LASER COOLING OF BUNCHED ION BEAM AT S-LSR*

H. Souda†, M. Ikegami‡, T. Ishikawa, M. Nakao, A. Noda, M. Tanabe, H. Tongu, M. Yamada, A. Wakita
Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan
T. Shirai
National Institute of Radiological Sciences, Inage, Chiba, 263-8555, Japan

Abstract

Bunched $^{24}\mathrm{Mg}^{+}$ Beams are cooled by a laser at small laser-equipped storage ring (S-LSR). With the use of a co-propagating laser and a broadband RF cavity, the longitudinal temperature of the beam is reduced to 18 K. In order to achieve lower temperature, three dimensional laser cooling is being carried out. The resonant coupling of longitudinal and horizontal oscillations are observed as sharp peaks of momentum spreads at two different tune conditions $(\nu_s, \nu_x) = (0.064, 2.065), (0.057, 2.054)$.

INTRODUCTION

Laser cooling is a cooling method with a strong cooling force. The attained minimum temperature of laser-cooled ion beams are in the order of mK[1]. In such a low temperature, ion beams are considered to have a phase transition to a crystalline state[2], if the storage ring satisfy some conditions[3].

A Small laser-equipped storage ring[4] is newly designed to satisfy these conditions and is constructed at Institute for Chemical Research, Kyoto University. Laser cooling experiments have been carried out since January 2007. We found that a coupling of the longitudinal and transverse temperatures by an intra-beam scattering limits the longitudinal temperature of the beam in the experiment of laser cooling of coasting beams[5]. In order to achieve lower temperature, transverse temperature must be cooled.

H. Okamoto has suggested a method to enable 3-dimensional laser cooling with use of an RF cavity placed on a dispersive section[6]. In this method, the transverse temperature is transmitted to longitudinal direction by means of the coupling of betatron and synchrotron oscillations.

To realize this method, we have to cool bunched beams. Since bunched beams are rotating in a longitudinal phase space, particles with a certain momentum absorb the laser and are pushed inside of the separatrix[7].

We have achieved 1-dimensional bunched beam cooling as a premise of 3-dimensional laser cooling. This paper reports the result of 1-dimensional cooling and the recent experiment trying to 3-dimensional cooling of the bunched $^{24}\mathrm{Mg}^{+}$ beams.

ONE-DIMENSIONAL LASER COOLING

The specification and the layout of S-LSR is shown in Table 1 and Fig. 1. 40 keV $^{24}\mathrm{Mg}^{+}$ beams come from a plasma ion source upstream. A circulating beam interacts with a laser of 280 nm wavelength in a straight section. In this section, two aperture plates are installed as alignment targets for both the ion beam and the laser. The crossing angle of the ion beam and the laser is reduced less than 0.35 mrad by means of COD correction with these apertures[8].

Table 1: Specification of S-LSR

Circumference	22.557 m
Curvature Radius	1.05 m
Ion species	$^{24}\mathrm{Mg}^{+}$ (40 keV)
Revolution Frequency	25.192 kHz
Transition Level of $^{24}\mathrm{Mg}^{+}$	$3s^2S_{1/2} \rightarrow 3p^2P_{3/2}$
Transition wavelength	280 nm

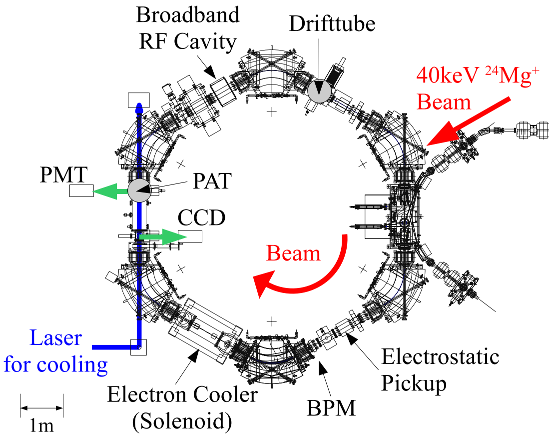

Figure 1: Layout of S-LSR.

The injected beam is bunched by a broadband RF cavity. The frequency and the voltage of the RF are 125.96kHz (h=5) and 3.05V, respectively.

The bunch length of the circulating beam is measured by parallel-plate electrostatic pickups with a length of 140 mm. Signals from the pickups are amplified by +46 dB by preamplifiers and combined by an RF combiner. The

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[*] Work supported by the Advanced Compact Accelerator Development project, the 21COE "Center for Diversity and Universality in Physics" at Kyoto University, and a Grant-in-Aid for the JSPS Fellows.

[†] souda@kyticr.kuicr.kyoto-u.ac.jp

[‡] Present Address is: Kansai Photon Science Institute, Japan Atomic Energy Agency, Kizugawa, Kyoto, 619-0215, Japan

combined signal is measured by a oscilloscope (Tektronix TDS2014). From the waveform and revolution frequency, the bunch length (2σ) is calculated.

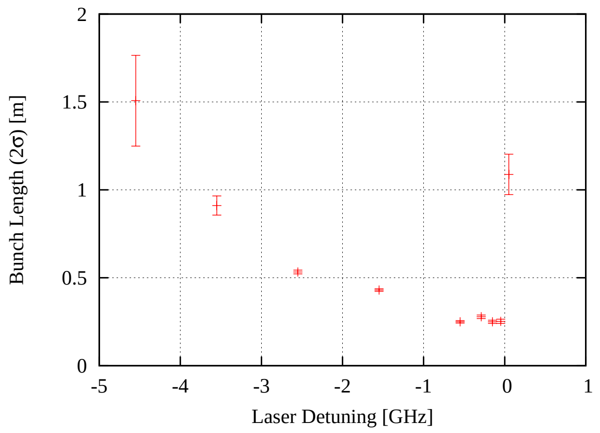

Figure 2: Bunch length after laser cooling with changing laser detuning.

Figure 2 is the result of bunch length measurement. In this experiment, the betatron tunes are $(\nu_x, \nu_y) = (1.64, 1.20)$. The particle number in the storage ring is 6×10^6. The laser frequency is changed and represented as detuning, which means the frequency deviation of the laser from the resonant frequency, 1074116 GHz, determined by Doppler effect. The time for cooling is about 1 second.

If the detuning becomes closer to zero, the temperature of the beam becomes lower because the particles are driven into a smaller region of longitudinal phase space. The minimum bunch length is 0.25 m.

Here we derive the momentum spread, $\Delta p/p$, and longitudinal temperature, $T_{\|}$, from the bunch length, L_{bunch}, as

$$\frac{\Delta p}{p} = \frac{L_{\mathrm{bunch}}}{\beta^2} \frac{2\pi f_s}{\beta c \alpha} \frac{E_s}{m_0 c^2}, \quad T = \frac{m(\beta c)^2}{k_B} \left(\frac{\Delta p}{p} \right), \quad (1)$$

where α, f_s, E_s and k_B are momentum compaction factor, revolution frequency, total energy, and Boltzmann constant, respectively. Therefore the minimum longitudinal temperature is 18 K for 6×10^6 particles. This minimum temperature agrees with the result of coasting beam cooling, 3.6 K for 2×10^4 particles and $T_{\|} \propto N^{0.32}$[5]. This is considered as a limitation of 1-dimensional cooling.

3-DIMENSIONAL LASER COOLING

Toward a beam with lower temperature, we started 3-dimensional laser cooling. To realize this method, the resonant condition $\nu_s - \nu_x =$ integer and $\nu_x - \nu_y =$ integer must be satisfied. ν_s, ν_x, ν_y are a synchrotron tune, a horizontal betatron tune, and a vertical one. If ν_s becomes close to zero, ν_x, ν_y also become close to an integer and the beam lifetime becomes steeply short because of the integer resonance. Therefore large ν_s is preferable.

On the other hand, the broadband RF cavity has a large diameter of 158 mm and long effective length of the electric field. With a large harmonic number, the effective acceleration voltage becomes smaller because of a small transit time factor (TTF).

To resolve this problem, we have newly designed a small drifttube with a diameter of 35 mm, as shown in Fig. 3. Compared with the broadband cavity, the TTF is improved from 0.36 to 0.91 at h=100, and maximum ν_s from 0.05 to 0.11.

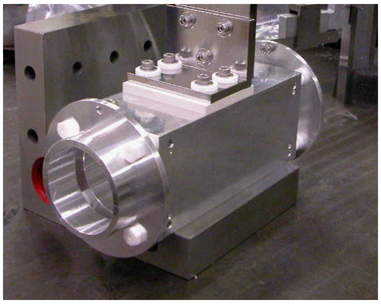

Figure 3: A photograph of the small drifttube

With harmonic number 100, the interval of the bunch is comparable with the length of the pickups. Therefore momentum spread measurement by means of bunch length cannot be applied to this experiment. We have therefore designed a post acceleration tube (PAT)[9] and have installed it in the cooling section with the downstream aperture plate as shown in Fig. 4.

Figure 4: Post acceleration tube and aperture plate

The voltage applied on PAT changes the velocity of the beam locally. If a particle have a momentum deviation corresponding to the energy offset given by PAT voltage, it gives a spontaneous emission in the PAT. Therefore we can observe luminescences from particles with a certain velocity by a photomultiplier tube (PMT). If the PAT voltage is swept, momentum profile of the beam is derived from the time-variation of the PMT counts. We sweep the PAT voltage from +100 V to 0 V to measure the momentum spread up to 6×10^{-4}.

At first, we tried to observe longitudinal-horizontal coupling. We changed the synchrotron tune by changing the

RF voltage, and measured the momentum spread by means of PAT sweeping. Initial momentum spread is 1×10^{-3}, and the cooled momentum spread is measured 0.5 s after injection. The data sets of betatron tune $(\nu_x, \nu_y) = (2.064, 0.814)$ and $(\nu_x, \nu_y) = (2.054, 0.826)$ are obtained.

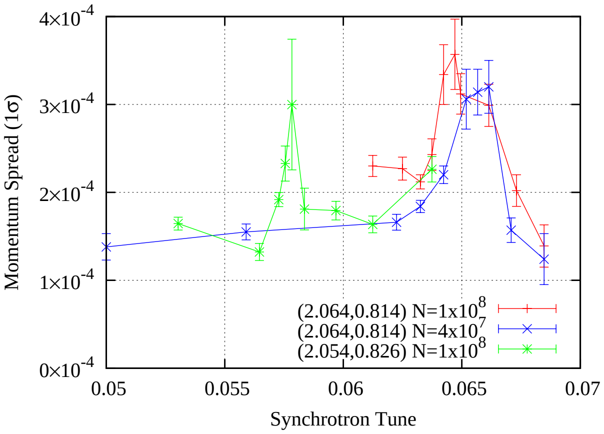

Figure 5: Longitudinal momentum spread measured by a PAT with changing synchrotron tune.

Figure 5 shows the result of longitudinal-horizontal coupling measurement. We find distinct peaks of momentum spreads at $(\nu_s, \nu_x) = (0.064, 2.065)$, $(\nu_s, \nu_x) = (0.057, 2.054)$, both satisfy the coupling condition. We consider that the uncooled horizontal temperature is transferred into longitudinal direction at these condition, therefore large momentum spreads are observed. This result indicates the dispersive coupling[6] of longitudinal and horizontal directions.

At last, we have started 3-dimensional cooling experiments. The coupling of horizontal and vertical oscillation is realized by a solenoidal field in a electron cooler. The field strength and the effective length of the solenoidal field is 40 Gauss and 0.8 m, respectively. The betatron tune is set to $(\nu_x, \nu_y) = (2.068, 1.069)$. In this condition we confirmed the $x - y$ coupling. The beam is oscillated horizontally by an RF knock out and the vertical oscillation is observed as a subtraction of the signals from the upper and the lower electrodes of a beam position monitor (BPM).

Transverse temperature of the beam is measured by observing the luminescence from the beam interacting with laser. We obtain the vertical profile of the luminescence by CCD camera(Hamamatsu Photonics C7190-11W) and derive the beam size as 1σ of gaussian fitting.

Figure 6 shows the result of beam size measurement with changing synchrotron tune. The injected particle number is 3×10^7, and the profile is taken as an average of 10 s, with 0.2Hz injection of ^{24}Mg$^+$ beams (2 times in 10 s). In this measurement, no sharp decrease of beam sizes are observed yet. At $\nu_s = 0.71$, which is close to the resonant tune, the beam size is a little smaller than other points nearby, but is still in the same order as 1-dimensional cooling[5].

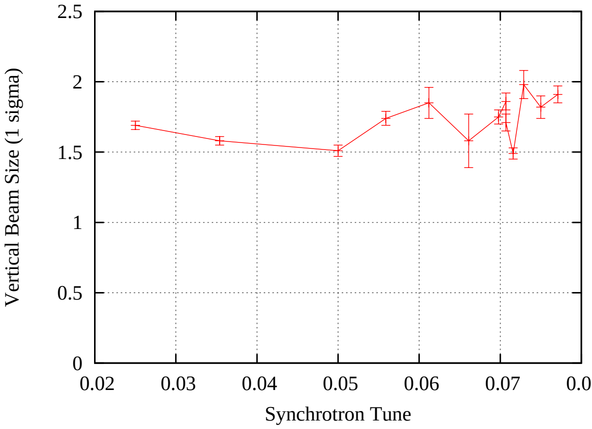

Figure 6: Vertical beam size measured by a CCD camera with changing synchrotron tune. The betatron tunes are $(\nu_x, \nu_y) = (2.068, 1.069)$ and solenoidal field of 40 Gauss is applied.

The reason why no decrease of a vertical beam size is observed is not clear yet, but the heating from non-adiabatic capturing by a constant RF voltage is considered as one of the obstacle to further cooling. We will carry out more precise experiment of 3-dimensional cooling with resolving such problems in the near future.

SUMMARY

The laser cooling experiments of bunched ^{24}Mg$^+$ beam has been carried out at S-LSR in order to realize 3-dimensional cooling. 1-dimensional cooling produced the minimum temperature, 18 K, which is consistent with the results of coasting beam cooling. 3-dimensional laser cooling experiment has been started and longitudinal-horizontal coupling is confirmed by a increase of momentum spread at resonant tune. The results of two betatron tunes show this increase is due to the resonant coupling. Further experiments trying to observe a reduction of a transverse beam size will be performed soon.

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