

BEAM COOLING AT S-LSR*

A. Noda, H. Fadil, S. Fujimoto, M. Ikegami, T. Shirai, M. Tanabe, H. Tongu

ICR, Kyoto University, Uji-city, Kyoto, 611-0011, Japan

K. Noda, T. Takeuchi, NIRS, Inage-ku, Chiba, 263-8555, Japan

M. Grieser, MPI für Kernphysik, Heidelberg 69029, Germany

Meshkov, E. Syresin, JINR, 141980, Dubna, Moscow Region, Russia

H. Okamoto, Y. Yuri,

Hiroshima University, Higashi-Hiroshima-City, 739-8530, Hiroshima, Japan

Abstract

S-LSR is an ion accumulation and cooler ring with the circumference and maximum magnetic rigidity of 22.589 m and 1.0Tm, respectively. Electron beam cooling will be applied for laser-produced hot ion beam after phase rotation. Laser cooling of $^{24}\text{Mg}^+$ ion with low energy (35 keV) is also planned in 3-dimensional way with use of synchro-betatron coupling so as to realize ultra cold beam. Construction of S-LSR is to be completed in this fiscal year and beam commissioning will be started in next spring..

INTRODUCTION

For the purpose of demonstrating the feasibility of utilization of the laser-produced beam as the injection beam for cancer dedicated synchrotron, S-LSR has been under construction at ICR, Kyoto University in collaboration with NIRS. S-LSR aims at electron beam cooling of laser-produced hot ion beam after phase rotation with an RF electric field synchronized to the pulse laser [1]. In addition, 3-dimensional laser cooling will be also applied to $^{24}\text{Mg}^+$ beam in order to investigate the possibility of realizing ultra-cold ion beam.

ELECTRON BEAM COOLING OF HOT ION BEAM

Feasibility Test of Hot Ion Beam Cooling

Electron cooling has, so far, been considered to be effective only for rather cool ion beams with the energy spread of the size comparable with that of the region where the electron beam cooling force is eminent ($\sim \pm 0.1\%$)[2]. So as to make the cooling force effective for the ion beam with the energy spread of $\pm 1\%$ as our present case, a sweeping scheme of the relative velocity between the ion and electron beams is proposed [1]. So as to test the feasibility of such a scheme, experimental studies have been made utilizing the existing facility, TSR at MPI für Kernphysik, Heidelberg, Germany. The longitudinal cooling time has been found to be reduced from 2.8 second to ~ 0.4 second with use of relative velocity sweeping for the ion beam with a small transverse emittance as used for the experiments [3] although it is anticipated that the cooling time largely depends on the transverse emittance size. Such dependence is to be clarified at S-LSR quantitatively.

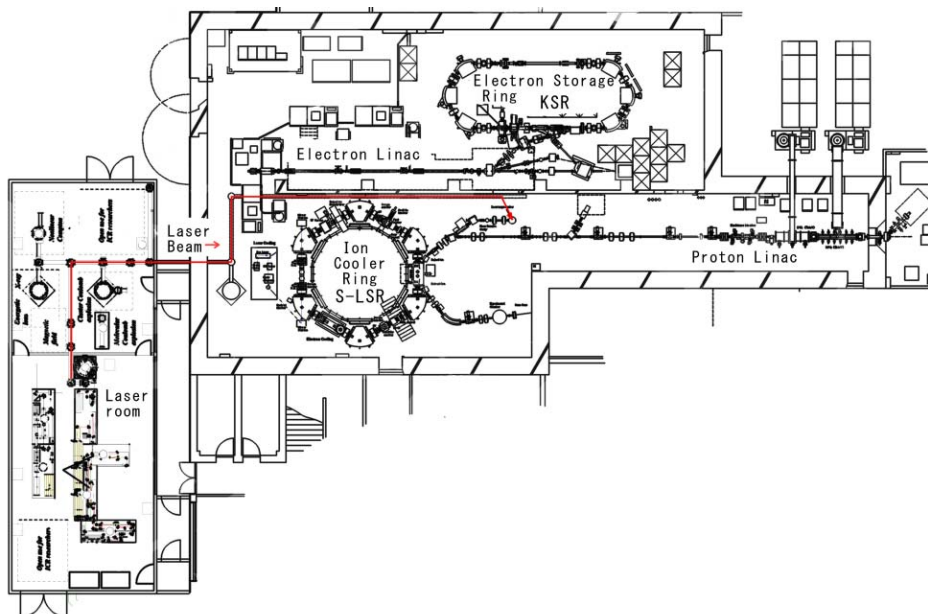


Figure 1: Layout of the S-LSR and T6 Laser at Institute for Chemical Research, Kyoto University.

*noda@kyticr.kuicr.kyoto-u.ac.jp

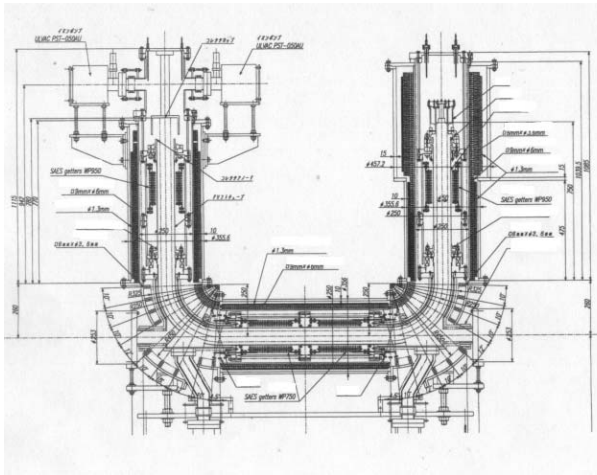
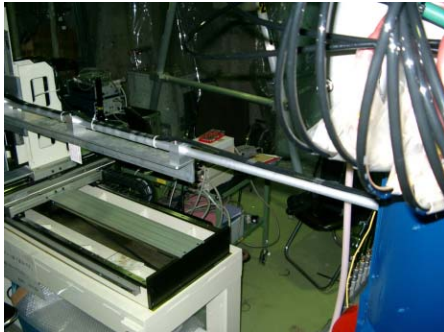


Fig.2 Fabricated Electron Cooler for S-LSR.

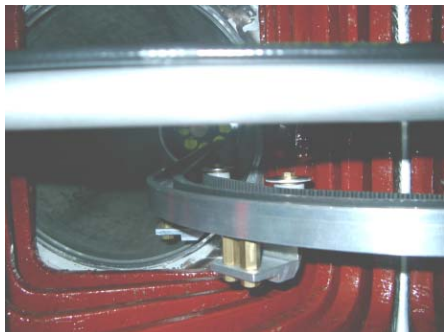
Electron Cooler for S-LSR

In order to apply our scheme utilizing the laser-produced ion beam as the injection beam for a pulse synchrotron dedicated for cancer therapy [4], it is inevitable to evaluate the cooling time for real laser-produced ion beam. For this purpose, a cooler ring, S-LSR, equipped with a laser ion source followed by a phase rotator and an electron cooler is now under construction. As is shown in Fig. 1, a high power (~10 TW) short pulse (~50 fs) laser is to be guided into the room of S-LSR and laser-produced ion beam with the central kinetic energy of 2 MeV/u is to be phase rotated by an RF cavity synchronized to the pulse laser before injection into the S-LSR.

In order to be installed into a rather limited straight sec-



(a) Measurement with a Hall-probe drove in a Cartesian coordinate.



(b) Measurement with a Hall-probe drove by a curved guide rail.

Fig.3 Field measurement of the Electron Cooler.

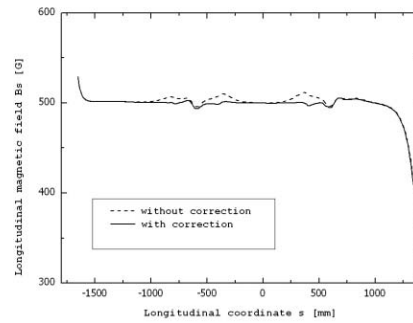


Fig.4. Field distribution with and without correction.

tion 1.86 m in length, a compact electron cooler has been constructed. In Fig.2, the layout of the fabricated electron cooler for S-LSR is shown [5]. The elliptical shape is adopted for the drift tube in the central solenoid. The magnetic fields created with solenoids and troids are evaluated by field measurements using a Hall-probe drove with a Cartesian driving mechanism or the one using curved guiding rail as shown in Fig. 3 (a) and (b). In Fig. 4, the overall longitudinal field distribution is shown for the cases with and without correction for the longitudinal field. The corrections with use of additional coils at both ends of the central solenoid and at the exit of the gun solenoid have been studied.

3-D LASER COOLING

Laser cooling is, at least in principle, a very powerful compared with other methods and can cool down the ion beam until the limit of the order of mK or even lower. The cooling time is extremely short although it depends on the initial beam temperature. The laser cooling force is, however, effective only for the longitudinal beam motion. In order to realize efficient cooling, a laser is introduced in a long straight section of the ring and is overlapped with the beam along some distance. In this process, the cooling force received by the beam always operates in the longitudinal direction and cooling in the transverse degree of freedom is not expected (rather diffusive heating is anticipated by random spontaneous emission and absorption of photons). We may expect some indirect transverse cooling induced through intra-beam scattering, which is inefficient in ordinary "hot" initial beams and is thus generally negligible.

In order to manage this difficulty in the actual application of the laser cooling technique, a simple practical method, utilizing artificial coupling of potentials and resonance between a lattice structure and accumulated ion beam has been proposed [6],[7]. This "Resonant Coupling Method" enables us to achieve very fast 3-dimensional laser cooling; which requires introduction of some sources of linear coupling into the cooler ring keeping resonance conditions as

$$Q_x - Q_y \approx m, Q_x - Q_s \approx n,$$

where m and n represent integers and Q_x and Q_y are betatron tunes in the horizontal and vertical directions, re-

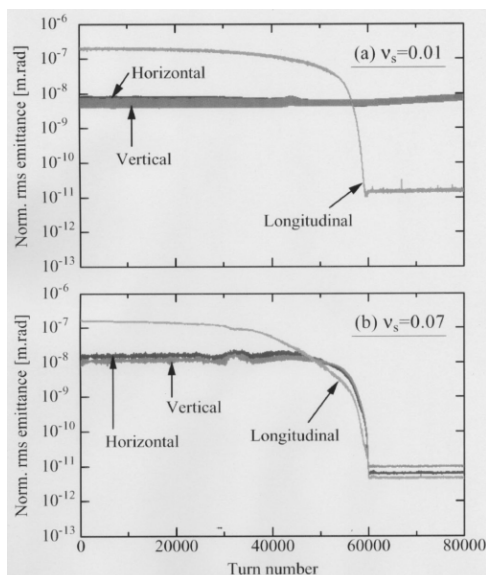


Fig. 5. Results of computer simulation of laser cooling at S-LSR.

spectively while Q_s is the synchrotron tune. In S-LSR, an RF cavity is to be installed at one of the straight sections and the coupling induced by momentum dispersion can be employed [7].

Numerical simulation has been performed with use of newly developed multi-particles tracking code “CRYSTAL” [8]. Not only the lattice structure of beam optics and inter-particle Coulomb forces but also the interaction between laser photons and an accumulated ion beam can be incorporated into this code. The molecular dynamics method is employed to calculate Coulomb interaction among particles. The absorption and emission processes of the laser photons are simulated with the Monte Carlo method. We have confirmed that the code gives the correct Doppler limit.

For laser cooling, a co-propagating laser and a counter-propagating laser are introduced at two different straight sections. As the sweep range of the laser frequency and output laser power, we have assumed reasonable values, taking the commercially available ring dye-laser into account. The initial temperature of a beam is set at over 10^4 K in the three degrees of freedom. In order to suppress the loss of the tail particles, slow laser sweep time of about 2 seconds is assumed. Main parameters assumed in the present simulation are listed up in Table 1.

Linear coupling between the horizontal and vertical directions has been realized installing a weak skew quadrupole magnet. As $Q_x = 2.067$, $Q_y = 1.073$, transverse tunes have already satisfied the resonance condition. In order to excite a synchro-betatron resonance, $Q_s = 0.07$ is required. A simulation result for this case is shown in Fig. 5(b) while Fig. 5(a) represents a off resonance case. The total number of particles used for the present simulation is 10,000 (number of particles per bunch is 100). We observe that the cooling efficiencies in all three degrees of freedom are equalized and extremely fast 3-dimensional

cooling is achieved. The transverse cooling time is roughly 200 msec. The final normalized rms emittance is of the order of 10^{-11} in the three directions, which is definitely the highest quality compared with any beams ever realized. It has also been shown that no transverse cooling takes place when the resonance condition is completely broken (Fig.5 (a)).

Reducing the particle number per bunch to less than 10, normalized rms emittance of 10^{-12} can be reached. Then, the final ion distribution in the real space becomes the so called “string” which executes a periodic transverse oscillation as discussed in Ref. [9]. By increasing the synchrotron tune or particle number, we can transform the “string” into the oscillating “zigzag”. We have confirmed that these ordered structures are rather stable and remain ordered for several thousands to several tens thousands turns after the laser cooling force is stopped [8]. These simulation results indicate that the realization of “crystal-line beams” can be expected at S-LSR now under construction.

Table 1 Main parameters of Laser Cooling at S-LSR

Ion Species	$^{24}\text{Mg}^+$
Beam Energy	35 keV
Betatron Tune	(2.067, 1.073)
Super periodicity	6 (without skew-Q)
RF Harmonic number	100
Saturation Parameter	1.0
Laser Spot Size	5 mm in radius (Gaussian)

PRESENT STATUS

At S-LSR, the 3 dimensional laser cooling is expected to be realized with the normal lattice with finite momentum dispersion together with electron cooling of “hot” ion beam.. In addition, we are preparing the mode without momentum dispersion throughout the whole circumference by the overlap of the radial electric field with the dipole magnetic field [10]. We want to start the commissioning of S-LSR from coming spring after precise alignment scheduled in this autumn.

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