EXPERIMENTAL STRATEGY FOR REALIZATION OF 3-D BEAM ORDERING WITH USE OF TAPERED COOLING AT S-LSR *

A. Noda, M. Ikegami, S. Fujimoto, T. Shirai, H. Souda, M. Tanabe, H. Tongu
ICR, Kyoto University, Uji, Kyoto, Japan
H. Okamoto #, Hiroshima University, Higashi-Hiroshima, Japan
K. Noda$, NIRS, Chiba-city, Chiba, Japan
I. Meshkov $, A. Smirnov$, JINR, Dubna, Moscow Region, Russia

Abstract

Experimental plan at S-LSR to realize ordered state with ultra-low temperature by application of laser cooling for $^{24}Mg^{+}$ ions with kinetic energy of 35 keV has been surveyed. By normal mode with finite dispersion, 1 dimensional ordering and 2 dimensional zigzag structure of crystalline beam are expected if strong enough laser cooling force is applied with resonant coupling method. Three dimensional crystal is expected to be attained by the dispersion free mode with coupling cavity although limited at 1 layer level. With "tapered cooling" utilizing Wien Filter, multi-layer 3 dimensional crystal state is expected to be realized.

INTRODUCTION

Phase transition from gaseous phase of normal beam in the accelerator to the liquid and solid states had attracted many researcher's interests in these decades since the first report of 1 dimensional ordering of proton beam by application of electron beam cooling at NAPM [1]. For heavy ions, measurements of one dimensional ordering by electron beam cooling when the particle numbers are reduced have been reported from GSI and Stockholm [2, 3]. When the beam cooling process goes to its extreme, the beam temperature is expected to become very low to such a level as a few m Kelvin if the well strong cooling force such as the laser cooling is applied. The low temperature state is expected to be ordered and begins to have spatial extent when the number of the particles in the beam becomes larger and the line density of the beam increases [4].

Theoretical approach together with beam simulation by molecular dynamics clarified various conditions needed for creating ordered state stably. The following two conditions so called "formation and maintenance conditions" are required to maintain the beam crystal stably [5],

(a) operate below transition energy,

(b) betatron tune satisfies $\upsilon_{H,V} \le \frac{N_s}{2\sqrt{2}}$,

where υ_H and υ_V are betatron tunes in the horizontal and vertical directions, respectively and N_s is the superperiodicity of the storage ring lattice. The ion storage and cooler ring, S-LSR, completed at ICR, Kyoto University in October, 2005, was designed to satisfy these conditions and is to be utilized to realize the crystal beam, especially multi-dimensional crystal stably. In this paper, the present status of the S-LSR is described briefly at first, together with hardware development for laser cooling experiments. Then possible scheme of "Tapered Laser Cooling" is presented leading to the future experimental program in order to create the ordered beam with very low temperature.

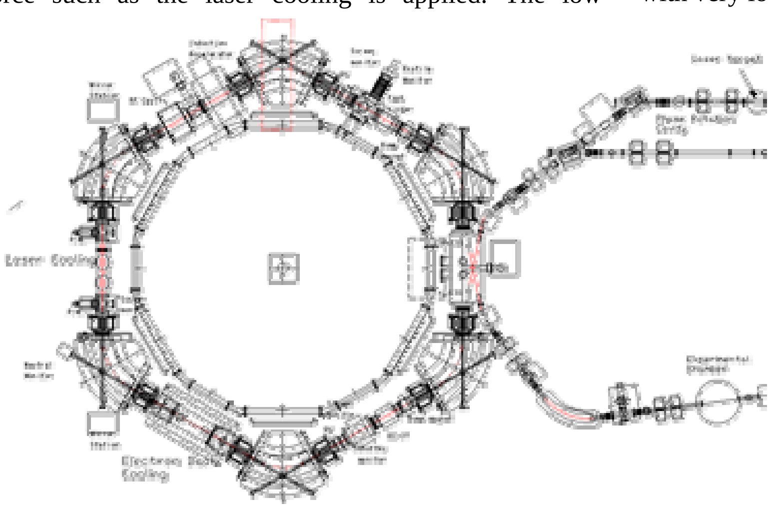


Fig.1 Layout of S-LSR

PRESENT STATUS OF S-LSR

The ion storage and cooler ring, S-LSR shown in Fig.1 was first beam commissioned early in October, 2005 and the electron beam cooling of hot proton beam with 7 MeV was also successfully demonstrated [6], which was one of the main scopes of the Advanced Compact Accelerator Development Program [7]. In table 1, the main parameters of S-LSR have been listed up.

Early in 2006, the possibility to realize the one dimensional ordered state of 7 MeV protons with use of electron cooling has been studied reducing the particle number based on the computer simulation utilizing the code BETACOOL [8], which tells us that the momentum spread of the

*Work supported by Advanced Accelerator Development Project of Ministry of Education, Culture, Sports, Science and Technology (MEXT).
noda@kyticr.kuicr.kyoto-u.ac.jp

Table 1 Parameters of S-LSR

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
1.45 (H) , 1.44 (V)	1.872(H), 0.788 (V)
Bending Magnet	(H-type)
Maximum field	0.95 T
Curvature radius	1.05 m
Gap height	70 mm
Pole end cut	Rogowskii cut+Field clamp
Deflection Angle	60°
Weight	4.5 tons
Quadrupole Magnet	
Core Length	0.20 m
Bore radius	70 mm
Maximum field gradient	5 T/m

level of ~10^{-6} is expected to be the transition point to the ordered state. Such transition, however, has not yet been attained as shown in Fig. 2. Further noise reduction is needed to reach the ordered state.

HARDWARE DEVELOPMENT FOR LASER COOLING

In order to reach such a low temperature as several m Kelvin, the strong cooling force of laser cooling is inevitable. At the moment, the atoms with high velocities, which can be laser cooled, are limited to $^{7}Li^{+}$, $^{9}Be^{+}$ and $^{24}Mg^{+}$ due to limitation of the wavelength of the available laser. We have chosen $^{24}Mg^{+}$ as the candidate to be laser cooled. In table 2, the parameters related to the laser cooling of $^{24}Mg^{+}$ ion are listed up.

The $^{24}Mg^{+}$ ion source with the extraction voltage of 35 kV shown in Fig. 3(a) is utilized directly as the injector for S-LSR merging with the beam line of 7 MeV proton as shown in Fig. 3(b). The beam injection was performed

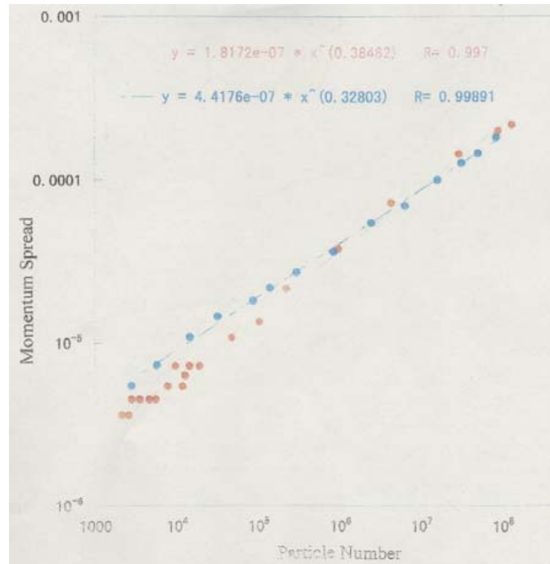


Fig. 2 The dependence of the momentum spread on the particle number.

with use of the same magnets as 7 MeV proton at the down stream parts of the beam transport line. Up to now, $^{24}Mg^{+}$ ions of the intensity of 10 μA has been extracted from the ion source and is transferred and injected into S-LSR. The beam life of the $^{24}Mg^{+}$ ion was measured to be

Table 2 Laser parameters of $^{24}Mg^{+}$ ion laser cooling

parameter	value
Lower state	$3s^2S_{1/2}$
Upper state	$3p^2P_{3/2}$
Lifetime of upper state	3.7 ns
Natural line width	42.7 MHz
Transition wave length	280 nm
Satulation Intensity	254 mW/cm^2

14 seconds at the optimum condition for the average vacuum pressure of ~10^{-8} Pa, which is considered to be long enough to apply the laser cooling. The commissioning with electrodes for dispersion free mode

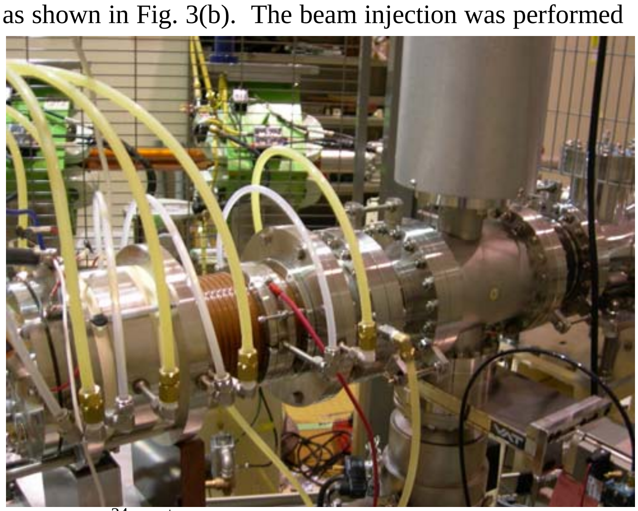


Fig. 3(a) $^{24}Mg^{+}$ ion source with the extraction voltage of 35 kV.

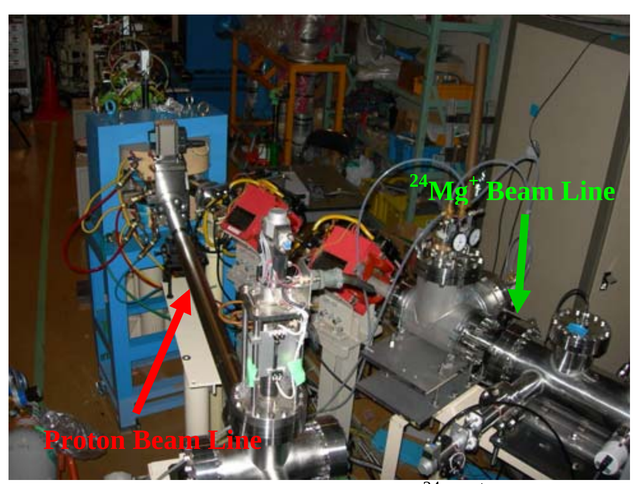


Fig.3 (b) Merging of the beam line for $^{24}Mg^{+}$ (right) and proton beam line (left).

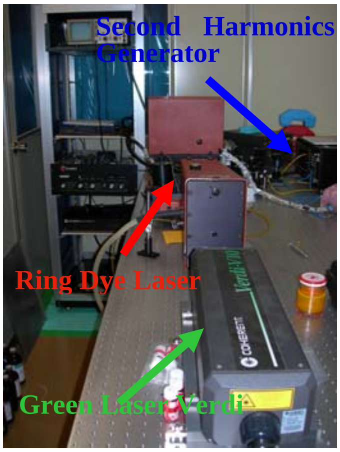


Fig.4 Ring dye laser tuned up for laser cooling.

with rather small horizontal aperture of 30 mm in all 6 deflection sections is to be performed from now on with careful orbit correction.

The tuning of the ring dye laser has also been performed in a clean room set in an experimental hall of S-LSR and average power up to 30 mW has become available. Guiding optics to the straight line of the S-LSR is to be prepared at the time of the break down of the vacuum system of S-LSR scheduled at the end of June, 2006, replacing the vacuum window by the one suited for guiding of the laser for cooling.

EXPERIMENTAL PROGRAM FOR CRYSTALLINE BEAM

The lattice parameters, operation points and cooling methods of three modes to be utilized at S-LSR concerning the laser cooling to realize crystalline structures are shown in Fig. 6 and table 3.

Normal Mode with Finite Dispersion

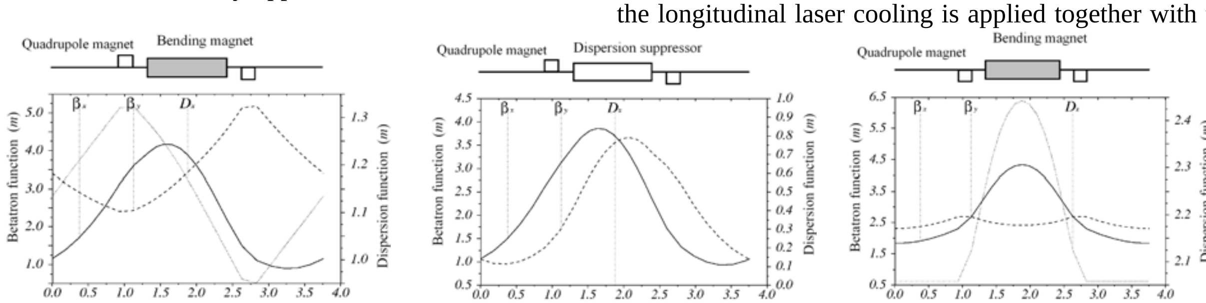
By the normal mode of S-LSR with finite dispersion at the operation point of (2.07, 1.07) and synchrotron tune of 0.07 as shown in Fig. 6(a), 3 dimensional laser cooling is expected to be realized by application of the laser in the

Fig. 5 Vacuum window to guide the laser inside of the S-LSR vacuum system. The window is to be replaced by the one suited for laser guiding at the next vacuum breaking.

direction of ion beam passage and an RF acceleration at finite dispersion position [9]. For this purpose, the guiding of the laser into the vacuum vessel at the long straight section of the S-LSR through the optics system and laser window is to be performed to realize one dimensional string and 2 dimensional zigzag structure as shown in Fig. 7 (a) and (b), respectively.

Dispersion Free Mode

In order to suppress the shear heating for the case where beam has the horizontal extent with increase of its line density, a dispersion free lattice has been proposed for S-LSR [10]. In this case, however, a coupling cavity producing the longitudinal RF electric field, the strength of which depends on the horizontal position [11], becomes necessary in order to realize the 3 dimensional laser cooling. In Fig. 8, the decrease of the transverse emittances is shown together with longitudinal one when the longitudinal laser cooling is applied together with the



(a) $(\nu_x, \nu_y) = (2.07, 1.07)$ normal

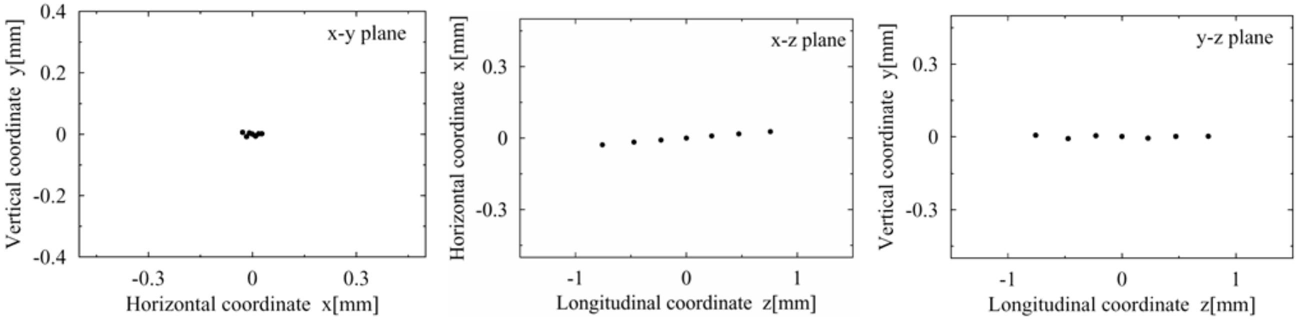
(b) $(\nu_x, \nu_y) = (2.07, 2.07)$ dispersion-free

(c) $(\nu_x, \nu_y) = (1.44, 1.44)$ normal

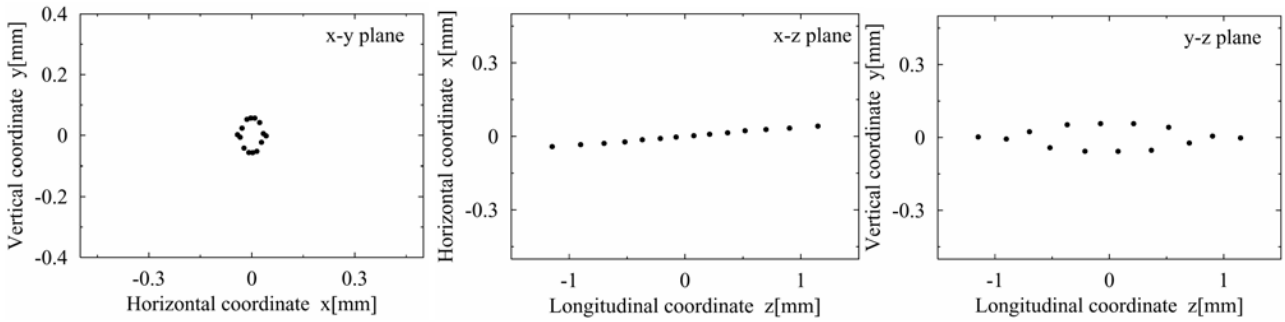
Fig.6 Various lattice modes for future experiments.

Table 3 Experimental Plans to be performed at S-LSR

parameter	normal mode 1	dispersion-free	avoiding coherent resonance
betatron tune	(2.07, 1.07)	(2.07, 2.07)	(1.44, 1.44)
synchrotron tune	0.07	0.07	arbitrary
cooling method	Resonant coupling method with a normal rf cavity	Resonant coupling method with a coupling cavity	Tapered cooling



(a) 1 dimensional ordering



(b) 2 dimensional zigzag structure

Fig. 7 Expected ordered structure for normal mode with finite dispersion for 35 keV $^{24}Mg^{+}$ beam by application of laser cooling with resonance coupling with a normal RF cavity.

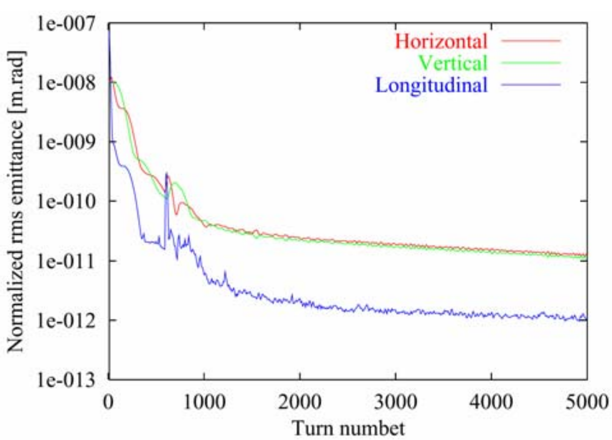


Fig.8. 3 dimensional laser cooling of 35 keV $^{24}Mg^{+}$ beam assuming coupling cavity applied for dispersion free

coupling cavity. With this mode, one layer 3 dimensional crystal is expected to be realized as shown in Fig. 9, because shear heating is suppressed by compensation of the orbit dispersion at every bending section. According to recent study, however, it is known that in such a case where the size of the crystal structure becomes large, the strong resonance crossing makes the crystal structure unstable and in order to avoid this situation, the phase advance per super-period is required to be less than 90° [12], which is much stringent condition than "maintenance condition" described in introduction [5]. So formation of multi-layer crystal is not expected to be realized with this mode.

Normal Mode with Tapered Cooling by Wien Filter

In order to suppress the shear heating with normal mode with finite dispersion, "tapered cooling"[13], which cools down the ion beam to such energies dependent on the horizontal position becomes needed [14]. As the possible way to realize such a "tapered cooling", localization of laser cooling only inside a Wien Filter is proposed [15]. In Fig.10, the principle of the tapered

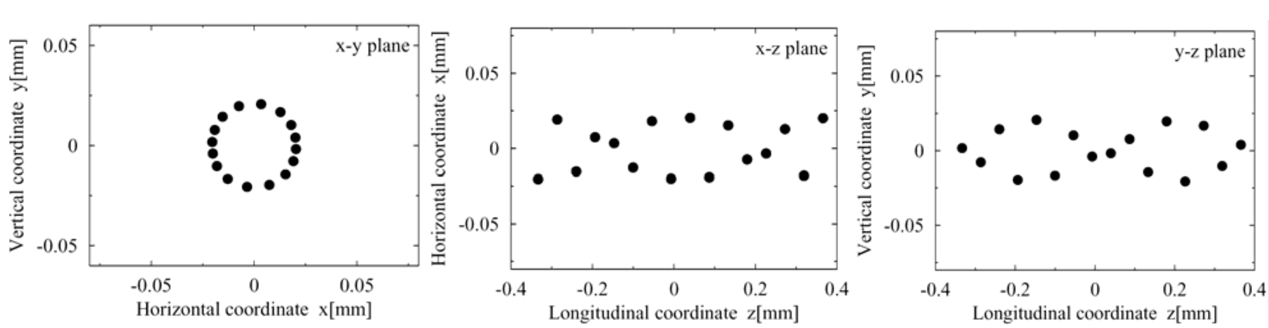


Fig. 9 1layer 3 dimensional crystal structure expected for $^{24}Mg^{+}$ beam with use of "tapered cooling" at S-LSR.

cooling with confined application of laser cooling only inside of the Wien Filter is illustrated. Existence of the transverse electric field creates the electrostatic potential dependent on the horizontal position, which results in the "tapered cooling" if the excitation of the ion to the upper state by the laser is confined only inside of the Wien Filter. As illustrated in Fig.10, all the $^{24}Mg^{+}$ ions are cooled down to the same energy and they are accelerated or decelerated according to their horizontal positions when they go out from the Wien Filter. Assuming the field strength of the magnetic field and electric field to be B and E, the kinetic energy, T, of $^{24}Mg^{+}$ ion with respect to their horizontal position, x, can be written as

$$T = T_0 + eEx, \quad (1)$$

where T_0 is the kinetic energy of the ion circulating at the central orbit and e is elementary electric charge. Utilizing the relation: $T = m_0 V^2/2$ (m_0 and V are the rest mass and the velocity of the ion, respectively) in the non-relativistic case, the following approximate relation is obtained for the case with small spatial spread as the present case:

$$V = V_0 (1 + \frac{eE}{m_0 V^2} x). \quad (2)$$

So as to satisfy the condition required for "tapered cooling" to keep the angular velocity at the bending section to be equal for all radial positions for ion passage, the relation

$$\frac{eE}{m_0 V^2} = \frac{2\pi}{2\pi\rho_0 + 6L_s} \quad (3)$$

is required to hold, where ρ_0 and L_s are radius of curvature at the central orbit and the length of the long straight section of S-LSR with 6-fold symmetry, respectively. Substituting the values of 1.05 m and 1.86 m and 35 keV for ρ_0, L_s and $m_0 V^2/2$, respectively, E is calculated to be 24.8 kV/m. Between B and E of the Wien Filter, the following relation;

$$\vec{E} = -(\vec{V} \times \vec{B}) \quad (4)$$

should hold and B is calculated to be 0.047 T. Both values of B and E are considered to be technically well attainable ones. As the former scheme to realize local overlap between laser and ion beams with use of orbit chicane[15] is claimed to violate "formation and maintenance condition" reducing the super-periodicity to 1, a new scheme to modulate the laser intensity along the direction of ion passage is proposed [16].

With use of such a "tapered cooling", the operation mode at (1.44, 1.44) with finite dispersion as listed up in Fig. 6(c) and table 3 can provide the experimental possibility of creating multi-layer 3 dimensional crystalline structure avoiding the strong resonance crossing effect owing to the rather small betatron tune. It should be noted that this tapered cooling force automatically realizes the coupling between the longitudinal and horizontal degrees of freedom needed for 3 dimensional laser cooling without resonant coupling

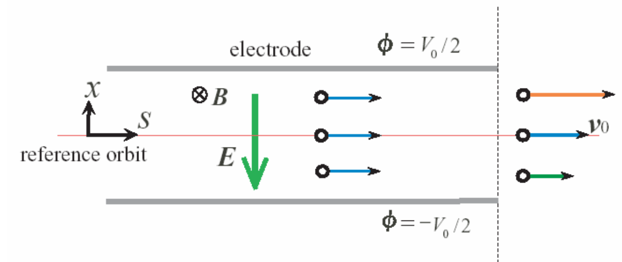


Fig.10. Principle of the "tapered Cooling" with use of the

method, although the resonant coupling between the horizontal and vertical directions with use of a solenoid magnetic field is needed to cool down the vertical temperature.

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