RECENT STATUS OF BEAM COOLING AT S-LSR*

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Abstract

At S-LSR in ICR, Kyoto University, electron cooling of 7 MeV protons has been applied. A relative velocity sweep scheme reduced the cooling time from 30.4 s to 1.7 s for the initial momentum spread of 1 %. One dimensional ordering by electron cooling was also realized at a proton number of approximately 2000, resulting in 2K and 11 K in the longitudinal and the horizontal directions, respectively. With the combination of electron cooling and phase rotation techniques a very short bunch length of ~3 ns was realized, which should be used for bio-medical irradiation. For multi-dimensional laser cooling of $^{24}\mathrm{Mg}^{+}$ ions, synchro-betatron coupling has been applied for a bunched ion beam. The realized beam temperatures are 24K and ~200 K for the longitudinal and horizontal directions, respectively at resonance, while the corresponding values are 15K and ~600 K, respectively at the off resonance condition.

INTRODUCTION

A small laser equipped storage ring (S-LSR) was constructed at ICR, Kyoto University, in order to investigate acceleration of hot laser-produced ion beams. The ion beams produced by laser plasma interaction has a large energy spread. The capability of efficient electron cooling of these hot proton beams by a relative velocity sweep was investigated at S-LSR. S-LSR is also oriented for the beam cooling research to realize ultra low beam temperature. For this purpose, the S-LSR lattice was designed with a rather large super symmetry of 6 to satisfy the so called maintenance condition [1]. With deflection elements composed of magnetic and electric fields, a dispersion less lattice can be realized [2]. In Fig.1 the S-LSR is shown together with other accelerators in our accelerator building. The main parameters of S-LSR are listed up in table 1 and the layout of S-LSR with its injectors is shown in Fig. 2.

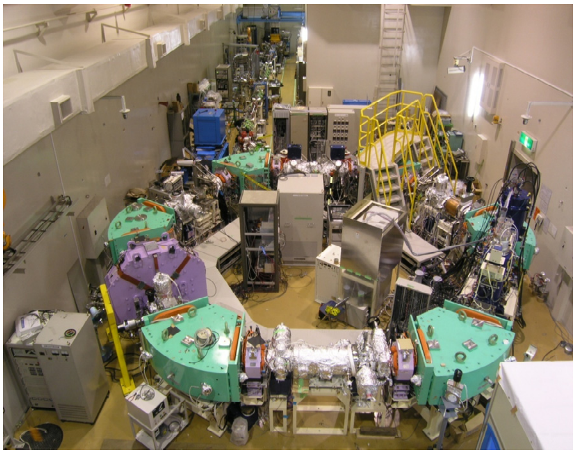

Figure 2. Photograph of S-LSR and its injector.

Up to now, we have applied electron cooling to a 7 MeV proton beam to realize one dimensional ordering [3]. "Synchrotron-betatron coupling " [4], was applied for the laser cooling experiments using 40 keV $^{24}\mathrm{Mg}^{+}$ ions, where the beams, however, still have a rather hot transverse temperatures.

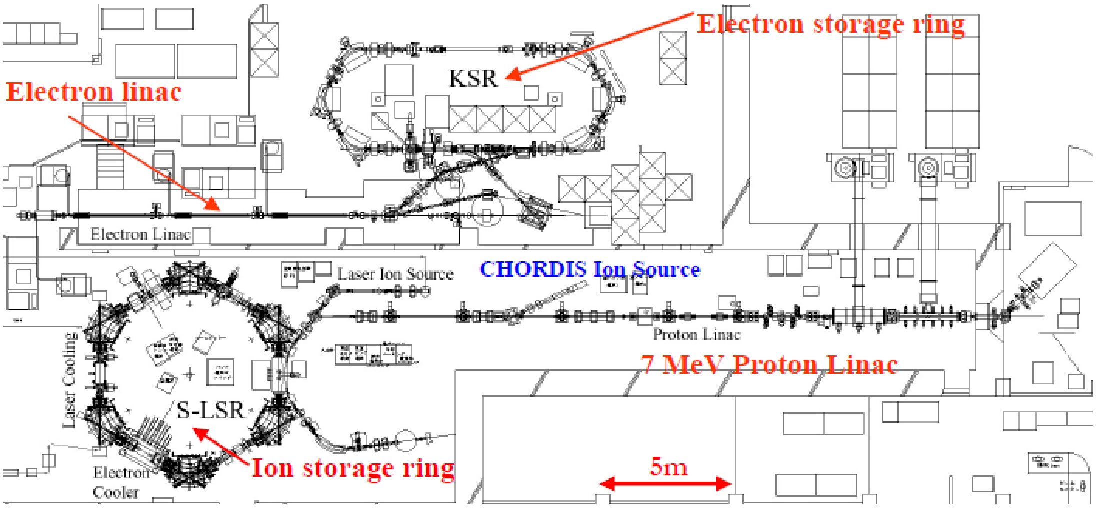

Figure 1. Layout of S-LSR located in the accelerator building together with other accelerators.

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[*] project by MEXT of Japanese government. It is al so supported by GCOE project at Kyoto University, "The next generation of Physics-Spun from Universality and Emergency.

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Table 1: Main parameters of S-LSR

Ion, Kinetic Energy	proton, 7 MeV ^{24}Mg$^+$, 40 keV
Circumference of the ring	22.557 m
Average radius of the ring	3.59 m
Length of long straight section	1.86 m
Radius of curvature	1.05 m
Betatron tune	(1.645, 1.206) :proton (2.068, 1.105) :^{24}Mg$^+$
Momentum Compaction	0.502
Average Vacuum Pressure	~10^{-8} Pa
Electron Cooling	
Electron Energy	3.8 keV
Electron Density	2.2×10^6 /cm^3
Effective Cooler Length	0.44 m
Expansion Factor	3
Temperature at transition to ordered state	$T_\parallel$=2 K, $T_\perp$=11 K
Laser Cooling	
Synchrotron tune	0.0376~0.1299
Laser frequency	1074110.3 GHz± 0.05GHz
Laser detuning	≤-0.2GHz±0.05GHz
Laser power at exit window	11~20 mW

CHARACTERISTICS OF S-LSR

Ring Lattice Symmetry

In order to suppress the shear heating effect [1], the S-LSR has a symmetry of 6 with the operating point of (ν_H, ν_V)=(1.645, 1.206) (for electron beam cooling of protons) and (2.068, 1.105) (for laser cooling of ^{24}Mg$^+$ ion beams) [4], satisfying the so called maintenance conditions given by the following relations [1],

$$\gamma < \gamma_t \qquad (1)$$

$$N_s > 2\sqrt{\nu_H{}^2 + \nu_V{}^2}\ , \qquad (2)$$

where γ_t and N_s are Lorentz γ at the transition energy and the super periodicity of the ring, respectively. At S-LSR, its super periodicity was chosen to be 6 to fulfil the Eq. (2). At this S-LSR settings, formation of one dimensional ordering has been realized for a proton beam.

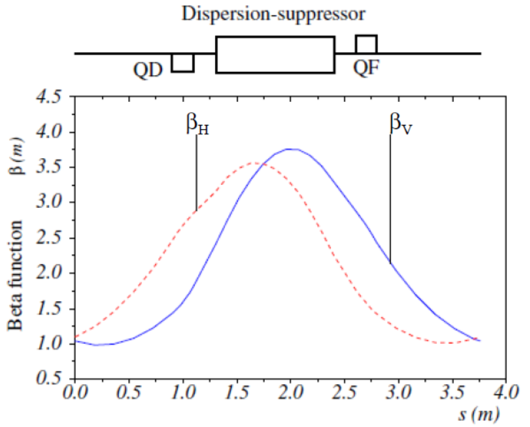


Figure 3. Beta-functions in the dispersion free operation mode of S-LSR. The operating point is (ν_H,ν_V) = (2.07, 2.07)

Laser cooling

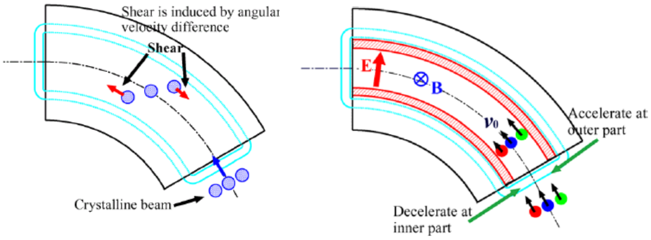


Figure 4. Basic concept of dispersion suppressor. (taken from ref.[2])

Dispersion Suppressed Lattice

The deflection elements at S-LSR with a deflection angle of 60 degrees have another unique capability as the realization of dispersion free straight sections as shown in Fig. 3 by applying additional electrostatic field $\vec{E}$ satisfying the following relation:

$$(1 + {}^{1}\!/_{\gamma^2})\vec{E} = -v_0 \times \vec{B}\ , \qquad (3)$$

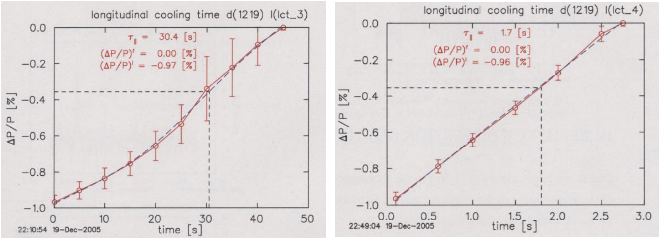
where $\vec{B}$ is the magnetic field in the deflection elements [2]. As shown in Fig. 4, the ions cooled to a certain energy in the straight section get the different energy change due to their radial positions in the electrostatic field, $\vec{E}$ and thus they have the same angular velocity, which suppresses the shear heating.

ELECTRON COOLING OF PROTON BEAM

The motive force to construct S-LSR was the demonstration of post acceleration of laser-produced ion beams to realize a compact cancer therapy ion accelerator, guided by the Advanced Compact Accelerator development project by MEXT of the Japanese government.

Efficient Electron Cooling of Hot Ion Beam by Relative Velocity Sweep

A laser-produced ion beam, usually has a relatively large energy spread, where most of the ions cannot interact



(a) (b)

Figure 5. Electron cooling of a 7 MeV hot proton beam without (a) and with (b) a relative velocity sweep.

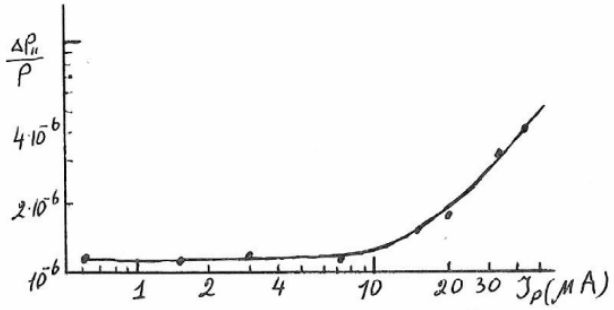


Figure 6. The first data claiming one dimensional ordering by application of an electron cooling..(borrowed from Ref. [7])

effectively with the electron beam due to the very small cooling force in the large relative velocity (v_i) range, where the electron cooling force (F), scales as

$$F \propto 1/v_i^2 . \qquad (4)$$

The measured cooling time of a 7 MeV ion beam for different momentum spreads are shown in Fig. 5(a). However, a fast cooling can be achieved if we apply an external force to assist the electron cooling force in the large relative velocity range. We utilize an induction accelerator to rapidly push the ions toward the stable point of the cooling force. An alternative method to reduce the cooling time is a change of the electron velocity by sweeping the cathode potential. With this scheme of the relative velocity sweep, the cooling time was reduced from 30.4 s to 1.7 s (Fig.5(b)). This scheme has previously been tested at TSR of MPI-K in Heidelberg for $^{12}C^{6+}$ ion beams [6].

One Dimensional Ordering of Proton Beam

Stimulated by the data shown in Fig. 6, reported at ECOOL84 from NAP-M at Novosibirsk, many efforts have been made world wide to attain an ordered state. At ESR and SIS in GSI, Darmstadt and CRYRING in Stockholm, a clear sudden jump in the momentum spread and/or transverse beam size has been reported at a certain beam particle number for heavy ions [8, 9] and even for $^{12}C^{6+}$ ions [10]. For proton beam, however, due to its single charge, the electron cooling force is very weak compared with other ions and a clear jump in the momentum spread or beam size had not been observed so far. Owing to the high S-LSR symmetry of 6 suited for stable beam dynamics, we can observe a sudden jump in the momentum spread as indicated in Fig. 7 after various improvement of power supplies of the ring magnets and high voltages for electron cooler in collaboration among

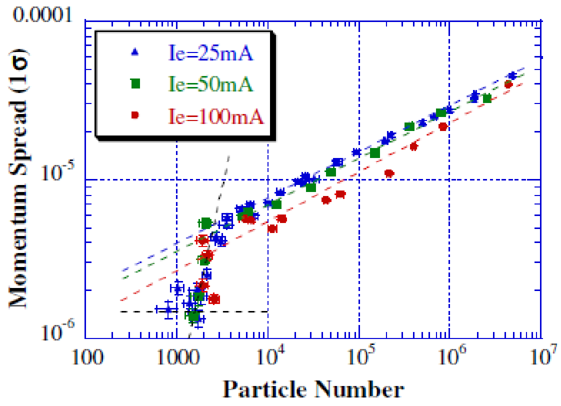


Figure 7. Clearly observed sudden jump of the momentum spread of a 7 MeV proton beam at S-LSR, which is considered as one dimensional ordering [3].

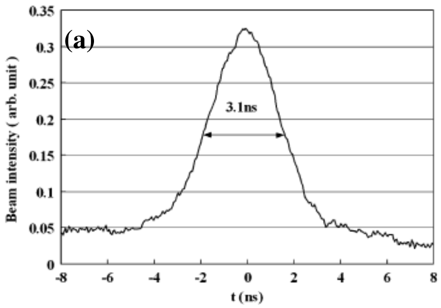
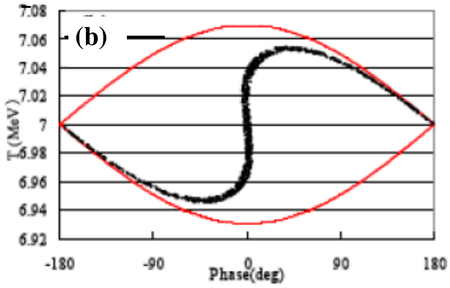


Figure 8. (a) Realized shortest proton bunch (3.1 s at 2σ) by application of phase rotation as illustrated in (b).



(b) Illustration of the phase rotation scheme after electron cooling to create a short bunch beam after electron beam cooling.

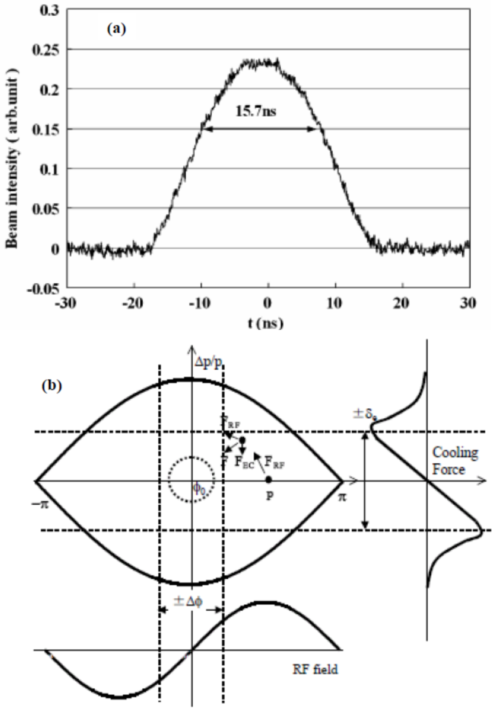


Figure 9. Short bunch formation by bunched beam cooling.

JINR, Dubna Moscow, MPI-K, Heidelberg and ICR, Kyoto [3]. The attained beam temperatures at the transition to the ordered state are ~2 K and ~11 K for the longitudinal and vertical directions, respectively.

Short Bunch Formation and Its Fast Extraction

Recently DNA double strand break with the use of laser-produced proton beam was reported [11], which is considered to be due to the very high peak intensity of the laser-produced proton beam. In order to provide a much higher proton beam peak intensity, mainly for bio-medical irradiation with much more flexibility and controllability, we have combined electron cooling with phase rotation techniques.

Phase Rotation of Electron Cooled Beams.

With electron cooling (RF off) the coasting proton beams are cooled to a very small momentum spread. Then an RF electric field was applied in a quarter period of the synchrotron oscillation as indicated in Fig.8(b), the beam becomes a very short length as shown in Fig. 8(a) [12] With this scheme, a very short bunch of ~3 ns can be realized for an initial beam intensity of 1.4 × 10^8 protons (7 MeV). The extraction efficiency of about 20%, however, is not so high, because of the formation of a hallow tail as indicated in Fig.8 (b) .

Electron Cooling of RF Bunched Beam

In order to reach higher extraction efficiencies, a scheme to apply electron cooling after ion capturing into the separatrix was also studied. This method, illustrated in Fig. 9 (b), can create a beam bunch of 15.7 ns as is shown in Fig. 9(a). The resonator voltage in this measurement was 800 V with a harmonic number 2, which was the same as the case of phase rotation case above mentioned. With this scheme, the bunch length measured at a proton number of 1.4 × 10^8 is about 5 times longer compared with the other scheme. The extraction efficiency, however, is almost 100 % and the peak intensity is almost the same order of ~10^{16} particles/s, which is to be irradiated into the transverse beam radius of 2 mm (FWHM).

Bio-medical Irradiation System with Vertical Beam

Our both beam cooling and extraction schemes above mentioned have the beam size of 2 mm in FWHM resulted in the estimated proton flux of ~2×10^6 $\mathrm{mm^{-2}ns^{-1}}$, which well surpasses the one in Ref. [11] with ~10^3 $\mathrm{mm^{-2}ns^{-1}}$. In consideration of the fact that our scheme is operated below 1 Hz of Ref. [11] due to needed cooling time, it surpasses this scheme because of the available flux range, flexibility and easiness to control by using accelerator based beams. We are now trying to develop a beam course mainly oriented for bio-cell irradiation, which can irradiate cells kept in a breeding liquid by a vertically bent up beam in collaboration with NIRS.

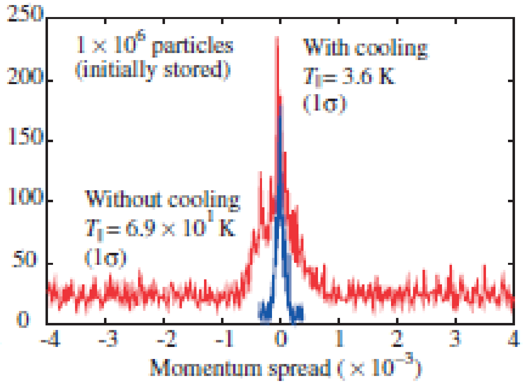


Figure 10. Momentum distributions of 24Mg+ ion beam without (a) and with (b) the laser cooling.

LASER COOLING OF MG IONS

Laser Cooling of Coasting Beam in the Longitudinal Direction

From the point of view of attaining the lowest possible beam temperature, it is required to apply laser cooling because of its strong longitudinal cooling force. In the first step, we have applied laser cooling for 40 keV $^{24}\mathrm{Mg}^+$ ion beams with an intensity of 10^6 ions. In Fig. 10 a typical result of longitudinal laser cooling of a coasting beam is shown. The reached longitudinal equilibrium temperature is limited to 3.6 K due to the heat flow from transverse directions to the longitudinal one by intra-beam scattering (IBS).

Transverse Laser Cooling by Synchro-Betatron Coupling

The transverse beam temperature has been decreased by laser cooling with the use of intrabeam scattering [13] and dispersive cooling [14], which have been found to be insufficient to reach such low beam temperature to realize a crystalline structure. To realize a much stronger cooling rate in the transverse direction, the above mentioned "Synchro-Betatron Coupling" has been proposed [4]. We have tested this scheme experimentally.

Observation of Horizontal Beam Size

In order to evaluate the horizontal beam temperature, measurements of the horizontal beam size are necessary. We have observed spontaneously emitted photons from the laser-excited Mg ions [15]. In Fig. 11, the observation system to detect the horizontal beam size is shown. To measure the size of the ion beam, exited by a laser beam

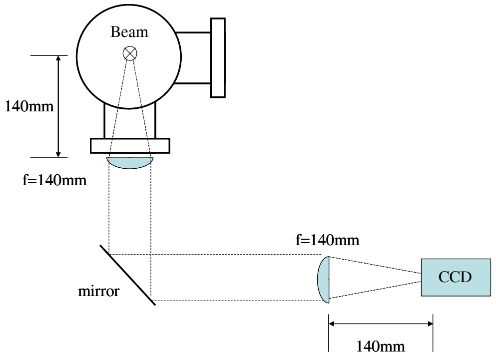
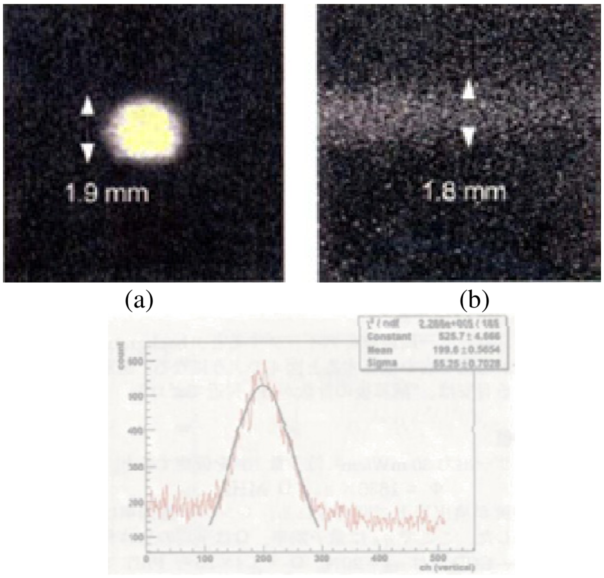


Figure 11. Observation scheme of the horizontal beam size of $^{24}\mathrm{Mg}^+$ ion beam.



(a) (b)

(C)

Figure 12. (a)Transverse laser profile (FWHM 1.9 mm) used to measure the spontaneous emission from the excited $^{24}Mg^{+}$; ions, (b) Observed spontaneous emitted photons and (c) Fitted results of the observed photon intensity resulting in a horizontal beam size of 1.8 mm (FWHM).

with a size of 1.9 mm (FWHM) (Fig.12 (a)), the spontaneously emitted photons from the $^{24}Mg^{+}$ ions are observed by a cooled CCD camera (Hamamatsu Photonics C7190-11W:-20℃) as shown in Fig.12 (b). The intensity profile of the spontaneous emitted photons is fitted, as shown in Fig.12 (c), resulting in a horizontal ion beam size of 1.8 mm (FWHM).

The above results are evaluated in connection with the synchro-betatron resonance together with the equilibrium momentum spread after laser cooling, measured by a voltage sweep applied to a PAT (Post Acceleration Tube) [15]. The present experimental measurements have been performed at the operation point of (ν_H, ν_V)=(2.068, 1.105). The measured horizontal beam size has a local minimum at a synchrotron tune of about 0.068 (upper) while the momentum spread has a local maximum at the same synchrotron tune (lower) as shown in Fig. 13, which is an experimental demonstration of "Synchro-Betatron Resonance Coupling".

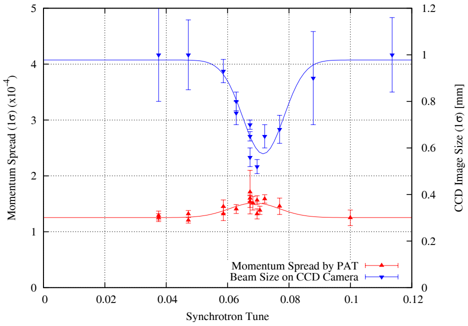


Figure 13. Experimental demonstration of synchro-betatron resonance coupling. Longitudinal momentum spread after laser cooling has a local maximum at ν_s~0.068 (lower), while the horizontal beam size has a local minimum at the same position (upper).

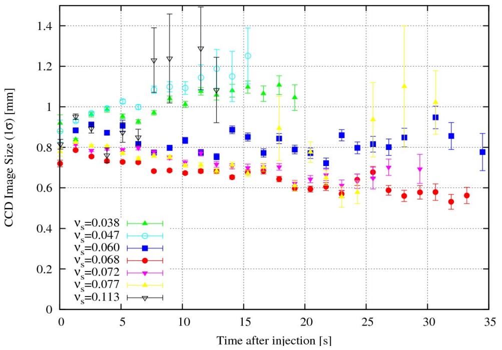


Figure 14. Time variation of the horizontal beam size for various synchrotron tunes.

At the peak of this resonance, the beam temperatures are evaluated to be 24 K and ~200 K (1σ) for the longitudinal and horizontal directions, respectively. At the off resonance condition, the longitudinal and horizontal temperatures are ~15 K and ~600 K, respectively.

In Fig.14, the developments of the horizontal beam width as a function of time for different synchrotron tunes are shown. According to the data shown in Fig.14, the transverse laser cooling rates by our present system seems to be comparable with the IBS rate, which is insufficient to realize crystalline ion beams.

Evaluation of Results and Further Perspectives

In our laser cooling system of bunched beam, above mentioned, a fixed laser detuning after optimization is utilized, as shown in Fig. 15. Recent reinvestigation of the results, shown in Fig.14, pointed out that the $^{24}Mg^{+}$ ion beam includes two components plasma with different life times as shown in Fig. 16. The time domain beam signals observed by an oscilloscope at the time of 10 s, 60 s and 150 s after injection (when laser cooling starts) are shown in Fig.16 (a), (b) and (c), respectively. These data demonstrate that the $^{24}Mg^{+}$ ion beam has two components with different beam life times. By fitting these data, the life times of these two components are determined to be ~26 s and ~42 s for un-cooled and cooled beams,

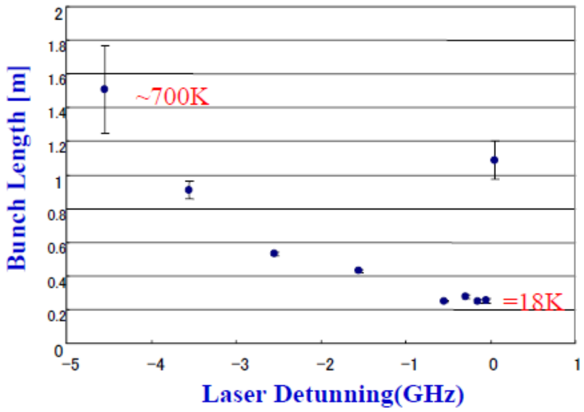
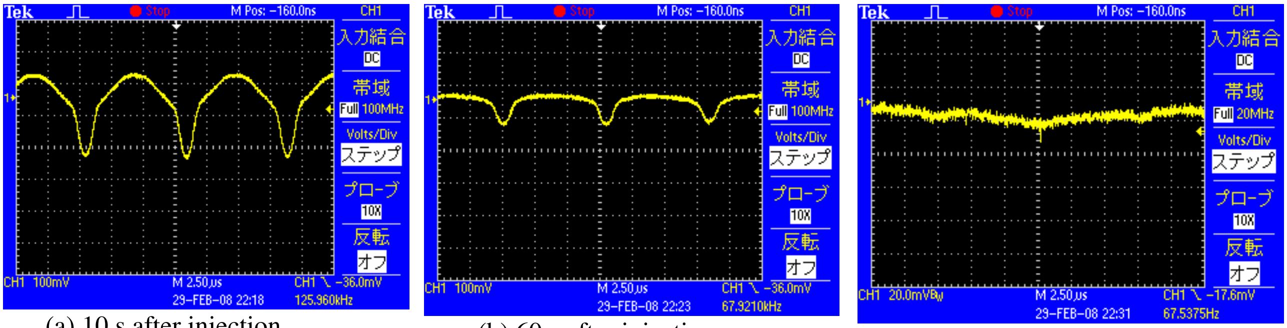


Figure 15. Optimization of laser detuning for bunched beam laser cooling.



(a) 10 s after injection

(b) 60 s after injection

(c) 150 s after injection (almost no beam)

Fig. 16. Time domain beam signals observed after 10 s. (a), 60 s (b) and 150 s after injection. The laser cooling start at the injection time and these times also represent the time after the start of the cooling. Judging from the data of (c), almost no significant noises are included in these beam signals.

respectively as shown in Fig. 17 [16].

Up to now, the beam cooling time in the longitudinal direction has been evaluated by a spectrum analyzer using Schottky signals in the frequency domain, which however, seems to includes both two components, laser cooled and un-cooled ions, which might be the reason why our laser cooling time is rather long and realized temperature is rather high compared with the theoretical prediction.

Our recent investigation on transverse laser cooling with the use of "Synchro-Betatron Coupling" has to be improved by sweeping the laser detuning or equivalently sweeping the RF frequency for bunching.

Another possible approach to much lower beam temperature is the application of pre-electron cooling for 40 keV $^{24}Mg^{+}$ ion beams. As the corresponding electron energy of 0.9 eV for the 40 keV $^{24}Mg^{+}$ ion beam seems to be too low to attain enough current for electron cooling, a scheme to use a higher voltage of ~12.5 V for the extraction from the cathode and a ensuing deceleration to the ion velocity before reaching to the cooling section is under investigation.

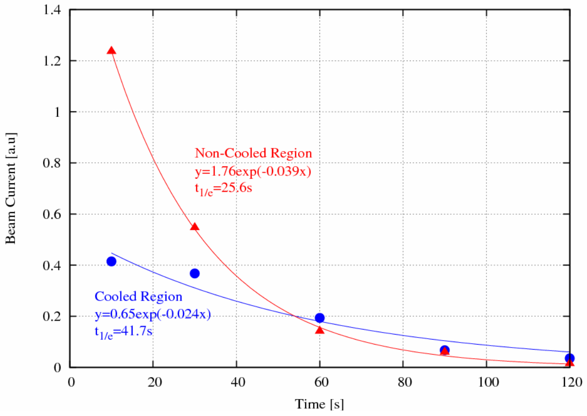


Fig.17. Fitted life times of the two components in the $^{24}Mg^{+}$ ion beam during laser cooling..

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