PRESENT STATUS OF ION STORAGE AND COOLER RING, S-LSR*

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Abstract

Electron cooling time of hot proton beam having a momentum spread of 1 % was improved significantly by almost 1 order of magnitude. Applying the proton energy sweep with induction acceleration, the cooling time was reduced from 30.4 s to 1.7 s. For the first time, the creation of the 1D ordered state of a 7 MeV proton has been demonstrated at a particle number ~2000 by observing a clear jump in the momentum spread. The threshold current of the coherent vertical instability excited during the E-Cool stacking process has been increased from 600 μA to 800 μA by application of a feedback damping system. A very short bunched beam with a duration of 2.5 ns created by a phase rotation after electron cooling was successfully extracted from S-LSR by a fast extraction.

INTRODUCTION

At ICR. Kyoto University, an ion storage and cooler ring, S-LSR was completed in October, 2007 and beam commissioning has been started. In Fig. 1, the layout of S-LSR and its injectors is shown together with the existing electron facility as KSR. Owing to careful design studies with 3 dimensional electro-magnetic field calculations, beam circulation and electron beam cooling of a 7 MeV proton beam has been successfully performed with the design parameters, on the first commissioning. Up to now, electron beam cooling of a hot ion beam by sweeping the relative velocity between proton and electron beams has been tested experimentally, further a one dimensional ordered state of a proton beam with reduction of the particle number under application of electron beam cooling has been successfully attained. Suppression of the vertical coherent instability with a feedback damping system was also demonstrated increasing the threshold current of the instability. Formation of a very short bunch by application of electron beam cooling, phase rotation and fast extraction was also realized. Laser cooling of Mg ions is under development. In the present paper, an overview of these research activities is given.

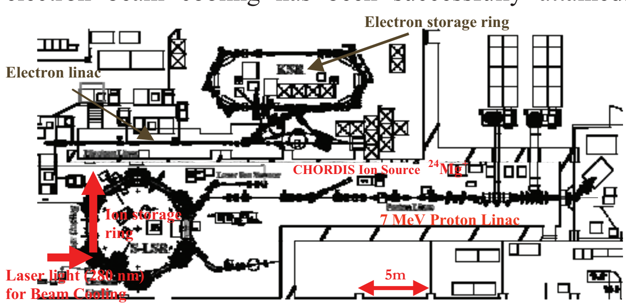
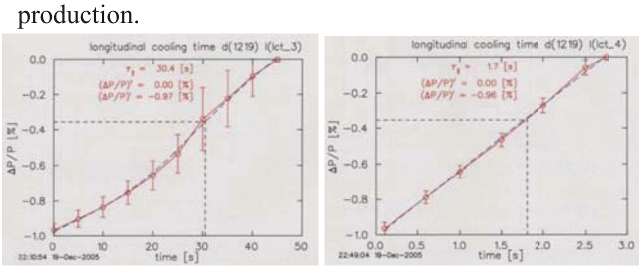


Figure 1: Layout of S-LSR and its injectors set in the experimental hall in the accelerator building at ICR.

ELECTRON BEAM COOLING OF HOT ION BEAM

One of the main objectives of the S-LSR is to show the feasibility of fast electron beam cooling with a relative velocity sweep between ion and electron beams in order to show the capability of improving the characteristics of the laser-produced ion beam by combination of phase rotation [1] and electron beam cooling. The proof of principle was performed at the TSR storage ring using a carbon ion beam with 73.3 MeV (6.1 MeV/u). The cooling time to cool down the beam with the momentum spread of 1 % was reduced from 2.8 s to 0.6 s and 0.35 s by the energy sweep of carbon and electron beams, respectively [2]. At S-LSR, similar electron beam cooling experiments with a relative velocity sweep has been performed for a 7 MeV proton beam. The cooling time of a beam with 1% momentum spread was reduced from 30.4 s to 1.7 s by a relative velocity sweep with an induction acceleration as shown in Fig. 2. In the case of S-LSR, the cooling time reduction was almost the same by sweeping the proton energy and electron energy, because the induction acceleration voltage is not limited as is the case at TSR. This enables the realization of a beam with an improved characteristics by laser ion production.



(a) (b)

Figure 2 Measured capture time of 1 % momentum difference without (a) and with (b) induction acceleration.

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E-COOL STACKING AND FEEDBACK DAMPING OF COHERENT INSTABILITY

Beam stacking with electron beam cooling (E-Cool stacking) has been applied to achieve a high current of 7 MeV proton beam, which is limited at 600 μA by the onset of coherent beam instabilities in the vertical direction. By applying a feedback damping system using a pickup for the vertical position detection and a vertical kicker for the RF knockout as shown in Fig. 3, the threshold current of the instability could be increased up to 800 μA [3]. Similar feedback damping has been also successfully applied by using digitized electronics to treat higher harmonic components [4].

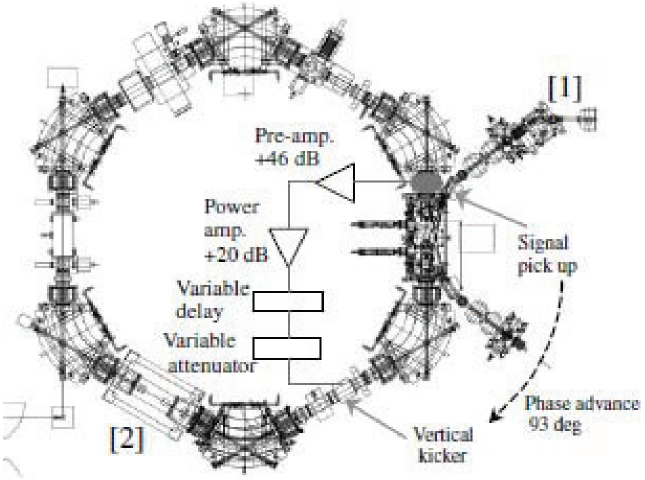


Figure 3 Feedback damping in the vertical direction to suppress the coherent beam instability at S-LSR.

1 D ORDERING OF 7 MEV PROTON

By application of electron beam cooling, reduction of momentum spread down to ~10^{-6} has been reported from NAPM at ECOOL84 for 65 MeV proton beam when its intensity was reduced less than 10^{6} particles, which is explained by the formation of 1 dimensional ordered state [5]. Since then, there were hot discussions and experiments to realize such a situation at several laboratories in the world. Several years ago, a formation of 1D ordered state was reported from ESR at GSI in Germany [5] and CRYRING at MSL in Sweden [6] for ions heavier than carbon. For proton with weaker cooling force due to its single charge, however, no clear indications of such an ordering had been observed in spite of experimental trials [7].

A computer simulation using the Betacool code, indicated the realization of 1D ordering of 7 MeV proton at S-LSR for particle numbers lower than 3000 as shown in Fig. 4 [8]. We have investigated the low temperature limit realized by electron cooling, by reducing the number of the stored protons with cutting the beam using a scraper. After careful reduction of the ripples in high voltage power supplies of the electron cooler and power supplies of the ring dipole magnets and significant reduction of the head amplifier noise of the Schottky-signal pickup, a clear

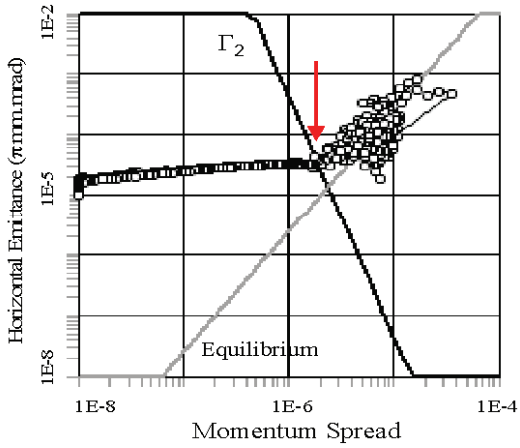


Figure 4 Prediction for 1 dimensional ordering of 7 MeV proton beam at S-LSR by computer simulation with Betacool [8].

jump in momentum spread has been finally observed at particle numbers around 2000 as shown in Fig. 5 [9]. It should be noted that such experimental studies have become possible by attainment of a ultra-high vacuum at S-LSR, the measured average pressure of which, is $4x10^{-9}$ Pa [11]. Recent further investigation of the ordered state of protons at S-LSR revealed the fact that gradual dependence of momentum spread on the particle number slower than $N^{0.3}$ (N: number of protons) is needed for beam ordering [12].

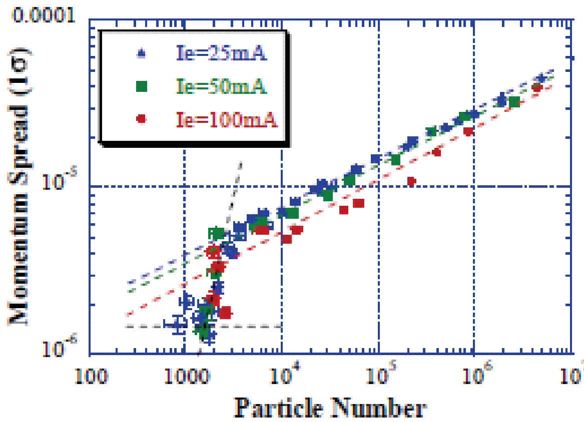
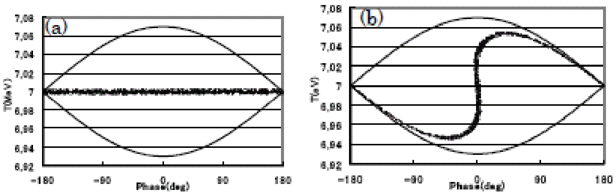


Figure 5 Jump observed in equilibrium momentum spread at particle number ~2000 indicating 1 dimensional ordering [9].

FORMATION OF SHORT BUNCH BEAM BY ELECTRON COOLING

In order to respond to the requirement of short-pulsed ion beams to investigate the radiation effect by free radicals on the biological cells by pulse radiolysis, a fast beam extraction system to provide a very short duration (~a few ns) after application of the electron beam cooling was constructed at S-LSR. It consists of a pair of bump magnets, a fast kicker magnet with a rise time less than 80 ns and a septum magnet. For the formation of short bunches, the following two methods are applied, (1)phase



(a) (b)

Figure 6 Phase rotation scheme in the longitudinal phase space. (a)after beam injection and electron beam cooling for coasting beam and just after sudden application of an RF electric field. (b)after phase rotation of ~90°.

rotation in a longitudinal phase space and (2)bunch formation after capturing into a stationary RF bucket. Recent experimental studies realized a short-pulsed 7 MeV proton beam with the duration of ~2.5 ns using the phase rotation method (Fig.7) [10].

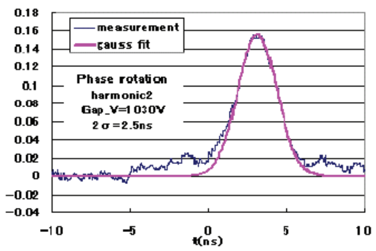


Figure 7 Very short bunch created at S-LSR by application of the electron cooling and phase rotation.

LASER COOLING OF MG IONS

Laser cooling of $^{24}Mg^+$ ions with the kinetic energy of 40 keV has been performed with the use of a ring dye laser and the frequency doubler, which provides a laser light with a wavelength of 280 nm [13]. The orbit of the Mg ion beam was overlapped with the laser by a precision better than ±1mm using 2 mm$^{\phi}$ apertures [14]. By the measurement of the equilibrium momentum spread for $^{24}Mg^+$ ions of the 10^8 intensity, keeping the laser frequency fixed with the induction deceleration voltage of 6mV (corresponding ~3 meV/m cooling force), the momentum spread was reduced from 1.7×10^{-3} to 2.9×10^{-4} (1σ) as shown in Fig. 8. The longitudinal equilibrium temperature for this case is estimated to be 3 Kelvin. Such a rather high equilibrium temperature is attributed to

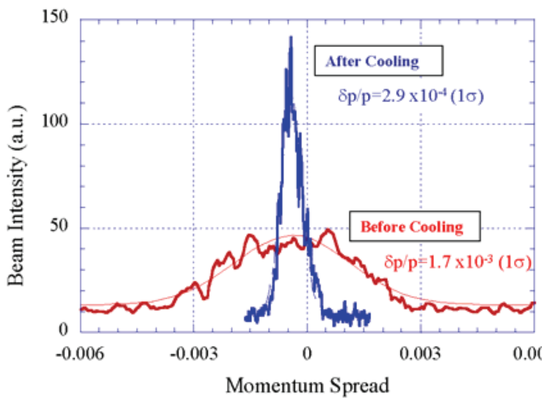


Fig. 8 Momentum spread of $^{24}Mg^+$ with the intensity of $\sim 10^8$ keeping the laser frequency at the fixed value and applying induction decelaration volatage of 6mV.

energy transfer from transverse degree of freedom to the longitudinal one by intra-beam scattering. In order to suppress the effect of intra-beam scattering, reduction of the number of cooled Mg ions has been tried, however, it was hard to detect the Schottky-signal of ions lower than several times 10^5 obscured by the poor S/N ratio. To improve this situation, a detection system for the emitted light, produced by the transition from the upper to the lower levels was developed. For the purpose of a precise energy measurement of laser cooled Mg ions, a post acceleration tube (PAT) which covers the cooled Mg ions is now under development. Sweep of its electrostatic potential changes the ion energy and enables the detection of the velocity spread of the laser cooled ion beam [15].

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