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 cooling
- Crystallization

Summary
Beam Crystallization

A Coulomb crystalline state of an ion beam strongly cooled in a storage ring

A Characteristics:
  A Ultralow emittance
  A Coulomb coupling constant > 170
  A Periodic oscillation with the external focusing force
  A 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

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

• Motion of real particles is integrated in a symplectic manner.

• Coulomb potential --- Periodic boundary condition imposed

\[ \phi = \sum_j \left( \phi_{\text{short}}^{(j)} + \phi_{\text{long}}^{(j)} \right). \]

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

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

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

• 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)

**Machine (S-LSR at Kyoto Univ.)**
- Circumference: 22.56 m
- Superperiodicity: 6

**Lattice**
- Tunes:
  - Case-I ($\nu_x, \nu_y, \nu_z$)\sim(2.07, 1.12, 0.07)
  - Case-II ($\nu_x, \nu_y, \nu_z$)\sim(2.07, 1.07, 0.07)
- RF bunching voltage: \sim40 V
- Harmonic number: 100
- Adiabatic capture: 5,000 turns (0.2 sec)

**Beam**
- Ion species: 40-keV $^{24}$Mg$^+$
- Lorentz factors: $\beta=1.89\times10^{-3}$, $\gamma=1.00000179$
- Revolution frequency (period): 25 kHz (40 $\mu$sec)
- Initial RMS emittance ($\varepsilon_x=\varepsilon_y$):
  - Normalized: $1\times10^{-9}$ $\pi$ m.rad
  - Un-normalized: $5\times10^{-7}$ $\pi$ m.rad
- Initial $dp/p$ (rms): $3\times10^{-4}$

From the measurement result
MD Simulation Conditions (2)

A Laser (1 co-propagating laser)
- Power: 8mW
- Spot radius \( w \) (2sigma): 0.66 mm (Peak Saturation Power \( \approx 4.6 \))
- Detuning \( \Delta \) (fixed): -200 MHz
- Cooling time: 3 sec

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

\[
F = \frac{1}{2} \frac{\hbar k_L \Gamma}{1 + S_L + (2\Delta / \Gamma)^2} \frac{S_L}{S_0}
\]

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

Laser detuning: \( \Delta \approx \omega \gamma \left[ 1 - \beta \left( 1 + \frac{\delta p}{p} \right) \right] - \omega_0 \)
The vertical direction is cooled through the Coulomb interaction between ions, although no artificial cooling force is introduced.
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 $\varepsilon = 4.6 \times 10^{-11} \ [\pi \text{m.rad}]$
- $T_x = 18 [\text{K}]$
- Radius $\sigma = 0.18 \text{mm}$

**Vertical**
- Norm. rms $\varepsilon = 2.6 \times 10^{-11} \ [\pi \text{m.rad}]$
- $T_y = 3.8 [\text{K}]$
- Radius $\sigma = 0.22 \text{mm}$

**Longitudinal**
- Rms $dp/p = 2.2 \times 10^{-5}$
- $T_z = 0.45 [\text{K}]$
- Radius $\sigma = 1.3 \text{mm}$

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

The beam is three-dimensionally cooled, but the ordered configuration cannot be seen.
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.
MD Results (4: Crystallization)

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!!
MD Results (5: Ideal case)

- More than 90% ions are laser-cooled.
- Transverse norm. rms emittance $\sim 1 \times 10^{-11} \, \text{\textmu m.rad}$ ($T_x,y \sim 10K$)
- Longitudinal momentum $dp/p \sim 1 \times 10^{-5}$ ($T_z \sim 0.1K$)

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

Case-II $(\nu_x, \nu_y, \nu_z) \sim (2.07, 1.07, 0.07)$

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