# 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 wave length of 280 nm of the power ~50mW, the ion longitudinal temperature has been cooled down to 3. 6 Kelvin for ion number of $3x10^{4}$, 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.

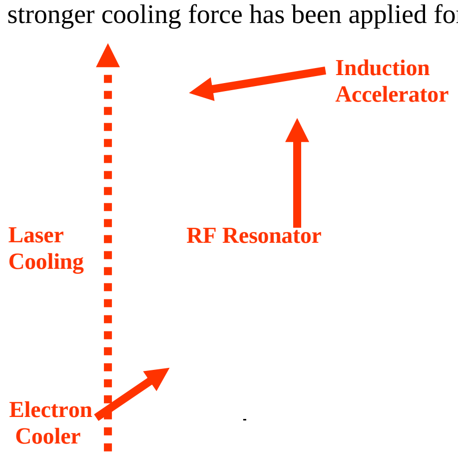


Figure 1 Layout of S-LSR

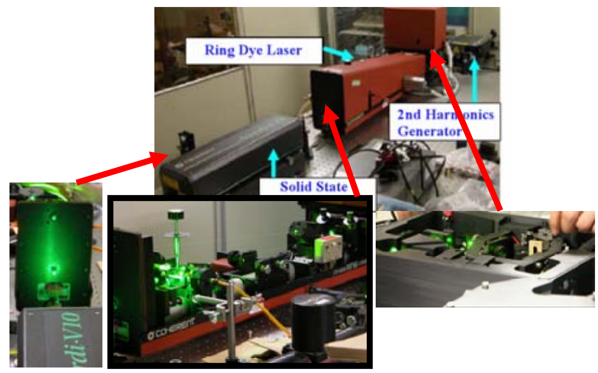


Figure 2. Laser system for cooling of $^{24}Mg^{+}$ at S-LSR.

## 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

| 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 |

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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.

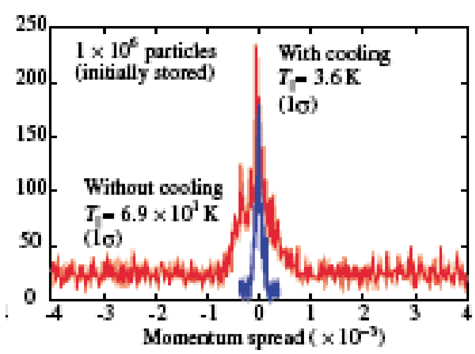
## *One Dimensional Laser Cooling of Coasting Beam*

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:

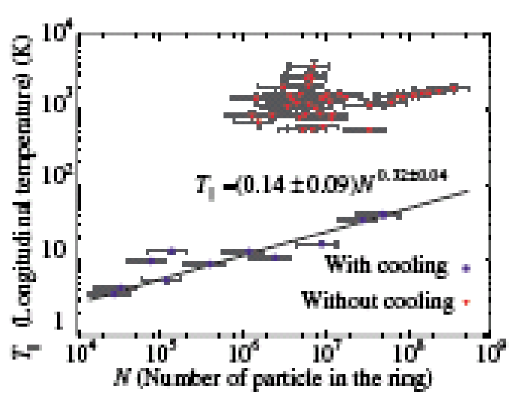
$$k_B T_L = m v_0^2 \left(\frac{\Delta p}{p}\right)^2 , \qquad (1)$$

where $k_B$, m and $v_0$ are Boltzmann constant, mass of the ion and the central velocity, respectively. The ring-averaged transverse temperature, $T_\perp$, can be written as,

$$T_\perp = m v_0^2 \frac{1}{C} \frac{\sigma_\perp^2}{\beta_\perp} 2\pi \nu_\perp , \qquad (2)$$




(a) Momentum spread




(b) Dependence of longitudinal temperatue on particle number

Figure 3 Experimental results of longitudinal laser cooling of coasting beam [5]..

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 $3\times10^4$, 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,

$$T_L \propto N^{0.32\pm0.04} , \qquad (3)$$

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]

$$T_L = 0.02 T_\perp . \qquad (4)$$

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 straight forward 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, ($\nu_x$, $\nu_y$, $\nu_s$)=(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 mm x 2.1 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 MeV proton electron cooling. With the operation point of ($\nu_x$, $\nu_y$)=(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

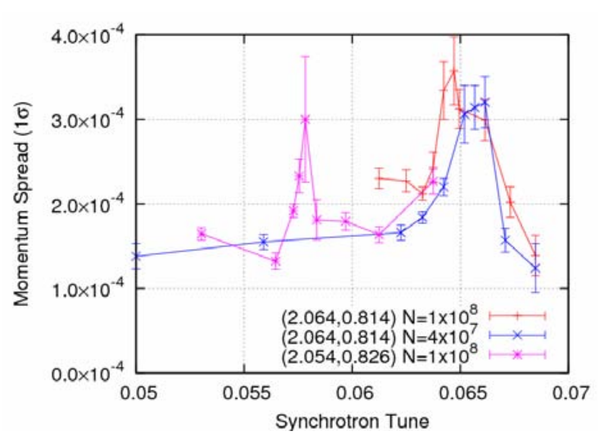



Figure 4. Synchrotron tune dependence of momentum spread with application of laser cooling.

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 s) around $\nu_s$~0.05 is not

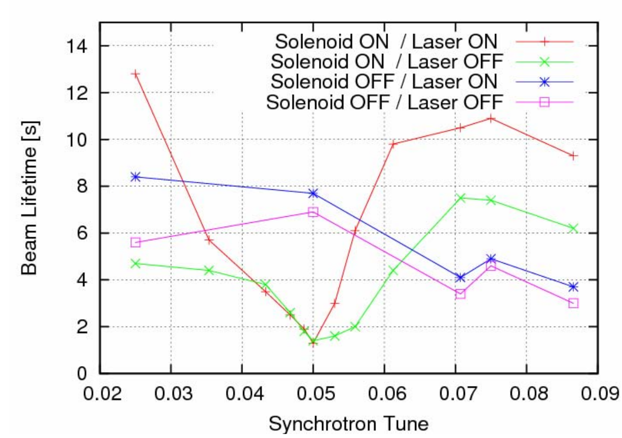



Figure 5 Dependence of beam life on synchrotron tune.

yet well explained, which needs further investigation from now on.

## 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 synchro-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.

## ACKNOWLEDGEMENTS

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