HORIZONTAL-VERTICAL COUPLING FOR THREE DIMENSIONAL LASER COOLING*

T. Hiromasa#, M. Nakao, A.Noda, H. Souda, H.Tongu
ICR, Kyoto University, Uji-city, Kyoto, Japan
K.Jimbo, IAE, Kyoto University, Uji-city, Kyoto, Japan
T.Shirai, NIRS, Chiba-city, Chiba, Japan

Abstract

In order to achieve three dimensional crystal beam, laser cooling forces are required not only in the longitudinal direction, but also in the transverse directions. With the resonance coupling method, transverse temperature is transmitted into longitudinal direction, and we have already demonstrated the horizontal laser cooling experimentally. In the present paper, we will describe an approach to extend this result to three dimensional cooling. The vertical cooling requires that the horizontal oscillation couples with the vertical oscillation. For achieving horizontal-vertical coupling, the solenoid in electron beam cooling apparatus is utilized with an experiment (ν_x =2.07, ν_y=1.07). For various solenoidal magnetic fields from 0 to 100 Gauss, horizontal and vertical betatron tunes are measured by beam transfer function. For a certain region of the solenoidal magnetic field, these tunes are mixed up each other.

INTRODUCTION

At ICR, Kyoto University, the ion beam cooling experiment has been conducted with Small Laser-equipped Storage Ring (S-LSR) [1]. Several techniques, such as electron cooling, stochastic cooling, and laser cooling, have been available to cool down the temperature of ion beams. Especially, laser cooling techniques can achieve the lowest temperature. But this technique cannot cool transverse direction. This reason is the photon pressure operates only in the longitudinal direction. The dissipative force generated by a laser light is known to work only in the longitudinal direction. In order to overcome this problem, the resonant coupling method [2] was proposed.

This method is employed to extend the longitudinal direction cooling force to the transverse direction [3]. In past study, existence of crystal beam has been confirmed by simulation [4]. A possible coupling source that induces sufficient correlation between the longitudinal and transverse direction is a regular RF cavity installed at the position with finite dispersion. And the two transverse degrees of freedom can be correlated by a solenoid magnet or a skew quadruple magnet [5]. We turn on a solenoid magnet in electron beam cooling apparatus to couple the horizontal and vertical directions.

For three-dimensional laser cooling, the following two conditions have to be satisfied,

$$\nu_s - \nu_x = \text{integer} \qquad (1)$$

$$\nu_x - \nu_y = \text{integer} \qquad (2),$$

where ν_x and ν_y are the betatron tunes of a storage ring and ν_s is the synchrotron tune. Using this method, we have already demonstrated the horizontal laser cooling experimentally.

Table 1: Main parameter of S-LSR

Circumference	22.557 m
Average Radius	3.59 m
Length of straight section	1.86 m
Radius of curvature	1.05 m
Revolution frequency	25.192 kHz
Super periodicity	6
Ion species	$^{24}Mg^{+}$
Kinetic beam energy	40 keV
Transition wavelength	280 nm

The purpose of the laser cooling experiment is the study of three dimensional crystal beam. S-LSR was constructed to achieve three dimensional laser cooling. Table 1 shows the main parameters of S-LSR. In this paper, we will report experiments for achieving three dimensional crystal beam.

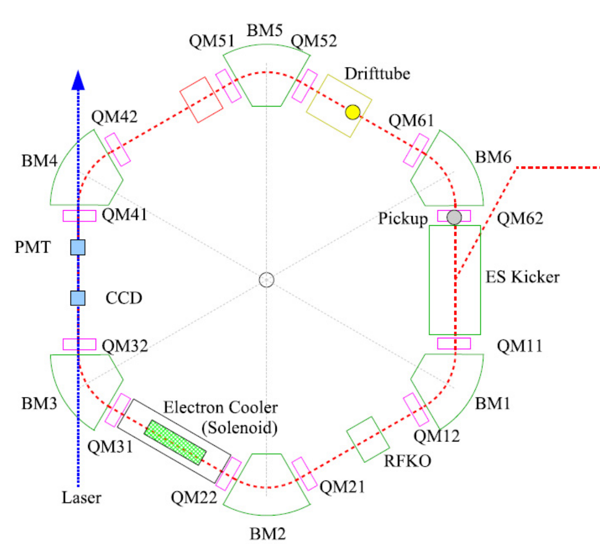

Figure 1: Layout of the S-LSR

*Work supported by Advanced Compact Accelerator Development Project of MEXT, the Global COE program "The Next Generation of Physics, Spun from Universality and Emergence".
#hiromasa@kyticr.kuicr.kyoto-u.ac.jp

LASER COOLING

S-LSR

S-LSR was constructed for laser beam cooling experiment. In order to achieve crystal beam, Ring parameter is required the following two conditions. [4]

$$\gamma < \gamma_t$$

$$\nu_{x,y} < \frac{N_{SP}}{2\sqrt{2}},$$

where γ is the Lorentz factor, γ_t is the transition energy, N_{sp} is the lattice super periodicity of the ring. Under these conditions, the lattice of S-LSR was designed.

The ion species which can be cooled is limited, because the available wavelength of the laser is absorbed only to a specific ion. Our laser cooling experiment is applied to $^{24}Mg^{+}$ beams, which are produced in the plasma ion source CHORIDIS and accelerated by a DC high voltage of 40 kV. The incident beam generated by the ion source is injected into the ring and is cooled by the laser cooling method.

The laser system consists of a 532 nm solid laser, a 560 nm Ring Dye laser and a 280 sub harmonic generator. For this experiment, the required wavelength and power is 280 nm, 100 mW. The cooled beam is measured by PMT and a high sensitive cooled CCD camera.

The resonant coupling method

With the betatoron tunes (ν_x = 2.07, ν_y = 1.07), we have experimented for the three dimensional laser cooling using the coupling resonance method. Since large RF voltage is needed in order to set the synchrotron tune at a large value, which disturbed laser cooling too much, betatron tunes and resonant synchrotron tune needed to be kept small. The parameter in which it meets the above-mentioned requirement is ν_x = 2.07, ν_y = 1.07 and synchrotron tune is adequately low under this condition.

We turn on a solenoid magnet in electron beam cooling apparatus to couple the horizontal and vertical directions. In order to minimize the lattice symmetry breaking, a lower solenoid magnetic field B_{sol} is preferable. We estimated maximum value B_{sol} = 40 Gauss by MD simulations [6]. This field is sufficiently weak. In this experiment, we have observed the variation of horizontal and vertical betatron tunes for investigating horizontal-vertical coupling.

MEASUREMENT

Measurement of the betatron tunes

For the purpose of observation of the variation of betatron tune, Solenoid magnetic field varies from 0 to 100 Gauss. The solenoid magnet is installed in the electron cooler. In this experiment, we have used only the central coil. Figure 2 shows the inner structure of electron cooler.

Betatron tunes are adjusted by the current of QM1(focus) and QM2(defocus) in Fig.1. Horizontal and vertical betatron tunes are measured by beam transfer function. Figure 3 shows the conceptual diagram of the measurement. The procedure of the measurement is as follows.

- The vibration is excited by RFKO.
- The resonance frequency of the beam is detected with Pickup.
- The sideband is measured with Network Analyzer.

When QM current varies, the difference is observed by the behavior of sidebands. The distinction of the horizontal and vertical is identified by this behaviour. The synchrotron tune is adjusted by RF voltage at drifttube.

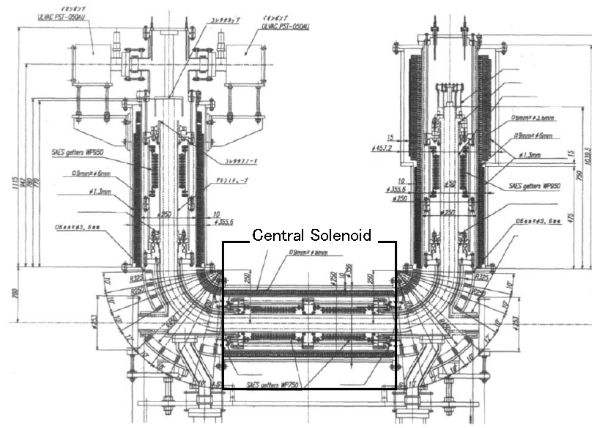

Figure 2: The electron cooler of S-LSR

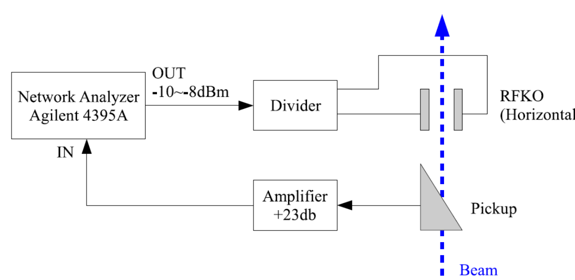

Figure 3: Conceptual diagram of Measurement of beam transfer Function

Measurement of the vertical oscillation

To confirm the oscillation of horizontal direction transfers to a vertical direction, the horizontal oscillation is excited to the beam with RFKO, and the oscillation of a vertical direction is measured with a spectrum analyzer. The oscillation of vertical direction is obtained by observing the difference of the signal of an upper and a lower electrode in BPM.

RESULT AND DISCUSSION

For generating three dimensional crystal beam, we have studied the laser cooling with the coupling resonance method. In order to mix up horizontal and vertical betatron tunes, we have observed betatron tunes for solenoid current from 0 to 40 A. Figure 4 shows the dependence of betatron tunes on solenoid current. The green dots show vertical betatron tunes, and the red dots show horizontal.

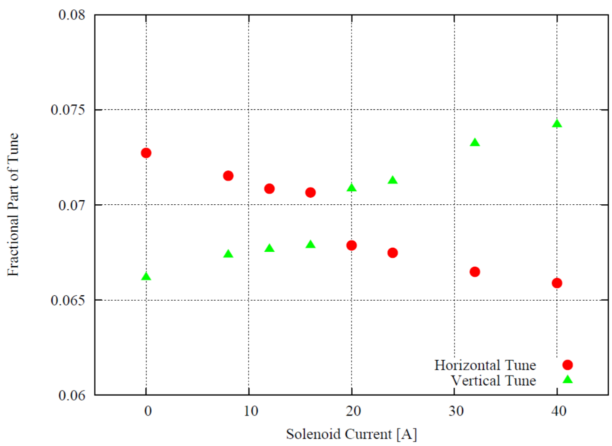

Figure 4: Solenoid current dependency of horizontal and vertical betatron tunes

Horizontal and vertical tunes are varied by changing the excitation level of the solenoid and they are mixed up at a certain region of the solenoid current around 17-20 A as sown in Fig.4, which indicates the coupling between horizontal and vertical degrees of freedoms in these solenoid values. Table 2 shows the parameters of experiment for measuring the betatron tunes.

Table 2: Parameters of experiment for measurement of the betatron tunes

Betatoron Tune	(2.07, 1.07)
Solenoid Current	0 – 40 A
QM1 Current	12.63 A
QM2 Current	23.25 A

Figure 5,6 show the amplitudes of the vertical oscillations, when solenoid current is set to 0, 16 A, respectively. The green and red lines show the cases without and with RFKO, respectively.

For RFKO turning on, the peak is seen at 2.52116 MHz, corresponding to the fractional tune of 0.07 for the current of solenoid 16 A. However, it is not seen for 0 A. Since RFKO oscillation operates only horizontal direction, this means that transfer of oscillation from horizontal to vertical by solenoidal magnetic field. Table 3 shows the parameters of the experiment for measuring the vertical oscillation.

Table 3: Parameters of experiment for measurement of the vertical oscillation

RFKO Frequency	2.521158MHz
Solenoid Current	0, 16 A
QM1 Current	13.2 A
QM2 Current	23.6 A

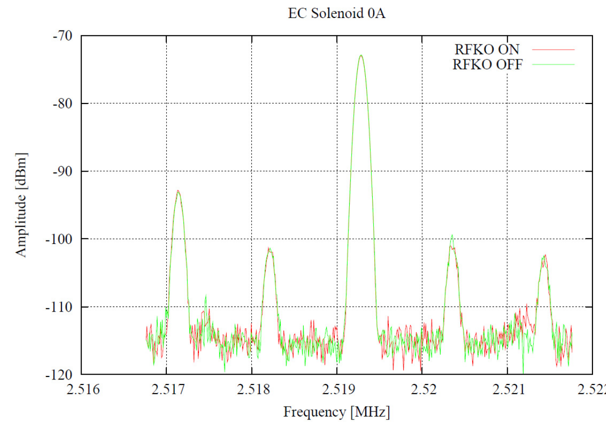

Figure 5: Signal of vertical oscillation (Solenoidal Current: 0 A)

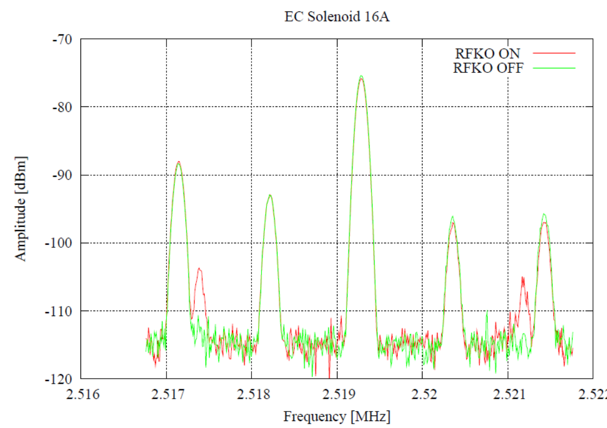

Figure 6: Signal of vertical oscillation (Solenoidal Current: 16 A)

SUMMARY

In this experiment, horizontal and vertical coupling have been confirmed with a certain excitation of a solenoid magnetic fields. By optimization of such a coupling, we aim to proceed to three dimensional laser cooling.

REFERENCES

[1] A. Noda, M. Ikegami and T. Shirai, "Approach to ordered structure of the beam at S-LSR", New J.Phys. 8, 288(2006).
[2] Y. Yuri and H. Okamoto, "Generating Ultralow-Emittance Ion Beams in a Storage Ring", Phys. Rev. Lett. 10.1103(2004).
[3] J. Wei, H. Okamoto and A. M. Sessler, Phys. Rev. Lett. 80 2606(1998).
[4] T. Kihara, H. Okamoto, and Y. Iwashita, Phys. Rev. E. 59 3594(1999).
[5] Y. Yuri, "Feasibility of beam crystallization in a cooler storage ring", Phys. Rev. STAB. (2005)
[6] Y. Yuri and H. Okamoto, Phys. Rev. STAB 8, 114201(2005)