TRANSVERSE LASER COOLING BY SYNCHRO-BETATRON COUPLING*

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Abstract

Transverse laser cooling with the use of a synchrobetatron coupling is being carried out at S-LSR. Bunched 40 keV ^{24}Mg^{+} beams are cooled by a co-propagating laser with a wavelength of 280 nm. Synchrotron oscillation and horizontal betatron oscillation are coupled by an RF drifttube at a finite dispersive section (D = 1.1 m) in order to transmit longitudinal cooling force to the horizontal degree of freedom. The time evolution of horizontal beam size during laser cooling are measured by a CCD camera. The measured beam size after 35 s is reduced to 0.55 mm on the resonance, compared to 0.85 mm measured or larger at non-resonance conditions. Momentum spreads are 1.7×10^{-4} on the resonance otherwise 1.2×10^{-4}. These results indicate that the horizontal heat is connected to the longitudinal direction by the synchro-betatron coupling, which is cooled down by a longitudinal bunched beam laser cooling.

INTRODUCTION

Beam cooling have played a great role on the study of the physics of space charge dominant beam. Compared with electron cooling or stochastic cooling, Laser cooling [1] has a very strong cooling force in longitudinal direction, which can cool the beam to the order of millikelvin. Such a ultra-low temperature is considered to be necessary in order to achieve crystalline beams [2]. However, it is not possible to cool transverse beam temperature directly by laser cooling. Intra-beam scattering (IBS) couples the longitudinal and transverse temperature 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 [3]. 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 [4]. S-LSR satisfies necessary conditions [5] for realizing crystalline beams. After the experiment of one-dimensional cooling of coasting beams [6] and bunched beams, the laser cooling experiment with the resonant coupling has been carried out since 2008. This paper reports present results of the laser cooling experiment.

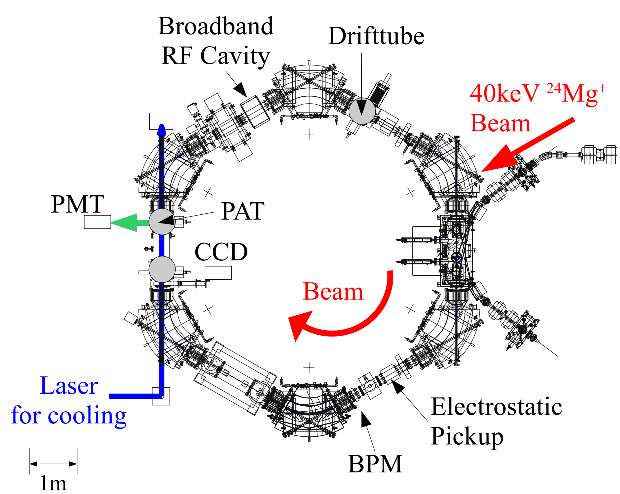

Figure 1: Layout of S-LSR

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

EXPERIMENTAL SETUP

The layout and specification of S-LSR is shown in Fig. 1 and Table 1. The beams of 40 keV ^{24}Mg^{+} ions come

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from an ion source (Danphysik 921A). A small 2-gap drift-tube, shown in Fig. 2 is installed in a dispersive section ($D = 1.1$ m) to realize longitudinal-transverse coupling through dispersion [3]. The RF voltage is applied adiabatically using amplitude modulation of the signal generator (Agilent E4400B). Horizontal tunes are controlled by two series of quadrupole magnets, QM1(QF) and QM2(QD).

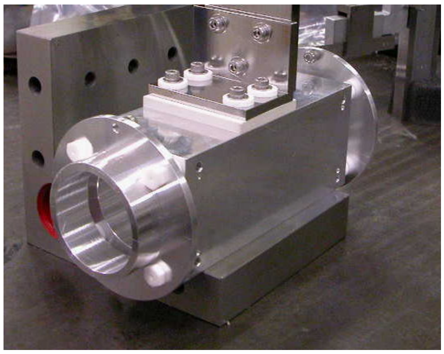

Figure 2: 2-Gap Drifttube for bunching. Gap length of 112.8 mm is designed for harmonic number 100 of 40 keV $^{24}Mg^{+}$.

Horizontal-vertical (x-y) coupling is achieved by solenoidal field of an electron cooler. Preparatory measurement of x-y coupling is reported in Ref. [7]. In this experiment, we have aimed to realize horizontal-longitudinal coupling at first, therefore solenoidal field for x-y coupling was not applied.

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 [8].

The laser system consists of a ring dye laser (Coherent 699-29), Nd:YVO_4 pumping laser (Coherent Verdi V-10) and a frequency doubler (Coherent MBD-200). Nd:YVO_4 laser pumps the dye laser by a CW laser with a wavelength of 532 nm and a power of 6.6 W. Dye laser outputs a CW laser with a wavelength to 560 nm and a power of 600 ± 50 mW with use of Rhodamine 560 Chloride dye jet. A laser of 560 nm is lead to frequency doubler and changed to 280 nm UV laser with a power of 50 ± 5 mW. The dye laser has a feedback system which keeps the frequency of the laser within 10 MHz. 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 laser spot size is 0.9 mm and the power is 15 ± 2mW in the cooling section.

The ion beam must overlap with the laser beam in a good precision to maximize the cooling force. The closed orbit distortion (COD) is corrected to be less than ± 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 aperture holes. The crossing angle between the ion beam and the laser was corrected to be less than 0.35 mrad [9].

The optical measurement system consists of a post acceleration tube (PAT) for momentum spread measurement and A CCD camera (Hamamatsu Photonics, EB-CCD) for horizontal beam size measurement. The CCD camera sees the beam upward from the bottom window of the chamber measures horizontal beam profile. Details of optical measurement system are presented in Ref. [11].

Betatron tunes and synchrotron tunes must be measured precisely in order to realize the resonance condition. Figure 2 shows the block diagram of tune measurement using beam transfer function. Beams are kicked using a network analyzer (Agilent 4395A) and a parallel-plate electrode. Beam oscillation in longitudinal and transverse direction is observed by a triangle-plate pickup, which is one plate of a beam position monitor.

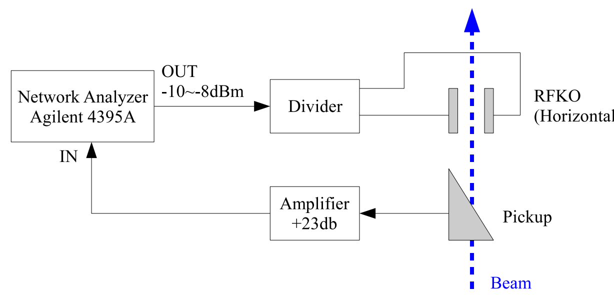

Figure 3: Block diagram of tune measurement by beam transfer function. Betatron tunes and synchrotron tunes are measured simultaneously.

RESULT

The experiment to measure cooled transverse beam size was carried out with parameters shown in Table 2. Figure 3 shows a result of betatron and synchrotron tune measurement. Currents of quadrupole magnet (QM1, QM2) were fixed to (12.85A, 24.00A) and RF voltage of the cavity was varied from 10 V to 93 V. The relation of synchrotron tune and RF voltage can be written as:

$$\nu_s = \sqrt{-\frac{heV\eta\cos\phi_s}{2\pi\beta^2 E_s}} \tag{1}$$

, where $h, e, V, \eta, \phi_s, \beta, E_s$ are harmonic number of RF frequency, elementary charge, RF voltage, slippage factor, phase of synchrotron oscillation, lorentz beta, and total energy of the particle, respectively. In this measurement only V was changed and other parameters were fixed, therefore ν_s is proportional to the square root of the RF voltage. Horizontal betatron tune deviated from original value 0.068 when RF voltage is 20 V to 40 V. In this region, synchro-betatron coupling appeared as a mixing of measured tune values. Vertical betatron tune did not change because there are no coupling with synchrotron tune.

Figure 4 shows the change of the horizontal beam size with laser cooling for various synchrotron tunes. CCD Intensity corresponds to particle numbers, it was maximum

Table 2: Parameters for Beam Size Measurement

Parameter	Value
Initial Particle Number	4×10^7
Initial Momentum Spread	1×10^{-3}
Initial Horizontal Beam Size	0.9 mm (1σ)
Betatron Tune (ν_x, ν_y)	(2.068, 1.105)
Synchrotron Tune	$0.038 \sim 0.120$
RF Frequency	2.51926 MHz
RF voltage (1 Gap)	$10 \sim 93$ V
Dye laser Detuning	-0.10±0.02 GHz
Laser Power	15±2 mW
Saturation Parameter	$0.8 \sim 1$

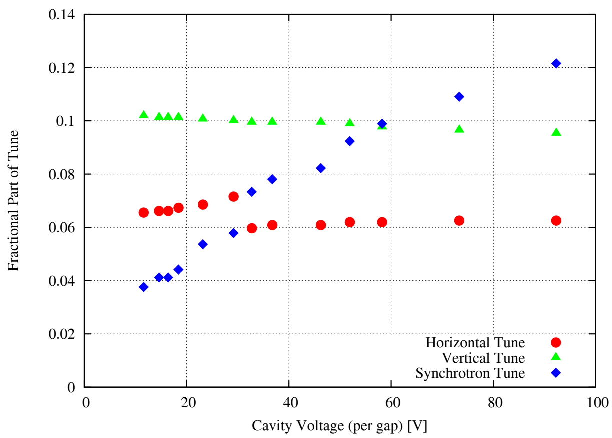

Figure 4: Result of betatron and synchrotron tune measurement with various Cavity RF voltages. Ordinate shows the fractional part of tunes. Measurement errors of the tunes are smaller than ± 0.001.

at the injection and was reduced by beam lifetime of 5∼20 seconds. When $\nu_s = 0.038$ and 0.047, which are far from resonance condition, the initial beam size was 0.9 mm and the beam size blew up due to the intra-beam scattering. When $\nu_s = 0.060$, beam size was kept as 0.8 mm. This is considered as a equilibrium of resonant transverse cooling and heating by IBS. When ν_s was 0.068 and 0.069, which are close to the resonance condition, the initial beam size was 0.8 mm and was reduced to 0.55 mm. These differences of beam size after cooling by changing synchrotron tunes indicates the change of transverse cooling force by resonant coupling.

A beam size of 0.55 mm corresponds to a horizontal temperature of 150 K. On the other hand, Momentum spreads of 1.7×10^{-4} measured by PAT corresponds to a longitudinal temperature of 30 K. In the non-coupled longitudinal cooling [6], the longitudinal and transverse beam temperature at the same particle number were 11 K and 500 K, respectively. Compared with this former experiment, larger transverse cooling force by the resonant coupling was indicated from this result. Systematic measurement of transverse and longitudinal temperature will be carried out to

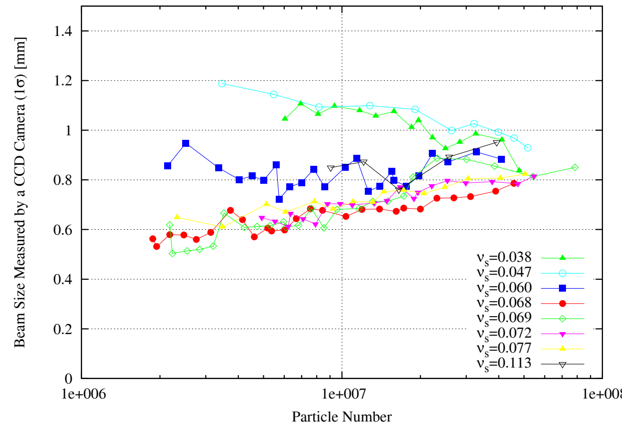

Figure 5: Beam size measurement with laser cooling with betatron tunes of $(\nu_x, \nu_y) = (2.068, 1.105)$. Beam profile is measured as an integration of 1 second by a CCD camera and beam size is evaluated by 1σ of Gaussian fit.

ensure resonant coupling. For the purpose of systematic quantitative measurement, further stabilization of the ring dye laser, which now suffers due to a sharp spiky noise, might be inevitable.

SUMMARY

Laser cooling was applied on the resonant coupling condition. Tune values were measured using beam transfer function in order to confirm resonant coupling. Horizontal beam size were measured by a CCD camera, and the beam size was reduced from 0.85 mm to 0.55 mm with betatron and synchrotron tunes of $(\nu_x, \nu_y, \nu_s) = (2.068, 1.105, 0.068)$.

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