ULTRALOW EMITTANCE BEAM PRODUCTION BASED ON DOPPLER LASER COOLING AND COUPLING RESONANCE*

A. Noda#, M. Nakao, NIRS, Chiba-city, Japan
H. Okamoto, K. Osaki, HU/AdSM, Higashi-Hiroshima, Japan
Y. Yuri, JAERA/TARRI, Takasaki, Gunma, Japan
H. Souda, Gunma Univ. Maebashi, Gunma, Japan
H. Tongu, ICR, Kyoto Univ. Uji-city, Kyoto, Japan
K. Jimbo, IAE, Uji-city, Kyoto Japan
M. Grieser, MPI-K, Heidelberg, Germany
Z. He, FRIB, East Lansing, Michigan USA; TUB, Beijing, China
A. Smirnov, JINR, Dubna, Russia

Abstract

Doppler laser cooling has been applied to low-energy (40 keV) $^{24}\text{Mg}^+$ ions together with the Synchro-Betatron Resonance Coupling (SBRC) method at the S-LSR in ICR, Kyoto University. The S-LSR storage ring has a high super periodicity of 6 preferable from the beam dynamical point of view. Following the realization of one dimensional (1D) ordering of a 7 MeV proton beam, three dimensional (3D) laser cooling has been experimentally demonstrated for ions with non-negligible velocity ($v/c=0.0019$, $c$: light velocity). So as to suppress heating effects due to intra-beam scattering (IBS), the circulating ion beam intensity has been reduced by scraping and the normalized emittances: $\varepsilon_\parallel$ of $1.3\times10^{-11}$ $\text{m}\cdot\text{rad}$ and $8.5\times10^{-12}$ $\text{m}\cdot\text{rad}$, corresponding to 6.4 K and 2.1 K, have been realized for the horizontal and vertical directions, respectively with a beam intensity of $\sim10^4$, which are the lowest temperatures ever attained by laser cooling. Molecular Dynamics (MD) computer simulation predicts the realization of the lowest beam temperatures of $\sim0.001$ K and $\sim0.1$ K corresponding to $6.4\times10^{-11}$ $\text{m}\cdot\text{rad}$ and $10^{-12}$ $\text{m}\cdot\text{rad}$ for the longitudinal and transverse directions, respectively. With the same condition as utilized for the real experiments at S-LSR, formation of a 1D longitudinal string is expected if the laser spot size and laser detuning are adjusted to the proper values of 1.5 mm and $\sim42$ MHz, respectively with ramping of the detuning. 3D ordered state is also predicted for a coasting beam with laser cooling utilizing dispersive cooling.

INTRODUCTION

Historically, beam cooling was invented from the need of secondary produced beam of anti-proton for the elementary particle physics research, which was finally realized by stochastic cooling [1] more suitable for hot ion beams [2]. Electron cooling invented by G.I. Budker [3] for the same purpose has been more appropriate for cooling of colder ion beams and has been utilized for various precision measurements. Following the realization of 1D ordered states with an electron cooling for heavy ions at ESR and SIS in GSI and CRYRING in Stockholm [4,5,6], a 7 MeV proton beam having the smallest charge state, was electron cooled to the 1D ordered state at S-LSR by reducing the particle number to $\sim2000$ for the first time for single charged ions (Fig. 1(a)) [8]. In these cases, adjacent ions cannot take over each other but be repulsed back just before collision being aligned in a line with distance oscillation, which is different from the crystalline state. The lattice of S-LSR is designed to suppress beam blow up, satisfying the so called maintenance conditions [11],

$$\gamma \leq \gamma_f \quad (1)$$

$$N_{sp} \geq 2\sqrt{v_t^2 + v_f^2} \quad (2)$$

Thus the S-LSR ring has been designed to have a rather high super-periodicity of 6 [12]. The above mentioned 1D ordered state is based on such characteristics of S-LSR.

Figure 1: (a) Reflection probabilities of heavy ions at ESR of GSI and S-LSR at ICR. (○ and □ are borrowed from Refs. [4], [7], respectively and data ● are taken at S-LSR [8].) The contour plots of the reflection probabilities are taken from Ref. [9]). (b) Plasma Parameter, $\Gamma_p$, dependence of Heating ratio[10], where $\Gamma_p$ is defined as

$$\Gamma_p = \frac{E_{\text{Coulomb}}}{E_{\text{thermal}}} = \frac{ae^2}{4\pi\epsilon_0 \omega WL^2 I_{\text{ion}}}$$

where $a_{WS}$, $q$ and $n_{ion}$ are Wigner Seitz radius, charge state and 3 dimensional density of the ion beam, respectively.

- Work supported by Advanced Compact Accelerator Development project by MEXT of Japanese government. It was also supported by GCOE project at Kyoto University. *The next generation of Physics-Spun from Universality and Emergency. 
#_a_noda@nirs.go.jp

MOZA01 05 Beam Dynamics and Electromagnetic Fields

28 D03 High Intensity in Circular Machines - Incoherent Instabilities, Space Charge, Halos, Cooling
For crossing the hill of the heating rate shown in Fig. 1(b) with much stronger cooling force, laser cooling established by Steven Chu, Claude Cohen-Tannoudji and William D. Phillips for trap atoms [13] was also applied for ion beams circulating in a storage ring although the applicable ion species have been limited to ⁶Li⁺ (metastable), ⁷Be⁺, ⁲⁴Mg⁺ and ¹²C⁺⁺ (only with high β~0.5) due to the limitation of available lasers with an appropriate wavelength and enough power. A further restriction of laser cooling is the one dimensional direction of the cooling force, oriented to the laser beam direction. This limitation has been tried to be removed by various schemes.

In the present paper, the historical approaches in Doppler laser cooling of a circulating ion beam are briefly given and then our attainment at S-LSR utilizing an active 3D laser cooling by SBRC is presented. Finally, our experimental approach to realize a crystalline structure is discussed in connection with the recent results of MD simulations.

**DOPPLER LASER COOLING APPLIED FOR MOVING ION BEAMS (HISTORY)**

**Passive 3 D Laser Cooling Scheme**

The temperature of the ion beam circulating in a ring, representing the distribution of the velocity of the beam particles in the centre of mass frame and is defined as:

\[ T_{\parallel} = \frac{k_B T}{m} \left( \frac{p}{\beta} \right)^2 \]  

\[ T_{\perp} = \frac{k_B T}{m} \left( \frac{\sigma_{\perp}}{\beta} \right)^2 \]  

where \( k_B \) is Boltzmann constant, \( m \) is ion mass, \( \beta \) is ratio of ion velocity to light velocity, \( \sigma_{\perp} \) and \( \beta \) are beta-function in y-direction at the point of observation, respectively. It has been applied to various ion beams starting from the first experiment at TSR [14], which, however, was limited only in the longitudinal direction. The extension of the laser cooling to the transverse directions with the use of IBS was performed by H.J. Miesner et al. also at the TSR [15], however the equilibrium temperatures were limited at rather high values of 4000 K and 500 K for the horizontal and vertical directions, respectively due to the passive scheme of heat exchange among the degrees of freedom. By application of position shifted lasers from the ion beam orbit in parallel at the cooling section (dispersive cooling), the equilibrium temperature could be somewhat reduced to ~500 K and ~150 K for the horizontal and vertical directions, respectively at the TSR [16]. With the IBS cooling scheme, transverse temperatures down to ~20 K could be obtained at ASTRID in Aarhus [17] for an ion beam number of \( 7 \times 10^6 \) and kinetic energy of 100 keV. The attained temperatures are still not sufficient to realize the crystalline state. The lowest obtained temperatures reported in Ref. [17] results in \( T_{\parallel} \sim 0.04 \) far below the heat rate peak shown in Fig. 1(b).

**Active 3 D Laser Cooling Scheme**

The SBRC scheme proposed by H. Okamoto, A. Sessler and D. Möhl [18] uses a coupling between the longitudinal and the horizontal degrees of freedom under the condition

\[ v_H - v_V = \text{integer}, \]  

while it assumes the coupling between the horizontal and the vertical directions with a solenoid or a skew quadrupole magnet under the condition

\[ v_H - v_V = \text{integer}, \]  

where \( v_H \), \( v_V \) and \( v_\perp \) are the horizontal, vertical and the longitudinal tunes, respectively. This active scheme is expected to attain more efficient cooling force and MD computer simulation predicted a crystalline beam for an ideal system [19, 20] and for the S-LSR lattice with a ²⁴Mg⁺ beam of the energy 35 keV [21].

**DOPPLER LASER COOLING AT S-LSR TOWARD LOW ION TEMPERATURE**

**Laser Cooling at S-LSR with Coasting Beam**

At first, laser cooling at S-LSR was applied for a coasting beam using counter deceleration with an induction accelerator [22]. The block diagram of the laser cooling system is illustrated in Fig. 2. The laser light with the wavelength of 280 nm, the output of a ring dye laser pumped with a solid state green laser of the wavelength 532 nm, is doubled in its frequency by a second harmonics generator, is co-propagated with the ²⁴Mg⁺ ion beam. The direction of the laser beam as well as the Mg⁺ ion beam is defined by two apertures in the cooling section (Fig. 2) of different sizes (2mm for laser) and (firstly 10 mm and later 6 mm for the ion beam). The laser photon excites the transition from ³s²S₁₂ to ³p²P₂₂.

The momentum spread of the circulating ion beam was observed utilizing the Post Acceleration Tube (PAT) developed at TSR [23] and ASTRID [24]. The longitudinal temperature had reached 3.6 K for \( 3 \times 10^4 \) 40 keV ²⁴Mg⁺ ions, which was limited as cooling was only efficient in the longitudinal direction and the IBS heating was not negligible with the beam intensity attainable enough S/N ratio for optical observation by PAT.
Active $3\,D$ Laser Cooling for Bunch Beam

The SBRC scheme has been experimentally applied at S-LSR. With a drift tube cavity, located at a straight section with finite dispersion ($\sim1m$), two period downstream from the laser cooling section (Fig. 3), the RF voltage was applied to the ion beam. The 40 keV $^{24}$Mg$^+$ ion beam directly coming from the CHORDIS ion source, without further acceleration, was single turn injected into the ring of S-LSR and captured into a separatrix with an RF voltage as shown in Fig. 4(a). The laser detuning was optimized to minimize the captured bunch length as illustrated in Fig. 4(b).

Figure 3: Layout of the Doppler laser cooling system and beam size observation system with a CCD and scrapers [25, 26]. Inlet of the figure shows the optical system using a CCD camera. The distances from the beam and CCD camera to the nearby lenses are set to their focal lengths (140 mm) and the image size is the same as the beam dimension.

OBSERVATION OF TRANSVERSE TEMPERATURE

Optical Measurement by Cooled CCD

Evaluation of the transverse laser cooling effect needs the transverse beam size measurement and the horizontal beam size was observed with a CCD camera cooled down to $\sim-30^\circ\text{C}$, followed with an optical system shown in Fig. 3.

SBRC has been attained at the operating point of (2.068, 1.105) at first for 2D coupling between the longitudinal and horizontal degrees of freedom under the condition satisfying only Eq. (5) for a beam intensity larger than $10^7$

which attains enough S/N ratio for optical observation [25]. With this rather higher ion beam intensity, however, the beam temperature became equilibrium at rather higher level as $\sim200\,\text{K}$ (corresponds to: $\epsilon_n$ of $\sim4\times10^{-10}\,\pi\,\text{mrad}$) due to heating by IBS [25].

Beam Size Measurement by Scraping

Increase of the overall laser cooling efficiency in all three dimensions, requires further reduction of the ion utilized optical system, we have established a new beam

Figure 7: Transversely laser cooled ion beam sizes by SBRC together with deceleration by INDAC.

Figure 6: Comparison of beam sizes among, 2D, 3D laser cooling with solenoid on and off and additional deceleration by an induction accelerator.
Figure 8: MD simulated 3D laser cooled ion beam temperature [30].

Figure 9: Predicted longitudinal ordered state from MD simulation assuming Δ = -42 MHz and laser spot size of 1.5 mm (corresponds to the left part of Fig. 10 (b) of Ref. [30])

scraping scheme for evaluation of the transverse beam sizes. After defining the circulating ion beam intensity with the use of H Scraper 1 (Fig. 5(a)), the horizontal or vertical beam size was obtained by observing the survival beam intensities for various positions of H Scraper 2 or V Scraper, respectively as illustrated in Fig. 5 (b) [26]. Suppression of IBS by reducing the beam intensity to 10^4 with this scheme, resulted in the equilibrium beam temperature of 20 K and 29 K, respectively at an ion beam intensity of 10^4, which corresponded to 8.1 K and 4.1 K (both correspond to \( \varepsilon_n \) of 1.3×10^{-11} \( \pi \) m·rad) [26]. Further study was performed with deceleration by an induction accelerator in order to give a counter force against ion beam acceleration due to laser photon absorption at every turn. With a laser detuning of -190 MHz, the transverse beam sizes were reduced to 0.09 mm and 0.18 mm for the horizontal and the vertical directions, respectively at an ion beam intensity of 10^4, which corresponded to 8.1 K and 4.1 K (both correspond to \( \varepsilon_n \) of 1.3×10^{-11} \( \pi \) m·rad) [26].

Further we applied 3D laser cooling moving the operation point to (2.072, 1.120) [26]. For the operation point of (2.067, 1.070) satisfying Eq. (6) together with Eq. (5) for the coupling among the longitudinal, horizontal and vertical freedoms. In Fig. 6, the attained transverse beam sizes in the (a) horizontal and (b) vertical directions are shown for various conditions. The horizontal and vertical coupling was found to be optimum for the solenoid field of 22.5 Gauss at the electron cooler section, which was found to be different from the simulation as is described later. With such coupling, the vertical beam size was reduced drastically, while the horizontal beam size gets worse by heat transfer from the vertical direction. The cooled equilibrium beam sizes were 0.20 mm and 0.30 mm for the horizontal and vertical directions, respectively, converted to ring averaged temperatures \( T_H \) and \( T_V \) of 40 K and 11 K, respectively [27].

Further study was performed with deceleration by a laser as described later. In that case, the horizontal beam size was measured with a cooled CCD after optimization of the laser size at the position where the horizontal beta-function was 0.89 m. The main parameters of this experiment are listed up in Table 1. The horizontal beam size could be measured only for an ion beam intensity larger than 3×10^4 to get the needed S/N ratio. The reason why we can now observe much lower intensity beams with our optical system compared with the previous observation, is that the beam density increased by the application of transverse laser cooling.

At an intensity of 3×10^4 ions, the horizontal beam size could be reduced to 0.08 mm and with vertical scraping, 0.13 mm was obtained for an ion number of 10^4. These results correspond to the horizontal and vertical average beam temperatures of 6.4 K and 2.1 K, respectively (Fig. 7), corresponding to \( \varepsilon_n \) of 1.3×10^{-11} \( \pi \) m·rad and 8.5×10^{-12} \( \pi \) m·rad, respectively [27]. They are already far below the ones of any regular beams except for the one at circular trap with a very low velocity [28], but are not enough cold to reach the crystalline state.

**EXPERIMENTAL ATTAINMENT AND FUTURE PROSPECT BY SIMULATION**

The experimental approaches above mentioned, have been simulated with the use of a MD simulation code “CRYSTAL” [29], taking into account the dissipative force induced by a laser photons.
Bunched Beam 3D Doppler Laser Cooling with SBRC

The recent simulation, changing the laser spot size (defined as the size of the laser waist at the center of the cooling section) from 0.3mm to 6 mm gives the result as shown in Fig. 8 [30]. It shows us we had better to choose the laser spot size a little larger around 1.5 mm instead of our real experimental value of 0.3 mm in March last year. It also gives an optimized field value of the solenoid magnet as 65 Gauss for H-V coupling, which differs from our experimental one (22.5 G), the reasons of which are to be investigated. The MD simulation assuming the same laser power and operation point, but changing only laser spot size and the laser detuning, Δ, to 1.5 mm and -42 MHz, respectively with RF voltage ramping in time, predicts realization of longitudinal ordered state (1D string) aligned in a longitudinal direction without oscillation composed of 78 ions in a single bunch as shown in Fig. 9 [30], where the beam temperatures are 0.001K and 0.1K (corresponds to εn of 10^{-13} and 10^{-12} πm^2rad), for the longitudinal and transverse degrees of freedom, respectively. This is an important step to reach our experimental goal at S-LSR to realize a crystalline string.

Dispersive Cooling of Coasting Beam

For a coasting beam circulating in the S-LSR ring, Y. Yuri predicted formation of a 3D ordered state with a MD simulation [31] assuming usage of coupling between the horizontal and longitudinal degrees of freedom by dispersive laser cooling described in Ref. [16]. The estimated temperature is a little bit higher compared with the above simulation for a bunched beam with SBRC [30] due to ~7 times larger beam density. With such a condition as a laser spot size (16), laser displacement from the ion beam orbit and a final laser detuning are 2.5 mm, 3 mm and -61 MHz, respectively, the lowest temperature of a coasting beam and hence creation of 3D ordered state is predicted for the ion beam intensity of 9×10^5 at the operation point of (1.44, 1.44) as shown in Fig. 10. The betatron tunes are suppressed to 1.20 in the equilibrium due to the space-charge force. In the present case, the phase-space configuration of the ordered beam is hexagonal as shown in Fig. 10(c) different from the case of the crystalline beam of linear configuration [21]. 3D ordered state was reported by Kjærgaard and Drewsen for an ion trap [32, 33], but it is predicted for an ion beam circulating in a ring with a certain velocity for the first time [31].

![Figure 10](image-url)

Figure 10: Real space and phase space configurations of the created 3 D ordered state by 3D laser cooling combining SBRC with the dispersive cooling [31].

Table 2: Comparison of Laser Cooled Ion Beam Temperatures (Shaded Columns Represent the Recent MD Simulations)

<table>
<thead>
<tr>
<th>Year Ring</th>
<th>Method</th>
<th>Ion</th>
<th>Kinetic Energy</th>
<th>Intensity</th>
<th>Beam Density</th>
<th>T // (K)</th>
<th>T H (K)</th>
<th>T V (K)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 TSR</td>
<td>IBS</td>
<td>9Be+</td>
<td>7.3 MeV</td>
<td>2.0×10^7</td>
<td>3.6×10^3</td>
<td>15</td>
<td>4000</td>
<td>500</td>
<td>[15]</td>
</tr>
<tr>
<td>1998 TSR</td>
<td>Dispersive cooling</td>
<td>9Be+</td>
<td>7.3 MeV</td>
<td>1.0×10^7</td>
<td>1.8×10^2</td>
<td>few tens</td>
<td>-500#</td>
<td>-150#</td>
<td>[16]</td>
</tr>
<tr>
<td>1999 ASTRID</td>
<td>IBS</td>
<td>24Mg+</td>
<td>100 keV</td>
<td>7×10^6</td>
<td>1.8×10^3</td>
<td>2-5</td>
<td>17</td>
<td>21</td>
<td>[17]</td>
</tr>
<tr>
<td>2001 PALLAS</td>
<td>RFQ</td>
<td>24Mg+</td>
<td>1 eV</td>
<td>1.8×10^4</td>
<td>5.0×10^3</td>
<td>&lt;0.003</td>
<td>T_⊥&lt;0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008 S-LSR</td>
<td>IBS</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>11</td>
<td>-</td>
<td>500</td>
<td>[22]</td>
</tr>
<tr>
<td>2009 S-LSR</td>
<td>W SBRC (2D)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>27</td>
<td>220$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012 S-LSR</td>
<td>WO SBRC</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013.2 1. S-LSR</td>
<td>W SBRC (3D)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>(0.4)</td>
<td>20</td>
<td>29</td>
<td>[26]</td>
</tr>
<tr>
<td>2013.3 7 S-LSR (Δf=190 MHz)</td>
<td>W SBRC (3D) (INDAC ON)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>-</td>
<td>8.1</td>
<td>4.1</td>
<td>[27]</td>
</tr>
<tr>
<td>2013.3 22 S-LSR (Δf=26 MHz)</td>
<td>W SBRC (3D) (INDAC ON)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>1.0×10^6</td>
<td>4.4×10^3</td>
<td>-</td>
<td>6.4 (3×10^3)</td>
<td>2.1</td>
<td>[27]</td>
</tr>
<tr>
<td>Simulation with MD (Δf=42 MHz)</td>
<td>W.SBRC (3D) (RF ramping)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>7.8×10^3</td>
<td>6×10^3</td>
<td>-0.001</td>
<td>-0.1</td>
<td>-0.1</td>
<td>[30]</td>
</tr>
<tr>
<td>Simulation with MD (Δf=61 MHz)</td>
<td>W.SBRC (3D) (W Dispersive cooling)</td>
<td>24Mg+</td>
<td>40 keV</td>
<td>9×10^3</td>
<td>4.0×10^3</td>
<td>0.003</td>
<td>0.6</td>
<td>0.6</td>
<td>[31]</td>
</tr>
</tbody>
</table>
REFERENCES