Conditions (1)

Schematic view of S-LSR



- Machine (S-LSR at Kyoto Univ.)

Circumference	22.56 m
Superperiodicity	6

- Lattice

Tunes	Case-I (ν_x, ν_y, ν_z)~(2.07, 1.12, 0.07)
	Case-II (ν_x, ν_y, ν_z)~(2.07, 1.07, 0.07)
RF bunching voltage	~40 V
Harmonic number	100
Adiabatic capture	5,000 turns (0.2sec)

- Beam

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

From the measurement result

MD Simulation Conditions (2)

- Laser (1 co-propagating laser)

Power	8mW
Spot radius *w* (2sigma)	0.66 mm (Peak Saturation Power~4.6)
Detuning Δ (fixed)	-200 MHz
Cooling time	3 sec

From the experiment

These parameters are rather limited as compared to past experiments in TSR & ASTRID.

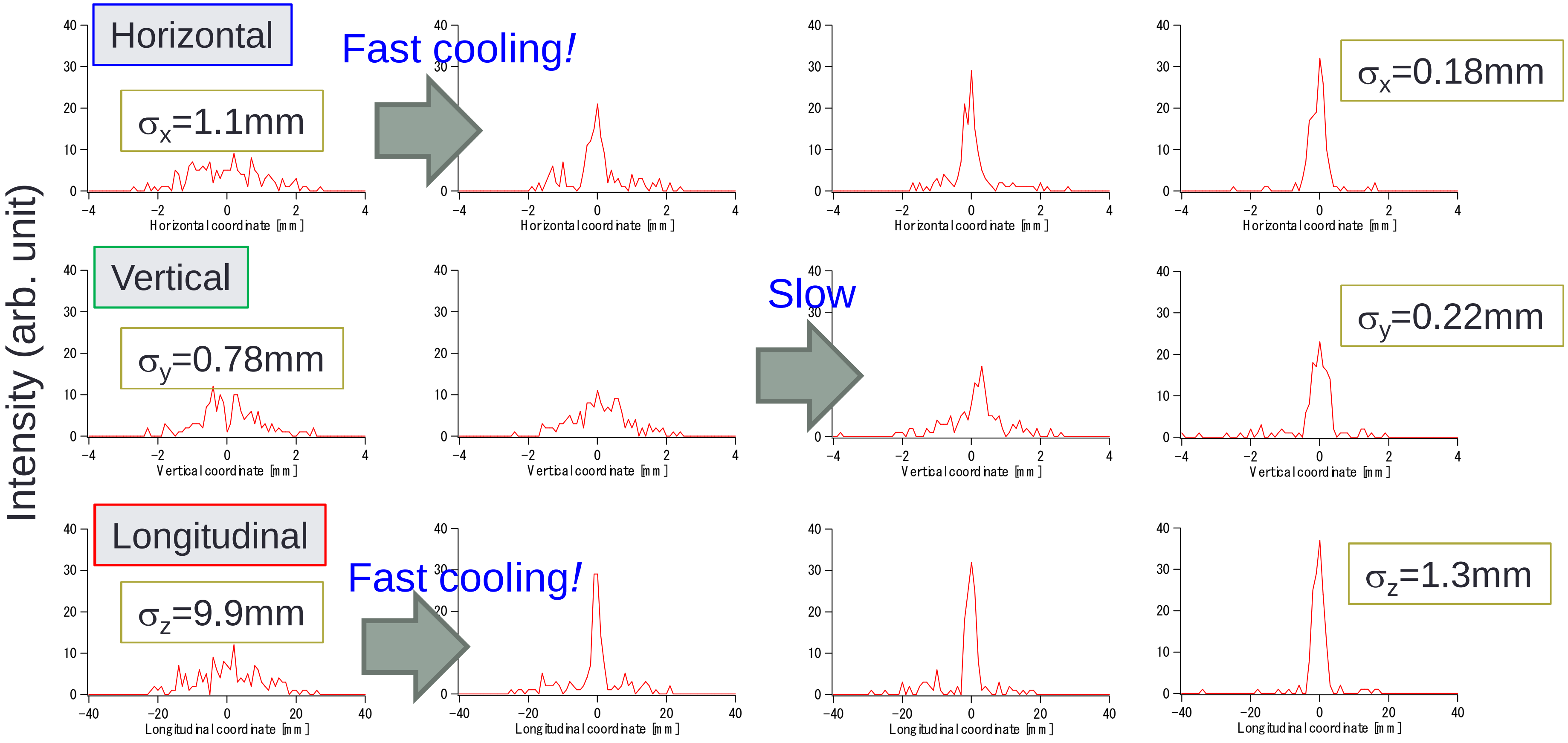
Cooling force: $$F = \frac{1}{2}\hbar k_L \Gamma \frac{S_L}{1 + S_L + (2\Delta/\Gamma)^2}$$

Saturation parameter : $$S_L = S_0 \exp\left[-\frac{2(x^2+y^2)}{w^2}\right]$$

Laser detuning : $$\Delta \approx \omega\gamma\left[1-\beta\left(1+\frac{\delta p}{p}\right)\right]-\omega_0$$

Case-I
(ν_x, ν_y, ν_z)
~(2.07, 1.12, 0.07)

MD Results (1: Time evolution)



(a) Before cooling
(cooling time=0s)

(b) 1,000 turns later
(cooling time=0.04s)

(c) 3,000 turns later
(cooling time=0.12s)

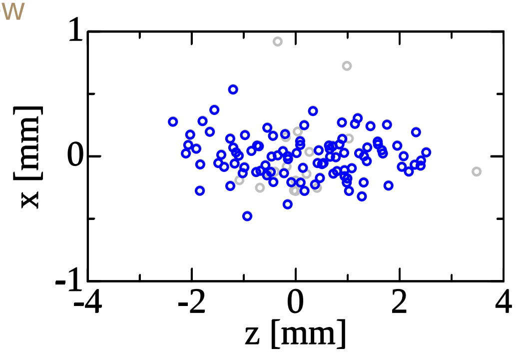
(d) 15,000 turns later
(cooling time=0.6s)

The vertical direction is cooled through the Coulomb interaction between ions, although no artificial cooling force is introduced.

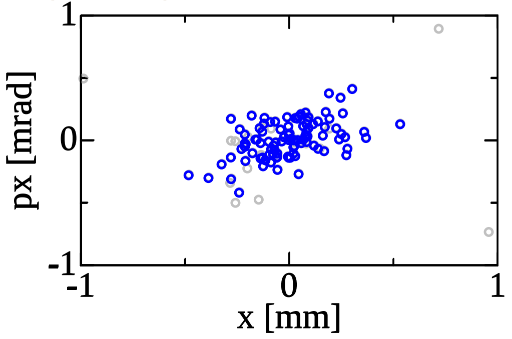
Case-I
(ν_x, ν_y, ν_z)
$\sim(2.07, 1.12, 0.07)$

MD Results (2: Equilibrium state)

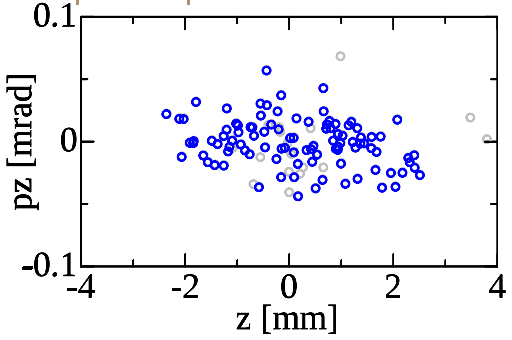
Top-view



Horizontal phase space



Longitudinal phase space



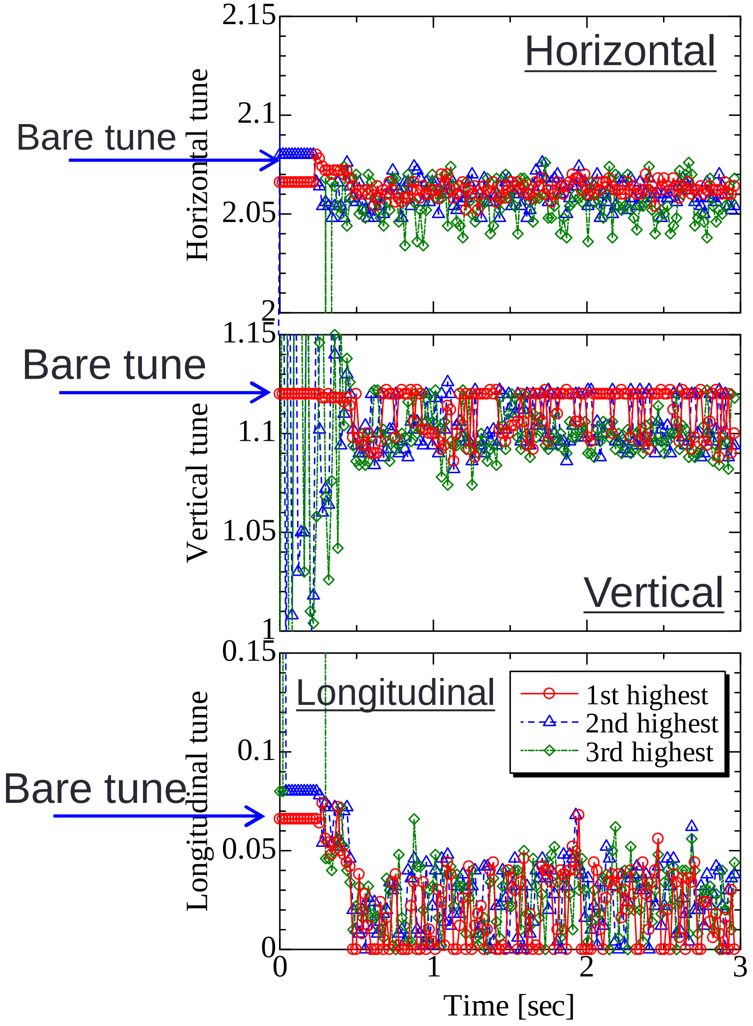
- The ion number of the cooled part (blue ions in the picture) is about 100. Namely, the cooling efficiency is about 70%.
- Horizontal
  - Norm. rms $\varepsilon=4.6\times10^{-11}$ [πm.rad]
  - Tx=18[K]
  - Radius $\sigma=0.18$mm
- Vertical
  - Norm. rms $\varepsilon=2.6\times10^{-11}$ [πm.rad]
  - Ty=3.8[K]
  - Radius $\sigma=0.22$mm
- Longitudinal
  - Rms dp/p $=2.2\times10^{-5}$
  - Tz=0.45[K]
  - Radius $\sigma=1.3$mm

These values agree well with the observation result in S-LSR*!!*

The beam is three-dimensionally cooled, but the ordered configuration cannot be seen.

Case-I
(ν_x, ν_y, ν_z)
~(2.07, 1.12, 0.07)

MD Results (3: Tune shift)



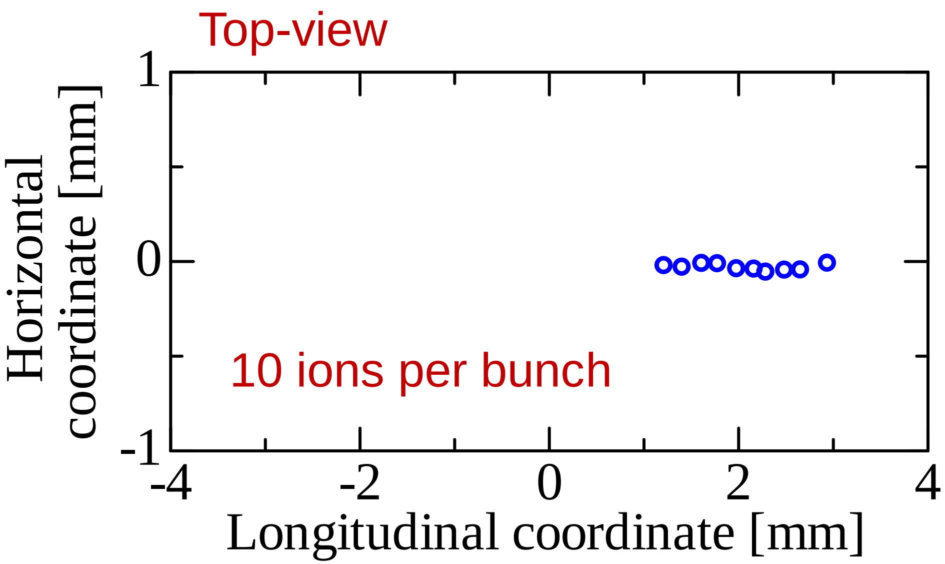
- The orbits of several ions are Fourier-transformed to see the time evolution of tunes in all three directions.
- The three highest peaks in the power spectrum (right pictures) are plotted.
- Result: tune shift
  - Horizontal 2.07 --> 2.05~2.06
  - Vertical 1.12 --> 1.09~1.10
  - Longitudinal 0.07 --> 0.00~0.04

- The synchrotron tune is almost damped by laser cooling.
- The beam is still oscillating in the transverse direction.

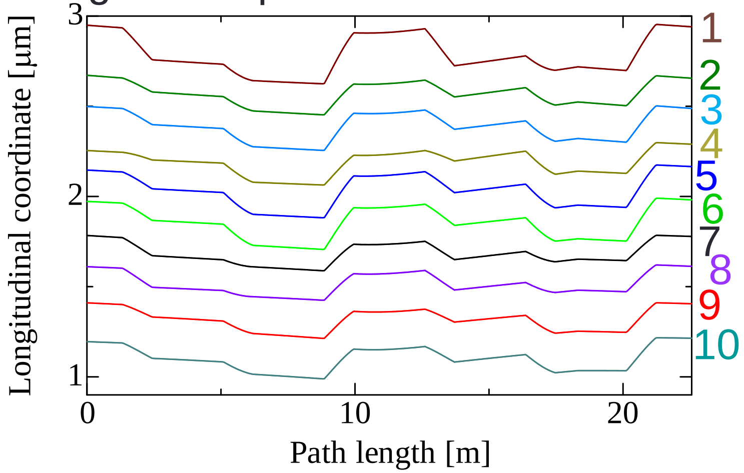
The laser-cooled beam is three-dimensionally space-charge-dominated.

Case-I
(ν_x, ν_y, ν_z)
$\sim(2.07, 1.12, 0.07)$

MD Results (4: Crystallization)



Time evolution (one turn) of the longitudinal positions of the 10 ions



- Even with the limited laser-cooling condition, 1D string crystal can be formed when the beam current is sufficiently low and detuning is small.

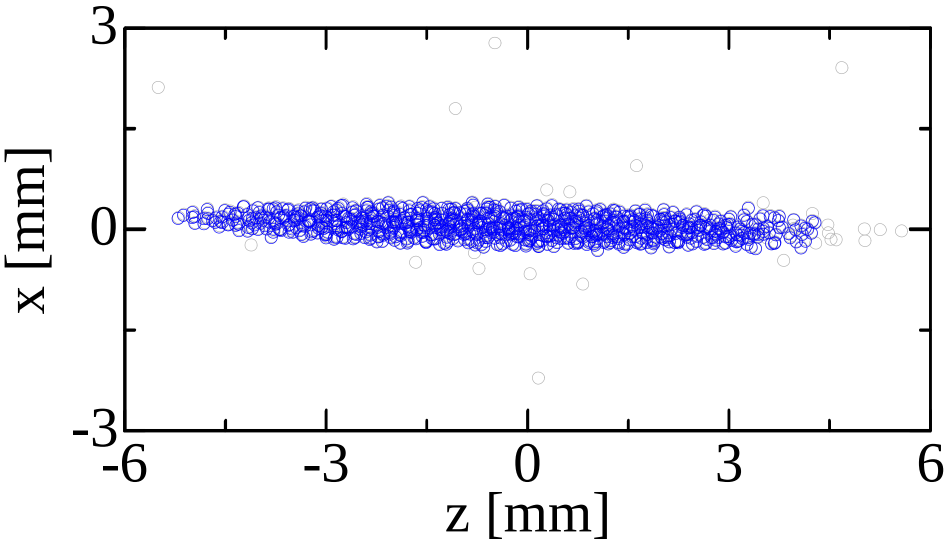
- Each ion does not pass by neighboring ions.
- The synchrotron oscillation is fully depressed.

Note that the bunch is positioned forward because the beam is pushed by the co-propagating laser.

Beam crystallization is feasible at S-LSR*!!*

Case-II
(ν_x, ν_y, ν_z)
~(2.07, 1.07, 0.07)

MD Results (5: Ideal case)



- 1000 ions per bunch
- 3D-resonant tunes:
  - (ν_x, ν_y, ν_z)=(2.07, 1.07, 0.07)
  - Weak solenoid B=80G
- Laser conditions:
  - 2 lasers (co- and counter-propagating)
  - High power (100mW)
  - Frequency scanned (-4GHz to -40MHz for 1sec)

- More than 90% ions are laser-cooled.
- Transverse norm. rms emittance~1x10^{-11} πm.rad (Tx,y~10K)
- Longitudinal momentum dp/p~1x10^{-5} (Tz~0.1K)

The highest-quality heavy-ion beam can be formed just by improving the laser system in S-LSR*!!*

Summary

- 3D laser cooling of the heavy-ion beam in S-LSR was studied using the MD simulation technique.
- The three-dimensionally low-temperature bunched ion beam was generated through resonant coupling.
- The MD result agreed well with the observation result in the recent experiment in S-LSR.
- Beam crystallization (1D string at low line density) is possible even in a limited cooling situation.
- An ultra-low-emittance bunched beam can be formed at a high intensity by a combination of powerful laser cooling and resonant coupling.