Recent Status of Laser Cooling for Mg Realized at S-LSR *

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Abstract

Laser cooling has been applied for $^{24}$Mg$^+$ ion beam with the kinetic energy of 40 keV. By application of laser light with the wavelength of 280 nm of the power ~50 mW, the ion longitudinal temperature has been cooled down to 3.6 Kelvin for ion number of $3\times10^4$, which is considered to be limited due to heat transfer from transverse degree of freedom to longitudinal one. Longitudinal and transverse temperatures are found to be coupled linearly. By application of synchro-betatron coupling, the coupling between longitudinal and transverse temperature has been tried to be increased on purpose to cool down the transverse temperature by the laser cooling, indication of which has been experimentally observed for bunched beam cooling.

Introduction

By application of beam cooling such as an electron cooling and laser cooling, realization of ultra low temperature of the beam has been investigated following the report on ordered state of proton beam from NAP-M [1]. A storage ring optimized for the above purpose satisfying the formation and maintenance conditions[2], S-LSR is constructed at ICR, Kyoto University[3]. With use of S-LSR, one dimensional ordering of 7 MeV protons by application of electron cooling has been demonstrated [4]. In order to approach to the crystallized structure of the circulating beam, laser cooling with much stronger cooling force has been applied for $^{24}$Mg$^+$ ion with 40 keV. In the present paper, the present status of laser cooling experiments is described together with the recent approach to couple transverse degrees of freedom with that of longitudinal direction by synchro-betatron coupling.

Laser Cooling of Coasting Beam at S-LSR

S-LSR is an ion storage and cooler ring completed in autumn of 2005 at ICR, Kyoto University [1]. Its circumference and average radius are 22.557 m and 3.59 m, respectively. Magnesium ion with kinetic energy of 40 keV is transported directly after extraction from an ion source and is injected and accumulated in S-LSR. In Fig. 1, the layout of S-LSR is shown indicating major equipments related to beam cooling. Laser cooling in the longitudinal direction has been applied at one of the six straight sections of S-LSR overlapping the ion beam with

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>22.557 m</td>
</tr>
<tr>
<td>Average radius</td>
<td>3.59 m</td>
</tr>
<tr>
<td>Length of straight section</td>
<td>1.86 m</td>
</tr>
<tr>
<td>Number of periods</td>
<td>6</td>
</tr>
<tr>
<td>Betatron Tune</td>
<td>Horizontal: 2.07</td>
</tr>
<tr>
<td></td>
<td>Vertical: 1.07</td>
</tr>
<tr>
<td>Type of Laser</td>
<td>Wave Length</td>
</tr>
<tr>
<td>Pumping Laser</td>
<td>532 nm</td>
</tr>
<tr>
<td>Dye Laser</td>
<td>560 nm</td>
</tr>
<tr>
<td>2nd Harmonics</td>
<td>280 nm</td>
</tr>
<tr>
<td>Typical Power</td>
<td>10 W</td>
</tr>
<tr>
<td></td>
<td>600 mW</td>
</tr>
<tr>
<td></td>
<td>50 mW</td>
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</tbody>
</table>

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Figure 1: Layout of S-LSR

Figure 2: Laser system for cooling of $^{24}$Mg$^+$ at S-LSR.
the co-propagating laser beam. A laser beam with the wavelength of ~280nm created by frequency doubling with MDB-200 of an output of the ring-dye laser with the use of Rhodamine (CRR699-29) pumped by a solid state green laser (VERDI V-10) with a wave length of 532 nm, all provided by Coherent. Co. Ltd. The laser system is shown in Fig. 2. In Table 1, main parameters of S-LSR are given together with the laser parameters.

One Dimensional Laser Cooling of Coasting Beam

Laser cooling has been applied successfully for $^{24}$Mg$^+$ beam by simultaneous use of an induction deceleration. In Fig. 3 (a), typical momentum distributions are shown for the cases with and without laser cooling. The longitudinal temperature of the $^{24}$Mg$^+$ ion beam, $T_L$, is given by the relation:

$$k_B T_L = m v_0^2 \left( \frac{\Delta p}{p} \right)^2,$$

where $k_B$, $m$ and $v_0$ are Boltzmann constant, mass of the ion and the central velocity, respectively.

The transverse temperature, $T_\perp$, can be written as,

$$T_\perp = m v_0^2 \frac{1}{C} \sigma^2 2 \pi \nu_\perp \beta_\perp,$$

where $C$, $\sigma \perp$, $\nu_\perp$ and $\beta_\perp$ are the circumference of the ring, transverse beam size, transverse betatron tune and the beta-function at the beam observation position, respectively.

At these experiments, the longitudinal ion beam temperature has been cooled down to 3.6 Kelvin for the ion number of $3 \times 10^4$, which is considered to be limited due to heat transfer from transverse degree of freedom to longitudinal one through intra-beam scattering. Such coupling between transverse and longitudinal motions has been systematically studied changing the number of the cooled ion beam. The dependence of longitudinal temperature on the ion number, $N$, has been obtained as shown in Fig. 3 (b) and can be written as,

$$T_L \propto N^{0.32 \pm 0.04},$$

which is consistent with a linear dependence of the longitudinal temperature, $T_L$, on the transverse temperature, $T_\perp$, if we take systematic error into account.

The relation between $T_L$ and $T_\perp$, can be written as [5]

$$T_L = 0.02 T_\perp.$$

In order to realize much lower beam temperature than the one above described, it is required to reduce the transverse heat ether by application of pre-cooling such as an electron cooling [6] or take away it by transferring to longitudinal one by synchro-betatron coupling and cool down by a longitudinal laser cooling [7]. The former capability is now under consideration but it needs some modification of the electron cooler of S-LSR, which has been oriented only for protons with 7 MeV and carbons with 2 MeV/u, while pre-cooling of 40 keV of $^{24}$Mg$^+$ ion requires much slower electron beam (~1eV). This needs some replacement of power supplies and so on. The latter is more straightforward approach toward the three dimensional laser cooling and we have tried to realize synchro-betatron coupling by applying RF voltage at the position with a finite dispersion. Details of such measurements are given in our other paper to this conference[8]. In the next section, the experimental result is discussed although it is not yet well understood.

Bunched Beam Laser Cooling Toward Three Dimensional Cooling

Coupling between Longitudinal and Horizontal Degrees of Freedom

The laser cooling has also been applied for bunched beam with application of the RF voltage by an RF resonator newly fabricated and set in the position as shown in Fig. 1. The momentum spread of the $^{24}$Mg$^+$ ion beam has been measured by observing the simultaneously emitted light during the process of sweep of applied potential to the ion beam. In Fig. 4, typical results of synchrotron tune dependence of the momentum spread is shown. These measurements are performed with the
operation points, \((v_x, v_y, v_z)= (2.064, 0.814, 0.065)\) and 
\((2.054, 0.826, 0.057)\)[8]. Using Eq.(1), the longitudinal 
temperature, \(T_L\), is estimated to be increased from \(-20\) 
Kelvin to \(-80\) Kelvin, while the transverse temperatures 
are estimated by Eq.(2) to be \(-800\) Kelvin and \(-400\) 
Kelvin for horizontal and vertical directions, respectively 
from the observed size of \(1.3\ \text{mm} \times 2.1\ \text{mm (H x V)}\) of 
the injected ion beam. Thus the kinetic energy is 
considered to be transferred from the transverse degree of 
freedom to longitudinal one. Observation of reduction of 
the transverse beam size is our next goal but it has not yet 
successful up to now obscured by the background level of 
optical beam size monitoring.

**Coupling between Horizontal and Vertical Motions**

Transverse motions in horizontal and vertical 
directions can be coupled with the use of a solenoidal 
field or a skew quadrupole field. In the present research, 
a solenoidal field for an electron cooling is utilized while 
the field strength is set at a rather lower value of 40 G 
compared with 500 G for the case of \(7\ \text{MeV}\) proton 
electron cooling. With the operation point of \((v_x, v_y)= (2.068, 1.069)\), the beam life has been measured 
changing the synchrotron tune for both with and without 
solenoidal field (Fig. 5). [8]

Without a solenoidal field, beam life has no sharp 
dependence on synchrotron tune both with and without 
laser cooling. With a solenoidal field, the beam life 
sharply reduced around the synchrotron tune of \(-0.05\), 
while the beam life is much longer at both side of this 
synchrotron tune. The beam life is enlarged at both sides 
of this point by application of laser cooling, which is 
considered to be due to the horizontal betatron oscillation 
aperture widening due to the longitudinal laser cooling 
because the ring lattice has a finite dispersion.

The resonant behaviour of the beam life around the 
synchrotron tune \(-0.05\) is considered to be due to 
presence of the solenoidal field, but the reason why the 
beam life becomes very short (\(-1\ \text{s}\)) around \(v_x\)-0.05 is not 

**SUMMARY**

One dimensional laser cooling of a coasting beam has 
successfully applied by simultaneous application with an 
induction deceleration reaching an equilibrium 
longitudinal temperature of 3.6 Kelvin. Bunched beam 
cooling to couple two degrees of freedom satisfying 
syncho-betatron coupling has been performed, which 
showed the resonant increase of the longitudinal 
momentum spread at the condition of syncro-betatron 
resonance, although observation of the transverse size 
reduction is not yet attained. Horizontal and vertical 
coupling with a solenoidal field raised a resonant decrease 
of beam life around a certain synchrotron tune, the reason 
of which is not yet clarified.

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