PRESENT STATUS OF BEAM COOLING AND RELATED RESEARCH AT S-LSR*

A. Noda, M. Nakao, H. Souda, H. Tongu, ICR, Uji, Kyoto, Japan, T. Fujimoto, S. Iwata, S. Shibuya, AEC, Chiba, Japan, K. Ito, H. Okamoto, HU/AdSM, Higashi-Hiroshima, Japan, K. Jimbo, IAE, Uji, Kyoto, Japan, M. Grieser, MPI-K, Heidelberg, Germany, K. Noda, T. Shirai, NIRS, Chiba, Japan

Abstract

Proton beam with 7 MeV has been electron cooled and one dimensional ordering has been demonstrated at a beam intensity of about 2000 particles, resulting in a transition temperature of ~2 K and ~11 K for the longitudinal and transverse directions, respectively. With the combination of electron cooling and RF voltage, a very short bunch length of ~3ns was realized, which is to be used for bio-medical irradiation. Laser cooling has been successfully applied for both coasting and bunched $^{24}Mg^{+}$ ion beams in the longitudinal direction resulting in equilibrium temperatures of 3.6 K and 18 K for coasting and bunched beams, respectively, while the horizontal temperature remains $\geq$~200 K in the present scheme.

INTRODUCTION

At ICR, Kyoto University, a small laser-equipped storage ring, S-LSR was constructed in order to demonstrate the efficiency of electron cooling of hot laser-produced ion beams. S-LSR is also to be used to approach ultra low temperature beams [1]. After the demonstration of electron cooling of a hot proton beam, one dimensional ordering has been demonstrated for the first time for proton beams [2]. Electron beam cooling has been also applied for 7 MeV proton beam to create a short bunched beam, resulting in a very short bunch length of 3.1 ns (2σ) with the use of phase rotation after electron cooling [3], which is now under development for bio-cell irradiation applications with a very high peak intensity.

Ultra-low temperature beams are realized with laser Cooling. For laser cooling, $^{24}Mg^{+}$ ion beams are accelerated to 40 keV with the high voltage platform of the ion source, the transported and single turn injected into S-LSR. After the successful demonstration of longitudinal laser cooling of a coasting beam [4] and a bunched beam [5], extension of the laser cooling force to the transverse direction by "synchro-betatron coupling" [6] has been experimentally demonstrated.

Table 1: Parameters of S-LSR and Electron Beam Cooling System of 7 MeV Proton

Ion, Kinetic Energy	proton, 7 MeV
Circumference of the ring	22.557 m
Average radius of the ring	3.59 m
Radius of curvature	1.05 m
Betatron tune	(1.645, 1.206)
Momentum Compaction	0.502
Average Vacuum Pressure	~10^{-6} Pa
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_{//}$2 K, $T_{\perp}$11 K

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#noda@kyticr.kuicr.kyoto-u.ac.jp

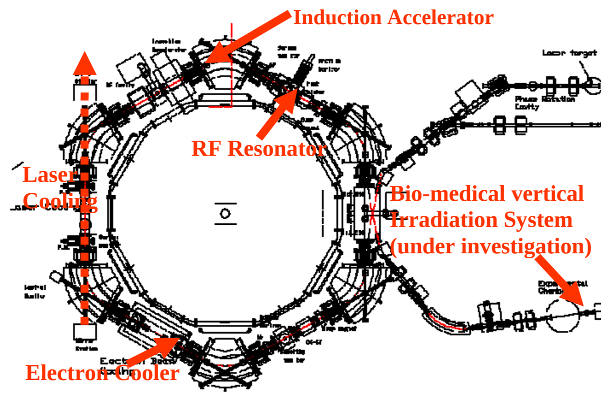


Figure 1: Electron Cooling and Laser Cooling system at S-LSR.

ELECTRON BEAM COOLING OF 7 MEV PROTON BEAM

Realization of one Dimensional Ordering

The proton beams are accelerated to 7 MeV with the proton linac composed of RFQ and Alvarez cavities. These beams are multi-turn injected into S-LSR ring and cooled with electron cooling. One dimensional ordering of a proton beam as shown in Fig. 2 has been experimentally demonstrated after improvement of the stability and ripples of the ring magnet and high voltage power supplies for the electron cooler. The attained beam

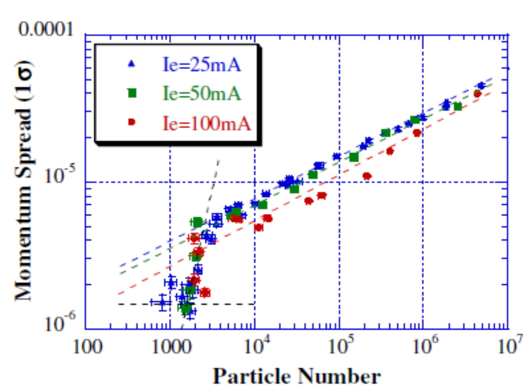


Figure 2 Demonstrated one dimensional ordering by electron beam cooling [2].

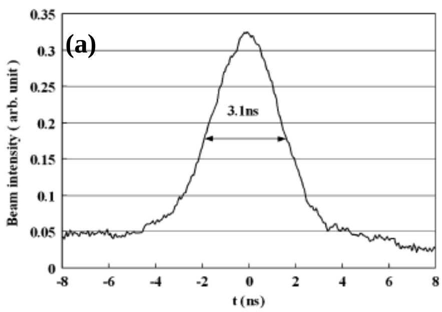
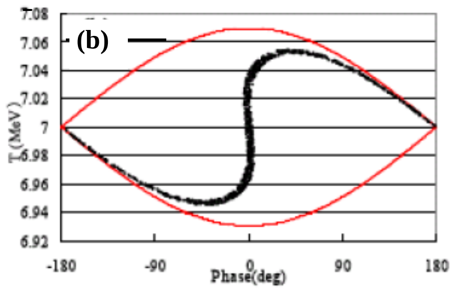


Figure 3(a) Realized shortest proton bunch (3.1 sec. at 2σ) by application of phase rotation as illustrated in (b).



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

temperatures at the transition to the ordered state are ~2 K and ~11 K for the longitudinal and vertical directions, respectively.

Formation of Very Short Bunched Beams

Based on a recent result of DNA double strand break by laser-produced proton beams with a peak intensity of ~2.4 $\times 10^4$ into 1 mm^2 cell layer with 1 Hz [7], the importance of the high peak intensity effecting bio-medical cells has been noticed. In order to enable a more quantitative experimental research, the development of bio-medical beam course has been performed in collaboration with NIRS and AEC has been performed using S-LSR. In Fig.3(a), the realised shortest proton bunch length of a proton beam with 7 MeV and beam intensity of 1.4 × 10^8 is shown by application of phase rotation with an RF electric field after electron beam cooling as illustrated in Fig.3(b). Even in consideration of the fact that our system can only operate every few minutes due to the needed cooling time and the transverse beam size is 2 mm (FWHM), our irradiation system surpasses well the dose rate in Ref. [7] with much flexibility.

LASER COOLING OF 40 KEV MG IONS

Laser Cooling of Coasting Beam in the Longitudinal Direction

In order to reduce further the beam temperature, a stronger laser cooling force is required, which however, needs the coupling between three degrees of freedom in order to extend the longitudinal cooling force to the other two directions. For the active energy transfer scheme among the different degrees of freedom, "synchro-betatron Coupling" by acceleration/ deceleration at a

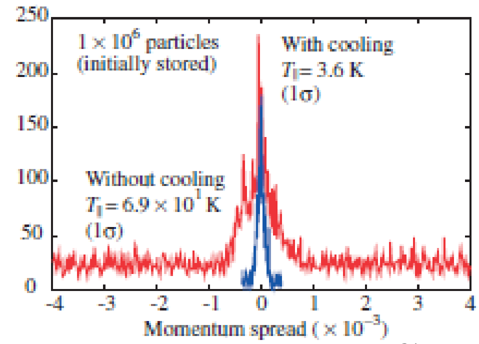


Figure 4 Momentum distributions of a $^{24}Mg^+$ ion beam with an intensity of 1 × 10^6 with and without laser cooling [8].

finite dispersion has been proposed theoretically [6]. With longitudinal laser cooling of a coasting beam, a beam temperature of 3.6 K was realized in the longitudinal direction at a beam intensity of 1 × 10^6, as shown in Fig. 4 [8]. The reason of the relatively high equilibrium temperature is the heat flow from the transverse direction to the longitudinal direction by intra-beam scattering.

Transverse Laser Cooling by Synchro-Betatron Coupling

The transverse beam temperature has been decreased by laser cooling with the use of intrabeam scattering [9] and dispersive cooling [10], which have been found to be insufficient to reach such a low beam temperature to realize a crystalline structure. To realize much stronger cooling force in the transverse direction, the above mentioned "Synchro-Betatron Coupling" has been proposed [6]. We have tested this scheme experimentally.

Observation of Horizontal Beam Size

For the purpose of evaluating the horizontal beam temperature, it is required to measure the horizontal beam size. We have observed spontaneously emitted photons from the laser-excited Mg ions [11]. In Fig. 5, such a observation system to detect the horizontal beam size is shown. With the use of a laser beam of a size of 1.9 mm (FWHM) as shown in Fig.6 (a), spontaneously emitted photons from $^{24}Mg^+$ ions are observed by a cooled CCD camera (Hamamatsu Photonics C7190-11W:-20℃) as shown in Fig.6 (b). The intensity profile of the spontaneous emitted photons is fitted (Fig.6 (c)), resulting in an ion beam size of 1.8 mm (FWHM).

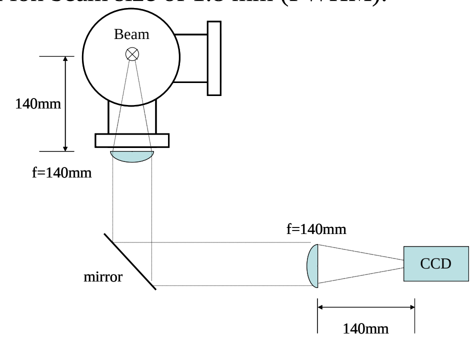
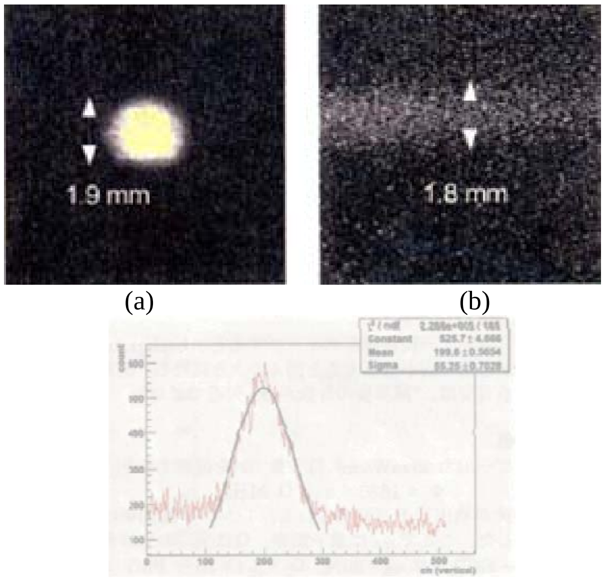


Figure 5 Observation scheme of the horizontal beam size of $^{24}Mg^+$ ion beam.



(a) (b)

(C)

Figure 6 (a)Transverse laser profile (FWHM 1.9 mm) used to measure the spontaneous emission from 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).

The above results are evaluated in connection witn 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) [11]. The present experimental measurements have been performed at the operation point of (ν_H, ν_V)=(2.068, 1.105). In table 2, the main parameters of the laser cooling system at S-LSR are given. The measured horizontal beam size has a local minimum at a synchrotron tune around 0.068 (upper) while the momentum spread has a local maximum at the same synchrotron tune (lower) as shown in Fig. 7, which is an experimental demonstration of “Synchro-Betatron Resonance Coupling”.

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.8, the development in time of the horizontal beam width for different synchrotron tunes is shown.

Table 2: Main parameters of laser cooling system at S-LSR

Ion species and energy	$^{24}Mg^{+}$, 40 keV
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	1074110.3 GHz±0.05GHz
Laser detuning	-0.2GHz±0.05GHz
Laser power at exit window	11~20 mW

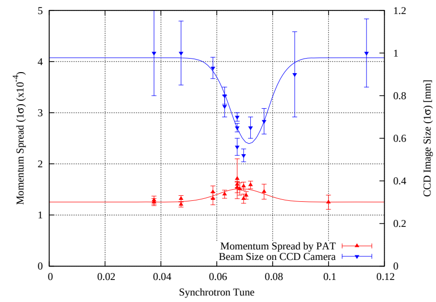


Figure 7 Experimental demonstration of synchro-betatron resonance coupling. Longitudinal momentum spread after laser cooling has a local maximum at ν_s~0.068 (lower), while the horizontal beam size has a local minimum at the same position (upper).

The data shown in Fig.8 point out that the transverse laser cooling rates by our present system are comparable with the IBS rate, which is insufficient to realize crystalline ion beams.

We think further optimization of the laser detuning and/or rejection of uncooled hot beams lower than the laser detuning will contribute to much colder temperature. Our major efforts are oriented to this direction from now on.

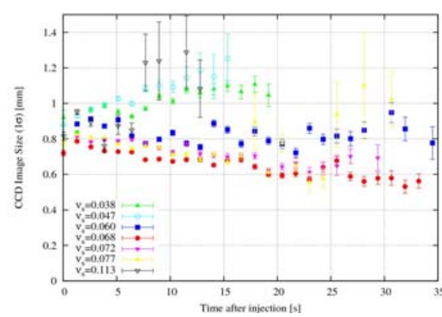


Figure 8 Time variation of the horizontal beam size for various synchrotron tunes.

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