RECENT APPROACH TO CRYSTALLINE BEAM WITH LASER-COOLING AT ION STORAGE RING, S-LSR*

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Abstract

Approach to realize a crystalline beam for 40 keV $^{24}Mg^{+}$ ion at S-LSR has been continued in these several years. Based on a success of longitudinal laser cooling, transverse laser cooling by application of synchro-betatron coupling has been studied. Heat transfer from the horizontal direction to the longitudinal one is indicated by an observation of momentum spreads using PAT around the resonance condition. A direct observation of reduction of a horizontal beam size has also been applied measuring spontaneous emissions from Mg ions and ion beam size reduction from ~1.1 mm to ~0.8 mm has been detected which, however, is saturated at much higher transverse temperature (~300 Kelvin) compared with longitudinal one and further investigation is needed to clearly demonstrate a transverse laser cooling, needed for creation of crystalline beam.

INTRODUCTION

By application of beam cooling, which takes away a kinetic energy of the beam (heat) in its center of mass system, beam temperature can be drastically reduced. Electron beam cooling has realized one dimensional ordered beam for heavy ion beams [1,2] and recently we have demonstrated 1 D ordered state also for proton beam with a kinetic energy of 7 MeV at S-LSR by electron beam cooling [3], which, has long been studied in several places in the world but has not yet been realized. This fact, we believe, demonstrates superior characteristics of S-LSR well stabilized against beam instabilities. In order to attain much lower beam temperature and realize a crystalline beam in S-LSR, much stronger cooling force is needed, and we have developed a laser cooling system for 40 keV $^{24}Mg^{+}$ beam [4].

At PALLASS in LMU, Munich, 3 dimensional crystalline beam has already been created [5] but it is reported that the crystal is destroyed when it is accelerated higher than 1 eV by a “shear heating”, which is induced at the bending section due to the difference of radius of curvature for beams with different momenta. In order to realize a crystalline beam with some amount of fraction of a light velocity, we are studying a capability of transverse laser cooling with the use of “Synchro-Betatron coupling”. In the present paper, after describing recent experimental results for such an approach, an experimental strategy toward the realization of a crystalline beam for 40 keV $^{24}Mg^{+}$ ion beam is presented.

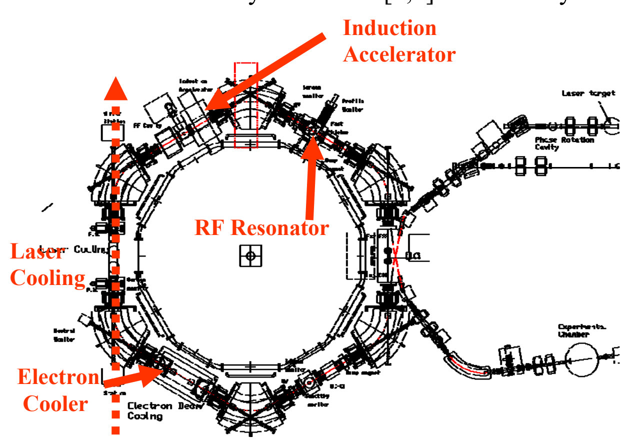

Figure 1: Layout of an ion storage and cooler ring, S-LSR. Laser cooling is appied to $^{24}Mg^{+}$ ion beam at one of 6 straight sections.

Table 1: Main Parameters of S-LSR

Ring Lattice	
Circumference	22.557 m
Average radius	3.59 m
Length of straight section	1.86 m
Number of periods	6
Betatron Tune (Hor., Ver.)	(2.07, 1.10), (1.44, 1.44)

APPROACH FOR TRANSVERSE LASER COOLING

An ion storage and cooler ring, S-LSR, has a super-periodicity of 6 in order to avoid beam instabilities due to lower order structure resonances. In Fig.1, the layout of S-LSR is shown [6]. Ion beam of $^{24}Mg^{+}$ extracted from an ion source by a high voltage of 40 kV is transported through a beam line and then is injected into S-LSR by a single turn injection using a septum magnet, an electrostatic septum and an injection-kicker. The beam size in a horizontal direction is measured to be 1.3 mm (1σ), which is overlapped with a laser in one of long

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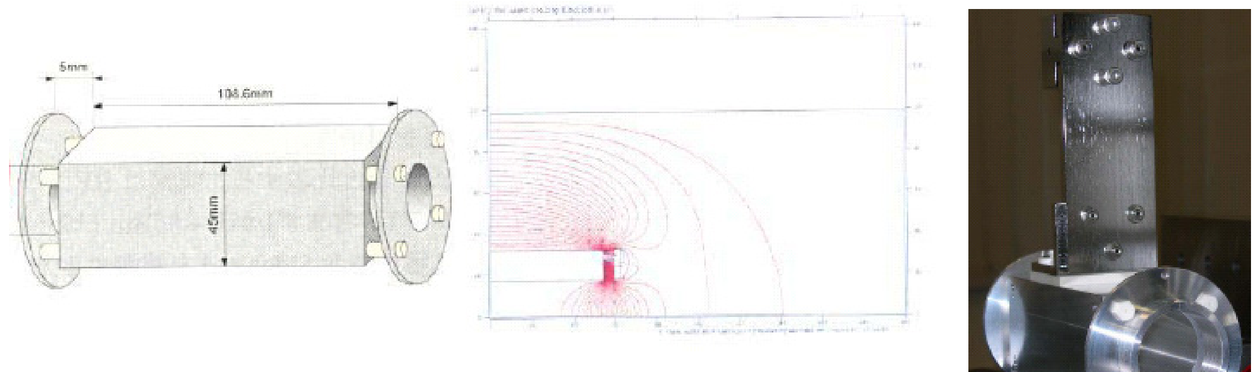

(a) (b) (c)

Figure 2: Drift tube with two gaps for RF acceleration. (a) structure and geometrical dimensions, (b) electric field distribution calculated by Poisson code and (c) a fabricated drift tube for RF acceleration.

straight sections as shown in Fig. 1. RF acceleration voltage is applied by a drift tube with two gaps at both sides (Fig. 2), which is located just before the injection straight. In table 1, main parameters of S-LSR lattice are given.

Longitudinal Laser Cooling System

For the purpose of taking away the longitudinal temperature from the circulating $^{24}Mg^{+}$ ion beam, a frequency doubled ring dye-laser with a wave length of 560nm pumped with a solid green laser (532nm) is utilized. It is overlapped with the ion beam co-propagating in one of straight sections, utilizing a transition between $3s^2S_{1/2}$ and $3p^2P_{3/2}$. The schematic view of the longitudinal laser cooling system of a coasting beam counteracting with deceleration by an induction accelerator is illustrated in Fig. 3. With such a scheme, we have reached to a longitudinal temperature of 3.6 Kelvin for the beam intensity of $3\text{x}10^4$ [7]. Such an equilibrium temperature is limited by trade off between laser cooling force and the heating due to intra-beam scattering.

Extension of Laser Cooling to Transverse Degree of Freedom

At the experiments described in the last section, the transverse heat is also removed by a laser cooling indirectly, but the reached transverse temperature is rather

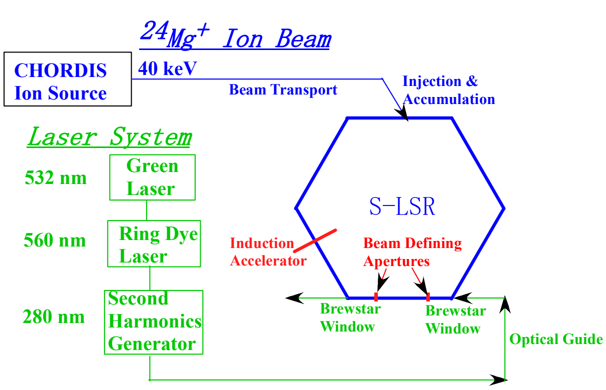

Figure 3: Schematic view of a longitudinal laser cooling system of $^{24}Mg^{+}$ ion beam at S-LSR.

high as 500 Kelvin for a beam intensity of ~10^7. For the purpose of realizing equally efficient transverse cooling as the longitudinal direction, we have applied a "Synchrotron-Betaron Coupling" scheme proposed by H. Okamoto et al.[8]. For this purpose, we have switched off the induction accelerator in the scheme shown in Fig. 3 and applied an RF voltage by a drift tube type RF equipment shown in Fig.2. Locations of these equipments are indicated in Fig.1 and the RF acceleration system is located at the position where a dispersion function is finite (~1.1 m). When the following condition;

$$\upsilon_s - \upsilon_H = m(\text{int}\,eger) \ , \tag{1}$$

where υ_s and υ_H are synchrotron and betatron tunes, respectively, is satisfied, it is expected that the kinetic energy of a horizontal motion is coupled with that of longitudinal motion and efficient horizontal cooling (equally rapid as longitudinal cooling) is well expected. Keeping parameters as listed up in table 2, our experiments have been performed. The momentum spread of the circulating $^{24}Mg^{+}$ ion beam has been measured by sweeping the applied electro-static potential to PAT (Post Acceleration Tube) and was found to make peak at the synchrotron tune satisfying the "Synchro-Betatron Resonance" as shown in Fig. 4.

Beam size and position were measured using a cooled CCD camera. The beam intensity was estimated from the measurement of Schottky signals [9,10]. From the measurements changing the synchrotron tune by varying the RF voltage, it is known that the initial horizontal beam size of ~1.1 mm (1 σ) is reduced to ~0.8 mm (1σ) at around the tune close to the fractional part of a horizontal

Table 2: Parameters of Experiments for Transverse Laser Cooling

Betatron Tune	(2.067, 1.100) (2.065,1.097) with laser
Initial Ion Nuimber	$4 \text{ x } 10^7$
Initial Momentum Spread	$8 \text{ x } 10^{-4}$
Dye Laser Frequency	537058.00±0.02 GHz
Laser Power	11~16 mW

tune [9]. The reached transverse temperature, however, is rather high as ~300 Kelvin and is far from equilibrium with the longitudinal one (~20 Kelvin), which needs further investigation by obtaining much quantitative experimental data in order to clearly demonstrate the capability of efficient transverse laser cooling by resonance coupling.

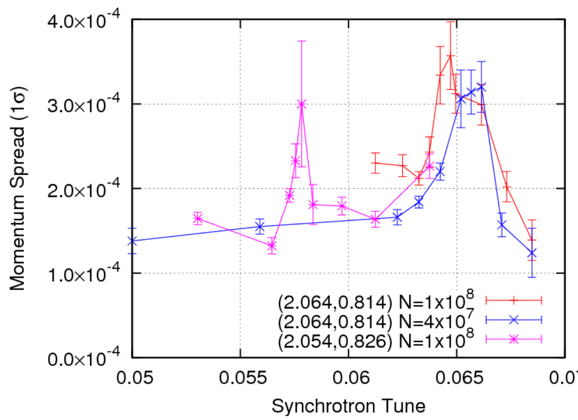

Figure 4: Dependence of the equilibrium momentum spread after bunched beam laser cooling on the synchrotron tune.

STRATEGY FOR CREATION OF CRYSTALLINE BEAM AT S-LSR

Although the transverse laser cooling described in the former section is not so decisive, such a transverse laser cooling is well expected to be realized by further improvement of RF and laser control systems. According to the MD simulation assuming S-LSR lattice, deviation from the superperiodicity of the ring, is anticipated to destroy the crystalline beam [11]. As it is impossible to apply laser cooling and RF acceleration at all the long straight sections of the ring, careful investigations about the extent to which a deviation from super-periodicity is allowed as a higher order correction, is needed in order to judge the attainability of 3 dimensional crystalline beam. At the moment, we want to aim at realization of one and two dimensional crystalline beams as illustrated in Fig. 5 expected for rather lower line densities of the beam [12].

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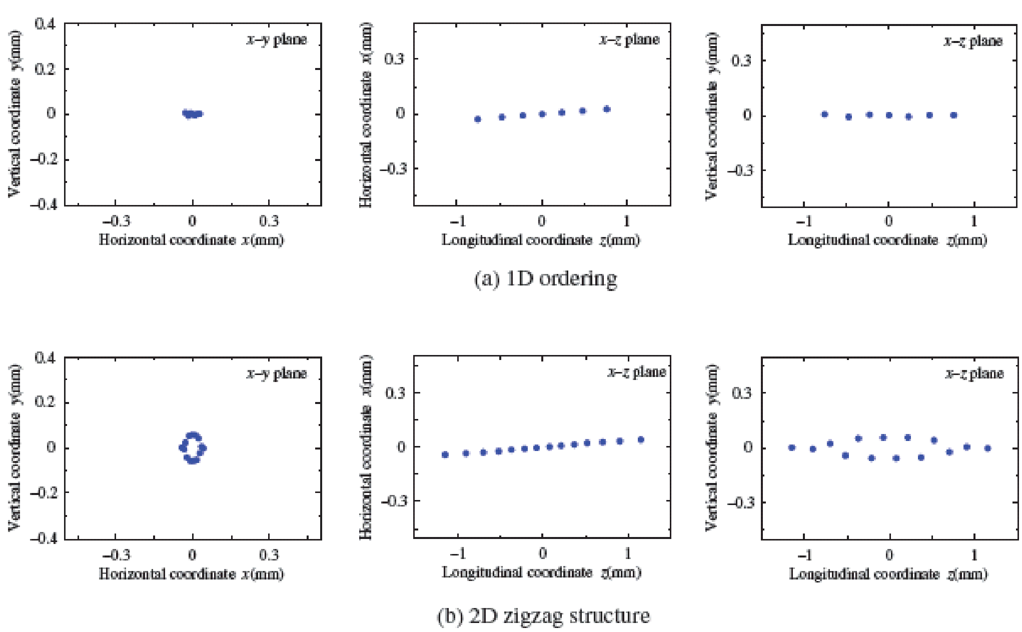

Figure 5: One (a) and two (b) dimensional crystalline beam expected at S-LSR by a MD simulation. (from Ref. [12])