

LATEST RESULTS OF EXPERIMENTAL APPROACH TO ULTRA-COLD BEAM AT S-LSR*

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Abstract

Utilizing S-LSR which has a super-periodicity of 6 and is designed to be tough against resonant perturbation to the circulating beam, we have tried to approach as low as possible temperature with laser cooled 40 keV $^{24}\text{Mg}^+$ ion beam. With the use of theoretically proposed Synchro-Betatron Resonance Coupling scheme, we have experimentally demonstrated the capability of active indirect transverse laser cooling. At first, the achieved transverse cooling efficiency was limited due to heating caused by intra-beam scattering (IBS). For the purpose of reduction of IBS heating, we have established a scheme to control the circulating ion beam intensity down to $\sim 10^4$ by scraping the outskirt of the beam with the use of a horizontally moving scraper, which enabled us to cool down the transverse beam temperatures down to 20 K and 29 K for horizontal and vertical directions, respectively for the operation tune without H-V coupling. They were modified to be 40 K and 11 K by the horizontal and vertical coupling with the difference resonance with an excitation of a solenoid of 22.5 G, which were further improved to 7.0 K and 2.1 K adding deceleration by an induction accelerator of 6 mV/m using a -26 MHz detuned laser.

INTRODUCTION

S-LSR has a high super-periodicity of 6 in order to realize a good performance for the beam dynamical point of view, which had been already demonstrated by 1D ordering realized at S-LSR for single charged 7 MeV proton beam [1]. Applying such characteristics of S-LSR, we have tried to realize a very low temperature ion beam with the use of laser cooling. According to computer simulations utilizing Molecular Dynamics [2], it is expected that a crystalline string of 1D or 2D will be created for ion numbers up to 10^3 if enough power and number of lasers are utilized. In real S-LSR experiments, however, only a single laser co-propagating with the 40 keV $^{24}\text{Mg}^+$ ion beam could be utilized. Because of the heating effect caused by intra-beam scattering (IBS), the efficiency of indirect transverse laser cooling was found to be poor as is described below for the ion beam intensity of $\sim 10^7$. We have applied beam scraping to reduce the IBS effect and found the fact that the efficiency of the transverse indirect laser cooling has been improved so much as the computer simulation expects [3] by reducing ion beam intensities

down to 10^4 , where we could attain needed S/N ratio to measure the transverse beam size, although attainment of crystalline string might need further one order of magnitude reduction of the ion beam intensity.

INDIRECT TRANSVERSE LASER COOLING

Synchro-Betatron Resonance Coupling (SBRC)

Among various cooling schemes, laser cooling has the strongest cooling force for the direction parallel to the beam path. The cooling efficiency in the transverse directions reported so far, however, is rather poor mainly due to heat transfer between the longitudinal and transverse directions caused by IBS [4] or parallel displacement of the laser from the ion beam orbit at a finite dispersion position [5].

An active indirect transverse laser cooling scheme which utilizes ‘‘Synchro-Betatron Resonance Coupling (SBRC)’’ has been proposed by H. Okamoto, A.M. Sessler and D. Möhl [6]. It utilizes a resonance coupling of the synchrotron and betatron motions in the longitudinal and horizontal phase spaces under the condition that

$$v_H - v_s = l \quad (l: \text{integer}), \quad (1)$$

where v_H and v_s are the numbers of horizontal betatron oscillation and synchrotron oscillation, respectively. Furthermore a coupling of the horizontal and vertical directions is required, leading to the condition

$$v_H - v_V = m \quad (m: \text{integer}), \quad (2)$$

where v_V represents the vertical betatron tune. Horizontal-vertical coupling can be realized by using a solenoidal magnetic field.

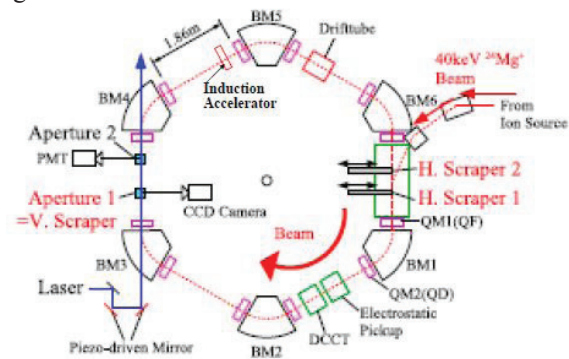


Figure 1: Layout of S-LSR and laser cooling equipments.

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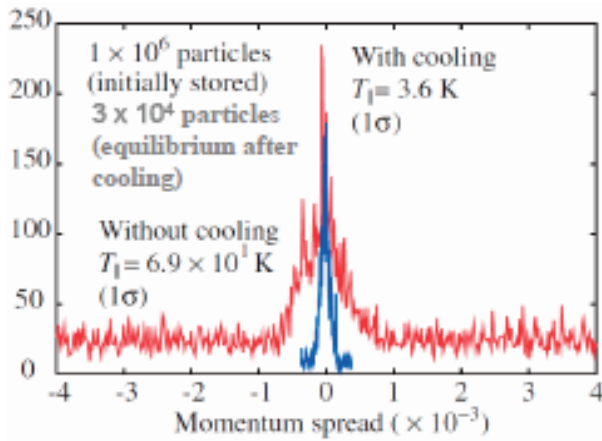


Figure 2: Momentum distribution of the $^{24}\text{Mg}^+$ ion beam with and without laser cooling.

Experimental demonstration of such a scheme has been performed at S-LSR for the first time [7]. In Fig. 1, the layout of S-LSR and its laser cooling equipments are shown.

An ion beam of $^{24}\text{Mg}^+$ with the kinetic energy of 40 keV provided from a CHORDIS ion source is single turn injected into S-LSR where laser cooling is applied using a co-propagating laser with a wave length of ~ 280 nm at a single straight section as shown in Fig. 1. In the first stage a coasting beam is cooled with laser cooling in the longitudinal direction. Counter-balancing the acceleration by laser absorption with the deceleration force provided by an induction accelerator with 6 mV, the longitudinal temperature of initially 1×10^6 ions which reduced to 3×10^4 due to interaction with the residual gas during cooling was cooled down to an equilibrium temperature of 3.6 K as shown in Fig. 2. This rather high equilibrium temperature was determined by a trade off between the laser cooling force and heating effect due to IBS [8].

Utilizing the above mentioned SBRC scheme, the laser cooling effect has been extended also to the transverse directions for an ion beam bunched with an RF system located at a position with finite dispersion function.

In the first stage, a horizontal and vertical tunes, (2.068, 1.105) satisfying only Eq. (1) was utilized [7]. In Fig.3,

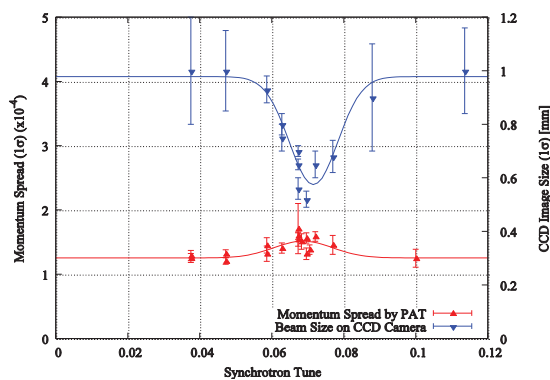


Figure 3: Synchrotron tune dependence of the momentum spread (red) and observed horizontal beam size (blue) after laser cooling.

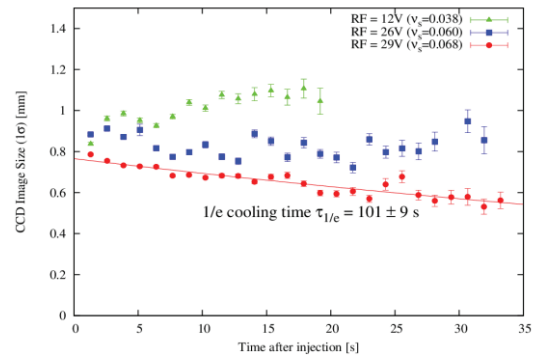


Figure: 4 Time variation of the horizontal beam size for various synchrotron tunes observed by a CCD camera.

the dependence of the momentum spread and the horizontal beam size of the laser cooled ion beam on the synchrotron tune are shown. It can be observed that the momentum spread after cooling has a local maximum and the horizontal beam size has a local minimum at the synchrotron tune around 0.068, satisfying Eq. (1). The time variation of the horizontal beam size has been measured for three conditions, (a) on the resonance condition satisfying Eq (1) ($v_s=0.068$), (b) in between on and off resonance ($v_s=0.060$) and (c) far from the resonance condition ($v_s=0.038$) as shown in Fig. 4. As is shown in the figure, the horizontal beam size increases with time due to heating by IBS at the resonance off condition (c), while it decreases gradually at the resonance condition (a). For the condition (b), horizontal cooling effect cancels out with heating and the horizontal beam size remains almost constant. Even on the resonance, however, cooling time was rather long as ~ 100 sec. ($1/e$ cooling time), which required further improvement of the cooling efficiency in order to realize crystalline string of the ion beam.

Beam Scraping for Improvement of Cooling Efficiency

To control the circulating ion beam intensity, a beam scraping scheme was proposed [9]. So as to clearly demonstrate the coupling between the longitudinal and

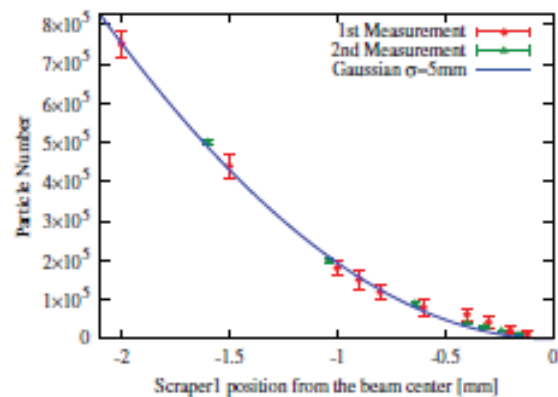


Figure 5: Correlation between the position of the scraper 1 and the survival circulating ion beam intensity in a ring of S-LSR.

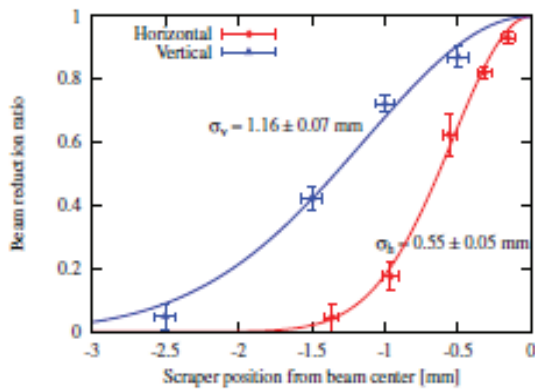


Figure 6: Typical examples of beam profile measurements for the horizontal and vertical directions. These data were taken for the ion beam intensity of 9×10^4 ions with application of laser cooling by SBRC.

horizontal directions, an operation point of (2.068, 1.105) has been used until recently (January, 2013). In Fig. 5, the correlation between the position of Scraper 1 and the remaining circulating beam intensity is given. It has been shown that once the operating point is fixed, the remaining ion beam intensity in the S-LSR ring can be well controlled with Scraper 1. With scraping, it is expected that we can come down to beam intensity of about 10^4 .

Beam Size Measurement by Second Scraper

The optical measurement scheme using a cooled CCD camera so far is not applicable for such low beam intensity as $\sim 10^4$ due to low S/N ratio therefore the second scrapers, (Scraper 2 and Vertical Scraper shown in Fig. 1 for the horizontal and vertical beam sizes, respectively) were used to determine the beam profile. This scheme enabled us to obtain both horizontal and vertical beam sizes simultaneously for a given experimental condition, because due to the limited number of a cooled CCD, an optical measurement system cannot be used simultaneously for both directions. Typical examples of such measurements of the horizontal and vertical beam sizes are shown in Fig. 6.

With this scheme, the cooling time of the indirect trans-

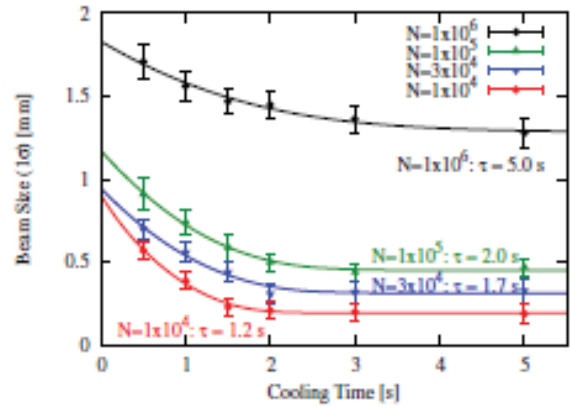


Figure 7: Time variations of the horizontal beam sizes for various beam intensities from 1×10^4 to 1×10^6 .

verse laser cooling has been evaluated; the results are shown in Fig. 7. Together with data in Fig. 4, it is clearly shown that the cooling time of indirect horizontal laser cooling has been reduced almost 2 orders of magnitude by reduction of the ion beam intensity from $(1\sim 3) \times 10^7$ to 1×10^4 .

TRANSVERSE BEAM TEMPERATURE ATTAINED BY LASER COOLING

By reducing IBS effects with the use of scraping, we could improve the efficiency of the indirect transverse laser cooling noticeable through the decrease of the cooling time as shown in Fig. 7. In Fig. 8, intensity dependence of the transversely cooled ion beam sizes are given ((a) and (b) horizontal and vertical ones, respectively). It is shown that the beam size is cooled down to ~ 0.2 mm and ~ 0.6 mm in the horizontal and vertical directions, respectively in the case of SBRC ON when the beam intensity is reduced to 10^4 by scraping, which corresponded to 20 and 29 K [12] as listed up in Table 1.

As described in the introduction, laser cooling effect in the transverse direction was at first observed with IBS coupling, which was only applicable at high ion beam intensity, therefore the realized temperature was rather high as revealed in Table 1 [4]

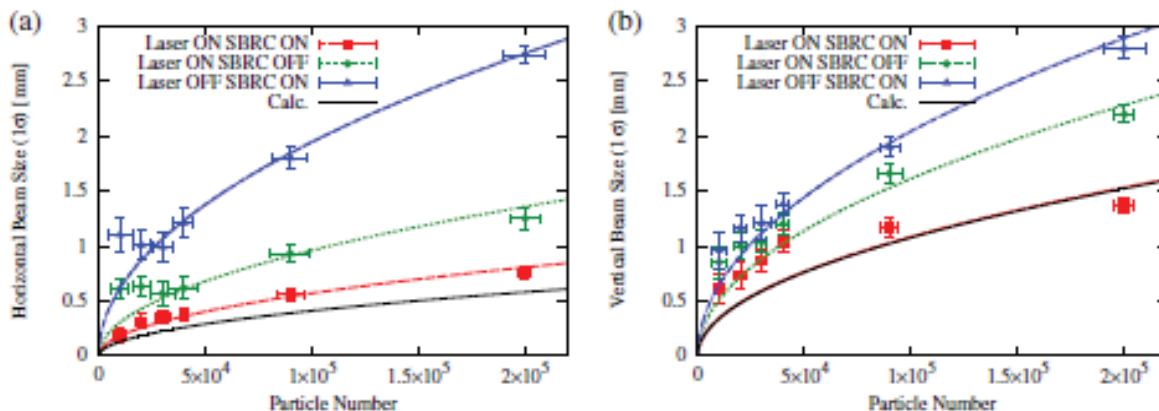


Figure 8: Beam size dependences on ion beam intensity, (a) horizontal and (b) vertical directions, for laser Off and On with and without SBRC.

Table 1: Comparison of Laser Cooled Ion Beam Temperatures

Year Ring	Method	Ion	Kinetic Energy	Intensity	T	T _H	T _V	Ref.
1996 TSR	IBS	⁹ Be ⁺	7.3 MeV	2.0 x 10 ⁷	15	4000	500	[4]
1998 TSR	Dispersive cooling	⁹ Be ⁺	7.3 MeV	1.0 x 10 ⁷	few tens	~500 [#]	~150 [#]	[5]
1999 ASTRID	IBS	²⁴ Mg ⁺	100 keV	7 x 10 ⁶	2-5	17	21	[10]
2001 PALLAS	RFQ	²⁴ Mg ⁺	1 eV	1.8 x 10 ⁴	<3 m	T _⊥ < 0.4		[11]
2008 S-LSR	IBS	²⁴ Mg ⁺	40 keV	1.0 x 10 ⁷	11	-	500	[8]
2009 S-LSR	W SBRC (2D)	²⁴ Mg ⁺	40 keV	1.0 x 10 ⁷	27	220 ^{\$}		[7]
2009 S-LSR	WO SBRC	²⁴ Mg ⁺	40 keV	1.0 x 10 ⁷	16			[7]
2012 S-LSR	W SBRC (2D)	²⁴ Mg ⁺	40 keV	1 x 10 ⁴	(0.4)	20	29	[12]
2013.2.1 S-LSR	W SBRC (3D)	²⁴ Mg ⁺	40 keV	1 x 10 ⁴	-	40	11	
2013.3.7 S-LSR (Δf=-190 MHz)	W SBRC (3D) (INDAC ON)	²⁴ Mg ⁺	40 keV	1 x 10 ⁴	-	8.1	4.1	
2013.3.22 S-LSR (Δf=-26 MHz)	W SBRC (3D) (INDAC ON)	²⁴ Mg ⁺	40 keV	1 x 10 ⁴	-	7.0 (3 x 10 ⁴)	2.1	

This situation could be improved a little bit by dispersive cooling where the transverse temperature were reduced somewhat, but it had a disadvantage due to the

utilizing SBRC, until the end of 2012, resulted in almost the same beam temperatures as obtained at ASTRID.

Approach to Realize Further Cooled Beam

So as to realize much colder ion beams to cross over the hill of heating rate as shown in Fig. 9 [13], further increase of cooling efficiency is inevitable. For this purpose, we tried to apply 3D laser cooling moving the operation point to (2.067, 1.070) satisfying Eq. (2) together with Eq.(1) for longitudinal, horizontal and vertical couplings. In Fig. 10, the attained transverse beam sizes (a) horizontal and (b) vertical directions are shown for various conditions. The horizontal and vertical coupling was found to be optimum for the solenoid field of 22.5 Gauss (excitation current of 9A) at the electron cooler section. With such coupling, it is shown that the vertical beam size is reduced drastically, while the horizontal beam size gets worse due to heat transfer from the vertical direction. The beam sizes get cooled down to 0.20 mm and 0.30 mm for the horizontal and vertical directions, respectively (data shown by blue triangles in Fig. 10), which correspond to ring averaged temperatures T_H and T_V of 40 K and 11 K, respectively obtained by the

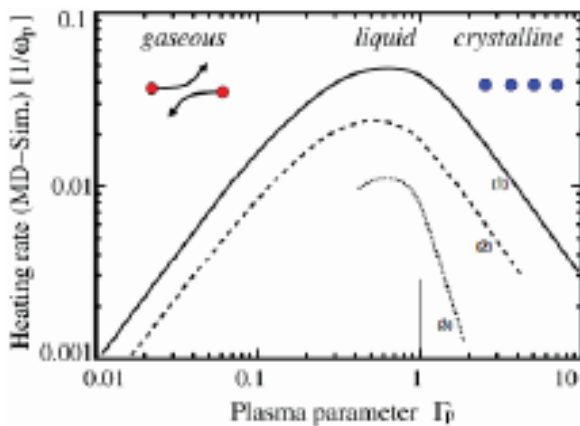
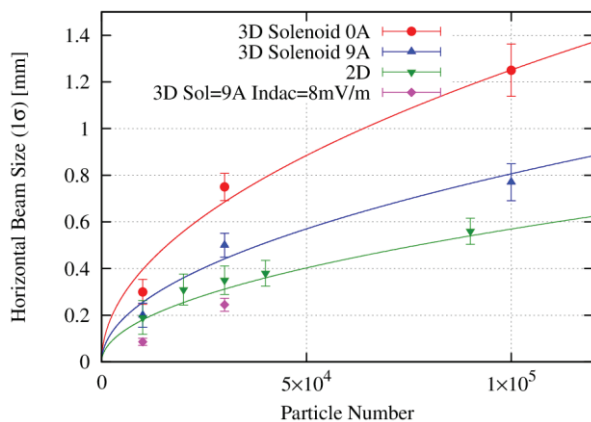
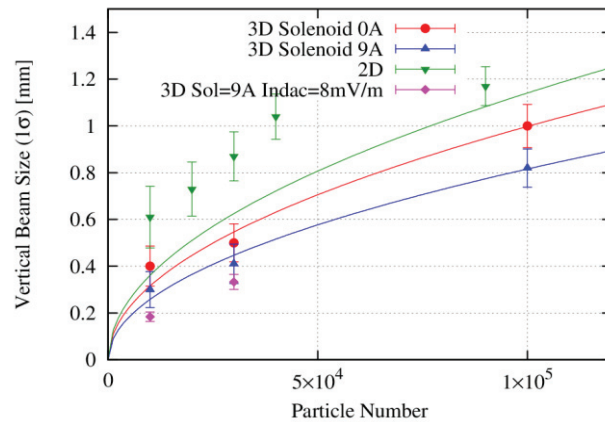


Figure 9: Heating rate dependence on the plasma parameter [13].

asymmetry of the relative position between laser and ion beam paths [5]. ASTRID has realized lower temperature for a 100 keV Mg ion beam [10]. Our experiments



(a) horizontal beam size



(b) Vertical beam size

Figure 10: Comparison of beam sizes among, 2D, 3D laser cooling with solenoid on and of and additional deceleration by an induction accelerator.

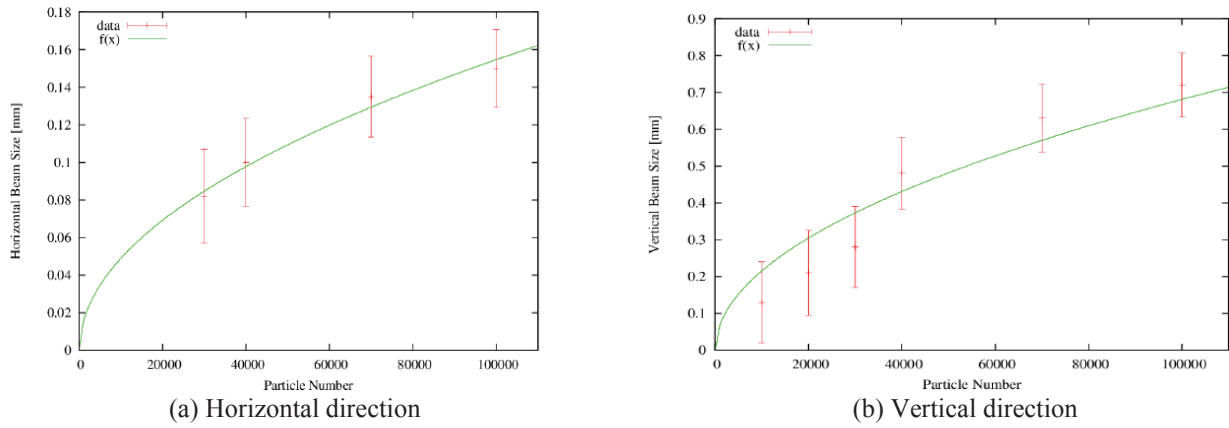


Figure 11: Beam sizes attained with application of Induction deceleration with optimized laser detuning of -26 MHz.

Table 2: Parameters of Experiment on 2013.2.1

Betatron Tune	(2.067,1.070)
Synchrotron Tune	0.072
Initial Particle Number	3×10^7 (Scraped to 1×10^4 - 1×10^5)
Initial Momentum Spread	7×10^{-4}
Revolution frequency	25.1735 kHz
RF Frequency	2.51735 MHz ($h=100$)
Solenoid Field	22.5 Gauss (Excitation current=9A)
Laser Spot Size	$\sigma = 0.30$ mm
Laser Power	5 ± 1 mW
Average Vacuum Pressure	9.5×10^{-9} P
Indac Voltage	6mV/m (deceleration)

following formula

$$T_y = \frac{1}{k_B} mc^2 \beta^2 \langle \gamma \rangle \frac{\sigma_y^2}{\beta_y}, \quad (3)$$

where k_B , m , β , $\langle \gamma \rangle$, σ_y and β_y are Boltzmann constant, ion mass, ion velocity in units of speed of light, c , ring averaged gamma factor of Twiss parameter which is given by $\langle \gamma \rangle = \frac{1}{C_0} \oint \frac{1+\alpha^2}{\beta} ds$ (C_0 : circumference of the ring), beam size in y-direction and beta-function in y-direction at a point of the beam size observation, respectively (data on 2013.2.1 in Table 2). Equation (3) is a little bit different from the definition of the temperature given in Ref. [12] taking into account of the effect of α .

Further optimization was performed with deceleration by an induction accelerator in order to give counter force against ion beam acceleration due to laser photon absorption. With laser detuning of -190 MHz, the transverse beam sizes were reduced to 0.09 mm and 0.18 mm for the horizontal and the vertical directions, respectively with the ion beam intensity of 10^4 as indicated in Fig. 10 by purple rhombi, which correspond to 8.1 K and 4.1 K (data taken on 2013.3.7). In this case, the laser power was ~ 15 mW in the most optimum condition. Further, the laser detuning was optimized and a detuning of -26 MHz resulted in the lowest beam temperature, as shown in Fig. 11. In that case, the horizontal beam size was measured with cooled CCD after optimization of the laser size at the position where the horizontal beta-function was 0.89 m. The main

parameters of this experiment are listed up in Table 2. The horizontal beam size could be measured only for an ion beam intensity larger than 3×10^4 to realize the needed S/N ratio. At an intensity of 3×10^4 ions, the horizontal beam size could be reduced to 0.08 mm and 0.13 mm was measured as the vertical beam size at an ion number of 10^4 , which corresponded to a horizontal and vertical average beam temperatures of 7.0 K and 2.1 K, respectively.

SUMMARY

By application of Synchro-Betatron Resonance Coupling for 40 keV $^{24}\text{Mg}^+$ ion beam, we could reduce the ring averaged beam temperature to 7.0 K (for 3×10^4 beam intensity) and 2.1 K (for 10^4 intensity) for the horizontal and vertical directions, respectively, which are the lowest transverse temperature ever attained by indirect transverse laser cooling. They, however, are not low enough to realize a crystal string. As pointed out in computer simulations [3], a crystal string will be attained at S-LSR by further reduction of the ion beam intensity attaining enough S/N ratio by improvement of diagnosis scheme.

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