PRESENT STATUS AND RECENT ACTIVITY ON LASER COOLING AT S-LSR *

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Abstract

Laser cooling of an 40 keV 10^8 - $^{24}Mg^+$ ion beam combined with induction deceleration reduced the momentum spread to 2.9×10^{-4} which was limited by intra-beam scattering. An optical observation system for laser cooling applicable for smaller number of ions has been developed and just installed into S-LSR. With the special feature of the S-LSR lattice allowing for reduction of the shear force and with the newly developed optical measurement system, further approaches towards the realization of a multi-dimensional crystalline ion beam are to be started from now on.

INTRODUCTION

At ICR of Kyoto University, an ion storage and cooler ring, S-LSR was constructed between 2001 and 2005 by collaboration with NIRS. Beam commissioning started in October, 2005. Up to now electron cooling of a hot ion beam [1] was studied. At very low proton numbers of 2000, a one dimensional ordered state of a 7 MeV proton beam could be achieved [2]. The onset of transverse coherent instabilities in the vertical direction, induced by electron cooling stacking, could be suppressed by a feedback system [3]. Furthermore the formation of very short bunches could be successfully realized by the application of the bunch rotation method and electron cooling [4]. In addition, the S-LSR is optimized to realize a multi-dimensional crystalline beam with laser cooling [5]. In the present paper, the special feature of the S-LSR in connection with the above motivation is described briefly and then recent experimental results by the laser cooling applied to 40 keV $^{24}Mg^+$ ions are presented together with an overview of the future development.

SPECIAL FEATURE OF S-LSR

Basic Structure

According to the theoretical studies using MD simulations to achieve a crystalline ion beam, the ring has to satisfy the following conditions

$$\gamma \le \gamma_t , \quad (1)$$

$$N_{sp} \ge 2\sqrt{\nu_H^{\,2} + \nu_H^{\,2}} , \quad (2)$$

where γ_t, $\nu_{H,V}$ and N_{sp} are the transition γ of the ring, the betatron tunes in horizontal, vertical directions and the superperiodicity, respectively. Eqs. (1) and (2) represent the so-called formation and maintenance conditions for a crystalline beam, respectively [6,7]. The ring S-LSR is designed with 6-fold symmetry in order to enlarge the region of operation points satisfying the above maintenance condition. A further condition to avoid the

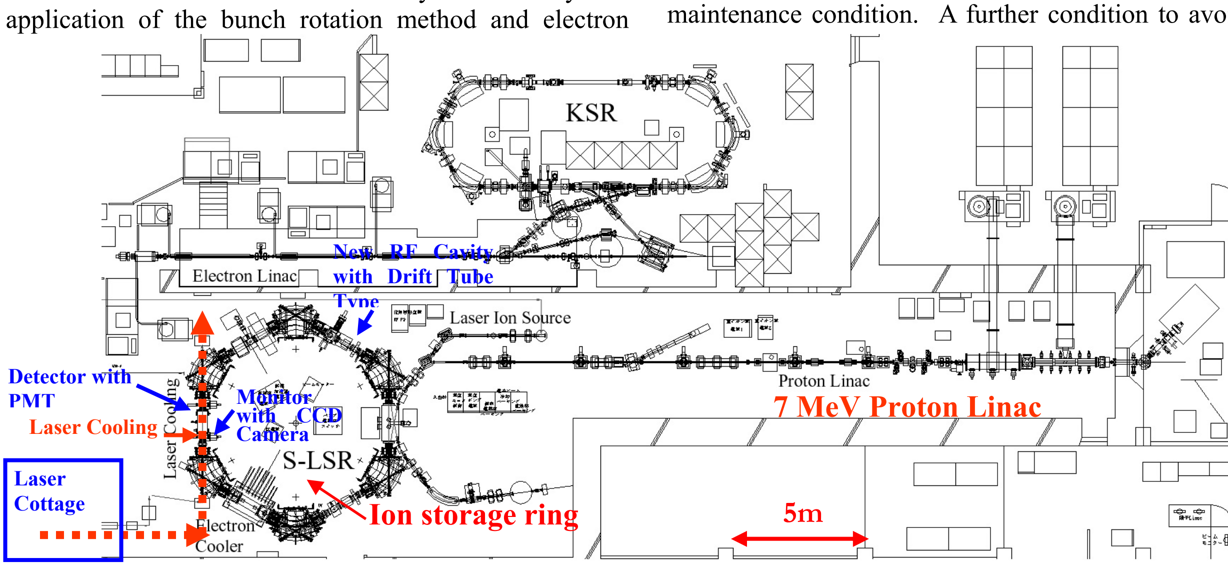

Figure 1: Layout of the radiation controlled experimental room where S-LSR is installed. As the injection beam for S-LSR, 7 MeV proton from the linac and 40 keV $^{24}Mg^+$ ion beam has been utilized up to now.

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Table 1: Main parameters of S-LSR

Circumference	22.557 m
Average Radius	3.59 m
Superperiodicity	6
Ion Species	Proton :7 MeV $^{24}Mg^{+}$:40 keV $^{12}C^{6+}$:2 MeV/u
Operation Point	(1.65, 1.21) :Electron Cooling (1.45, 1.44), (2.07, 1.07), (2.07, 2.07) : Laser Cooling
Radius of Curvature	1.05 m

effect of linear resonances in the cases of high beam line densities, the S-LSR lattice has to fulfil also the requirement [8]

$$N_{sp} \geq 4\nu_{H(V)}. \quad (3)$$

The superperiod of S-LSR consists of a dipole magnet and two quadrupole magnets at its both sides (Fig. 1).

Dispersion-Free Mode to Suppress Shear Heating

Laser cooling applied up to now for ion beams circulating in storage rings has been applied in the longitudinal direction. By dynamical coupling of the horizontal betatron motion and longitudinal synchrotron motion, laser cooling is extended to all three directions [9]. If a strong laser cooling force can be achieved for the three degrees of freedom, it is expected to create a multi-dimensional crystalline beam. The beam crystal, however, will be unstable caused by so called "Shear Heating" due to the increase of the beam line density [10, 11].

To avoid such "Shear Heating", a dispersion suppressed lattice with dispersion free bends consisting of crossed electric and magnetic fields was first proposed by Pollock [12]. For that purpose we have re-investigated this capability [13], developed electrodes, and installed them in all 6 dipole magnet chambers. All electrodes can be moved out from the beam aperture of the normal mode by a special driving mechanism without breaking the vacuum [14]. Only with the help of a coupling cavity [15], however, synchro-betatron coupling can be realized with the dispersion free lattice. Tapered laser cooling, an alternative to this scheme, is proposed, where the laser cooling force is applied only inside a Wien Filter, installed in a long straight section for laser cooling [16]. This idea, however, requires further fabrication of the needed hardware.

Operation Points

Table 2: Beam life of $^{24}Mg^{+}$ for various operation points

ν_x	ν_y	Beam Life
2.069	1.075	5.3 s
2.115	0.724	14.2 s
1.53	1.34	14.1 s
1.642	1.198	13.5 s

Up to now, several operation points of the working point are studied as listed up in table 2 [17]. The measured beam life time at the operating point of (2.07, 1.07), utilized for synchro-betatron coupling is shorter compared with the other operating points. The reason of this behaviour has to be investigated from now on.

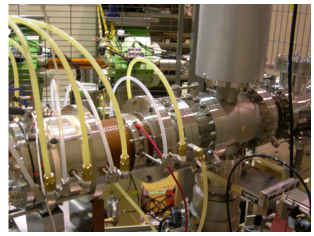


Figure 2 (a): Ion source of $^{24}Mg^{+}$ extracted by 40 kV.

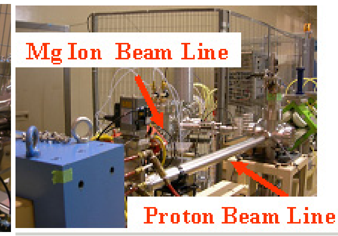


Figure 2 (b): $^{24}Mg^{+}$ ion beam merged with proton beam.

LASER COOLING SYSTEM

Ion Beam Orbit of $^{24}Mg^{+}$

The Mg ions produced from a CHORDIS ion source (Fig. 2 (a)) and extracted with a high voltage of 40 kV has been directly transported to the S-LSR merging with the transport line of 7 MeV proton (Fig. 2 (b)). The kinetic energy of the laser cooled Mg ion has been increased to 40 keV from the initial design of 35 keV due to the stable operation condition in the frequency region of the present laser system. The merged $^{24}Mg^{+}$ ion beam is transported through an injection septum magnet and then single-turn injected by an electric kicker with the duration covering over one revolution (~40 μs) with short turn-off time (a few tenth μs). As the duration of the injection kicker, usually 100 μs is utilized, while 10 μs duration is adopted for the purpose of beam observation with the use of an electrostatic pick up.

The closed orbit of the $^{24}Mg^{+}$ ion is adjusted to the central orbit. The correction is based on the measurement of the closed orbit by the electrostatic pick-ups. The closed orbit distortion after correction is smaller than ± 0.5 mm. In order to guarantee overlapping of the ion beam with the laser for cooling, the ion beam orbit in the straight section for laser cooling is defined by two apertures. The aperture size can be chosen from 2, 3, 6 and 10 mmϕ and the closed orbit is adjusted to realize a beam life of about 1 s using two apertures of 6 mm ϕ at positions illustrated in Fig. 3 [17].

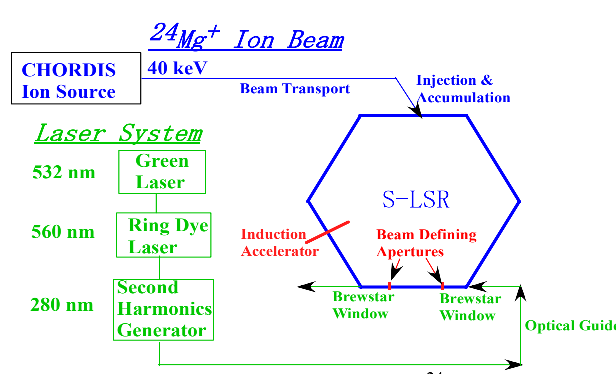
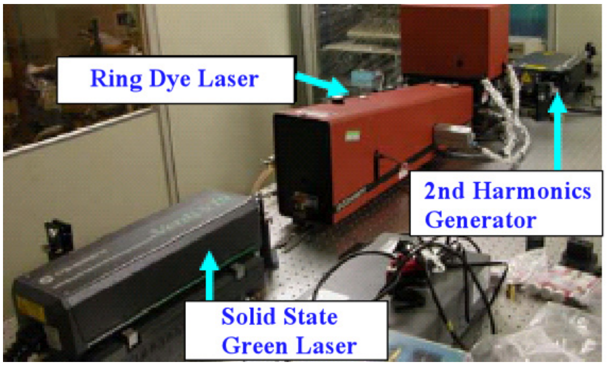
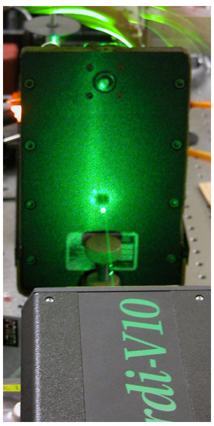


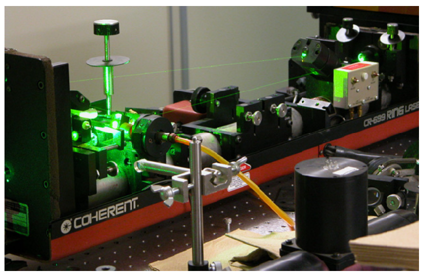
Figure 3: Laser cooling scheme for $^{24}Mg^{+}$ ion beam.



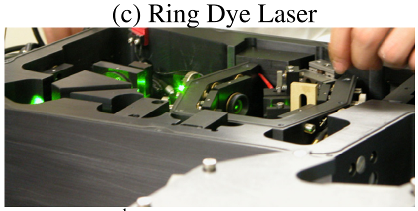
(a) Overall View of laser cooling



(b) Green Laser



(c) Ring Dye Laser



(d) 2nd Harmonics Generator

Figure 4: (a) An overall view of the laser system for beam cooling of Mg ions, consisting of (b) a solid state green laser (VERDI) with the wavelength 532 nm, (c) a ring dye-laser with the wave length ~560 nm pumped by the green laser and (c) a second harmonics generator for generation of the wave length of ~280 nm.

Laser System

In Fig. 3, the block diagram of our laser cooling system is shown. The laser system is set on a stage avoiding vibration, installed in a temperature and humidity controlled cottage, shown in Fig. 4 (a). A ring dye-laser (Fig. 4 (c)) pumped with a solid state green laser (COHERENT VERDI) with wavelength 532 nm and a peak power of 10 W (Fig. 4 (b)) is frequency doubled by a second harmonic generator (COHERENT MBD-200) (Fig. 4 (d)) to the wavelength ~280 nm, which is finally adjusted taking the small Doppler shift effect (0.19 %) into account [18].

The output of the 2nd harmonics generator with a power of about 40 mW is guided through the optical system composed of focusing lenses and reflection mirrors and injected into a long straight section of the S-LSR through a Brewster window. The laser path is defined by the two apertures defining the beam size. Final adjustment of the laser path is done with apertures of 2 mm ϕ chosen from several sizes of apertures by the linear driving mechanisms. The laser used for cooling is also monitored, taking out from S-LSR through a Brewster window at the down stream end of the laser cooling section.

LASER COOLING EXPERIMENTS

Up to now, laser cooling experiments have been performed with the normal lattice of finite dispersion by normal bends composed of pure dipole magnetic fields. A single laser which co-propagates with $^{24}Mg^+$ ion beam in the same direction has been utilized, because only one laser system of the wavelength ~280 nm is available at the moment. The sensitive momentum spread region for laser cooling is estimated to be ~2x10^{-5}. Two laser cooling schemes have been applied. In the first method, the ion beam is decelerated by a velocity independent induction voltage keeping the laser frequency fixed and in the second one, the laser frequency was swept so as to survey the total momentum region of the accumulated ions. The main parameters of laser cooling at S-LSR are listed up in Table 3.

Laser Cooling by Simultaneous Application of Induction Voltage with Fixed Laser Frequency

The Schottky signals observed before and after laser cooling are shown in Fig. 5 for an $^{24}Mg^+$ ion beam with an initial intensity of about 10^8 and a momentum spread of 1.7x 10^{-3} (1σ). The operation point of (2.1, 0.8) was utilized for this measurement. In this case, the laser frequency was fixed and deceleration with an induction voltage of about 6 mV was simultaneously applied. The relatively large momentum spread after cooling (2.9x10^{-4}) is considered to be due to momentum transfer from the transverse degree of freedom to the longitudinal one due to intra-beam scattering. The longitudinal temperature of the $^{24}Mg^+$ ion after laser cooling is estimated to be several tens Kelvin, which could be reduced to a few Kelvin by

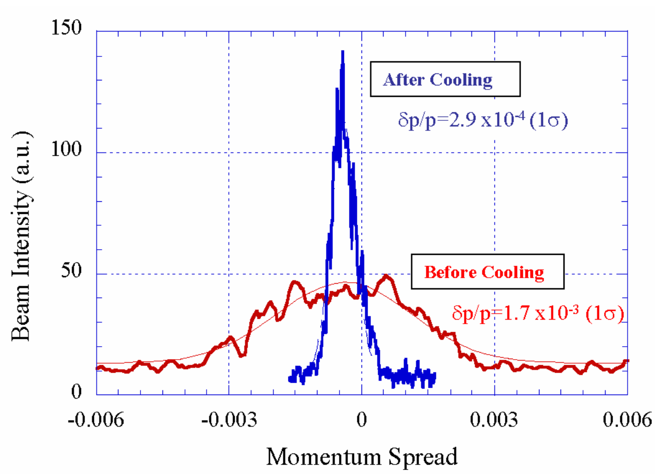


Figure 5: Effect of laser cooling on momentum spread of $^{24}Mg^+$ ions. Laser cooling keeping its frequency fixed was applied to $^{24}Mg^+$ ions with the intensity of ~10^8 together with an induction deceleration voltage of ~6 mV, which reduced the fractional momentum spread from 1.7 x 10^{-3} to 2.9 x 10^{-4}. The spectrum after cooling was measured 5 second after the start of laser cooling.

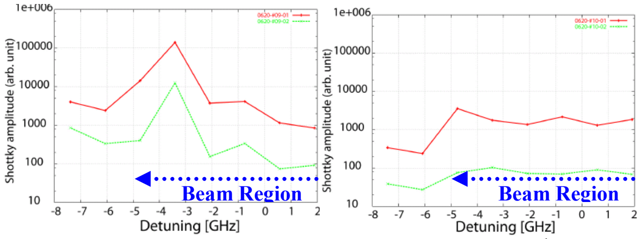


Figure 6: Dependence of the peak values of the 9^{th} (a) and 10^{th} (b) harmonics of the revolution frequency on the detuning frequency of the laser.

reducing the Mg ion number to 10^6. Achievement of much lower temperature requires further reduction of ion numbers, which has not yet been realized because it is difficult to observe the Schottky signal of a low intensity beam, which is expected to be solved by the recent development of the optical observation system (a photomultiplier or a CCD camera), using the emitted light, coming from the transition from upper to lower states, described in the next section.

Laser Cooling with Laser Frequency Shift

The positive frequency sweep of the single laser was applied to the $^{24}Mg^+$ ion beam in order to investigate the beam response to the longitudinal laser cooling force, although there was no equilibrium point for this case. In Fig. 6, the peak heights of the Schottky signal observed by an electrostatic beam pick up for various laser frequency detuning are shown for the 9^{th} (a) and 10^{th} (b) harmonics. The experiment was performed at an operation point of (1.53, 1.34). Strong coherent enhancement of the Schottky signal more than one order of magnitude is observed for odd harmonics just after the detuned frequency of the laser begins to overlap with ion beam region, while such an effect is not as strong for even harmonics as shown in Fig. 6, the explanation of which is a subject of our further investigation.

Table 3: Parameters of Laser Cooling at S-LSR

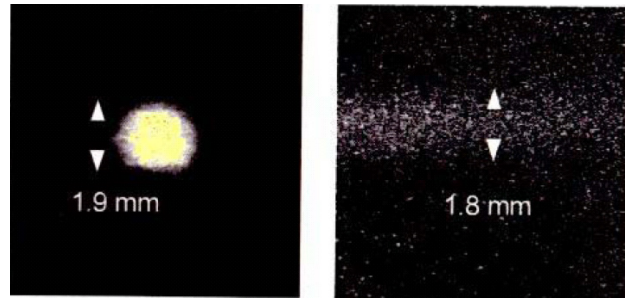
Cooled Ion	$^{24}Mg^+$
Kinetic Energy	40 keV
Transition	Lower State :$3s^2S_{1/2}$ Upper State:$3p^2P_{3/2}$
Laser Wavelength	280 nm
Beam Current	~2 μA
Revolution Frequency	25.2 KHz
Beam Life	>10 s (except for operation point of (2.07, 1.07))

FUTURE PROSPECT OF LASER COOLING AT S-LSR

Optical Beam Observation System

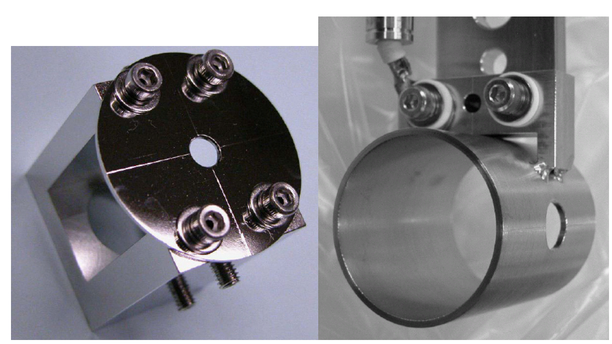
Because beam observation with the use of Schottky signals is rather difficult for beam intensities less than 10^6, which is required to suppress the effect of intra-beam scattering, an optical beam measurement system has been developed [19]. As indicated in Fig. 1, detectors of spontaneous emission light with a photo-multiplier (PMT) and a CCD camera are utilized. Up to now, the vertical size of the Mg ion beam is monitored by observation of spontaneous emission light, which is consistent with the laser spot size (1.9 mmϕ) observed by a fluorescent screen as shown in Fig.7. This observation, however, largely depended on the optical alignment of the laser. In many cases, the observation system suffered with heavy background, due to scattered laser light. Photon counting of the spontaneous emission with a photo-multiplier tube (PMT) was not possible because of severe background of the same origin. In order to improve this situation, an aperture shown in Fig. 8 (a) was installed just after the Brewster window for laser injection during the vacuum system break down at the end of August, 2007. We hope that the tail of the laser will be cut off with this aperture and the scattered laser light and, hence, the background photons will be largely reduced.

In parallel, PAT (Post Acceleration Tube) as shown in Fig. 8 (b) is also installed into the straight section for laser cooling in this summer. By counting the spontaneous emission coming through the side hole of the PAT with a PMT, sweeping an electrostatic potential applied to the PAT with a fixed laser-frequency, the velocity distribution of $^{24}Mg^+$ ion beam can be obtained. Such a



(a) Laser spot size (b) Vertical beam size

Figure 7: Laser spot size observed by a fluorescent screen (a) and vertical size of Mg ion beam by observation of the spontaneous emission light with the use of a CCD camera (b).



(a) (b)

Figure 8: Newly installed aperture, which is to reduce the scattered light of the laser to improve the optical beam measurement just after the Brewster window for introducing the laser into the vacuum system of the S-LSR (a) and newly installed PAT (Post Acceleration Tube) for observation of energy distribution of $^{24}Mg^+$ ion (b).

measurement is to be performed this fall. We have just finished the baking procedure after vacuum break down.

Bunched Beam Laser Cooling

The ferrite loaded un-tuned RF cavity used for 7 MeV protons has a gap (G) and an inner diameter (D) with sizes of 20 mm and 158.4 mm, respectively, the effective length of the RF electric field becomes 119.5 mm because of the poor aspect ratio (D/G) of ~8. The passing time of an 40 keV $^{24}Mg^+$ ion through this distance, ~210 ns, is almost comparable with the half period of the applied RF (2.52 MHz) with a harmonic number of 100. Such a situation results in the worse transit time factor of ~0.5 for the case of 40 keV $^{24}Mg^+$ ions compared with the value higher than 0.99995 for 7 MeV protons with harmonic number of 1. In order to improve such a situation, a new RF system with a drift tube has been fabricated [17] (Fig.9). The effective length of the drift tube is about 27 mm and and the inner diameter is 35 mm, resulting in a better aspect ratio of ~1.3. The new RF drift tube was installed into S-LSR in this summer. It will play an important role for the investigation of the bunched beam laser cooling in this fall.

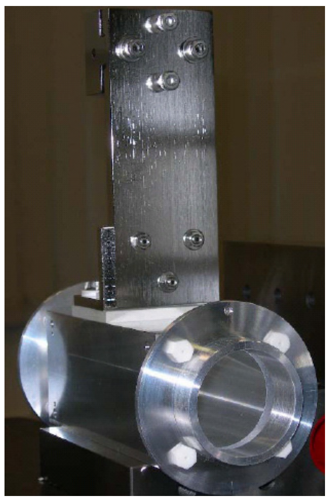


Figure 9: New RF cavity with better aspect ratio (~1.3) recently installed into S-LSR.

SUMMARY

Laser cooling has been applied at the S-LSR for a $^{24}Mg^+$ ion beam with kinetic energy of 40 keV. With the use of a single laser co-propagating with the ion beam together with an induction deceleration voltage of 6mV, the momentum spread (1σ) of 10^8 ions is reduced from 1.7×10^{-3} to 2.9×10^{-4} resulting in a longitudinal beam temperature of several tens Kelvin, which was reduced to a few Kelvin by reducing the number of stored ions to 10^6. For the achievement of much lower temperatures, further reduction of the ion number to suppress intra-beam scattering and transverse cooling is needed. Improvement of the optical measurement system has just been applied to enable cooling experiments with a lower intensity beam together with precise energy-spectrum measurement, which will be started this autumn.

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