PRESENT STATUS OF BEAM PHYSICS RESEARCH USING ACCELERATOR FACILITY OF ICR, KYOTO UNIVERSITY*

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Abstract

Laser cooling has been applied to $^{24}Mg^{+}$ beam with kinetic energy of 40 keV and equilibrium temperature in the longitudinal direction has been found to be 3.6 Kelvin limited by the heat transfer from transverse degrees of freedom due to an intra-beam scattering. By the measurements changing cooled beam numbers, longitudinal temperature is found to depend linearly on the transverse temperature as $T_L = 0.02T_\perp$ in the scheme of the present experiments. Bunched beam cooling has also been studied in order to approach to the 3 dimensional cooling, which indicated the capability of heat transfer by synchro-betatron coupling. Application of electron cooling together with phase rotation and fast extraction has realized provision of a very short proton beam with duration 3.1 ns (2σ) for the proton number of 1.4×10^{8}.

GENERAL ACTIVITY WITH ACCELERATOR FACILITY

The layout of our accelerator facility is shown in Fig. 1. After the first demonstration of 1 dimensional ordering of 7 MeV proton beam [1], our main efforts at S-LSR are oriented for a laser cooling. In addition, such approach as utilizes an electron storage ring, KSR for the studies of the structure of nucleus trapped into an ion trap: SCRIT (Self-Confining Radioactive Isotope Ion Target) set in a straight section of KSR (Fig. 2) has been persuit in these a few years by collaboration with the group at RIKEN and recently the principle of such a scheme has been safely demonstrated for stable ions as ^{133}Cs, although the final aim of such a scheme is to be applied for unstable nuclei [2]. The S-band electron linac with the maximum energy of 100 MeV is also utilized for the calibration of neutrino detectors to be used for T2K experiments.

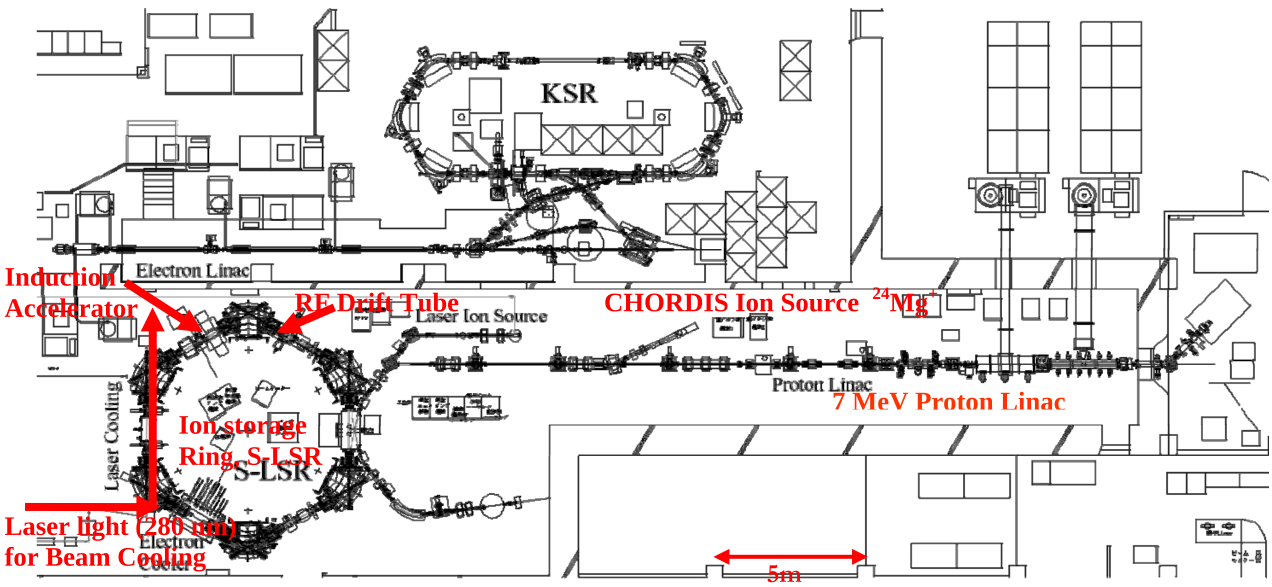

Figure 1 Layout of the accelerator facility of ICR, Kyoto University.

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Figure 2 An overall view of an electron storage ring, KSR, in which the SCRIT is installed.

LASER COOLING AT S-LSR

Laser Cooling of Coasting Beam

S-LSR is an ion storage and cooler ring, the circumference of which is 22.56 m and has 6-fold symmetry in order to satisfy the so-called maintenance condition to keep the beam crystal if it can be created [3]. In table 1, the main parameters of S-LSR are listed up. .At first, laser cooling of $^{24}Mg^{+}$ ion beam with the kinetic energy of 40 keV has been performed for the coasting beam with simultaneous application of induction deceleration voltage. By application of frequency doubled laser of the wavelength of 280 nm, which is equal to the level distance of the Mg ion, with the power of ~50 mW, Mg ions with the initial number of $1\mathrm{x}10^6$ are cooled down to 3.6 Kelvin (1σ) reaching the equilibrium between laser cooling force and heat transfer from the transverse degrees of freedom. The momentum distributions before and after the laser cooling are shown in Fig. 3.

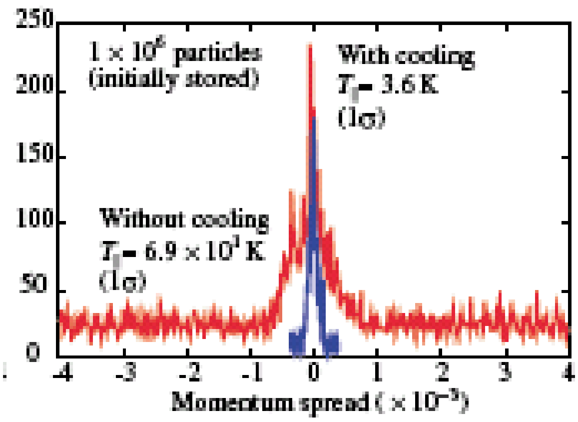

Figure 3 Momentum distributions before and after laser cooling for coasting beam [4].

Table 1 Main parameters of S-LSR

Circumference	22.557 m
Average radius	3.59 m
Length of straight section	1.86 m
Number of periods	6
Betatron Tune Horizontal	2.07
Vertical	1.07

The longitudinal equilibrium temperature has been studied changing the ion numbers to be cooled down, which resulted in the variation of the strength of heat transfer from transverse to longitudinal directions due to change of the strength of intra-beam scattering. In Fig. 4, the experimentally observed dependence of the longitudinal equilibrium temperature on the number of cooled ions is shown [4].

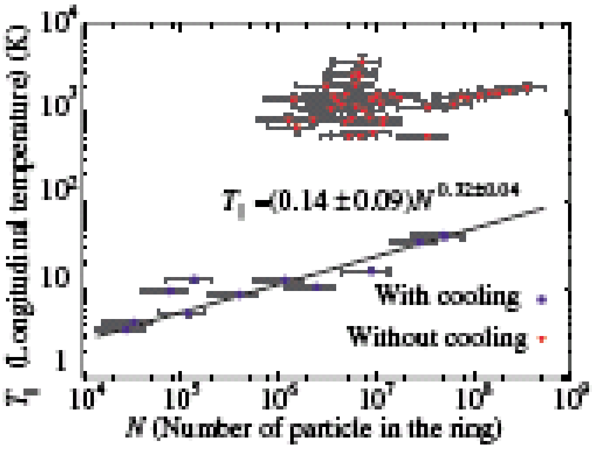

Figure 4 Relation between the number of cooled ions and the equilibrium longitudinal temperature [4].

Laser Cooling of Bunched Beam

In order to cool down the transverse temperature by a laser cooling, such a scheme as couples the transverse degrees of freedom with the longitudinal one actively with the use of "Synchro-betaron coupling" is required. [5]. For this purpose, bunched beam cooling has been applied at S-LSR with the operation tune of (ν_x, ν_y, ν_s)=(2.064, 0.814, 0.065), which satisfies the relation;

Figure 5 A drift tube for RF acceleration of 40 keV $^{24}Mg^{+}$.

$$\nu_x - \nu_s = m(\text{integer}) . \qquad (1)$$

The newly fabricated two-gap drift tube for RF acceleration as shown in Fig. 5 is set at the finite dispersion (~1 m) position indicated in Fig. 1. The equilibrium momentum after laser cooling is plotted for various synchrotron tunes in Fig. 6, which indicates the heat transfer into the longitudinal direction for synchrotron tunes satisfying Eq. (1). So as to establish the realization of transverse laser cooling, it is desirable to observe the reduction of horizontal beam size. As our optical measurement system of spontaneous emitted light by $^{24}Mg^{+}$ ion is capable of observation of only the vertical beam size limited by the available viewing port, it is not possible to measure the horizontal beam size at the moment.

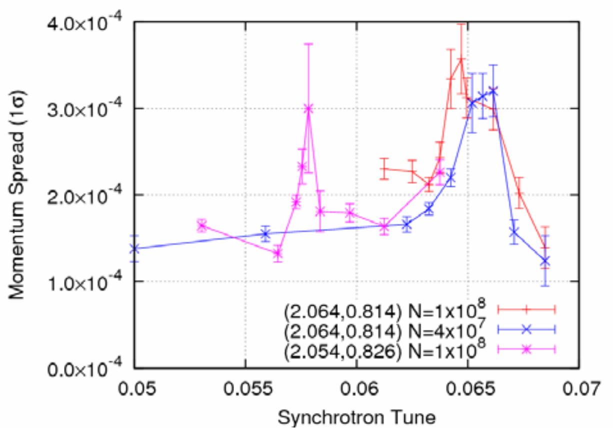

Figure 6 Relation between the equilibrium momentum spread and synchrotron tune for the case of application of a laser cooling.

SHORT BUNCH FORMATION WITH ELECTRON COOLING

For the investigation of free radicals, short bunch formation with the use of an electron cooling has been studied. Such a short bunch 7 MeV proton beam is fast extracted by an excitation a fast kicker magnet together with bump magnets, which creates orbit bump with much slower time constant than a kicker magnet. For proton beam with the intensity of $1.4x10^{8}$, phase rotation with the applied RF voltage of 800 V after application of an electron cooling compressing the fractional momentum spread to ±0.015 %, has attained a very short pulse with the duration of 3.1 ns (2σ) (Fig. 7 (a)) although its intensity is rather limited due to cut of beam filamentation. On the other hand, bunched beam electron cooling can provide higher intensity beam with ~100 % beam delivery to the extraction channel resulting a longer beam duration of 15.7 ns (2σ) (Fig.7 (b)) [6].

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REFERENCES

[1] T. Shirai et al, "One-Dimensional Beam Ordering of Protons in a Storage Ring", Phys. Rev. Lett. **98** (2007) 204801.

[2] M. Wakasugi et al., "Novel Internal Target for Electron Scattering off Unstable Nuclei", Phys. Rev. Lett. **100** (2008) 164801.

[3] J. Wei, H. Okamoto and A.M. Sessler, "Necessary conditions for attaining a crystalline beam", Phys. Rev. Lett. **80** (1998), pp2606-2609.

[4] M. Tanabe et al., "Longitudinal and Transverse Coupling of the Beam Temperature Caused by the Laser Cooling of $^{24}Mg^{+}$ ", Applied Physics Express, **1** (2008) 204801.

[5] H. Okamoto, "Transverse laser cooling induced through dispersion at an rf cavity", Phys. Rev. **E50** (1994) pp4982-4996.

[6] T. Fujimoto et al., "Formation and fast extraction of a very short-bunched proton beam for the investigation of free radicals", Nucl. Instr. And Meth. In Phys. Res. A588 (2008) pp330-335.

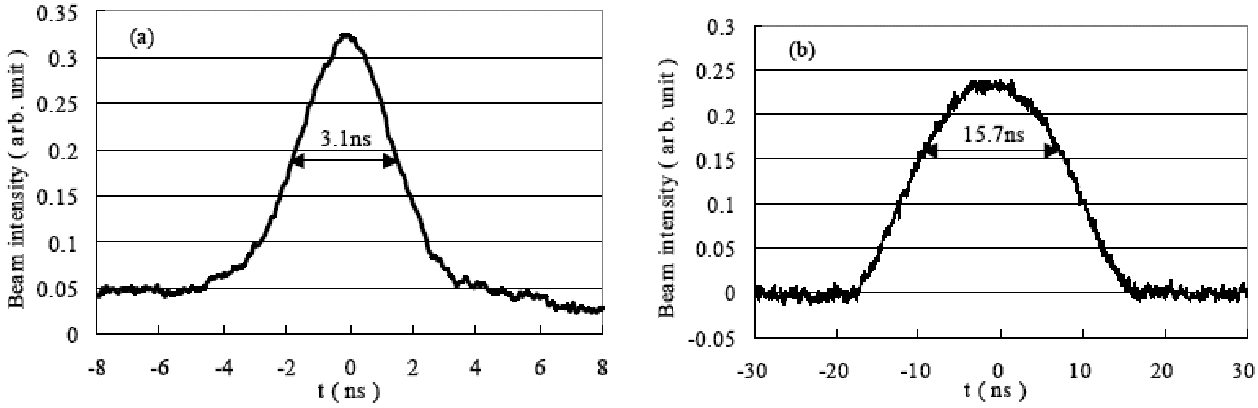

Figure 7 Short bunch of 7 MeV formed by phase rotation with 800 V after electron cooling (a) and bunched beam electron cooling (b)