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

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Abstract

The formation of three-dimensionally ultralow-temperature ion beams by means of laser cooling in a storage ring is studied with the molecular dynamics approach in which stochastic interaction between laser photons and ions is incorporated. The transverse motion of a coasting beam is cooled indirectly through horizontally-displaced lasers and resonant coupling at several different operating points. The indirect transverse cooling rate depends on the displacement and detuning of the lasers as well as on momentum dispersion. In the ultralow-temperature equilibrium state, a 3D ordered (but not crystalline) structure can be formed depending on laser-cooling conditions. The characteristics of the Coulomb-ordered beam are discussed in contrast to a 3D crystalline beam.

INTRODUCTION

Three-dimensional (3D) beam cooling is essential in order to generate an ultralow-emittance beam in a storage ring. It is expected that, at ultralow emittance, the beam is Coulomb-ordered where the relative particle configuration is arranged in order and, in the zero-emittance limit, Coulomb-crystallized where the betatron and synchrotron oscillations are fully suppressed [1]. A longitudinal, one-dimensional (1D) ordering phenomenon was already observed experimentally in ultralow-current (about 10^3 ions in the ring) ion beams using electron cooling [2-4]. It has been found, by theoretical studies, that ions in the ordered beam do not pass through each other longitudinally [5-7]. As to crystalline beams, however, even a 1D string crystal has not been realized up to now in spite of a laser-cooling experimental effort at a cooler storage ring S-LSR in Kyoto University [8]. It is actually very difficult to observe phase transition of a very low-intensity (about 10 ions per bunch) bunched beam clearly although the feasibility of 1D and 2D crystalline beams was predicted with a molecular dynamics (MD) simulation [9, 10].

We have recently demonstrated the feasibility of the three-dimensionally ordered state of an ion beam with 3D laser cooling for the first time [11]. In these proceedings, more detail MD simulation results are given on transverse laser cooling and the ordered state of heavy-ion beams. The stress is put on various characteristics of the Coulomb-ordered beam.

SIMULATION PARAMETERS

A dedicated MD simulation code CRYSTAL, in which stochastic interaction between laser photons and ions is incorporated, is employed for the present study [9]. An actual beam and lattice parameters of S-LSR (see Fig. 1) has been considered. The superperiodicity of the ring is six. The ring can fulfill the following requirements to reach an ultralow-temperature state of an ion beam [1, 12]: First, the storage ring must be operated below transition energy. Second, the bare betatron tune $\nu_{x,y}$ must be less than 0.35 per lattice period to avoid linear resonances at ultralow temperature. More desirably, it must be below 0.25 to avoid linear resonance crossing in the cooling process [13].

A coasting beam of 40-keV $^{24}Mg^{+}$ ions is assumed. The space-charge force is calculated efficiently by imposing a periodic boundary condition in the longitudinal direction. The initial transverse rms emittance and longitudinal rms momentum spread of the beam have been chosen from the recent experimental observation [8].

One co-propagating and one counter-propagating Gaussian cooling lasers with the waist radius of 5 mm are applied along one of the straight sections in the ring. The direct longitudinal laser-cooling force is extended to the horizontal direction through momentum dispersion by horizontally displacing the two Gaussian laser beams [14, 15, 10]. Moreover, the vertical direction is coupled with the horizontal one through a weakly-excited solenoid magnet by applying a resonant coupling scheme [16]. Three different operating points ($\nu_x = \nu_y = (\nu_0 =)$ 1.44, 1.60, and 1.90), which fulfil the above tune requirement, are chosen for comparison. To reduce the longitudinal momentum spread, the frequencies of the lasers are

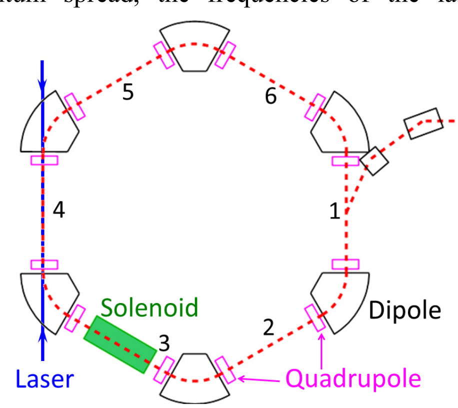

Figure 1: Schematic drawing of S-LSR. The circumference of the ring is 22.56 m. Six bending dipole and 12 quadrupole magnets have been excited so that the six-fold lattice superperiodicity can be realized. Numbers (1 to 6) in the figure express the number of straight sections for convenience. Two cooling lasers are injected along the fourth straight section. A solenoid magnet, installed in the middle of the third straight section, is excited for horizontal-vertical coupling.

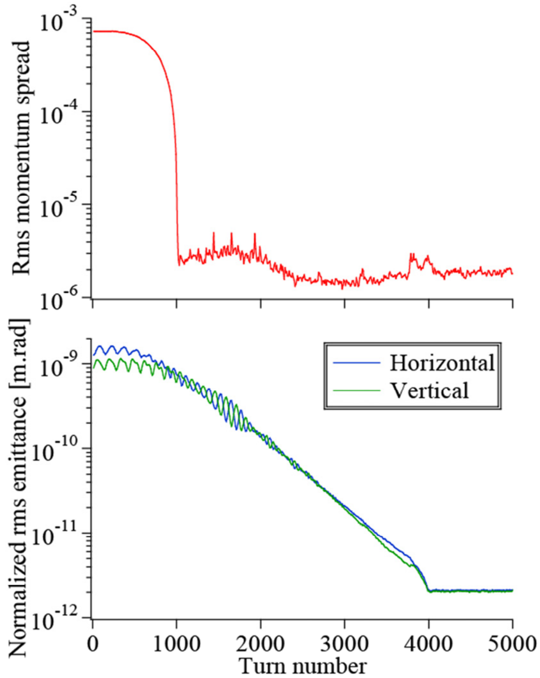

Figure 2: Time evolution of the longitudinal momentum spread and transverse emittance of the 40-keV $^{24}Mg^{+}$ ion beam during laser cooling. The bare betatron tune ν_0 is 1.44. The line density of the beam is 2.4×10^4 m^{-1}. The laser detuning is scanned in 1000 turns. The horizontal displacement and final detuning of the lasers are 3 mm and -81 MHz, respectively.

scanned from an initial detuning of -4.3 GHz to a final detuning on the order of -10 MHz in 1000 turns.

SIMULATION RESULTS

In the following, the result on ν_0 = 1.44 is mainly shown unless otherwise noted. A typical time evolution of the momentum spread and normalized rms emittance of the beam during laser cooling is shown in Fig. 2. The average dispersion function is 2.1 m in the laser cooling section for ν_0 = 1.44. The longitudinal momentum spread is decreased rapidly down to the order of 10^{-6} with the laser frequency scanning. The transverse emittance shrinks exponentially after the scanning is ended because the transverse cooling rate is higher at a smaller detuning. The 1/e cooling time is 20 ms after the laser scan in the present case. Similarly at the other higher tunes, beams with a line density on the order of 10^4 m^{-1} are laser-cooled down to the same order of the momentum spread and emittance. The cooling time is longer for higher tunes because of smaller dispersion. However, the dependence of the cooling rate does not always agree the linear theory that the transverse cooling rate is proportional to the dispersion [17].

Figure 3 shows the 3D ordered profile of the laser-cooled beam. Such ordered states of the laser-cooled beams can be generated also at ν_0 = 1.60 and 1.90, depending on the line density of the beam and the displacement and final detuning of the lasers. Although the snapshot views of the real-space configuration in Figs. 3(a) and 3(b) are similar to those of a single-shell crystal, the phase-space profile is very different. According to Ref. [18], the transverse phase-space configuration in an ideal crystalline beam is always linear. On the other hand, the phase-space configuration of the ordered beam is not linear but square in the present case, as clearly seen from Fig. 3(c).

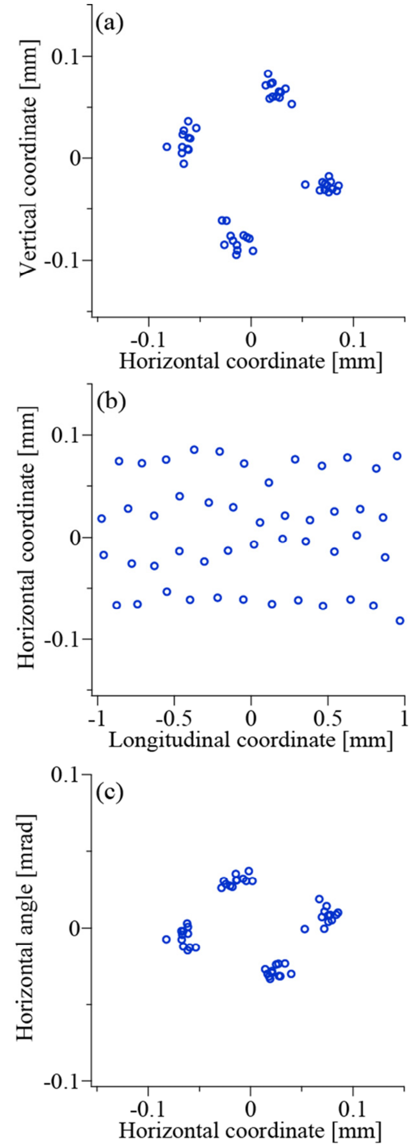

Figure 3: Real-space and phase-space configurations of the laser-cooled beam in Fig. 2. Each blue circle corresponds to a single $^{24}Mg^{+}$ ion.

Another difference is the time evolution of the single-particle orbit and the cross-sectional profile. The transverse orbits of three ions arbitrarily picked out from the ordered beam are plotted in Fig. 4. Unlike a crystal, the orbits are not periodic with the six-fold superperiodicity of the ring, and the ions are still executing betatron oscillation, as shown in Fig. 4(a). The betatron tunes have been depressed from 1.44 to 1.20 in the equilibrium due to the space-charge effect. The trajectories of the ions in the beam cross-section are

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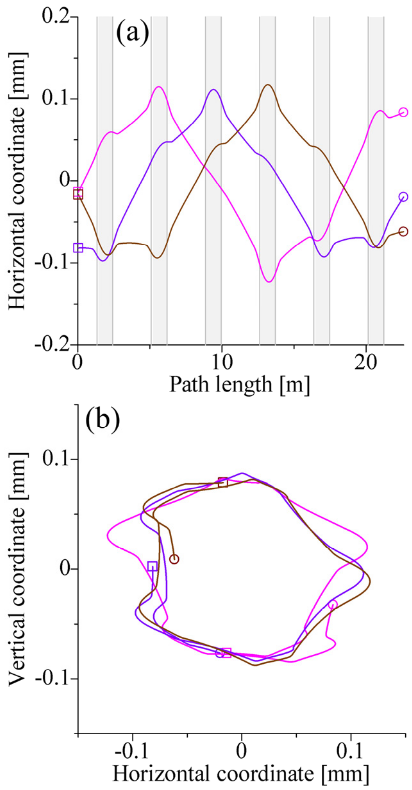

Figure 4: (a) Single-particle orbits of the beam in Fig. 3 while the beam circulates the storage ring once. The horizontal orbits of three ions arbitrarily picked out from the ordered beam are shown. The six gray shaded areas indicate the bending-magnet sections. (b) The trajectories of the three ions in the cross-sectional view are shown. In both panels, the square and circle symbols represent the initial and final coordinates of the ions during one turn, respectively.

shown in Fig. 4(b). It is obvious that the ions are rotating around the central axis. The rotation frequency while the beam goes around the ring once is 1.20, the same as the depressed betatron tune. Similarly, the ions rotate in both transverse phase planes. The dependence of the depressed tune and tune depression on the bare tune ν_0 is summarized in Fig. 5. It is worthy to note that an ordered beam is formed with a rather large tune depression at a high tune.

Since the longitudinal motion is almost frozen out by direct laser cooling, the longitudinal relative position does not change in the straight section. However, the relative position is changed due to the shear effect, depending on the horizontal coordinate in dipole bending magnets. In spite of this shear effect, the ordered configuration is stabilized: the shear effect is compensated because the horizontal coordinates of outer rotating ions are randomly changed every time the ions pass through the bending magnets.

The strength of the correlation in a beam can be estimated from a Coulomb coupling constant Γ [19]. The average temperature of the ordered beam in Fig. 3 is 3 mK in the longitudinal direction and 0.3 K in the

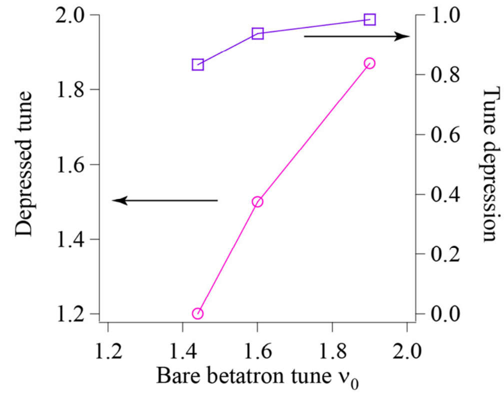

Figure 5: Depressed tune and the tune depression of 3D ordered beams formed at different operating points.

transverse direction. The longitudinal direction is sufficiently in a liquid phase ($\Gamma_{long} \sim 70$) while Γ of the transverse direction is relatively small ($\Gamma_{trans} \sim 0.7$) due to the rotation of ions.

SUMMARY

We studied 3D laser cooling of heavy-ion beams and the formation of the ordered structure in ultralow emittance with the MD simulation technique. The indirect transverse cooling worked well, depending on various laser and lattice parameters. The 3D ordered beams were formed by 3D laser cooling and exhibited unique characteristics such as the cross-sectional rotation unlike a crystalline beam. We have found that the 3D ordered beam is established in an excellent balance in spite of such anisotropy of the state.

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