EXPERIMENTAL APPROACH TO ULTRA-COLD ION BEAM AT S-LSR *

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Abstract

At S-LSR, abrupt reduction of momentum spread of 7 MeV proton beam to ~2 x 10^{-6} at proton number of ~2000 has been observed, which indicates phase transition to 1 dimensional ordered state. Attained proton temperatures after transition are 26 μeV and 1 meV for longitudinal and transverse directions, respectively, which compared with the corresponding values of 20 μeV and 34 meV for electron beam, indicates the magnetization of electron. Laser cooling of $^{24}Mg^{+}$ has also been started and momentum spread of ~10^8 ions is reduced to 2 x 10^{-4}, saturated with the momentum transfer from transverse degree of freedom by intra-beam scattering.

INTRODUCTION

Since the invention of electron beam cooling, the coldest temperature realized by the beam has been a big concern of the physicists and possibility of ordering was reported from NAP-M at Novosivirsk [1], which caused hot discussion and triggered many following related research activities. Recently, one dimensional ordering has been reported from GSI [2] and MSL [3] for heavy ions, which has an abrupt jump in momentum spread when the particle number is reduced to a certain number and the strength of intra-beam scattering is suppressed. For protons with a single charge, however, such an ordering accompanied with a jump in momentum spread has not yet been observed [4].

In parallel, theoretical and numerical simulation approach to the ultra-cold beam to be realized by a laser cooling has been performed and the conditions for realization of a three dimensional crystalline beam has been proposed [5]. In order to investigate the capability of realization of such cold beams, an ion storage ring, S-LSR has been constructed since 2001 [6] at ICR, Kyoto University in close collaboration with NIRS and was completed in the fall 2005. In the present paper, recent experimental attainments in one dimensional ordering of 7 MeV proton are presented together with the first result of laser cooling for $^{24}Mg^{+}$ ions, which is to be combined with the unique features of S-LSR to attain three dimensional crystalline beam.

Table 1: Main parameters of S-LSR

Circumference	22.557 m
Average Radius	3.59 m
Superperiodicity	6
Ion Species	Proton :7 MeV $^{24}Mg^{+}$:40 keV $^{12}C^{6+}$:2 MeV/u
Operation Point	(1.65, 1.21) :Electron Cooling (1.45, 1.44), (2.07, 1.07), (2.07, 2.07) : Laser Cooling
Radius of Curvature	1.05 m

OUTLINE OF S-LSR

S-LSR is a storage ring for 7 MeV proton provided by a linac and 40 keV $^{24}Mg^{+}$ ions directly transported from an ion source. In addition, $^{12}C^{6+}$, produced from a laser induced plasma and improved in its quality by phase rotation [7] is also to be injected in a near future. The circumference, radius of curvature of S-LSR are 22.56 m and 1.05 m, respectively. In Fig. 1, the layout of S-LSR is shown together with its beam injectors. In Table 1, main parameters of S-LSR are listed up.

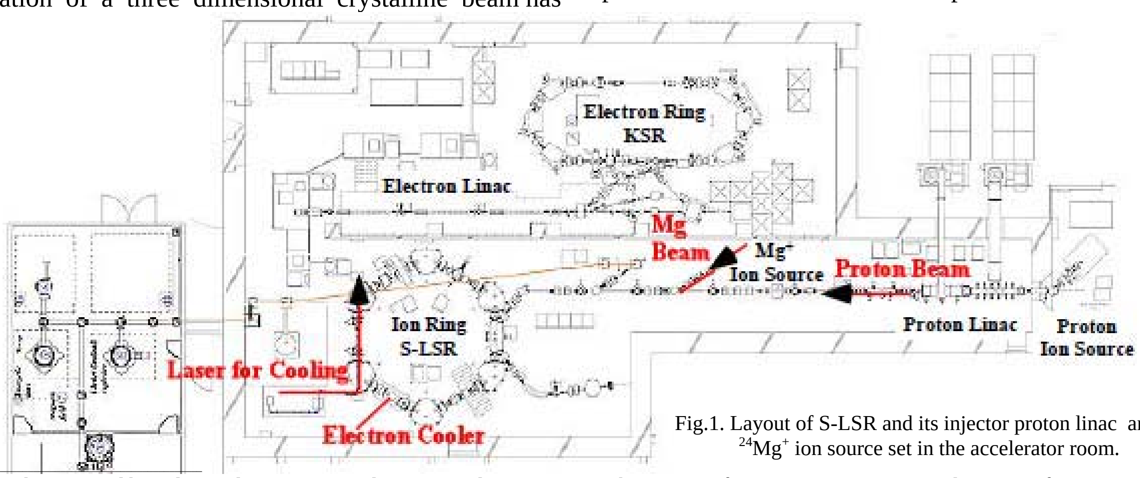

Fig.1. Layout of S-LSR and its injector proton linac and $^{24}Mg^{+}$ ion source set in the accelerator room.

* Work supported by Advanced Compact Accelerator Development Project by MEXT of Japanese Government and 21COE of Kyoto University-Center for Diversity and Universality in Physics
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Lattice of S-LSR

In spite of a limited available experimental area as shown in Fig.1, S-LSR is designed to have a superiodicity of 6, the largest possible value in the present circumstance, so as to keep the so-called formation and maintenance conditions to create crystalline beams given by [8]

$$\gamma < \gamma_t \quad (1) \quad \text{and}$$

$$N_{sp} > 2\sqrt{\nu_x^2 + \nu_y^2}. \quad (2).$$

All the operation points assumed for both electron beam cooling and laser cooling satisfy the above conditions, which is a unique feature of S-LSR compared with already experimentally tested operation points of existing rings such as TSR, ASTRID, COSY and ESR.

PHASE TRANSION TO ORDERED STATE OF PROTONS

Electron Beam Cooling System

A compact electron cooler has been developed for S-LSR so as to be equipped into a rather limited straight section, 1.86 m in length. For this purpose, the curvature radius of the toroids is chosen at 0.25 m. Three dimensional field calculation has been performed for the purpose of optimization of the geometry of the cooler for such a compact size [9].

Phase Transition to Ordered State by Electron Beam Cooling

Electron beam cooling applied to 7 MeV protons with the intensity of 2x 10^8 has reduced their fractional momentum spread from 4 x 10^{-3} to 2x 10^{-4} [10], which is determined by the trade off between intra-beam scattering and cooling force. In order to reduce this intra-beam scattering and reach as low temperature as possible, the equilibrium of the momentum spread was measured reducing the number of protons. At the beginning, the equilibrium level of the fractional momentum spread of the cooled protons was rather high (several x 10^{-6}) due to ripples in power supplies of dipole magnets of the ring and high voltage for electron cooler and thermal noise at the pick up of the beam signal and so on. Careful improvement of these devices enabled the observation of the fractional momentum spread as low as ~1x10^{-6}, which resulted in the observation of a abrupt jump of momentum spread at ~ 2000 protons as shown in Fig.2 [11]. The data was taken with the electron current of 25 mA and similar jump is also observed with the other electron currents of 50 mA and 100 mA and this jump can be well considered due to phase transition to 1 dimensional ordered state.

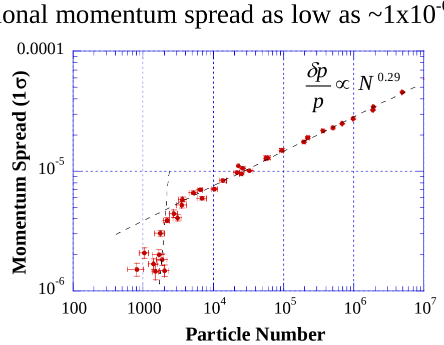

Fig. 2. Observed abrupt jump of momentum spread of 7 MeV proton beam at particle number ~2000, which is considered to be the evidence of the phase transition to 1 dimensional ordered state [11].

Table 2 Main Parameter of the Electron Cooler

Electron energy	5.0 keV (Max.) 3.8 keV (for 7 MeV p^+)
Electron current	25 mA – 300 mA
Diameter of electron beam	50 mm
Solenoid field strength	500 Gauss
Adiabatic expansion factor	3
Solenoid length in cooling section	800 mm
Curvature radius of Toroids	250 mm
Effective cooling length	440 mm

The reached temperatures of the proton beam after transition are 26 μeV and 1 meV in longitudinal and transverse directions, respectively. If we compare these values with the electron temperatures of 20 μeV and 34 meV (after adiabatic expansion) in longitudinal and transverse directions, respectively, proton temperature in the transverse direction is more than 30 times lower than the electron beam, which indicates that the effective electron temperature observed from protons is considered to be frozen due to "magnetization" [12].

LASER COOLING OF MG ION

Preliminary Experiment of Laser Cooling

Laser cooling has been applied to $^{24}Mg^+$ ion beam with the kinetic energy of 40 keV utilizing the laser light with the wavelength of 280 nm. The output of a ring dye-laser of the wave length 560 nm pumped with a solid state green laser is doubled in frequency. At the moment, a single laser can be available and is used to run parallel to the Mg ion beam. The laser cooling force was verified by the combined use of the laser and induction voltage. In Fig. 3, the Schottky signals observed before and after laser cooling are shown for $^{24}Mg^+$ ion beam with the initial intensity and momentum spread of ~10^8 and 1.7x

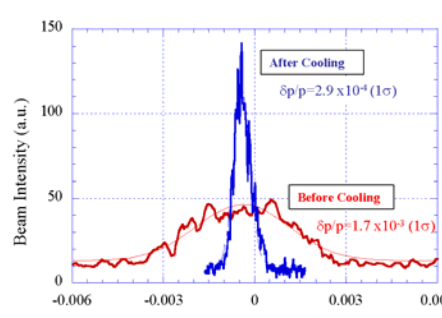

Fig. 3 Result of laser cooling on $^{24}Mg^+$ ions. Laser cooling was applied to ~10^8 $^{24}Mg^+$ ions together with an induction deceleration voltage of ~6 mV, which reduced the fractional momentum spread from 1.7 x 10^{-3} to 2.9 x 10^{-4}. The spectrum after cooling was measured 5 second after the start of laser cooling.

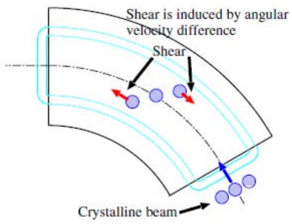

Fig.4 Illustration of shear [15].

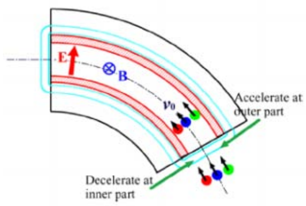

Fig. 5 Dispersion suppressor using a cross electric field with a magnetic field [15].

10^{-3} (1σ), respectively. In this case laser frequency was fixed and deceleration with an induction voltage of ~6 mV was simultaneously applied. The relatively large momentum spread after cooling (2.9×10^{-4}) is considered to be due to momentum transfer from transverse degree of freedom to longitudinal one by intra-beam scattering. Attainment much smaller momentum spread requires reduction of ion numbers to be cooled down, which is blocked by the difficulty of observing the Schottky signal of a low intensity beam. Recent development of observation system of an emitted light by the transition from upper to lower levels with the use of a photomultiplier is expected to respond to the above requirement.

Future Plan to 3-D Laser Cooling with Dispersion Free Lattice

A "shear heating" as is illustrated in Fig.4, is the biggest obstacle for creation of 3-dimensional crystalline beam [13]. So as to suppress such "shear heating", a dispersion suppressor, proposed by Pollock for storage ring for the first time [14], utilizing an electric field perpendicular to the magnetic field satisfying the relation, ,

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

(v_0 is the velocity of beam particle)

as shown in Fig. 5, is really utilized for bending elements at S-LSR [15]. In Fig. 6, electrodes installed inside of the vacuum vessel of each dipole magnet for S-LSR is shown. For the purpose of attaining good field homogeneity, 4 sets of intermediate electrodes are utilized. The electrodes can be moved out from the beam circulating region by position driving mechanism without vacuum breaking for the normal lattice operation with finite dispersion function, which has been used for all the experiments up to now.

Dispersion free lattice above mentioned with the operating point of (2.07, 2.07) is expected to realize 3 dimensional crystalline beam if synchro-betatron coupling is realized with use of a coupling cavity [16]. As the alternative to skip the usage of the coupling cavity and capability of realizing much higher density multi-shell crystal, normal lattice with finite dispersion of the operation point (1.45, 1.44), applying the laser cooling effectively only inside of a "Wien Filter" is proposed [17], which needs hardware construction from now on.

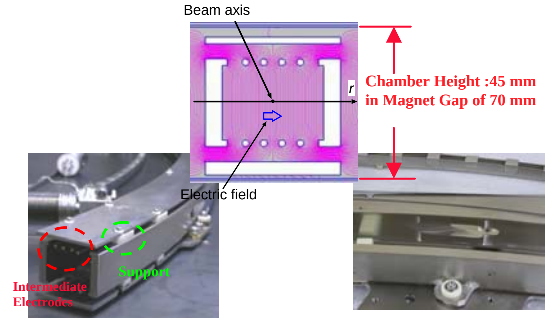

Fig. 6 Electrodes installed into each dipole magnet of S-LSR to suppress "shear heating."

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