LATTICE STUDY OF A COMPACT SYNCHROTRON FOR CARBON THERAPY

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Abstract

A magnet lattice of the carbon-ion synchrotron was studied for cancer therapy, which requires maximum 400 MeV/u carbon beam, at KIRAMS. In the study, we optimized the magnet lattice configuration to fit into the therapy purpose. Major requirements for the purpose are (1) long extraction time (about 1 second), (2) compact size, and (3) low cost. For the requirement (1), a slow extraction scheme was adopted by the use of third integer resonance. For (2) and (3), we minimized the circumference as 69.6 m and a number of the magnet elements as 16 and 20 for bending magnet and quadrupole magnet, respectively. The study was carried out by the use of a simulation codes for beam particle dynamics and optics. A detail of the conceptual lattice design of the carbon-ion synchrotron is described in the paper.

INTRODUCTION

The carbon-ion cancer therapy is known as most efficient treatment. The Bragg peak of carbon-ion at the human body is more localized than the proton beam. In addition, the relative biological effect (RBE) is much higher than the established beam treatment. Therefore, in these days, a construction of carbon-ion synchrotron for the cancer therapy is rapidly increasing. The study for the synchrotron has been carried out at the Korea Institute of Radiological And Medical Sciences (KIRAMS).

LATTICE DESIGN

A design study of the compact synchrotron was carried out through a beam dynamics simulation tool, WinAgile [1]. The Fig. 1 shows the designed layout of the synchrotron.

Table 1: Basic Machine Parameters

Specifications	
Particle	C^{6+}
Injection energy	7 MeV/u
Extraction energy	120 – 400 MeV/u
Circumference	69.6m
Super periodicity	2
Max. dipole filed	1.47 T
Max. filed gradient	4.4 T/m
Tune Q_x/Q_y	1.667/1.563
Natural chromaticity ξ_x/ξ_y	-0.024/-0.944

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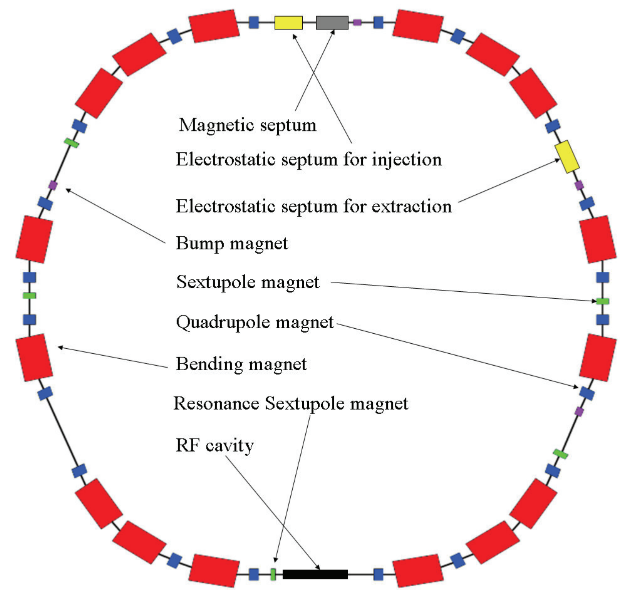

Figure 1: Layout of the synchrotron. Each colour indicates respective category of components. The red block, for example, correspond to the bending dipole magnet.

At the conception stage of the design, we required a compact size, a reasonably small aperture of the ring, and dispersion free region. The compact size of the synchrotron was required to minimize building cost for the facility in which the synchrotron will be placed. The small aperture size is necessary to reduce power consumption of the magnet component of the synchrotron. Lastly, the dispersion free region is required to place a resonance sextupole magnet, RF-cavity, beam injection, and beam extraction components. Thereby, we intended to avoid complex dynamics like a coupling effect between horizontal motion and vertical motion.

The circumference of the designed synchrotron is 69.6 m. The resultant diameter of the ring is 21.25 m. The number of bending dipole magnets and quadrupole magnets are 16 and 20, respectively. The magnetic rigidity of maximum energy (400 MeV/u) is 6.34 T m. The dispersion free region was obtained by adjusting field strength and position of each magnet component.

The resultant Twiss function is shown in Fig. 2.

The ranges of betatron function for horizontal and vertical space are 1.4 – 15.9 m and 5.0 – 15.8 m, respectively. The two dispersion free region of length of 4.2 m could be obtained, and a super periodicity of the synchrotron lattice is 2. To adjust a chromaticity, 4 families of sextupole magnet were implemented to the lattice. 2 families are horizontally acting sextupole magnets, and other 2 families are vertically acting

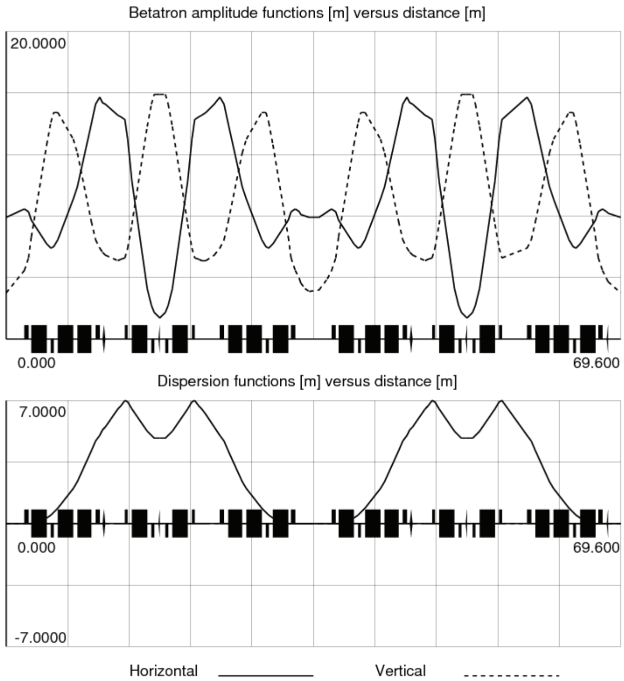

Figure 2: The betatron and dispersion functions. The solid line is for horizontal plane, and the dot line is for vertical plane. The Betatron function vs. distance (top) and the dispersion function vs. distance (bottom).

sextupole magnets. Each sextupole magnet is positioned in a diametrically symmetric way, to avoid the third order resonant excitation that is not desired at the cycle of injection and acceleration.

The basic lattice structure of the synchrotron comprises the bending magnets, the quadrupole magnets, and the sextupole magnets. Through the design study, we could achieve a compact size, reasonable size of betatron function, and implementation of dispersion free region.

INJECTION

The injection system from the linac to the synchrotron is one of most important part in the design of the synchrotron, because the initial beam condition affects the whole beam dynamics.

The system consists of one electrostatic septum, three orbit bump magnets. The beam from the linac is injected through electrostatic septum. A typical kick angle of orbit bump is around 2 mrad. The energy of injection beam is set to 7 MeV/u.

To achieve sufficient amount of beam in the ring, we chose a multi-turn injection scheme. For the horizontal phase space, the injected beam is filled in a desired horizontal total emittance realm by collapsing strength of the injection bump magnet. For vertical phase space, the mismatched injection beam is filled in a vertical total emittance to minimise the size of the vertical emittance. The resultant phase space of injected beam after 16 turns is shown in Fig. 3.

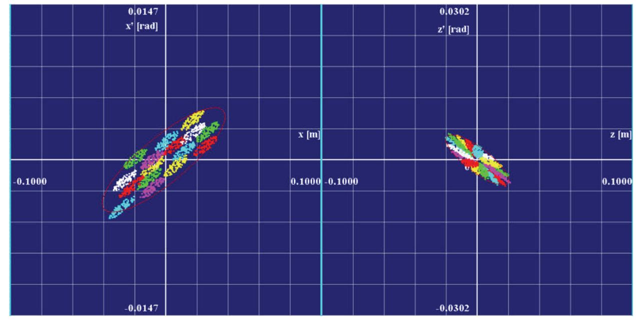

Figure 3: Phase space distribution of injected beam after 16 turn. The horizontal phase space of injected beam (left) and the vertical phase space of injected beam (right).

To optimize the injection efficiency, the working tune was set to 1.728 and 1.563 for a horizontal tune and a vertical tune, respectively. With emittance of 1 π mm mrad, the resultant total emittance for 16 turn injection is about 22 π mm mrad and 12 π mm mrad for horizontal phase space and vertical phase space, respectively.

EXTRACTION

The applied extraction scheme is the third integer resonance driving method. The extraction system consists of one electrostatic septum for beam deflection, three orbit bump magnets for orbit excitation at the electrostatic septum, and one magnetic septum for beam extraction. The extraction energy is 120 MeV/u to 400 MeV/u. The working tune for the extraction is set to 1.667 and 1.563 for a horizontal and a vertical phase space, respectively.

To excite the resonance, a resonance sextupole magnet is implemented. The resonance sextupole magnet is placed on the dispersion free region to avoid an influence on the chromaticity of the synchrotron. When the resonance sextupole is turned on, the separatrix is formed.

The electrostatic septum is located in a dispersion region of (D_x>0, D'_x<0). The first condition for efficient transfer to the electrostatic septum is the phase advance of 225° between the resonance separatrix and the electrostatic septum. The second condition for the transfer to the magnetic septum is the phase advance of 90° since the electrostatic septum. In the present design, the phase advance is 233° and 90°, respectively. The last condition for the extraction is satisfying the Hardt condition, which guarantees minimum beam loss at the septum. Fig. 4 shows the resultant phase space distribution of separatrix and extracting beam.

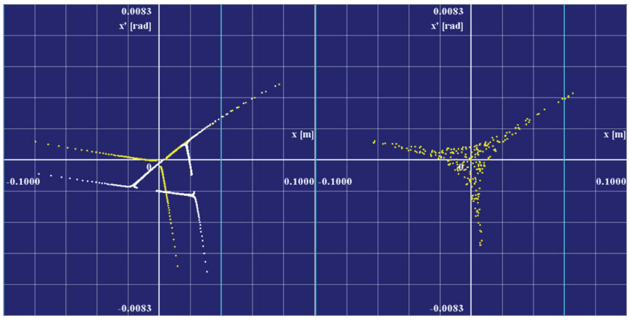

Figure 4: The horizontal phase space distribution of separatrix at extraction mode: the separatrix distribution for on-momentum beam and off-momentum beam (left) (the lines of separatrix at septum occupy same phase space for respective momentum by satisfying the Hardt condition); the phase space distribution of beam at extraction mode (right).

SUMMARY

The conceptual compact synchrotron for carbon-ion cancer therapy is designed and the circumference of the synchrotron is 69.6 m. The third integer resonance scheme, which generates slow beam extraction, was studied.

Further optimization work is in progress.

REFERENCES

[1] P. J. Bryant, in Proceedings of the European Particle Accelerator Conference 2000, Geneva, Switzerland, p. 1357.