COMPACT ACCELERATOR DEVELOPMENT AT S-LSR

A. Noda, H. Fadil, S. Fujimoto, M. Ikegami, Y. Iwashita, T. Shirai, M. Tanabe, H. Tongu
ICR, Kyoto University, Uji-city, Kyoto 611-0011, Japan
K. Noda, S. Shibuya, T. Takeuchi, S. Yamada#, NIRS, Inage-ku, Chiba, 263-8555, Japan
M. Grieser$, MPI, D-69029, Heidelberg, Germany
E. Syresin*, 141980, Dubna, Moscow Region, Russia

Abstract

At ICR, Kyoto University, a compact ion accumulation/cooler ring S-LSR with the circumference of 22.557 m is now under construction in collaboration with NIRS. Possibility of realizing laser produced $^{12}C^{6+}$ beam with 2 MeV/u in the energy bin of ±0.1% is to be studied by combination of phase rotation and electron cooling. Trial for downsizing of the accelerator by adopting compact sizes in electron cooler and conventional equipments such as beam monitors is also to be evaluated experimentally at S-LSR.

INTRODUCTION

Usage of the accelerators for various applications than basic physics has recently become more and more important. Carbon therapy, for example, has been found to be very effective to cure lung and liver cancers within a rather short treatment time (less than a week) due to its high radiobiological effectiveness (RBE). So as to realize widespread use of such facilities, downsizing of the facility is inevitable. From this point of view, Advanced Compact Accelerator Research Project has been promoted by Ministry of Education, Culture, Sports, Science and Technology since 2001 [1]. One of the major items of such approach is utilization of very high electro-magnetic field created by a high power laser for beam acceleration.

Phase space manipulation through phase rotation in the longitudinal phase space and beam cooling have been main scopes of the collaboration between ICR, Kyoto University and NIRS. Collaboration with APRC at JAERI Kansai Research Establishment on laser ion production has also take a very important role in the project. In the present paper, however, approach for the downsizing of the accelerator in connection with the construction of S-LSR is presented due to limit of available space.

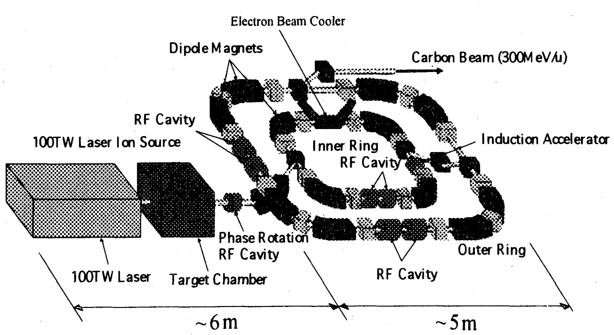

Figure 1:Scheme of the Compact Ion Synchrotron for Cancer Therapy

MATCHING IN PHASE SPACE

It is attractive to be able to attain ion beam up to several MeV/u directly by irradiation of a high power short pulse laser. The beam divergence, however, is very large due to the focusing condition of the laser to attain the laser power density higher than 10^{18}W/cm^2. The energy spectrum is also very wide (~100%) and we aim at collection of ions in the energy bin of ±5% around the central energy of 2 MeV/u. Rotations of the laser-produced ion beam in phase spaces both in longitudinal and transverse directions are needed.

Longitudinal Phase Space

The ion production by a high-power short-pulse laser has been reported from USA and Europe [2],[3]. The energy spectrum, however, amounts as large as 100 %, which causes serious limitation for real application of such a beam. So as to cope with such situation, we have proposed such a scheme to select the ion beam in the energy bin of ±5%, which is reduced to ±1% by the phase rotation in the longitudinal phase space with use of a debuncher synchronized to the pulse laser. In Figure 2, the completed phase rotation cavity, which is two gap quarter wave resonator, is shown. The ion beam is further reduced in fractional energy spread another one order of magnitude by the electron cooling in a cooler ring in order to match with the rather small energy acceptance of the short pulse synchrotron with the high peak magnetic field (~3 T) [4]. In Table 1, program of the reduction of energy spread of the laser-produced ion beam is listed up.

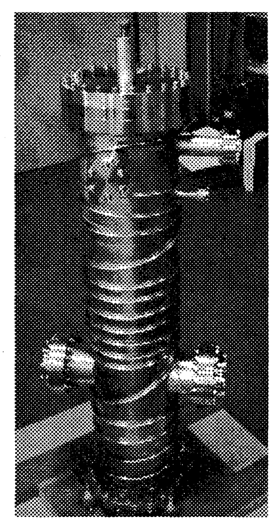

Figure 2. Phase Rotation Cavity

Table 1: Energy Spread of the Laser-Produced Ions (Design Specifications)

At the Production Target	After Phase Rotation	After Electron Cooling
±5%	±1%	±0.1%

Transverse Phase Space

The high-power short pulse laser is focused into a small size (~10μm in radius) and thus the laser-produced ion beam has a small size but a rather high divergence. So as to utilize such a beam as an injection beam for the RF accelerator, it is also needed to rotate such a divergent beam in the transverse phase space and make a almost parallel beam. One possible scheme for the transverse phase rotation is utilization of a solenoid because of its merit as can equally rotate both in horizontal and vertical directions The scheme, however, needs rather strong solenoid field realized only by superconducting technique and it needs some distance from the laser-irradiation target [5]. A scheme to install compact and strong quadrupole magnets made of permanent magnets just down stream of the target inside the vacuum vessel is also investigated as the alternative [6], which needs careful studies about magnetic force penetrating outside and strength flexibility. It is urgent requirement to establish the ion optics to guide the laser-produced ion beam to the phase rotation cavity and downstream momentum analysing magnets for evaluation of energy spread, which is to be investigated at JAERI, Kansai from now on. Based upon the results obtained there, improvement of such ion optics for phase rotation both in longitudinal and transverse phase spaces will become one of the major research scopes at S-LSR.

BEAM COOLING

Electron Cooling

For the application of laser-produced ion beam to rather precise experiment or injection to the following synchrotron, further reduction of energy spread is inevitable, which is expected to be accomplished by an electron cooling in our scheme. The electron cooling, however, has been believed to be effective only for rather cool beam [7] because cooling force given by the relation,

$$F(\vec{v}_i) = -\frac{4\pi n_e Z^2 e^4}{(4\pi\varepsilon_0)^2 m_e} \iiint L_C(u) f(\vec{v}_e) \frac{\vec{u}}{|u|^3} d^3 v_e \tag{1}$$

decreases according to the increase of ion-electron relative velocity: u (L_C is the Coulomb logarithm and n_e and m_e are electron density and electron mass, respectively). In order to improve this situation, we have proposed the scheme to sweep the relative velocity by chaging the ion energy with use of an induction accelerator (Figure 3(a)) or electron energy by changing the high voltage applied for the electron GUN (Figure 3(b)). Feasibility of such schemes has already been demonstrated by the experiments utilizing TSR for the injection beam from the MP Tandem and heated in the longitudinal or horizontal direction [8]. The cooling time, however, largely depends on the transverse beam size and experiments with real laser-produced ion beam is inevitable, which we plan at S-LSR. In Figure 4, the compact electron cooler to be installed in a straight section, 1.86 m in length, is shown. In Figure 5, very tight situation of the installation of the electron cooler is illustrated. Further the drift tube for electron beam in the central solenoid section is designed to be an elliptical shape so as to match with the troid radius as short as 0.25 m.

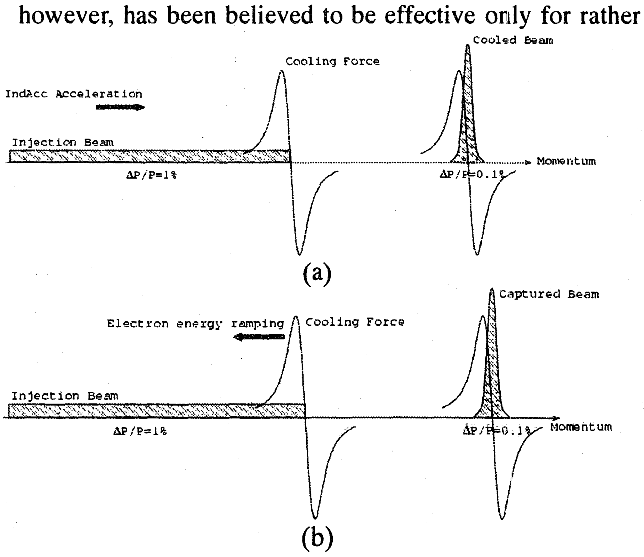

Figure 3 Schemes of electron cooling of hot ion beam, (a)ion energy sweep with use of induction accelerator, (b)electron energy sweep by ramping the high voltage to accelerate the electron.

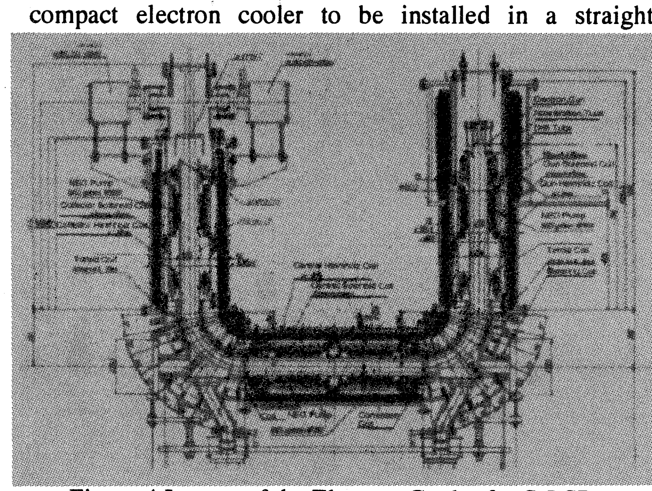

Figure 4 Layout of the Electron Cooler for S-LSR.

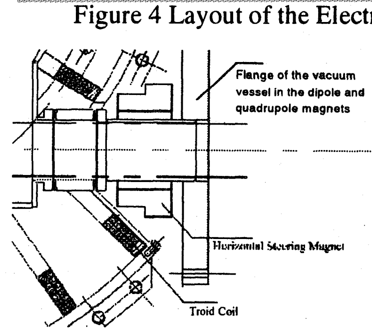

Figure 5 The position relation of the electron cooler in the straight section.

Laser Cooling

Utilizing S-LSR the 3-dimensional laser cooling proposed by H. Okamoto et al.[9] is also to be applied for $^{24}Mg^+$ ion with kinetic energy of 35 keV. At S-LSR, the following new approach towards the crystalline beam is to be applied.

Control of Dispersion Function in the Dipole

If the crystalline beam becomes 3 dimensional and the cooling force created by the CW laser drives all the ions to a certain energy, the shearing force will be applied to the beam because of the arc length difference. So as to avoid this difficulty, superposition of the electric and dipole magnetic fields is proposed [10]. Detailed design of the electrodes to be installed inside of a rather limited gap of 70 mm of the dipole magnet has been going on [11]. The vacuum chamber in the dipole is now under construction including the movable electrodes to provide such an electric field in case of beam crystal mode [12] as shown in Figure 5 [13]. It is expected the dispersion function in the dipole section can be controlled by adjusting the strength of the electric field relative to the magnetic field. Such scheme is also expected to make energy difference almost linear to the horizontal displacement of the beam from the central orbit by the acceleration and deceleration due to electric potential difference at the entrance and exit of the dipole section, which seems preferable for attainment of 3-Dcrystalline beam [14].

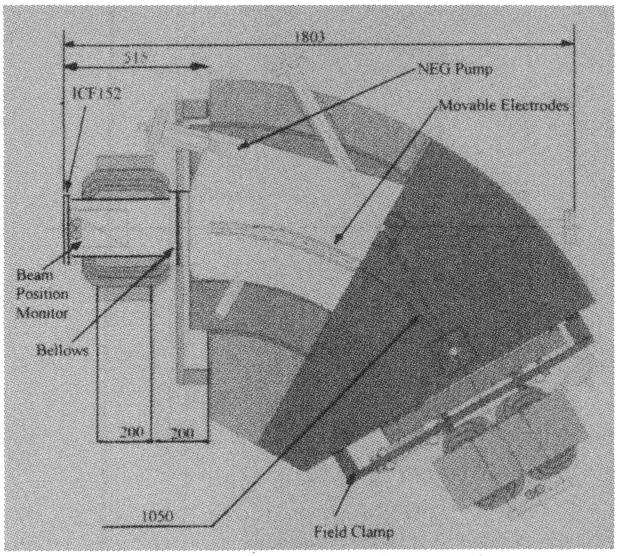

Figure 5. Vacuum chamber in the dipole and quadrupole magnets.

APPROACH TO COMPACTNESS

At S-LSR, ultimate limit of compactness attainable in the conventional accelerator has also been pursued. As is above mentioned, the size of the electron cooler is reduced as small as possible keeping the length of the effective cooling region of 0.5 m. In addition, the distance between the dipole and the quadrupole magnets is determined to be 200 mm, where interference of magnetic fields is anticipated. In the design of S-LSR, the presence of the adjacent magnet has been taken into account with use of 3-dimensional computer code, TOSCA [15]. The performance of such design procedure is to be evaluated by field measurements, which are now going on [16]. The beam position monitors to control the beam orbit distortion have been installed inside the quadrupole magnet as shown in Figure 6 in order to reduce the circumference [17].

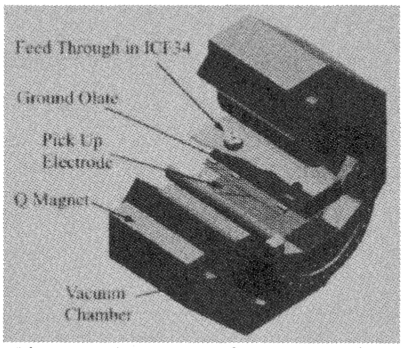

Figure 6. Beam Monitor Installed in the Q-Magnet

CONCLUSIONS

Approach to compact accelerator at S-LSR can be largely divided into two. One is the challenge to use the very high electro-magnetic field produced by a high power laser. Basic structure of such a scheme will be fixed by the test experiments just started using 100 TW, 20fsec laser at APRC, JAERI Kansai Research Establishment. At S-LSR, further improvement of the phase rotation system is planned together with electron cooling of laser-produced "hot" io beam. The other is pursuit of the limit of compactness using conventional accelerator technology. Such approach has become possible owing to recent rapid advance in computer science as 3-dimensional electromagnetic fields calculation. Circumference economy as installation of the position monitors inside the quadrupole magnets has also been investigated, which will be directly applicable to the conventional accelerator.

REFERENCES

[1] S. Yamada, Proc. of the invited talk at this meeting.
[2] P. Stephen et al., Physics of Plasma **7** (2000) pp2076-2082..
[3] E. L. Clark et al., Phys. Rev. Lett. **85** (2000) pp1654-1657.
[4] K. Endo et al., Proc. of EPAC2000 (2000) pp2515-2517.
[5] A. Noda et al., Beam Science and Technology, **8** (2003) pp22-24.
[6] S. Nakamura, private communication.
[7] D Möhl, Proc. of ECOOL84 (1984) pp293-301.
[8] H. Fadil et al., Accepted for the publication in Nucl. Instr. & Meth. In Phys. Res.
[9] H. Okamoto, A. M. Sessler and D. Möhl, Phys. Rev. Lett. 72 (1994) pp3977-3980.
[10] M. Ikegami et al., to be submitted to Phys. Rev. STAB.
[11] M. Tanabe et al., Proc. of this meeting (in Japanese).
[12] T. Shirai et al., Proc. of this meeting (in Japanese).
[13] H. Tongu et al., Proc. of this meeting (in Japanese).
[14] H. Okamoto, private communication.
[15] T. Takeuchi et al., Proc. of COOL03, in print.
[16] T. Takeuchi et al., Proc. of this meeting (in Japanese).
[17] S. Fujimoto et al., Proc. of this meeting (in Japanese).