ION COOLER-STORAGE RING S-LSR*

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Abstract

With S-LSR, electron cooling time of hot proton beam as large as 1% is found to be reduced from 40 sec. to 2.5 sec. by relative velocity sweep of the electron. Beam life time of 35 keV $^{24}Mg^{+}$ ion beam with normal mode of full aperture is measured to be 14 sec., which is considered to be long enough to apply laser cooling. Three dimensional laser cooling is to be applied for both modes with and without dispersion. Tapered laser cooling with use of the Wien filter is also planned for realization of multi-layer 3D crystal.

INTRODUCTION

Table 1: Parameters of S-LSR.

Ion Species (Energy)	H^{+}(7MeV)
	$^{12}C^{6+}$(2MeV/u)
	$^{24}Mg^{+}$(35keV)
Cooling Methods	Electron beam cooling
	Laser cooling
Circumference	22.557 m
Average radius	3.59 m
Length of straight section	2.66 m
Number of periods	6
Betatron Tune	
Crystalline Mode	Normal Operation Mode
ν_H=2.07, ν_V=2.07 (η=0),	ν_H= 2.07, ν_V=1.07 ($\eta \neq 0$)
ν_H=1.44, ν_V=1.44 ($\eta \neq 0$)	(η: dispersion function)
Bending Magnet	(H-type)
Maximum field	0.95 T
Curvature radius	1.05 m
Gap height	70 mm
Deflection Angle	60˚
Quadrupole Magnet	
Core Length	0.20 m
Bore radius	70 mm
Maximum field gradient	5 T/m

At ICR, Kyoto University, an ion cooler-storage ring, S-LSR, has been under construction since 2001, which is completed early in October 2005. Since that time, beam commissioning of S-LSR has been started. Main parameters of S-LSR are listed up in Table 1 and the layout of S-LSR and its injectors are shown in Fig. 1. Overall view of S-LSR is also shown in Fig. 2.

Proton beam with kinetic energy of 7 MeV is injected from the linear accelerator consisted of the RFQ and DTL with Alvarez type of the RF frequency of 433 MHz. Total feasibility of improving the quality of the laser-produced ion beam by the 10 TW laser with combination of the electron cooling and phase rotation [1] has to be demonstrated. As the ion to be laser cooled, $^{24}Mg^{+}$ with the kinetic energy of 35 keV is to be utilized. It is directly transported from the CHORDIS ion source without further acceleration and is injected into S-LSR

Figure 2: Overall view of S-LSR.

ELECTRON BEAM COOLING

With 7 MeV proton beam, electron beam cooling has been studied at first. For the feasibility study of utilization of laser produced ions as the injection beam for synchrotron dedicated for cancer therapy, the electron beam cooling of hot ion (proton) beam had been studied. By sweeping the relative velocity between ion and electron beams, the longitudinal cooling time of the proton with 1% fractional momentum difference was

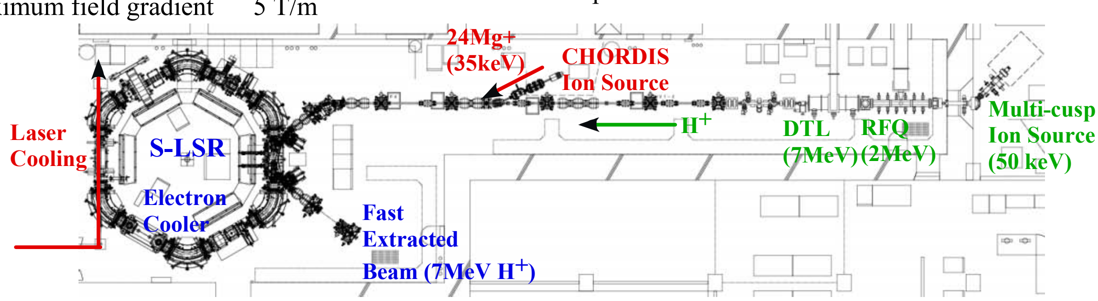

Figure 1: Layout of the ion storage and cooler ring, S-LSR and its injectors.

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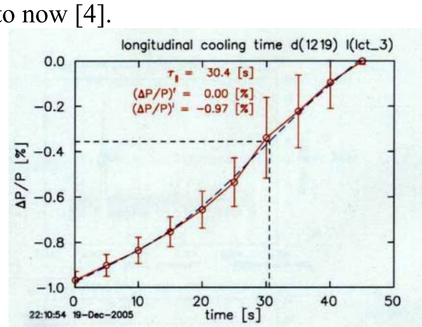
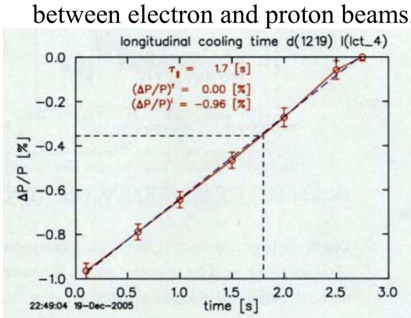
measured to be reduced from 40 seconds of the case without any sweep to 2.5 seconds with optimum sweep of the relative electron velocity [2]. This result is consistent with the previous measurements at TSR for $^{12}C^{6+}$ beam [3] if we take the cooling force difference between both cases into account.

The effect of the electron beam profile in radial direction on cooling time has also been investigated by application of electrostatic potential to the Pierce electrode. Application of positive voltage on the Pierce electrode resulted in the hollow electron beam, which, however, has net yet shown any improvement in cooling time up to now [4].



(a) without relative velocity sweep between electron and proton beams.



(b) with relative velocity sweep.

Figure 3: Cooling time needed to sweep the fractional momentum difference of 1% to the central one.

The possibility of realizing 1D ordered state of 7 MeV proton has also been investigated reducing the proton numbers as shown in Fig. 4. The reached momentum spread was found to have no dependence on the electron beam current. The increase of inclination angle between electron and proton beam axes indicates some effect to lower the equilibrium momentum spread, which needs further studies reducing noise in pickup and the high voltage in electron gun [6].

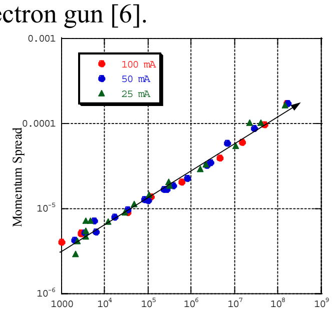


Figure 4: Dependence of final equilibrium momentum spread on particle number.

EXPERIMENTAL PLAN FOR LASER COOLING

Present Status

For laser cooling, $^{24}Mg^{+}$ ion beam with kinetic energy of 35 keV from CHORDIS ion source is to be utilized. Single turn injection has been already applied with the normal mode at the same operating point (1.62, 1.21) as the proton case. In this case, the pure dipole magnetic field is utilized as the deflection element with full aperture of ±100 mm in the deflection section. Beam current of ~3 μA has been stored and beam life of 14 sec. is attained for the average vacuum pressure of ~1x10^{-8} Pa, which seems to be tolerable to apply laser cooling.

Circulation of $^{24}Mg+$ beam with the dispersion free mode, where all the electrodes inside the dipole magnets are installed, is also to be tested gradually shifting from normal mode above mentioned changing electric and magnetic field strength step by step in order to cope with a very limited horizontal aperture of the total size of 30 mm in the deflection section [7].

Laser Cooling with Normal Mode

Based on the successful circulation of $^{24}Mg^{+}$ ion beam utilizing full aperture in the dipole, the first laser cooling experiment is planned to be applied with the normal mode with finite dispersion although the betatron operation point so far simulated is (2.07, 1.07) and is somewhat different from the one used in the above experiment in order to utilize the difference resonance to couple horizontal and vertical motions with use of solenoid. Test with this operation tune is to be performed soon. Synchro-betatron coupling needed for 3D laser cooling [8] is to be realized with the synchrotron tune of 0.07 realized by an RF voltage applied by the untuned cavity loading 8 ferrite cores capable to apply gap voltage up to 1.5 kV. The cavity is shown in Fig. 5 with upper cover removed during baking process [9]. By the computer simulation with use of molecular dynamics, 1D string and 2D zig-zag are expected to be realized with this mode [10, 11]

Longitudinal laser cooling is to be applied by a ring dye laser with the wave length of 560 nm pumped by a solid green laser, followed by a second harmonics generator (Fig.6), which provides the wavelength of 280 nm needed for cooling of $^{24}Mg^{+}$. At the moment combined use of a single laser with the induction accelerator shown in Fig. 5 is assumed for the first trial of laser cooling although the cooling rate is anticipated to be small due to rather limited force of the induction accelerator.

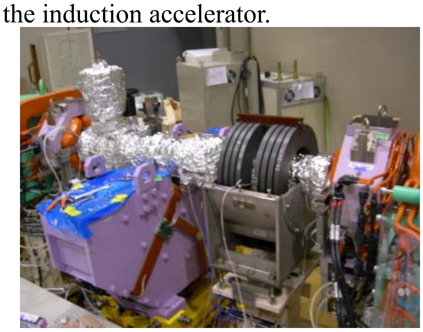


Figure 5: Untuned RF cavity with upper cover removed and the induction accelerator with upper part removed

Laser Cooling with Dispersion Free Mode

So as to avoid the effect of "shear" and realize 3D crystalline state, compensation of linear orbit dispersion by superposition of an electric field with the magnetic field has been proposed [12]. Electrodes to realize such an electric field, which are made to be movable for the case of full aperture operation, have been already installed in each dipole magnet of S-LSR. With this mode of (2.07, 2.07), if a coupling cavity, whose longitudinal RF electric field depends on the transverse position, is available, 3D crystalline structure with 1 shell structure is expected to be realized [13]. Larger shell structure, however, is anticipated not to be realized for the mode with the betatron tune higher than 1.5 because of strong resonance coupling during the process to be cooled down from the usual hot state of gas phase [14].

Figure 6: Ring dye laser followed by a second harmonics generator tuned to the average power level of -30mW.

Tapered Laser Cooling with Wien Filter

In order to realize the multi-layer shell structure in crystalline ion beam, betatron tune lower than 1.5 is needed to avoid strong resonance coupling during cooling down process above mentioned. Dispersion free mode utilizing electric field superposed with dipole magnetic field, however, results in rather strong radial focusing and cannot realize the stable operation point satisfying this condition. A tapered laser cooling with use of a Wien filter so as to avoid "shear" has been proposed [15] to be utilized for the operation tune of (1.44, 1.44) with finite dispersion. Although similar ideas had existed earlier for electron cooling [16] and laser cooling [17], the way to confine laser interaction with the ion beam only inside of the Wien filter is shown for the first time [15, 18]. The scheme to utilize an ion orbit chicane for localization of laser cooling in Ref.[15] might deteriorate the superperiodicity, the scheme to apply laser intensity modulation along the ion orbit and confine effective laser interaction with ions only inside of the Wien filter has been recently proposed [18]. It should be noted that such a device as a Wien filter confining the laser-ion interaction inside of its potential will couple the longitudinal and transverse degrees of freedoms and realize 3D laser cooling [19,20]. The electric and magnetic fields required for such Wien filter in the case of S-LSR are calculated to be 24.8 kV/m and 0.047 T, respectively [20], which seem to be well attainable values.

SUMMARY

Electron cooling experiments have already been successfully performed. Possibility of 1 D string for 7 MeV proton is under investigation experimentally. Laser cooling of $^{24}Mg^{+}$ is planned at both modes with and without dispersion, which is expected to enable creation of 3D multi-layer crystal.

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