COMPACT PROTON AND HEAVY ION SYNCHROTRON FOR CANCER THERAPY AND BIO-SCIENCE

K. Endo, S. Ninomiya and Z. Fang, KEK, Tsukuba, Japan
S. Yamada, NIRS, Chiba, Japan
Y. Ishi, S. Fukumoto, A. Teramoto, M. Takada and I. Uetomi, Mitsubishi Electric Co., Kobe, Japan
G. I. Silvestrov, BINP, Novosibirsk, Russia

Abstract

Compact proton and heavy ion synchrotrons are being discussed in order to promote their uses in the fields of the medicine and bio-science with a reasonable invest cost. Both synchrotrons can share the same components except for dipole and injector but with an enlarged circumference for the heavy ion ring. To realize a small accelerator without using the superconducting magnet that requires an infrastructure for the cryogenics, the use of the high field magnet is inevitable. Moreover, it also requires the wide range frequency modulation of the RF system at high acceleration voltage. This study includes the improved lattice designs for both rings that are envisaged as an actual proof of the compact synchrotron.

1 INTRODUCTION

The carbon ion therapy is now noticed for its remarkable improvement in the radiotherapy because the high LET particle gives a lethal damage to the tumor tissue almost independent of the cell cycle. It benefits in reducing the radiation treatment sessions compared to those of proton [1]. However, proton therapy also serves as an advanced modality of the medical treatment. Both accelerators for proton and carbon ion can share their roles as a hadron therapy which is recognized to be ideal because it can localize the depth dose to the tumor volume affecting little to the surrounding normal tissues. In general, the proton machine can be manufactured relatively cheaper than the heavy ion machine, so the former may be constructed at the locally distributed clinics around the medical centers which serve for the research and development of new therapeutics in addition to the complementary role to the local clinical centers.

This kind of accelerator does not belong to the small accelerators mainly dedicated to the radiotherapy such as cyclotrons and synchrotrons which are designed with established methods, but it depends on the potentialities existing in the well understood technologies and pursues their extremity [2, 3, 4]. To make the accelerator as small as possible, it must adopt the high field magnet of 3 T or higher which is challenging in the compact cyclotron [5].

From these view points, this study deals with the synchrotron which is expandable from the proton machine to the heavy ion machine based on the same concept [6]. As the laser-based heavy ion source will be developed in the same project, the injection energy of 1 MeV/u is assumed here.

2 LATTICE DESIGN

The ring circumference is almost determined by the field strength of the dipole magnet and the acceleration and deceleration periods are limited by the temperature rise of its coil. The required power is supplied by the discharge of the capacitor bank of about 100 kJ but the excitation current cannot be controlled during acceleration except for the peak current [7]. Therefore the gradient of the quadrupole magnet must be controlled precisely by tracking the dipole field or its current. After investigating several candidates of the lattice suitable to the compact synchrotron, the ODOFBF lattice for proton and the ODOFBFDFBF lattice for heavy ion are found promising and their parameters are given in Table 1.

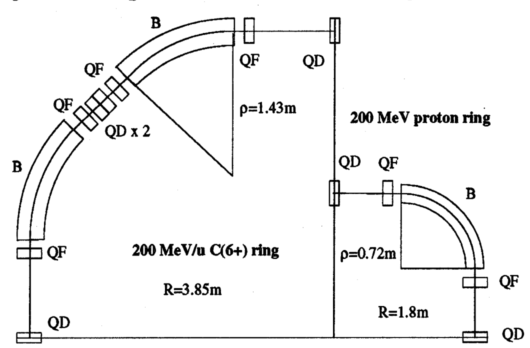
Table 1: Lattice parameters of the proton and C^{6+} rings.

Ring	Proton	C^{6+} ion
Max. energy (MeV/u)	200	200
Injection energy (MeV/u)	2	1
Max. dipole field (T)	3	3
Length of dipole (m)	1.126	1.126
Bending radius (m)	0.7165	1.4331
Number of dipoles	4	8
Max. quad gradient (T/m)	42	42
Length of quad (m)	0.1	0.1
Number of quads	12	28
Circumference (m)	11.3	24.2
Superperiod	4	4
Tunes (hor / ver)	2.25 / 1.25	2.75 / 1.75
Max. beta function (β_x / β_y)	4.42 / 11.33	4.40 / 14.73
Max. dispersion (m)	0.42	0.85
RF frequency (MHz)	1.7 - 15.0	0.6 - 7.0
Harmonic number	1	1
Max. Acc. Voltage (kV)	13	26
Acc. time (msec)	5	5
Number of RF cavities	2	4
Repetition (Hz)	<10	<10
Unit cell structure	ODOFBF	ODOFBFDD FBF

Focusing quads close to both ends of dipoles are introduced to increase the tunability as well as to allow the normal beam entry to dipoles which will relax the design of the dipole magnet ends. This choice also benefits in reducing the dispersion function a great deal by increasing the horizontal tune to 2.25 for proton and 2.75 for heavy ion. But the drawbacks are the increases of the maximum gradient and the betatron functions for both focusing and defocusing quads. As the vertical betatron function for the dipole remains small, it does not affect to the dipole gap height for both rings.

As the saturation of the quad yoke becomes serious at higher gradient level, it is desirable to increase the core length for the better tracking of the quad to the dipole field. The estimated saturation at 45 T/m for the present 10 cm core length is almost 40%.

Layouts are given in Fig.1 and their twiss parameters in Fig.2 for the proton and carbon ion ring.



Lattice configuration of C(6+) and proton rings

Figure 1: Magnet configuration for a superperiod of the proton (right half) and carbon ion ring (left half).

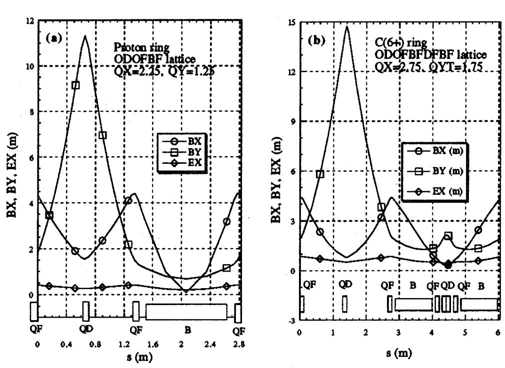


Figure 2: Twiss parameters for a superperiod of (a) proton (ODOFBF) and (b) carbon ion (ODOFBFDFBF) ring. BX and BY are the horizontal and vertical beta-function, respectively, and EX the horizontal dispersion function. Lattice structures are also shown at the bottom of each figure.

The fundamental RF parameters are given in Table 1. By choosing larger horizontal tune, the transition energy increases and the momentum excursion due to the synchrotron oscillation decreases. Other parameters are shown in Fig.3 for both rings. Acceleration of particle in a short time in a small ring requires the high RF voltage and wide frequency range [8].

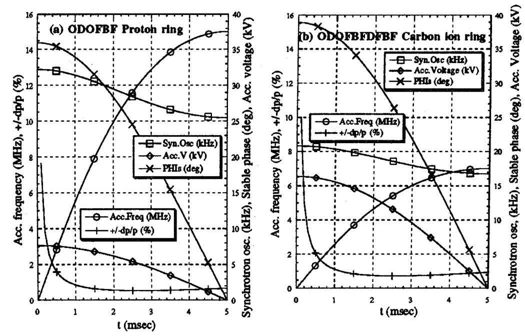


Figure 3: RF parameters for (a) Proton ring, and (b) Carbon ion ring.

3 BEAM APERTURE AND SEXTUPOLE COMPENSATION

Several limitations are imposed on the compact ring, that is, the useful beam aperture is within ±3 cm or so horizontally and ±2.5 cm or so vertically in the dipole magnet, the allowable momentum spread under the synchrotron oscillation is within ±1.5%, and the normalized emittance at injection is 10π mm•mrad or less which limits the beam intensity and requires higher machine repetition rate. Therefore, the dispersion function should be as small as possible to reduce the horizontal beam excursion by the large momentum shift.

The estimated beam aperture is given in Table 2 under the above limitations.

Table 2: Half beam aperture requirement (unit: cm). The COD is not included.

Ring	Proton	C^{6+} ion
ε_{norm} (hor./ver.) (π mm mrad)	10 / 10	10 / 5
Dipole (hor./ver.)	2.7 / 1.3	4.2 / 1.4
QF (hor./ver.)	3.2 / 1.7	4.4 / 1.6
QD (hor./ver.)	2.0 / 4.2	2.1 / 4.0
Long SS (hor./ver.)	3.2 / 4.1	4.3 / 3.9
Short SS (hor./ver.)	3.1 / 1.4	4.3 / 1.6

Most deteriorating field is the sextupole component in the dipole. The method of its compensation will be done by adding compensation windings to each dipole and/or independent sextupole magnets at straight sections. Both require the current control which tracks the dipole field. The beautiful compensation results from controlling the flux passage in the iron pole and yoke by the current of the embedded correction windings in the upper and lower magnetic poles. The flux distribution in the beam aperture is affected by the locations of the windings which should be determined by the numerical field calculations. The resultant field distributions by the static 2D calculation are given at the injection and maximum fields in Fig.4. The optimum winding position should be determined carefully by the 3D calculations.

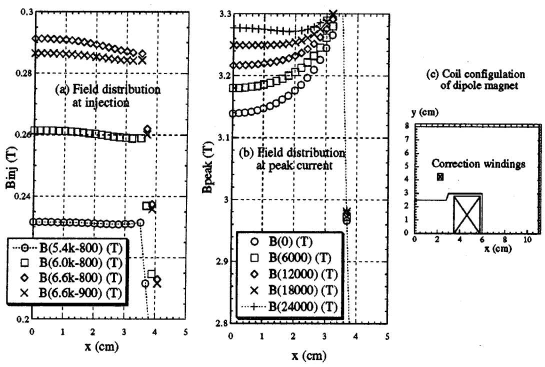


Figure 4: Improved field distribution with the compensation windings embedded in the magnet yoke at (a) the injection field and (b) the peak field (figures are the current in AT). (c) Cross-section of a quarter of the dipole.

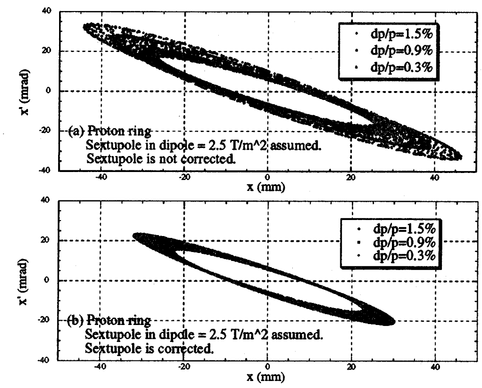


Figure 5: Effect of the sextupole component of the dipole (2.5 T/m^2) on the proton behavior in the horizontal phase space at injection. Sextupole component is (a) not corrected and (b) corrected. The effect of the synchrotron oscillation was considered.

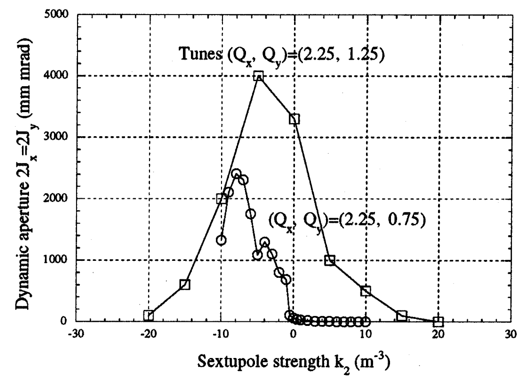


Figure 6: Dynamic aperture dependence on the sextupole field strength for dp/p=1.5% proton under the influence of the synchrotron oscillation. k_2=0.5B"/Bρ (Bρ=0.20 T•m at injection and 2.15 T•m at 200 MeV).

The auxiliary windings require the bipolar operation to compensate from the injection field to the maximum field against the induced voltage due to the main coil. Sextupole magnets is powerful to compensate the error sextupole field in addition to the chromaticity control.

Their effects on the beam stability is simulated using the beam tracing code assuming either that the sextupole component distributed over the entire dipole or that it exists at the middle of the dipole as a thin lens. As both cases gives the similar effect to the beam, only the latter cases are shown in Fig.5.

In simulations for the proton ring, beams with different momentum between -1.5 and 1.5% were traced for 2000 revolutions under the influence of the RF field assuming the sextupole component of 2.5 T/m^2 in the dipole for two cases with and without correction by 4 sextupole magnets symmetrically placed at 4 straight sections. If the sextupole field is not corrected, the betatron amplitude of proton with large momentum deviation grows beyond the aperture allowed for the present ring.

The beam aperture dependence on the sextupole field strength of the dipole is estimated for the same horizontal and vertical emittances. The synchrotron oscillation of proton with dp/p=±1.5% is assumed within stability limit considering the proton survival at injection for the imposed horizontal aperture of x=±3 cm. The dynamic aperture is defined here as the emittance at the beginning of the beam tracing if the proton survives after 5000 revolutions. Two cases are given in Fig.6 for tunes (QX, QY) = (2.25, 1.25) and (2.25, 0.75) for the same proton ring. Wider dynamic aperture is expected to the larger vertical tune.

Authors are indebted to Professor Y. Hirao of NIRS and M. Seya of NISTEP who have paid a great effort to materialize this project.

REFERENCES

[1] Y. Hirao, "Results from HIMAC and Other Therapy Facilities in Japan," CYCLOTRONS 2001.

[2] I.I. Averbukh et al, "Project of Small-Dimensional 200 MeV Proton Synchrotron," EPAC88, pp.413-6.

[3] L. Picardi et al, "Preliminary Design of a Technologically Advanced and Compact Synchrotron for Proton Therapy," Internal Report RT/INN/94/20, 1994. L. Picardi et al, "Preliminary Design of a Very Compact Protosynchrotron," EPAC94, pp.2607-9.

[4] K. Endo et al, "Table-Top Proton Synchrotron Ring for Medical Applications," EPAC2000, pp.2515-7.

[5] J. Kim, "Design Study of a Superconducting Cyclotron for Heavy Ion Therapy," CYCLOTRONS.

[6] I.I. Averboukh et al, "Compact Carbon-Ion Synchrotron for Cancer Therapy," APAC'01, to be puiblished.

[7] K. Endo et al, "Resonant Pulse Power Supply for Compact Proton and/or Heavy Ion Synchrotron," APAC'01, to be published.

[8] S. Ninomiya et al, "Non-Resonant RF Accelerating System," EPAC2000, pp.1981-3.