OPTICAL MEASUREMENT OF TRANSVERSE LASER COOLING WITH SYNCHRO-BETATRON COUPLING*

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Abstract

Laser cooling experiment of transverse direction for $^{24}Mg^+$ is performed at the small ion storage and cooler ring, S-LSR. We measured horizontal beam size with CCD camera, and longitudinal momentum spread with PAT (Post Acceleration Tube). The measured beam size with CCD camera is decreased from about 1mm to 0.55mm and longitudinal momentum spread measured with PAT increased near the resonant condition. This suggests transverse temperature was transferred to longitudinal direction with synchro-betatron coupling.

INTRODUCTION

There are several methods to cool ion beam, such as stochastic cooling, electron beam cooling, and laser cooling. Among these methods, laser cooling can achieve the lowest temperature due to its very strong cooling force. The first experiment of laser cooling of ion beam was carried out at TSR [1], and followed at ASTRID [2].

In laser cooling method, a laser is co-propagating or counter-propagating with the ion beam. Since momentum transfer between the laser and the ion beam occurs longitudinally, we can cool the beam particles mainly in the longitudinal direction. Although intra-beam scattering cools the beam transversely, cooling power is weak in usual particle density [3].

Resonant coupling method is proposed to cool ion beam transversely [4]. In the cases betatron tunes (ν_x, ν_y) and synchrotron tune ν_s have the following relations,

$\nu_s - \nu_x =$ integer

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and there is energy change at a position with a finite dispersion, laser cooling power transmits to transverse direction.

In a storage ring, if cooling power is stronger than heating power, beam will be cooled 3-dimensionally. To realize such beam crystallization, the lattice must be properly designed. A small laser-equipped storage ring (S-LSR) (Fig. 1) was constructed for this purpose [5]. The principal parameters of S-LSR, the beam and the laser used in the experiment are shown in Table 1.

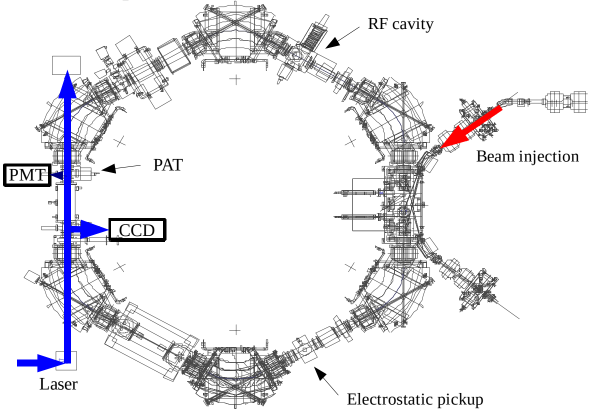

Figure 1: Layout of S-LSR.

Table 1: Parameters of Laser cooling at S-LSR

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
Initial momentum spread	$1*10^{-3}$
Initial particle number	$3*10^{7}$
Betatron tune	(2.068, 1.105)
Synchrotron tune	0.0376 ~ 0.1299
Laser frequency	1074110.3GHz± 0.05GHz
Detuning	-0.2GHz ± 0.05GHz
Laser power at exit window	11 ~ 20mW

The present purpose of experiments is show possibility of transverse laser cooling using resonant coupling method [6-7]. This paper reports optical measurement system of the ion beam and their typical results.

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OPTICAL MEASUREMENT SYSTEM

Detail of the laser generation and transformation system is described in Ref. 8. A Nd:YVO_4 laser (Coherent Verdi V-10; 523nm; 6.6W) pumps a ring dye laser using Rhodamine 560 Chloride (Coherent CR-699-21; 560nm; 600mW). By changing the frequency of the dye laser, detuning can be changed. And frequency doubler (Coherent MBD-200; 280nm; 50mW) doubles the frequency of laser, and then we get the ultraviolet laser to use experiment.

Transition level of $^{24}Mg^+$ using in this experiment is $3s^2S_{1/2}$ to $3p^2P_{3/2}$. Natural width of this transition is 42.7MHz and this corresponds to $2.1*10^{-5}$ of momentum spread. So this limits the precision of optical measurement.

PAT (Post Acceleration Tube)

To observe the momentum of circulating beam, we used PAT [9, 10]. PAT is installed in cooling section of S-LSR. It is insulated from vacuum chamber (Fig. 2) and connected to voltage supply driven by signal generator.

Concept of PAT is shown in Fig. 3. Beam particle in PAT is slightly decelerated by electrical potential. Sweeping the voltage of PAT, the speed of particles in PAT is also swept. Interaction between particle and laser occurs only if particle has some speed at which Doppler shift makes the interaction possible. And spontaneous emission life of excited particle is 3.7ns. And the particle runs 2.1mm in that time. This is so fast that excited particle in PAT is well considered to be excited in it.

Therefore, observing time variation of fluorescence when sweeping voltage of PAT means observing longitudinal momentum variation of particles. The fluorescence from the side window of PAT is observed with photo-multiplier tube (PMT).

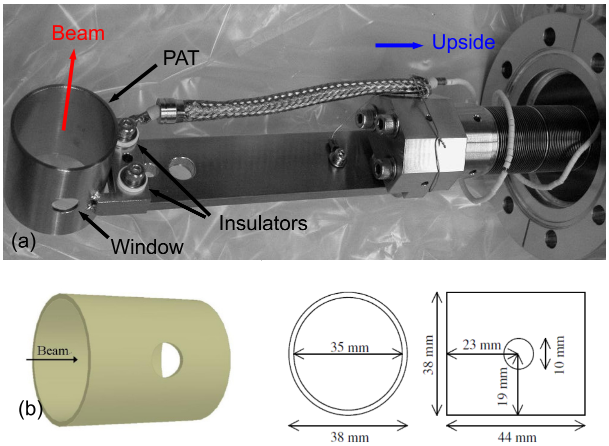

Figure 2: (a) Mounting of PAT and (b) schematic drawing of PAT.

The applied voltage to PAT is 100V. As beam energy is 40keV, it can measure momentum spread $2.5*10^{-3}$ max. This range is much larger than initial momentum spread.

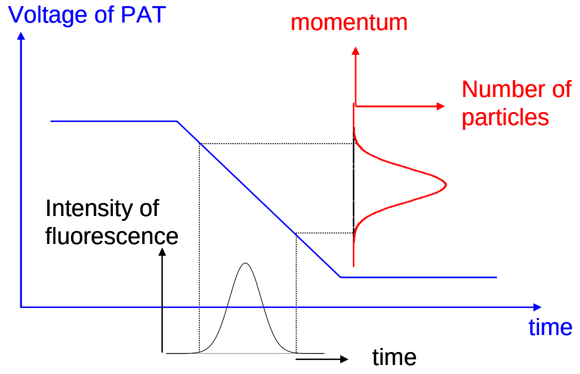

Figure 3: Concept of PAT.

Since particles interacting with laser in PAT are accelerated, this method is destructive measurement. To get time variation, we have to repeat the measurement changing the start time of voltage change. In present experiment, a sweep begins at the same time to inject the beam and begin cooling in order to measure before number of particles decay. Cooling time is much shorter than sweeping time.

An example of corrected and fitted result is shown in Fig. 4. Pedestal from noise is comparatively high. It is mainly refracted laser from chamber or PAT. But it is well fitted by Gaussian. It shows initial momentum spread $1*10^{-3}$ (measured by shottky signal method [10, 11]) is decreased to $1.3*10^{-4}$.

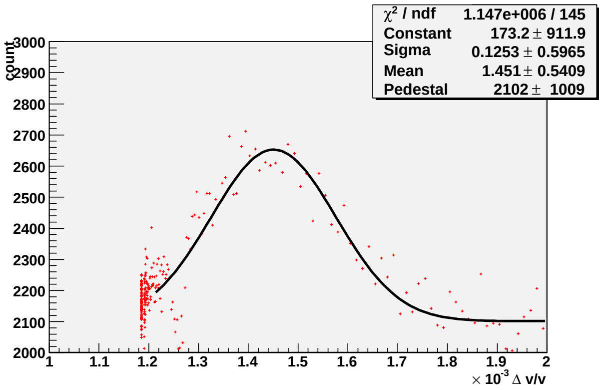

Figure 4: Example of data with PAT. This is after laser cooling.

CCD Camera

CCD camera (Hamamatsu C7190-11W) detects the fluorescence from the beam and determines a horizontal beam profile. The CCD camera can observe the beam through both the side window and the bottom window. The place of CCD camera is exchangeable, but it cannot observe horizontal and vertical beam size at the same time. We installed the CCD camera to look at the ion beam from bottom window to observe horizontal beam size (Fig. 5) [8].

CCD camera records sequential data to PC. It can determine exposure time but it has dead time of 0.25s. So we cannot take data of short time variation at once. To observe change of beam size in less than about 0.1s, we have to repeat injection and cooling.

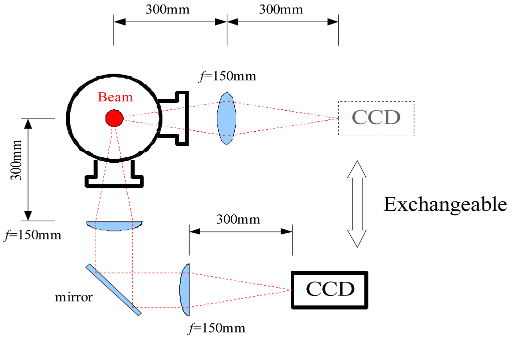

Figure 5: The schematic drawing of the observation system of the CCD camera.

RESULT

Detailed results and discussion of the experiments is given in Ref. 6. We show typical result here.

The data of the CCD camera is integration of 1s when intensity of light from beam becomes certain value. The data of PAT is taken with the method described above.

Theoretically, Synchrotron tune is proportional to square root of RF Voltage. But in near synchro-betatron coupling region, tune behaves differently [6].

Coupling region is considered to be from 20V to 40V. In this region, horizontal beam size measured by the CCD camera is shrunk. This means horizontal momentum spread declines. At the same time, longitudinal momentum spread measured by PAT is increased in a certain condition. This is considered that synchro-betatron coupling mixed cooled longitudinal momentum with horizontal momentum.

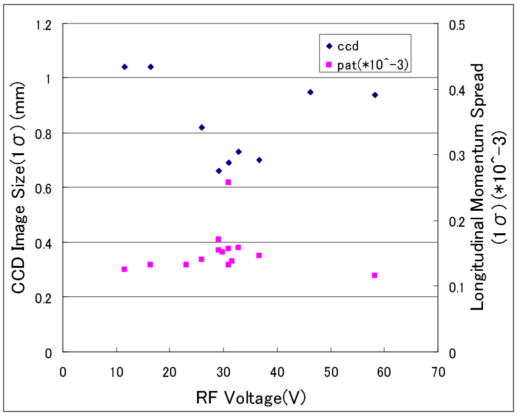

Figure 6: Typical result of CCD image size and longitudinal momentum spread measured with PAT when (ν_x, ν_y) = (2.068 1.105).

Time variation of horizontal beam size obtained by the CCD camera is shown in Fig. 7. Horizontal axis is intensity, so time evolution corresponds from right to left. In non-resonant condition, intensity and beam size is independent, but resonant condition, beam size shrinks as intensity decays (time passes).

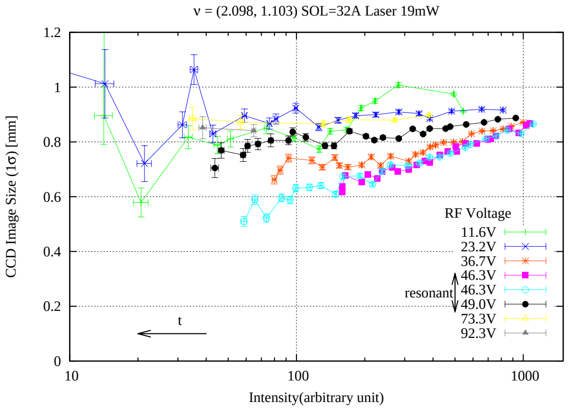

Figure 7: Typical result of intensity measured with CCD and CCD image size when (ν_x, ν_y) = (2.098 1.103).

PRESENT CONDITION OF LASER SYSTEM

We have started experiment of 3-dimension cooling [6-8], and a laser which has high frequency accuracy is inevitable. Doppler shift of 40keV Mg ion corresponds to 0.2% of laser frequency, so the momentum spread of 10^{-4} corresponds to $2*10^{-7}$ of laser frequency, 0.2Hz. And natural width of absorption of laser to is 0.27GHz. So, we have to settle error of the dye laser frequency much less than 0.1GHz.

For the purpose of realization of a crystalline beam by 3-dimensional laser cooling, stabilization of the ring dye laser, which now suffers so much due to a sharp spiky noise, is inevitable.

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