LASER COOLING EXPERIMENT WITH RESONANT COUPLING AT S-LSR*

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Abstract

Beams of $^{24}Mg^{+}$ ions were cooled by a laser at small laser-equipped storage ring (S-LSR) under a condition of longitudinal-horizontal resonant coupling. The time evolution of beam sizes are measured by a CCD camera. The beam size is decreased from 1.12 mm to 0.84 mm at a betatron tune of $(\nu_x, \nu_y) = (2.075, 1.090)$ and a synchrotron tunes near the resonant condition.

INTRODUCTION

Laser cooling has a very strong cooling force in longitudinal direction. The beam temperature in the order of millikelvin achieved by laser cooling is considered to be able to form an ordered or a crystalline beam. However, it is impossible to cool transverse beam temperature directly by laser cooling. Intra-beam scattering (IBS) couples the longitudinal and transverse oscillation weakly but its coupling constant is too small to cool beams transversely in a reasonable timescale. The resonant coupling with a strong coupling constant might cool beams transversely in the same order of longitudinal cooling[1]. In this method, the difference resonance condition ($\nu_x - \nu_s =$ integer) couples longitudinal and transverse temperatures.

A small laser-equipped storage ring (S-LSR) has a laser cooling system for $^{24}Mg^{+}$ ions[2]. S-LSR satisfies some conditions[3] which are necessary to realize crystalline beams[4]. After the experiment of one-dimensional cooling of coasting beams[5] and bunched beams, the laser cooling experiment with the resonant coupling has been carried out since 2008. This paper reports the experimental setup and current results of the laser cooling experiment.

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EXPERIMENTAL SETUP

The layout of S-LSR is shown in Fig 1. The beams of 40 keV $^{24}Mg^{+}$ ions come from an ion source (Danphysik 921A). A small 2-gap drifttube is installed in a dispersive section ($D = 1.1$ m) to realize longitudinal-transverse coupling through dispersion[1]. Figure 2 shows the RF system of this drifttube. The RF voltage is applied adiabatically using amplitude modulation of the signal generator (Agilent, E4400B). The voltage is increased parabolically from 0 V to the reference value in 0.125 s after injection.

The particle number circulating in the storage ring is measured by the induced signal amplitude of the bunched beam at a pair of parallel-plate electrostatic pickups. Beam lifetimes are measured with these pickups.

Table 1: Specification of S-LSR

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

The laser system consists of a ring dye laser of a wavelength of 560 nm and a frequency doubler. After passing the transport optics, the laser with a wavelength of 280 nm and a power of 30 mW irradiates the ion beam in a co-propagating direction.

The ion beam must overlap with the laser beam in a good precision to maximize the cooling force in the longitudinal direction. The closed orbit distortion (COD) is corrected by a correction system consisting of 6 beam position monitors and 6 correction currents of the bending magnets and 6 vertical electrostatic kickers, using the downhill simplex method. This correction realizes a maximum COD of ±0.4 mm and enables an operation close to an integer tune of $\nu_x = 2.029$. The COD in the laser cooling section is corrected more precisely with use of two plates with

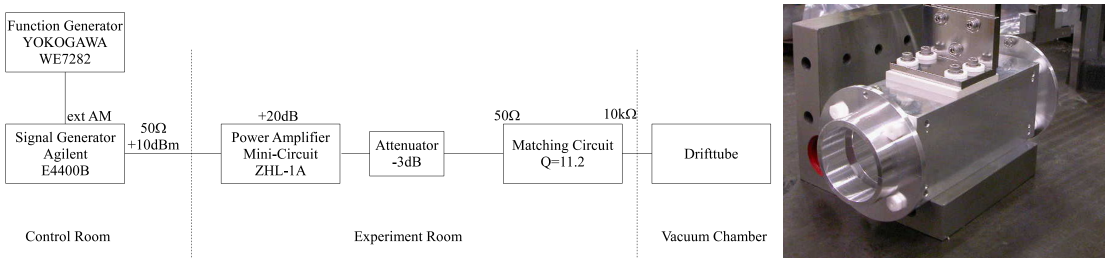

Figure 2: Block diagram of RF system and Drifttube

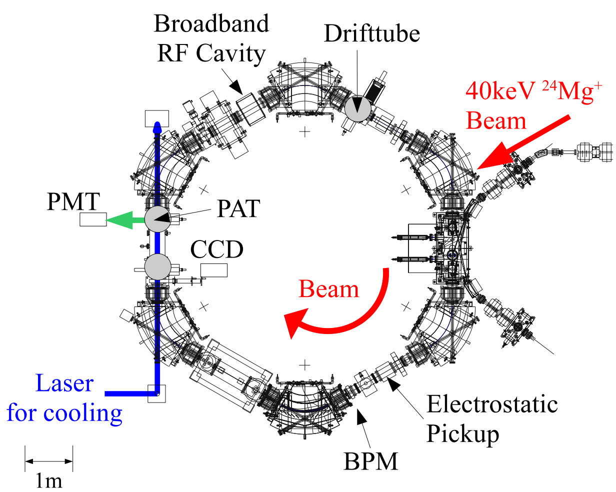

Figure 1: Layout of S-LSR

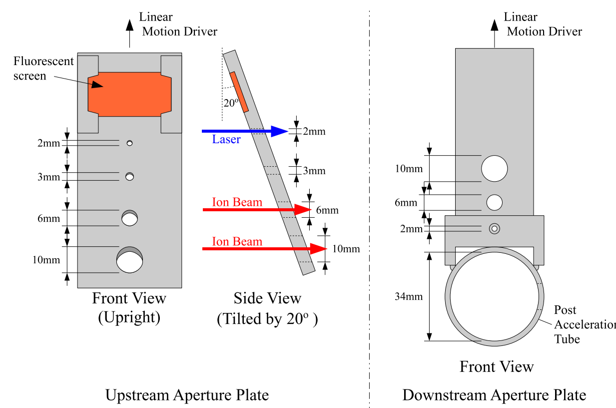

Figure 3: Aperture plates for precise alignment of an ion beam and a laser. Holes with diameter of 10 mm and 6 mm are used for beam orbit correction.

aperture holes shown in Fig. 3. If these aperture plates are inserted, the beam lifetime is sharply decreased from 10 s to 1 s with ϕ10 mm apertures and to 0.2 s with ϕ6 mm apertures. With these apertures, slight changes of the COD at the laser cooling section appear as a large change of beam lifetime and injection beam current as shown in Fig. 4. If the lifetime and injected beam signal amplitudes are maximized, the residual COD is smaller than 0.2 mm. The laser path is corrected in the same way, searching the peak of laser power passed through the ϕ2 mm aperture holes. After these corrections, the crossing angle between the ion beam and the laser are less than 0.35 mrad[6].

The optical measurement system is set in the laser cooling section. For momentum spread measurement, a post acceleration tube (PAT) shown in Fig. 3 and a window for a photomultiplier tube (PMT) is placed on a chamber downstream. Momentum profile is measured by observing the time-variation of fluorescence. Voltage applied on the PAT is swept in the measurement[7]. A CCD camera (Hamamatsu Photonics, EB-CCD) is placed at the chamber upstream. The CCD camera sees the beam upward from the bottom window of the chamber measures horizontal beam profile. Details of optical measurement are shown in Ref. [8].

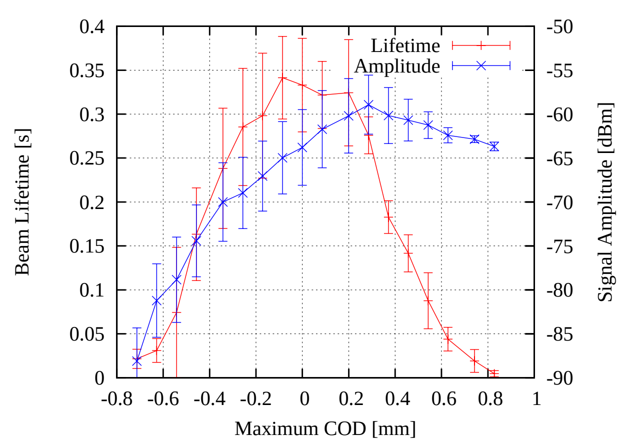

Figure 4: Variation of beam lifetime and pickup signal amplitude of injected beam current. Details of COD correction is shown in Ref. [6]

RESULT

The longitudinal momentum spreads measured by the PAT is shown in Fig. 5. With the condition of $(\nu_x.\nu_y, \nu_s) = (2.065, 0.814, 0.064)$, $(\nu_x, \nu_y, \nu_z) = (2.054, 0.826, 0.058)$, momentum spreads after cooling are 3×10^{-4}, which are larger than that of other conditions, $1.5 \sim 1.7 \times 10^{-4}$. This difference of momentum spreads after cooling implies an exchange of longitudinal and transverse temperatures[9].

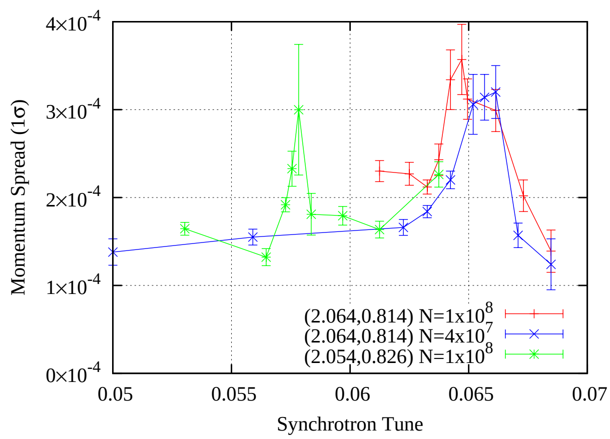

Figure 5: Momentum spread after laser cooling measured by a PAT. When the resonant condition ($\nu_x - \nu_s =$ integer) is satisfied, the momentum spread after cooling is larger than that without the resonant condition.

The experiment to measure cooled transverse beam size was carried out with parameters shown in Table 2. Figure 6 shows the time evolution of horizontal beam size with laser cooling. When ν_s is 0.0642, the initial beam size is 1.30 mm and the beam size does not change within 20 seconds. When ν_s is 0.0763, which is close to the resonance condition, the initial beam size is 1.12 mm and is reduced to 0.9 mm after 2 seconds, then it became almost constant after 2 s. The final beam size is 0.84 mm at 20 s after injection. Such a difference of beam size after cooling by changes of synchrotron tunes indicates the change of transverse cooling force by resonant coupling.

A beam size of 0.84 mm corresponds to a horizontal temperature of 250 K. On the other hand, Momentum spreads of 1.5×10^{-4} measured by PAT corresponds to a longitudinal temperature of 20 K. Therefore, in the present result, the transverse temperature is cooled lower than that of non-coupled condition but it is still higher than achieved longitudinal temperatures. Further systematic investigation of the best condition for coupling is needed.

SUMMARY

Laser cooling is applied at the resonant coupling condition. The interaction of the ion beam and the laser is realized by a COD correction using aperture holes. Horizontal beam size are measured by a CCD camera. The beam size is reduced from 1.12 mm to 0.84 mm with betatron and synchrotron tunes of $(\nu_x, \nu_y, \nu_s) = (2.075, 1.090, 0.0763)$.

Table 2: Parameters for beam size measurement

Parameter	Value
Initial Particle Number	4×10^7
Initial Momentum Spread	8×10^{-4}
Initial Horizontal Beam Size	1.3 mm (1σ)
Betatron Tune (ν_x, ν_y)	(2.075, 1.090)
Synchrotron Tune	0.0642, 0.0763
RF Frequency	2.51926 MHz
RF voltage (1 Gap)	$12 \sim 23$ V
Dye laser Detuning	-0.09±0.02 GHz
Laser Power	12±1 mW
Saturation Parameter	$0.8 \sim 1$

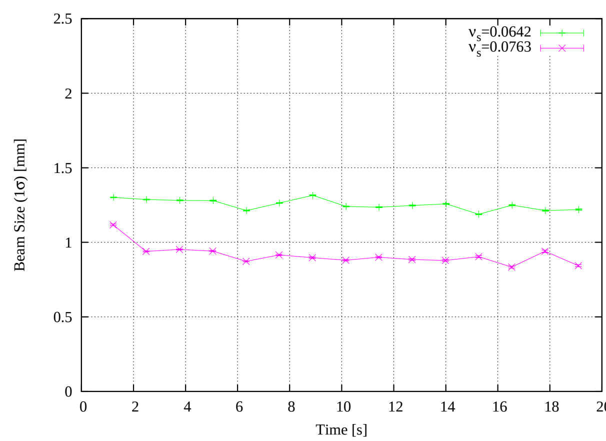

Figure 6: Beam size measurement with laser cooling with betatron tunes of $(\nu_x, \nu_y) = (2.075, 1.090)$. Beam profile is measured as an integration of 1 second by a CCD camera and beam size is evaluated by 1σ of Gaussian fit. The error bars include only fitting errors.

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