BEAM SCIENCE FACILITY WITH COMBINATION OF ION AND ELECTRON STORAGE RINGS

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Abstract

An accelerator complex which combines the heavy-ion cooler ring TARN II_(maximum magnetic rigidity, 6T·m) with the existing 300 MeV electron storage ring, KSR is proposed. Experimental test of beam crystallization, higher energy micro-beam, Coulomb explosion imaging of inter-molecular force and combined use of ion beam with synchrotron radiation is expected to be feasible.

1 INTRODUCTION

An accelerator complex consisting of storage rings of ions and electrons with their maximum energies of 290 MeV/u and 1500 MeV, respectively, has been studied as a future project to be built at the new campus of Kyoto University in these several years [1]. The new campus-cite recently decided, however, is found not so suitable for such an accelerator facility. On the other hand, the ion storage/cooler ring, TARN II with maximum magnetic rigidity of 6T·m at KEK Tanashi-branch has recently decided to be shut down because of closure of Tanashi-branch. The plan to realize an accelerator complex utilizing the TARN II together with the electron storage ring, KSR, just completed at ICR, Kyoto University [2], has been pursued recently. As the ion injector for KSR, the Tandem Van de Graaff with terminal voltage of 8 MV, which is under operation at Department of Physics, Faculty of Science, Kyoto University will be used. The main research themes of the facility are (1) experimental test of the feasibility of ion-beam crystallization with use of 3-dimensional laser cooling, (2) higher energy micro-beam with use of cooled beam to the ultra-low temperature, (3) Coulomb explosion imaging of heavy molecules slowly extracted from the ring with use of RF Knock out (RFKO) in combination with the third order resonance, (4) combined use of ion beam with synchrotron radiation and (5) study of atomic and molecular physics with use of ion-electron collisions.

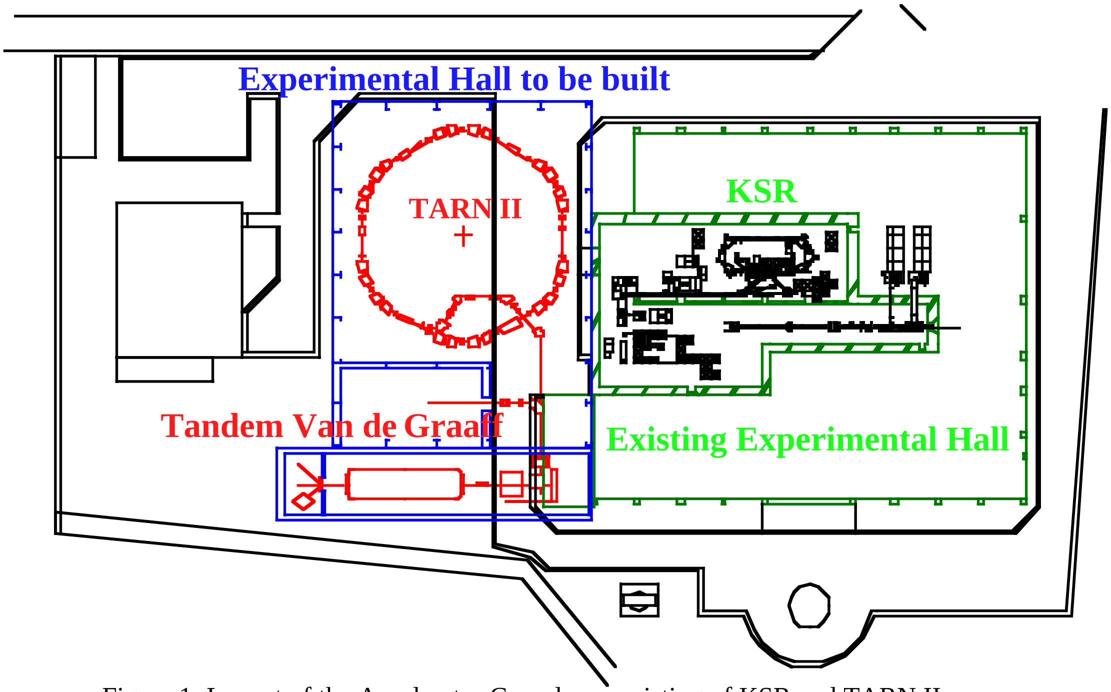

Figure 1; Layout of the Accelerator Complex consisting of KSR and TARN II.

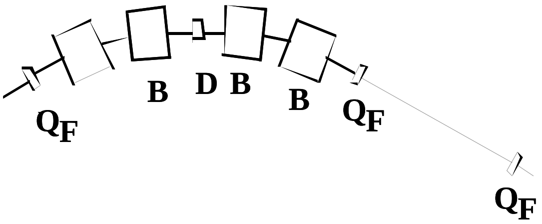

Figure.2: Lattice structure of a superperiod of TARN II. (Q_F, Q_D and B represent radially focusing, defocusing quadrupole magnets and bending magnet, respectively.)

2 POSSIBILE EXPERIMENTAL TEST FOR ION BEAM CRYSTALLIZATION

Beam simulation with the computer code utilizing molecular dynamics predicts beam crystallization for the case of TARN II lattice, which satisfies the so called maintenance condition, if sufficiently fast cooling force such as 3-dimensional laser cooling works [3]. The lattice structure of TARN II shown in Fig. 2, has a rather distributed focusing structure. Horizontal focusing is composed of radially focusing quadrupole QF and radial focusing in the dipole magnets with curvature radius of 4.01 m. Vertical focusing is obtained with combination of edge focusing of the angle of 7.5° at both ends of the dipole magnets and radially defocusing quadrupole QD. Such focusing structure might be effective for the beam cooling to the ultimately low temperature, which should be studied with the computer simulation.

In the simulation, $^{24}Mg^+$ with kinetic energy of 1MeV (42keV/u) is assumed as listed up in table 1. By the Tandem Van de Graaff with terminal voltage of 8MV, it is not so easy to realize such a low energy beam. One way is to make injection at 16 MeV and then decelerate to 1 MeV. The equilibrium charge state at such higher energy, however, is high and requirement for ultra-high vacuum is anticipated to be severe. To reduce the acceleration voltage of the Tandem Accelerator, usually only 1 acceleration column is used and the others are shorted. Such method, however, results in weak focusing and beam transmission at such a low voltage becomes very low. So we assume the method to accelerate and decelerate alternatively in the accelerating column in the tank of the Tandem Accelerator recently tested at Kyushu University [4]. With this method, high beam transmission is obtained owing to strong focusing, which is expected to be applicable for such a low terminal voltage as 0.5 MV required for the present case.

For this condition, the speed of the Mg ion is about 1 % of the light velocity and Doppler shift is very small ($\Delta\lambda$=2.64nm). So the wavelength required for the laser is almost similar to the one used at ASTRID, where $^{24}Mg^+$ with kinetic energy of 99.1 keV is laser cooled [5].

In order to achieve fast transverse laser cooling, the resonant coupling method [6] will be applied. Since the line density of a stored and laser-cooled heavy ion beam is usually low, the resonant coupling is expected to be quite effective until the beam becomes cold (even if the effect of tune shifts is taken into account). According to past molecular dynamics simulations based on the TARN II lattice [3], there is a possibility of reaching liquid or even crystalline states. For the purpose of stabilizing ground-state structures, however, a "tapered" cooling force is necessary [7]. In order to provide this special dissipative force, we will also try a recently proposed scheme [8] where two or more lasers with slightly different frequencies are used.

Table 1: Main Parameters of 3-dimensional laser cooling at TARN II [3].

Ring circumference, $2\pi r$	77.7 m
Betatron tunes (ν_x, ν_y)	(2.096, 2.104)
Radius of curvature in dipole	4.01 m
Skew quadrupole strength	0.001 m^{-1}
Lattice Superperiodicity	6
Transition gamma, γ_t	2.258
Ion species	$^{24}Mg^+$
Kinetic energy	1MeV
RF harmonic number	1000

3 HIGHER ENERGY MICROBEAM

Micro-beam utilizing the output beam from 4 MV Van de Graaff has been provided at Columbia University and Graylab. Such a micro-beam can selectively irradiate to the nucleus in the cell. For the risk evaluation of radiation to human body, it is important to study the effect of the single passage of the radiation, because for most publics the probability that a single nucleus in their cells receives more than 1 radiation is very low. By the micro-beam provided by 4MV Van de Graaff, the energy deposition to the cell nucleus is made at Bragg peak, where the fluctuation of the energy deposition is anticipated to be very large. Utilizing a rather higher magnetic rigidity of TARN II as 6 T·m, a micro-beam with the higher energy will be possible, where the energy deposition will occur at the flat part before Bragg peak with small fluctuation. In order to realize a small enough size of the extracted beam, a slow extraction method utilizing the RFKO together with the third order resonance is to be applied [9].

4 COULOMB EXPLOSION IMAGING

With use of the above mentioned slow extracted beam with combined use of RFKO and the third order resonance, it is expected that the rather longer beam spill (more than 1 second) will be realized. As the extracted beam direction is not changed during the whole extraction process, the beam size is expected to be small. With use of such a beam a Coulomb explosion imaging of the inter-molecular force will be possible as is successfully performed at TSR [10]. Owing to the rather higher magnetic rigidity 6 T·m of TARN II compared with 1.5 T·m of TSR, heavier molecules such as C_{10}^{+} and C_{60}^{3+} can be studied if suitable ion source will be developed.

5 OTHER POSSIBILITY OF THE FACILITY

5.1 Combined Use of Ion with Synchrotron Radiation

Photo ionization of highly ionized ions accumulated into TARN II by the synchrotron radiation from the electron storage ring, KSR will be a possible research subject although careful study about the event rate is needed because of the rather limited photon density due to low energy of 300 MeV.

5.2 Atomic and Molecular Physics Research

With use of the electron cooler at TARN II with the expansion factor of 100, studies of dissociative recombination of many molecular ions will be possible extending the work done at INS [11].

5.3 Cooling of Hot Ion Beam

It is considered that stochastic cooling is suited for cooling of hot beam and electron beam cooling is oriented for colder beam to be cooled down to much lower temperature [12]. Laser cooling aims at extremely cold temperature. The electron beam cooling, however, will be able to cool down from moderate temperature, (~1% in $\Delta p/p$) to lower temperature (less than 0.1% in $\Delta p/p$) by combined use with a induction accelerator (betatron core). This scheme is considered to be useful to improve the hot secondary beam produced at the target with large momentum spread to the characteristics acceptable by a usual accerelator.

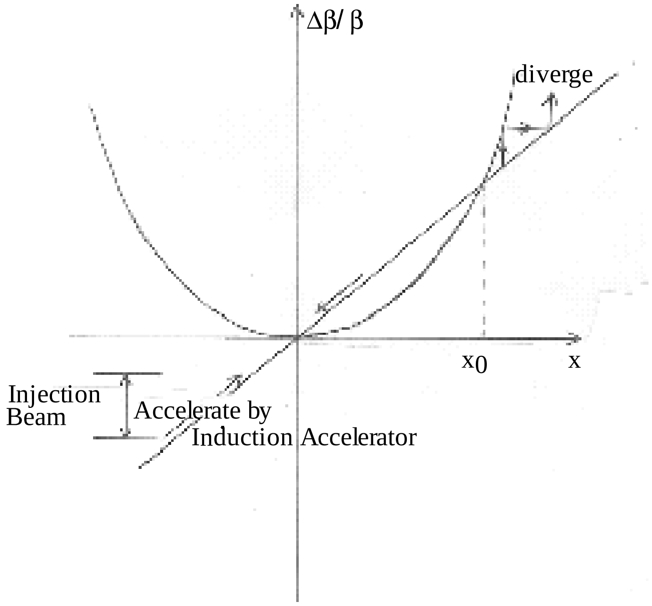

Figure 3: Velocity distribution of the electron beam.

The velocity distribution becomes hyperbola as shown in Fig. 3 because of space charge effect. Due to the finite value of the dispersion function at the cooler section (4.5 m for the case of Synchrotron Mode of TARN II), in the region outer than a certain value, x_0, ion beam will be continuously accelerated by the electron beam and diverges. In order to avoid this situation, hot beam is injected in the lower energy region as indicated in Fig. 3 and then accelerated by the induction accelerator. For the case of C^{6+} beam with kinetic energy of 6 MeV/u, cooling rate is estimated at 50 sec^{-1} assuming the maximum flux change and electron density of 0.6 V·sec and $8x10^{12}$ m^{-3}, respectively.

REFERENCES

[1] A. Noda, “Accelerator complex of ion and electron storage rings”, Nucl. Instr. and Meth. **A441** (2000) pp154-158.

[2] T. Shirai et al., “Beam Commissioning of the Electron Storage/Stretcher Ring (KSR)”, contribution to this Conf.

[3] T. Kihara et al., “Three-dimensional laser cooling method based on resonant linear coupling”, Phys. Rev. **E59** (1999) pp3594-3604.

[4] K. Sagara et al., Proc. of the 12th Meeting on Tandem Accelerator and Related Technology, (1999) pp121-124 (in Japanese).

[5] N. Madsen, “Dynamics of laser-cooled ion beams”, Ph.D. Thesis at Institute of Physics and Astronomy, University of Aarhus, Denmark.

[6] H. Okamoto et al., “Three-dimensional laser cooling of stored and circulating ion beams by means of a coupling Cavity”, Phys. Rev. Lett. **72** (1994) pp3977-3980; H. Okamoto, “Transverse laser cooling induced through dispersion at an rf cavity”, Phys. Rev. **E50** (1994) pp4982-4996.

[7] J. Wei et al., “Necessary Conditions for Attaining a Crystalline Beam”, Phys. Rev. Lett. **80** (1998) pp2606-2609; H. Okamoto & J. Wei, “Theory of tapered cooling”, Phys. Rev. **E58** (1998) pp3817-3825.

[8] T. Kihara & H. Okamoto, in preparation; see also, N. Kjaergaard & M.Drewsen, Phys. Lett. **A260** (1999) pp507-511.

[9] M. Tomizawa et al., “Slow beam extraction at TARN II”, Nucl. Instr. and Meth. **A326** (1993) pp399-406. K. Noda et al., “Slow beam extraction by a transverse RF field with AM and FM”, Nucl. Instr. and Meth. **A374** (1996) pp269-277.

[10] F. Albrecht et al., “Slow Extraction at the Heidelberg Heavy Ion Storage Ring TSR”, Proc. of the 5th European Particle Accelerator Conf. (1996) Sitges (Barcelona) (1996) pp2459-2461.

[11] T. Tanabe et al., “Evidence of Superelastic Electron Collisions from H_2^+ Studied by Dissociative Recombination Using an Ultracold Electron Beam from a Cooler Ring”, Phys. Rev. Lett. **83** (1999) pp2163-2166.

[12] D. Möhl, Proc. of ECOOL84, Karhlsruhe (1984).