APPROACH TO 2 DIMENSIONAL LASER COOLING AND ITS OPTICAL OBSERVATION SYSTEM*

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Abstract

Laser cooling for bunched Mg ion beam with the kinetic energy of 40 keV has been applied with S-LSR at ICR, Kyoto University. Up to now, clear peaking of equilibrium momentum spread after laser cooling has been observed at such a synchrotron tune as resonates with the horizontal betatron tune, which is considered to be due to heat transfer from the horizontal degree of freedom to the longitudinal one. In order to demonstrate transverse cooling by observation of reduction of the horizontal beam size, spontaneous emission from laser induced excited state of the Mg ion, has been observed with the use of CCD camera. Some reduction of horizontal beam size has been observed with a certain synchrotron tune, a little bit smaller compared with the fractional part of the horizontal tune.

OUTLINE OF S-LSR

S-LSR is an ion storage and cooler ring, where electron beam cooling of 7 MeV proton and laser cooling of 40 keV $^{24}Mg^{+}$ ion beam have been applied to realize a ultra-low temperature beam. Its circumference and radius of curvature are 22.557 m and 3.57 m, respectively [1]. This ring is designed with a super-periodicity of 6 in order to enable an operation satisfying the so-called “maintenance condition” of beam envelope [2]. In addition, S-LSR has special characteristics to suppress shear heating as described below. In Figs. 1 and 2, the layout of S-LSR and an overall view of S-LSR are shown.

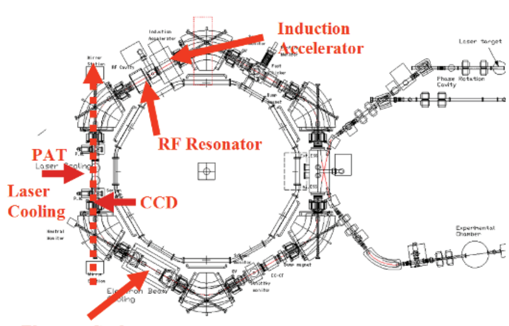

Figure 1: Layout of S-LSR.

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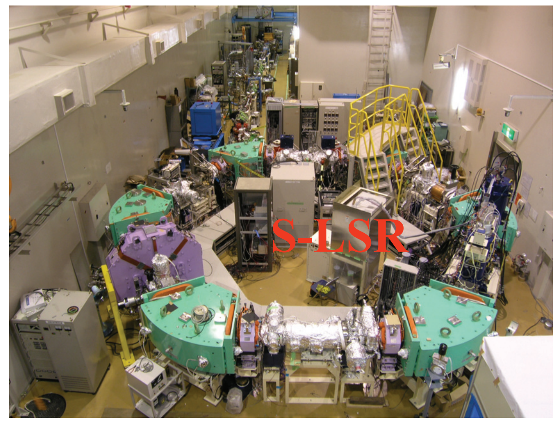

Figure 2: Overall view of S-LSR.

Special Feature of S-LSR Lattice with Use of Electrostatic Deflectors in Dipole Magnets

For the purpose of suppressing a shear heating, we have proposed a doubly achromatic ring lattice with a simultaneous use of an electrostatic field in each dipole magnet as illustrated in Fig. 3 [5, 6].

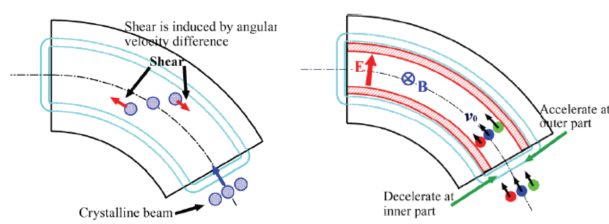

Figure 3: Scheme for suppression of a shear heating with the use of electrostatic field together with a dipole magnetic field.

The orbit dispersions in an electric and magnetic fields are given by the relations

$$\frac{d^2x}{ds^2} + \frac{3-n}{\rho^2}x = \frac{1}{\rho}\frac{\Delta W}{W} \quad (1)$$

and

$$\frac{d^2x}{ds^2} + \frac{1-n}{\rho^2} = \frac{1}{\rho}\frac{\Delta p}{p} \quad (2)$$

respectively.

In a non-relativistic case where

$$\frac{\Delta W}{W} = 2\frac{\Delta P}{P} \qquad (3)$$

is satisfied, these orbit dispersions cancel out between each other if the following condition,

$$2\vec{E} = -(\vec{v} \times \vec{B}) \qquad (4)$$

is satisfied by the electric, $\vec{E}$, and magnetic, $\vec{B}$, fields. In the case of the S-LSR lattice as shown in Fig. 1, each dipole magnet deflects the ion beam as much as 120° towards the inside while the electric field deflects it by 60° towards the outside, thus net 60° deflection to inner side is realized. Suppression of a shear heating is possible by realizing the same angular velocity accelerating or decelerating the ions with an electrostatic potential according to their radial positions.

Experimental Results so-far attained

Reflecting such a superiority of S-LSR as is optimized to stabilize ion beam dynamics, one dimensional ordering has been realized by an electron beam cooling with the beam number less than ~2000 for the first time for proton beam with 7 MeV as shown in Fig. 4 [3].

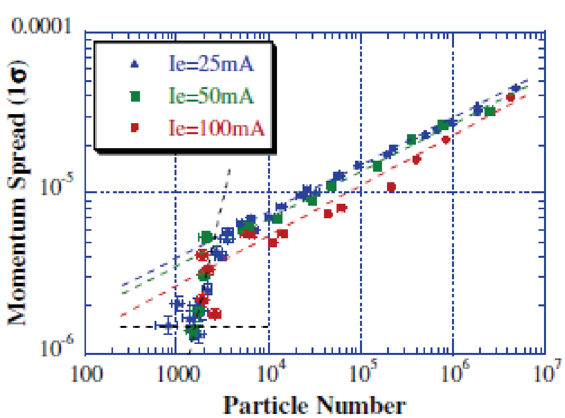

Figure 4: Phase transition to one dimensional ordered state by application of an electron beam cooling for 7 MeV proton at the particle number ~2000.

The cooled proton temperature is ~2 K and ~12 K for longitudinal and transverse directions, respectively.

In order to extend the cooled beam temperature toward much lower region, application of laser cooling with much stronger cooling force is inevitable and a laser cooling has been applied for coasting beam of $^{24}Mg^{+}$ ion beam with a kinetic energy of 40 keV. In Fig. 5, a laser cooling system consisting of a solid state green laser, a ring dye laser and its second harmonics generator, is shown.

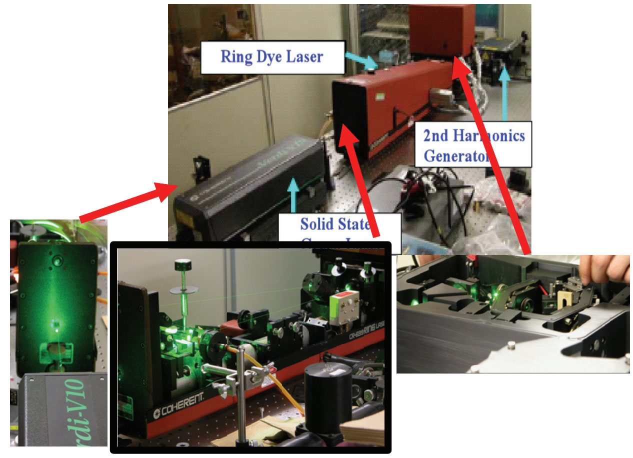

Figure 5: Laser cooling system for $^{24}Mg^{+}$ of 40 keV consisting of a solid green laser, a ring dye laser and the second harmonics generator.

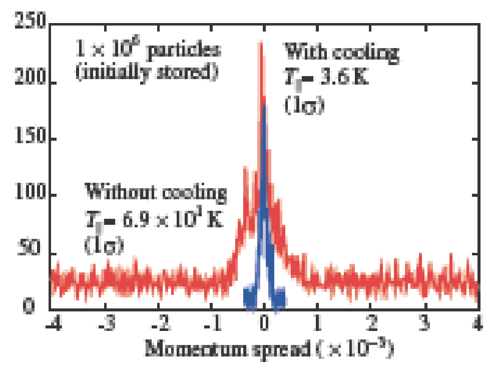

Figure 6: Experimental result of longitudinal laser cooling applied for a coasting beam counter balanced with an induction deceleration voltage.

In this system, the laser light co-propagates with $^{24}Mg^{+}$ ion beam and accelerates ion beam as large as hν (ν: laser frequency, h: Planck's constant) for excitation by a laser light, which is counterbalanced with deceleration by an induction accelerator. In Fig. 6, the experimental result of laser cooling applied for a coasting beam is shown.

Table 1: Main Parameters of S-LSR and its Laser Cooling

Ring Lattice		
Circumference	22.557 m	
Average radius	3.59 m	
Length of straight section	1.86 m	
Number of periods	6	
Betatron Tune Horizontal	2.07	
Vertical	1.07	
Laser for Beam Cooling		
Type of Laser	**Wave Length**	**Typical Power**
Pumping Laser	532 nm	10 W
Dye Laser	560 nm	600 mW
2^{nd} Harmonics	280 nm	50 mW

Equilibrium longitudinal beam temperature after cooling is estimated to be 3.6 K, which is limited by a heat transfer from transverse degrees of freedom due to intra-beam scattering because transverse temperature of the injected beam is rather high as ~500 K [7]. In Table 1, main parameters of S-LSR and its laser cooling system are given.

APPROACH TO 2 DIMENSIONAL LASER COOLING

After the achievement of above mentioned results, our main efforts are oriented to realization of crystalline beam, which is free from variation of inter-particle distance. For such a purpose, the following items need to be carefully investigated.

Resonant Coupling between Longitudinal and Transverse Degrees of Freedom

After laser cooling so far applied, the transverse equilibrium temperature is more than 2 orders of magnitude higher than the longitudinal one, because a laser cooling force is only applied in the longitudinal direction and heat transfer by intra-beam scattering so far observed is too weak. In order to improve such a situation, a scheme to couple the beam motions in longitudinal and transverse directions with the use of a "Synchro-Betatron Resonance" has been proposed [8]. For the purpose of experimental verification of feasibility of such a scheme, bunched beam laser cooling has been applied with the condition satisfying "Synchro-Betratoron Resonance" as is given by the formula,

$$\upsilon_s - \upsilon_H = m \text{ (integer)},$$

where ν_s and ν_H are synchrotron tune and betatron tune in horizontal direction, respectively, and with application of RF acceleration at the position with a finite dispersion function (~1 m).

In order to obtain the evidence of longitudinal and transverse coupling, an equilibrium momentum spread after application of laser cooling has been measured for various synchrotron tunes as shown in Fig. 7.

Existence of local maxima can be seen at the synchrotron tunes almost equal to the fractional part of the horizontal betatron tune, which, we think, is the indication of a coupling between the longitudinal and horizontal degrees of freedoms.

For direct demonstration of transverse laser cooling, observation of reduction of the horizontal beam size by a bunched beam laser cooling at the resonant condition of "Synchro-Betatron Resonance" has been tried. For this purpose, we have observed spontaneous emission from laser excited $^{24}Mg^{+}$ ions by an observation system described in the next section. In Fig. 8, preliminary result of such measurement of the horizontal beam size for various synchrotron tunes is shown.

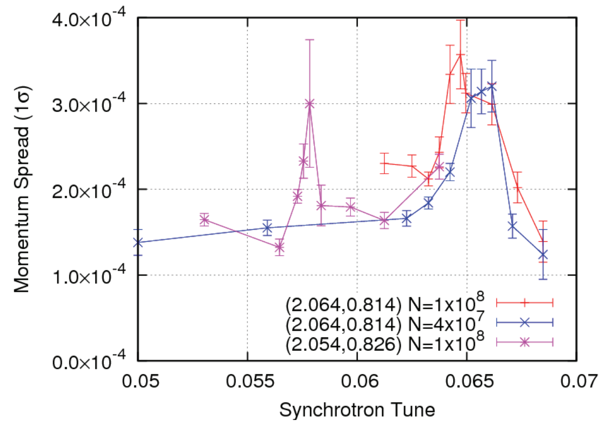

Figure 7: Equilibrium momentum spread after laser cooling for various synchrotron tunes.

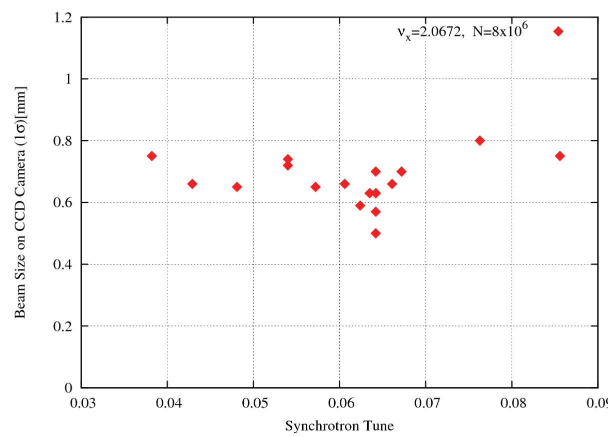

Figure 8: Variation of the horizontal beam size after laser cooling of bunched beam by RF acceleration at a position with the finite dispersion.

It is seen at a certain synchrotron tune, reduction of the horizontal beam size is indicated although this synchrotron tune is somewhat smaller compared with the fractional part of the horizontal betatron tune, which needs further investigation.

Reduction of Initial Transverse Temperature

As the injected $^{24}Mg^{+}$ ion beam is directly transported from the ion source after extraction from the ion source by a high voltage of 40 keV, transverse beam size is not yet well reduced, which is the reason of a rather higher transverse temperature of the injected beam. The reached longitudinal temperature after application of laser cooling remains at a rather higher value as 3.6 K for particle numbers of 3 x 10^4 due to heat transfer from the transverse direction through intra-beam scattering. So as to reach much lower final temperature, pre-cooling of injected beam by an electron beam cooling might be needed, which is to be applied from now on.

Figure 9: PAT (Post Acceleration Tube) for observation of momentum spread of the laser cooled Mg ion beam.

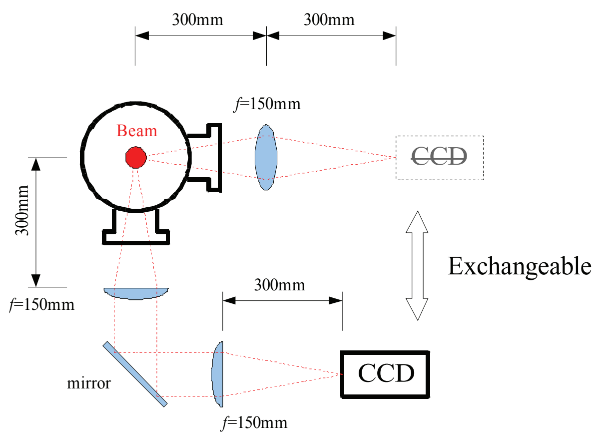

Figure 10: Observation system of the transverse beam profile with the use of CCD.

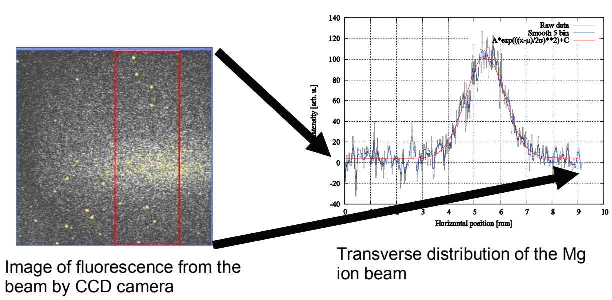

Figure 11: Observation of horizontal beam profile and beam size with the use of CCD.

OPTICAL OBSERVATION SYSTEM AT S-LSR

For observation of momentum spread and transverse beam size after cooling, the following optical observation system has been developed [9, 10].

Observation of Laser Cooled Momentum Spread

The momentum spread of the laser cooled $^{24}Mg^{+}$ ion beam has been measured by observing the emitted light from $^{24}Mg^{+}$ ions with a photo-multiplier through a hole at the side wall of a PAT (Post Acceleration Tube) as shown in Fig. 9 varying the applied potential to the PAT.

Mg ion can only be excited when their velocities are in a certain range satisfying Doppler Cooling condition and we can measure the momentum spread after laser cooling with observation of the intensity of emitted light by sweeping the applied voltage to the PAT as shown in Fig. 7.

Observation of Horizontal Beam Size by CCD

The transverse beam profile of the laser cooled $^{24}Mg^{+}$ ion beam has been measured by observation of emitted light from Mg ion with the use of CCD camera.

Beam size is obtained by fitting the observed profile after subtracting background as illustrated in Fig. 11.

At the beginning, the CCD was set to observe the vertical beam size, which however, was not efficient to detect coupling between longitudinal and transverse directions, because such a coupling occurs between longitudinal and horizontal directions. So the observation system by CCD has been modified to detect the horizontal beam profile by adding a view port from the bottom in summer 2008 and preliminary results as shown in Fig. 8 have become available.

SUMMARY

Laser cooling has been applied to $^{24}Mg^{+}$ ion beam with the kinetic energy of 40 keV at S-LSR. Longitudinal cooling has reduced the longitudinal temperature to 3.6 K, which is limited by heat transfer from transverse motion due to intra-beam scattering. Coupling between longitudinal and horizontal directions on purpose by using "Synchro-Betatron Resonance" has been investigated in these several months. Experimental indications of such a coupling has been obtained by observation of the cooled momentum spread and the horizontal beam size, which, however, needs further refinement in a more quantitative way from now on. Application of pre-electron beam cooling might also be investigated to realize much lower equilibrium temperature needed for creation of crystalline beam, where the special feature of S-LSR lattice will play an essential role.

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