CHALLENGE FOR MORE EFFICIENT TRANSVERSE LASER COOLING FOR BEAM CRYSTALLIZATION*

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Abstract

With the use of S-LSR at ICR, Kyoto University, $^{24}Mg^{+}$ ion beams have been successfully laser cooled both in longitudinal [1] and horizontal directions. The cooling rate of the indirect horizontal laser cooling using synchro-betatron resonance coupling (SBRC) [2], however, is not strong enough to realize the crystalline beam due to the heating because of intra-beam scattering (IBS) effect. So as to suppress this IBS, reduction of the beam intensity is inevitable, which however, had resulted in poor S/N ratio in the observation of the transverse beam size.

The observed beam size utilizing a scraper showed a clear dip at the SBRC condition due to indirect laser cooling, the efficiency of which, however, still remains at the same level or even smaller compared to the one coming from IBS even for the reduced beam intensity of 5 x 10^6 per ring.

INTRODUCTION

Ion beam of $^{24}Mg^{+}$ with the energy of 40 keV has been injected and accumulated in the ion storage and cooler ring, S-LSR as is illustrated in Fig. 1. In order to approach to the final goal of our research to attain a crystalline beam with ultra-cold temperature [3], multi-dimensional laser cooling has been experimentally studied [4]. In table 1, the main parameters of the S-LSR and its laser cooling system are given. Although the experimental demonstration of active indirect transverse laser cooling with the use of SBRC has been attained, it is found that such transverse cooling efficiency is not as high for a beam intensity of around 10^7 ions in the ring as it is shown in Fig. 2 [4]. Even for the central synchrotron tune satisfying SBRC, reduction of the horizontal beam

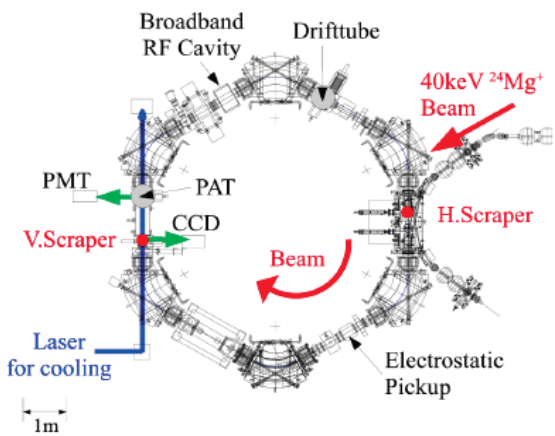

Figure 1: Layout of S-LSR.

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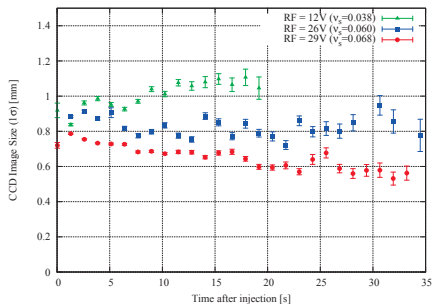

Figure 2: Experimental data demonstrating indirect horizontal laser cooling with the use of synchro-betatron couping. For a synchrotron tune of 0.068 satisfying the SBRC, the horizontal beam size is decreased gradually in some tens seconds [4].

Table 1: Main parameters of S-LSR and its laser cooling system

Circumference	22.557m
Average radius	3.59m
Length of straight section	1.86m
Radius of curvature	1.05m
Super periodicity	6
Ion species	$^{24}Mg^{+}$: 40keV
Natural width of $^{24}Mg^{+}$	$2\pi \times 42.7$ MHz
Initial momentum spread	1×10^{-3}
Initial particle number	5 x10^6 ~ 4×10^7
Betatron tune	(2.056, 1.118)
Synchrotron tune	0.0376 ~ 0.1299
Laser frequency	1074110.3GHz± 0.01GHz
Detuning	-0.1GHz ± 0.01GHz
Laser power at exit window	7 ~ 15mW

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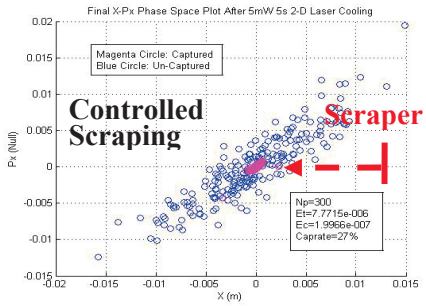

Figure 3: Illustration of controlled scraping. [5].

size is realized rather slowly in some tens seconds, which is too long for the realization of a crystalline beam. In the present paper, our trial to improve the cooling efficiency by reducing the beam intensity in order to suppress the IBS with the use of a scraper is described.

SUPPRESSION OF IBS BY SCRAPING

Computer simulation of beam scraping has been performed for the beam intensity up to 3 x 10^4 [5]. A typical example of 2D laser cooling simulation to evaluate the capability of scraping is shown in Fig. 3, although it is difficult to perform computer simulation taking the space charge effect into account for the intensity higher than 10^5 because of the too long needed CPU time. As is known from Fig. 3, it is expected that the beam image of the central part observed by an optical system will not be deteriorated if we can eliminate the beam located at the outskirt of the beam in the transverse distribution without any perturbation to the central part.

In order to study the capability of increasing the indirect transverse laser cooling efficiency to compete the heating rate, as is illustrated in Fig. 4 [6], and to reach the low temperature region in short enough times we tried to scrape out the outskirt beam in the horizontal distribution and investigated the capability to increase the cooling efficiency in the horizontal degree of freedom by indirect laser cooling.

MESUREMENT OF THE BEAM SIZE BY A SCRAPER

By inserting a horizontal scraper located at the position with a beta-function of the size 0.93 m located in

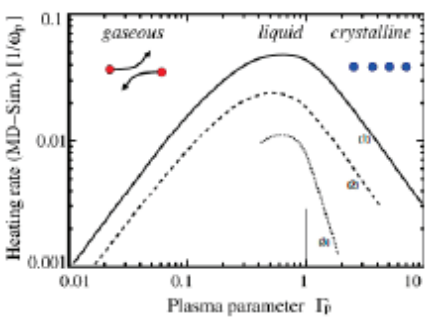

Figure 4: Dependence of heating parameter on plasma parameters,

$$\Gamma_p = \frac{Z_{ion}^2 e^2}{4\pi\varepsilon_0 \alpha_{WS} k_B T_{ion}}, \alpha_{WS} = (\frac{4}{3}\pi n_{ion})^{1/3}$$ [6,7]

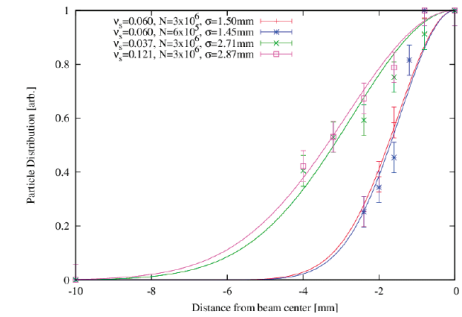

Figure 5: Beam distribution in the horizontal direction measured by a beam signal picked up with an electrostatic monitor changing the horizontal position of the scraper keeping the operation point at (2.056, 1.118) with application of the longitudinal laser cooling under fixed detuning of -0.1 GHz

the injection section as shown in Fig.1 with use of a pulse motor, we have measured the survival rate of the beam for various scraper position. The obtained beam distribution in the horizontal direction is shown in Fig. 5 for different synchrotron tunes and beam intensities keeping the operating point at (2.056, 1.118) with the application of laser cooling. The synchrotron tune dependence of the horizontal beam size obtained by such measurements is given in Fig. 6 (a) for both cases with laser on and off for the initial beam intensity of 5 x 10^6. It can be seen that for such a synchrotron tune satisfying the SBRC relation ,

$$\nu_s - \nu_H = m \quad \text{(integer)} \qquad (1)$$

the horizontal beam size has its local minimum. In the figure, the beam sizes at such synchrotron tunes which does not satisfy the above relation, are also reduced by application of longitudinal laser cooling, which is

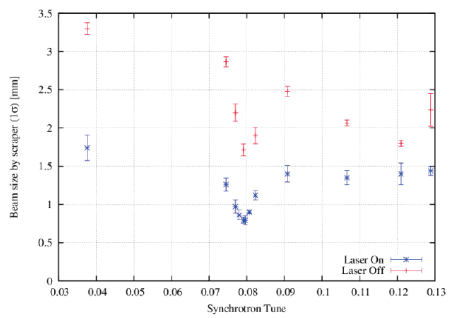

Figure 6(a): Horizontal beam size measured by a horizontal scraper for various synchrotron tunes.

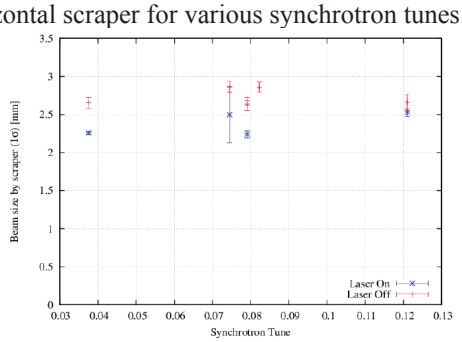

Fig.6 (b): Vertical beam size measured by a vertical scraper for various synchrotron tunes.

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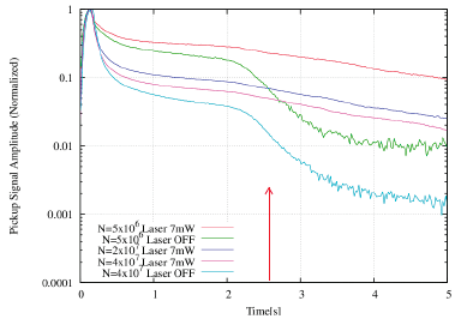

Figure 7: The time variation of the pick-up signal of the beam for different beam intensities for both laser cooling on and off. The horizontal scraper is inserted to the position 2.4 mm inner from the center.

considered to be due to the energy transfer between the longitudinal and the horizontal directions due to the IBS [8]. Similar measurements for the vertical beam size has also been performed with the use of the vertical scraper located at the laser cooling section (Fig.1) for the same beam intensity (5 x10^6). The obtained results are shown in Fig. 6 (b), which has no local minimum because the horizontal and vertical coupling condition as

$$\nu_H - \nu_V = n \quad \text{(integer)} \qquad (2)$$

is not satisfied by the present operation point of (2.056, 1.118). The small reduction of the vertical beam size by application of laser is also considered to be due to IBS. The difference of the beam size reduction in the horizontal and vertical direction is due to ~4 times larger horizontal beam emittance compared with the vertical one in the present case and the energy is transferred from the horizontal direction to the vertical one by IBS even the condition of Eq. (2) is not satisfied.

INTENSITY DEPENDENCE

The time variation of the pick-up signal of the beam under application of scraping is shown in Fig.7 for both laser cooling on and off for different beam intensities. For the measurement, the horizontal scraper, located at the position 15 mm inner from the beam center, is inserted to the position 2.4 mm inner from the center with the speed of 4.6 mm/sec. The red arrow in the figure indicates the time when the scraper stops at the position of 2.4 mm inner from the center and within a time lag of ~0.1 sec. the scraper starts to return back to the original position with the same speed. Without laser cooling, the beam begins to be cut off after ~2 sec. when the scraper come close to the position ~5 mm inner from the beam center, but with the indirect horizontal laser cooling, no beam is cut off by such a scraping. It is clearly seen that the loss rate of the beam is improved by reducing the beam intensity from 2~4 x 10^7 to 5 x 10^6, although this intensity is still too high to suppress IBS to such a level where its heating does not prevent the cooling as is illustrated in Fig.4 to reach the crystalline state.

In order to investigate the capability of further beam scraping, we inserted the horizontal scraper to the position 0.4 mm inner from the beam center and then the scraper

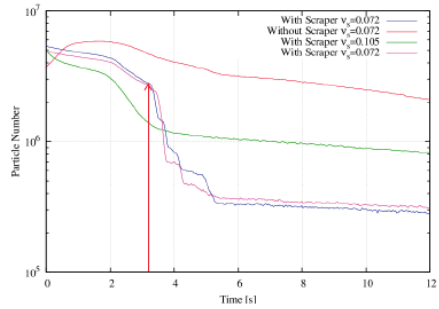

Figure 8: Time variation of the beam intensity during scraping to the position 0.4 mm inner from the beam center.

returned back to the original position like the previous measurement with the beam intensity of 5 x 10^6 and the operating point of (2.072, 1.124). The time variation of the beam survival rate is shown in Fig. 8, where the red arrow shows the timing when the scraper reaches the position 0.4 mm inner from the center. For ν_s=0.105, which does not satisfy SBRC (Eq.(1)), the horizontal beam size is not cooled down and the beam is scraped out by the insertion of the scraper to the position of 0.4 mm and then the beam cut off is stopped. For ν_s=0.072, satisfying the SBMC condition: Eq. (1), the beam intensity decreases suddenly with irregular behaviour, as shown in Fig. 8, even after the scraper begins to return back to its initial position, which is repeated in two measurements. We suspect the occurrence of some instability by the reduction of horizontal beam size with indirect horizontal laser cooling, which, however, needs further more quantitative investigation.

SUMMARY

The increase of the efficiency of indirect horizontal laser cooling by reduction of the IBS decreasing the beam intensity has been demonstrated. The observed beam size has been reduced by indirect transverse laser cooling, but its effect is still comparable or even smaller compared to the one due to IBS at the beam intensity of 5 x 10^6 , down to which we succeed to observe the beam size up to now. Further reduction of the beam intensity is inevitable by keeping the tolerable S/N ratio.

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