# OPTICAL MEASUREMENT SYSTEM OF LASER-COOLED Mg ION BEAM*

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*Abstract*

Experiments of transverse laser cooling for $^{24}Mg^+$ beam have been performed at a small ion storage and cooler ring, S-LSR. The horizontal beam size and momentum spread are optically measured with CCD camera and PAT (post acceleration tube), respectively. CCD camera can observe the beam size with particle number larger than $7*10^5$. The measured beam size is decreased from 1.12mm to 0.84mm ($1\sigma$) near the resonant condition.

## INTRODUCTION

As methods to cool ion beam, several schemes such as stochastic cooling, electron beam cooling, and laser cooling are well known and widely used. Laser cooling can achieve the lowest temperature among these methods. Laser cooling of ion beam in storage ring was first carried out at TSR [1] and followed at ASTRID [2]. In general, a laser is co-propagating or counter-propagating with the ion beam. Since momentum transfer between the laser and the ion beam occurs in the longitudinal direction, the beam particle is mainly cooled longitudinally. Though laser cooling cannot cool transverse direction directly, intra-beam scattering cools the beam very weakly in transverse direction [3].

Using resonant coupling method, where betatron tunes ($\nu_x$, $\nu_y$) and synchrotron tune $\nu_s$ have the following relations,

$$\nu_s - \nu_x = \text{integer}$$

$$\nu_x - \nu_y = \text{integer}$$

and energy change of the beam is applied at a position with a finite dispersion, then, a dissipation power of laser cooling is transmitted to transverse direction, and we can expect equally efficient transverse laser cooling as the longitudinal one.

If the storage ring whose lattice is properly designed, cooling power will be stronger than heating force, then it realize crystalline beam [4]. Small laser-equipped storage ring (S-LSR) (Fig 1) at Kyoto University was constructed to satisfy the required condition, and we aim at beam crystallization [5]. The main parameters of S-LSR are shown in table 1.

Experiments to demonstrate a feasibility of transverse laser cooling using longitudinal-transverse coupling is now underway [6, 7]. For such a purpose, optical observation system of the ion beam utilizing a spontaneous emission is needed. This paper reports on such observation methods and their typical results.

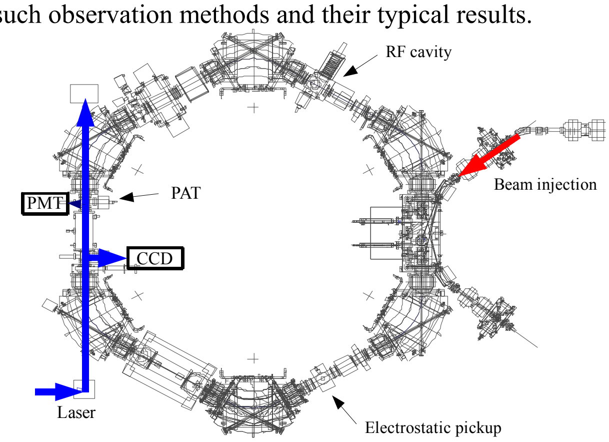


Figure 1: Layout of S-LSR

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 |

## MEASUREMENT SYSTEM OF BEAM MOMENTUM WITH PAT

For the purpose of observation of the circulating beam momentum, PAT (Post Acceleration Tube) as shown in Fig. 2 was installed into S-LSR (Fig.1) [8, 9]. When the electric potential of PAT is swept and it stays in a certain range where the $Mg^+$ ion in the PAT satisfies the Doppler

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cooling condition, Photo-multiplier Tube (PMT) looking at a side window of PAT can detect the spontaneous emission. With this method, the longitudinal momentum spread of the laser cooled $Mg^+$ ion beam has been measured as shown in Fig. 3. The peaks in this figure corresponding to synchrotron tune which almost equal to the fractional part of the horizontal tune are considered to be due to a situation the transverse heat has been transmitted to the longitudinal motion by the synchro-betatron coupling.

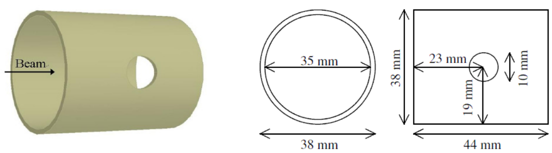


Figure 2: Schematic drawing of PAT

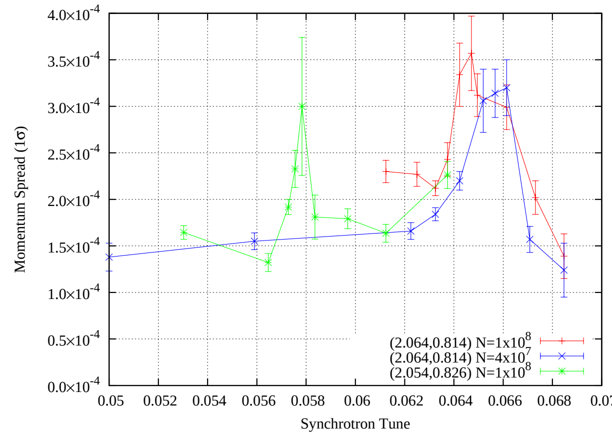


Figure 3: Longitudinal momentum spread of Mg ions

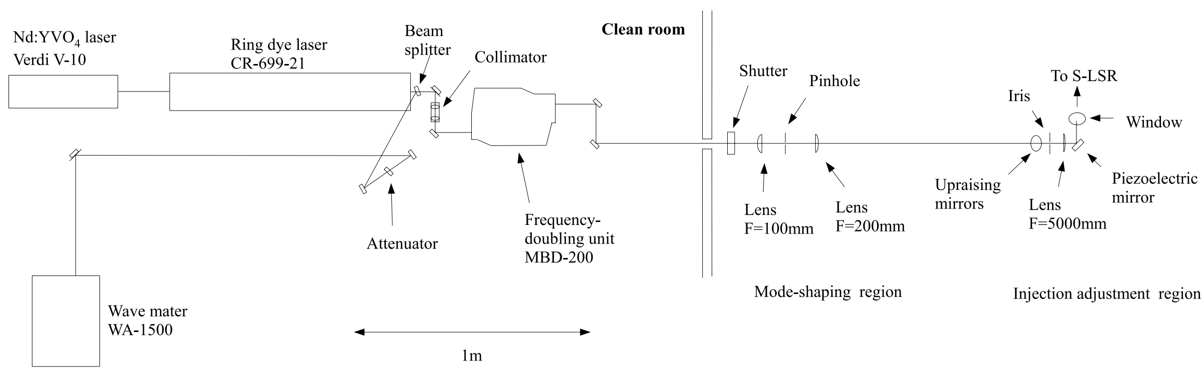


Figure 4: Laser and Transport System

## HORIZONTAL BEAM PROFILE MEASUREMENT SYSTEM

In order to observe the reduction of the horizontal beam size directly, we have developed a system to observe a horizontal beam profile by detection of a spontaneous emission from the laser cooled ions.

### *Laser System*

The laser generation and transfer system for the experiment is shown in Fig. 4. A solid state laser (Verdi V-10) (532nm; 6.6W) pumps a dye laser using Rhodamine 560 Chloride (CR-699-21) (560nm; 600mW). Detuning can be changed by changing the frequency of the dye laser and MBD-200 doubles the laser frequency (280nm; 50mW).

At the beginning, the laser spot size was 0.75mm (1σ) and we were afraid that the laser spot size was not larger than the beam size and the beam size was not measured correctly measured. In order to study this situation, we have made measurements by changing the laser direction as shown in Fig. 5. Each curve on Fig. 5 shows fluorescence distribution in each laser direction. The intensity of the fluorescent light at a position is proportional to the beam density. So the envelope of all curves gives the beam profile. The beam size estimated from the figure is 1.08 mm (1σ). So as to obtain correct beam size information, we expanded the laser size to 1.2mm (1σ). By such enlargement of the laser beam size, it is anticipated that the reduction of the laser density results in a weaker cooling force and weaker fluorescence light of spontaneous emission. As described in the next subsection, fortunately, our system could measure the beam profile correctly for the initial beam intensity larger than $10^7$.

### *Observation System with CCD Camera*

To observe a horizontal beam profile, we used a CCD camera and detect the fluorescence from the beam. The CCD camera is movable so as to observe the beam fluorescence through both a side window and a bottom window. In order to observe a horizontal beam size, we set the CCD camera to look at the beam from the bottom (Fig. 6).

Beam intensity was estimated by induced signal amplitude by bunched beams at parallel-plate pickups. The CCD camera can measure the beam width for every 1 second with particle number if more than $2*10^7$ at the time of injection and which is decreased to $\sim 7*10^5$ in 40 seconds.

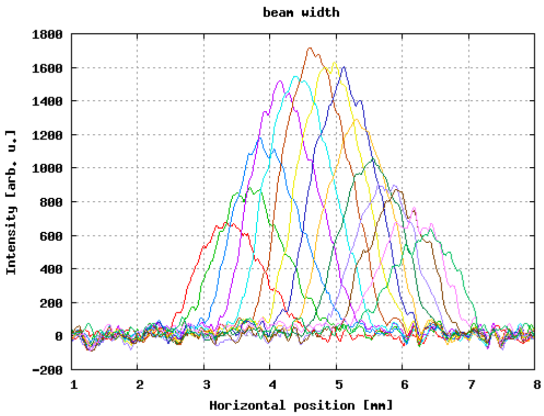


Figure 5: Transverse fluorescence distribution in each laser direction

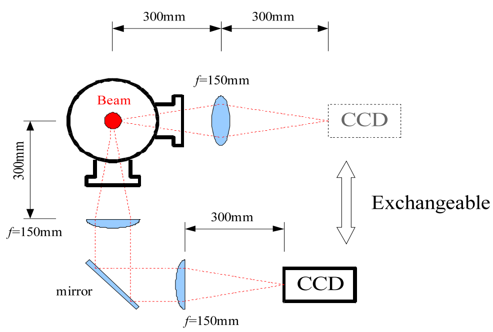


Figure 6: The schematic drawing of the observation system of the CCD camera

An image from the CCD camera is shown in Fig. 7(a). A red rectangle is the Region of Interest (ROI). Vertical axis of the image shows horizontal scale. Fig. 7(b) shows the horizontal beam profile after subtraction of the background noise, which is fitted by a Gaussian (red line).

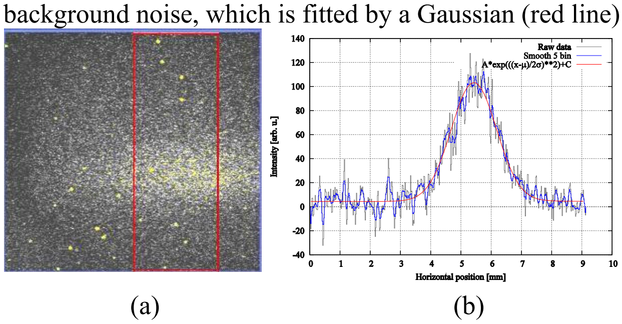


Figure 7: (a) Image of fluorescence from the beam detected with the CCD camera and (b) transverse distribution of the Mg ion beam.

## RESULTS AND DISCUSSION

Using this measurement system, we have studied a transverse laser cooling. Typical parameters of the experiments are listed up in Table 2. By a measurement using PAT, we have observed a peak of the momentum after cooling around the synchrotron tune corresponding to the fractional part of the horizontal tune. That indicates the heat transfer from the horizontal to longitudinal directions.

As for the reduction of the horizontal beam size by a laser cooling, a typical example of beam profile measurements with the CCD camera system is shown in Fig. 8. The precision of these measurements (fitting error to the curve in Fig.7 (b)) is less than 0.01mm and small enough if a systematic error can be neglected. Horizontal beam size reduction is indicated (1.12mm at 1s to 0.84mm at 20s after injection) for a synchrotron tune of 0.0763, while for the measurement with a synchrotron tune of 0.0642, far away from the resonance condition, no reduction of the beam size was observed (1.30mm at 1s to 1.25mm at 20s after injection), although further systematic studies are needed to make a definite conclusion on realization of the horizontal laser cooling.

Table 2: Typical parameters of experiment

| | |
|---|---|
| Ion | $^{24}Mg^{+}$ |
| Kinetic Energy | 40keV |
| Betatron Tune | (2.075, 1.090) |
| Synchrotron Tune | 0.012 - 0.108 |
| Initial Particle Number | $4 * 10^{7}$ |
| Initial Momentum Spread | $8 * 10^{-4}$ |
| Laser Frequency | 1074110.44GHz |
| Laser Power at exit window | 11 – 16 mW |

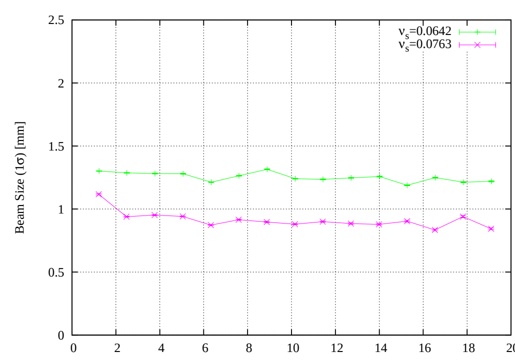


Figure 8: Beam size measured as integration of 1 second by the CCD camera.

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