DESIGN OF SYNCHROTRON AT NIRS FOR CARBON THERAPY FACILITY

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Abstract

Based on 10 years experience of carbon therapy at HIMAC, the conceptual design of the carbon therapy accelerator facility has been carried out in order to provide such beneficial treatment around Japan. It is required for the synchrotron to accelerate carbon ions from 4 MeV/u of injection energy to 400 MeV/u corresponding to the 275 mm range in water. In the design of the synchrotron, the radius of 10 m and the dipole-magnet filling factor of 43 % are achieved with FODO lattice structure. In this paper, the conceptual design of the synchrotron dedicated to carbon therapy is presented.

INTRODUCTION

Heavy-ion beams have attracted growing interest for cancer treatment due to their high dose localization at the Bragg peak as well as high biological effect there. Recently, therefore, heavy-ion cancer treatments have been successfully carried out and scheduled at various facilities around the world [1-3].

Clinical trials of heavy ion therapy in HIMAC (Heavy Ion Medical Accelerator in Chiba) [1] started on June 1994, and treatments of more than 1800 patients were successfully completed by February 2004. On the other hand, as one of the objectives of HIMAC, new technologies in heavy-ion therapy and related basic and applied research have been developed. Based on these developments and experiences of 10 years, the new facility design project [4] is in progress at National Institute of Radiological Sciences (NIRS). This project aims to design the hospital-based compact facility and to popularize it around Japan.

For this purpose, the design of a synchrotron ring for the new facility has been carried out according to the leading design strategies, which are 1) simple system, 2) compactness, 3) high reliability and 4) low cost. The main role of the synchrotron is to accelerate ions from 4 MeV/u of the injection energy to 400 MeV/u of the maximum energy, and to provide the enough number of ions for the treatment. Based on above consideration, the synchrotron dedicated for the compact therapy facility is designed and reported in this paper.

DESIGN CONSIDERATIONS AND SPECIFICATIONS OF MACHINE

According to 10 years experiences of clinical trials, the facility needs carbon ions with the range in water of 25 cm in patient body. Thus, the synchrotron has to accelerate enough number of carbon ions to a maximum energy of 400 MeV/u at least. Considering the leading design strategy, the FODO lattice structure is chosen, because this simple structure can increase the dipole-magnet filling factor while keeping the small beam size. The small beam size contributes to reduce the electric power consumption owing to the small aperture. The number of FODO cell is to be 6. The extraction system should be carefully designed to achieve the compact design, because the extraction component is the longest one around the ring. After the design studies on several lattices, the lattice structure is decided as shown in Fig. 1. In this lattice, each cell contains 3 dipole magnets having rectangular shape and two kinds of quadrupole magnets (QF and QD). Consequently the synchrotron is compact with a circumference of 61.5 m, because the dipole-magnet filling factor of 43 %. The main parameters are listed at table 1. Each short-straight section has enough length to install small component such as the correctors and the vacuum pumps.

While the horizontal tune has to be set close to 5/3 for the third-order resonant slow-extraction, the vertical tune

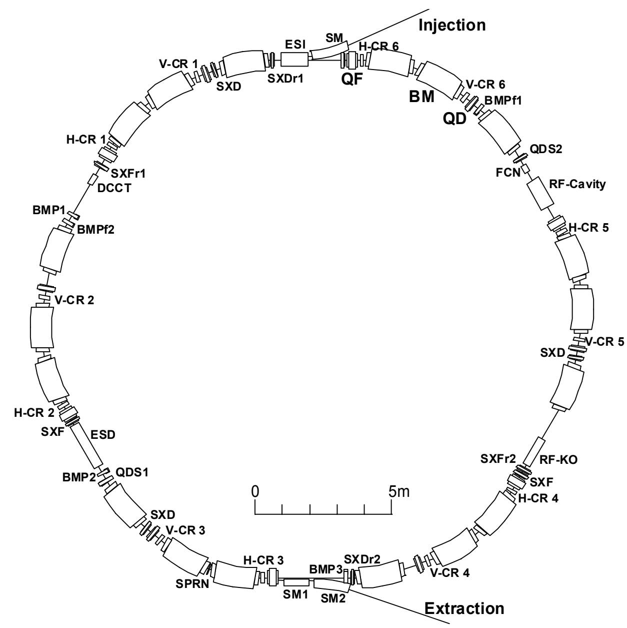

Figure 1: Layout of the synchrotron ring.
BM – Dipole magnet; QF/QD – Quadrupole magnet; BMP – Bump magnet; SM – Septum magnet; QDS – Fast quadrupole; SX – Sextupole magnet; CR – Correctors and pickups

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should be decided considering the beam size and the resonance characteristics. For the reduction of the dipole magnet gap, the vertical tune of 1.27 is optimum with the phase advance per cell of 76 degree. Since it is necessary to avoid the sector resonances of Qx+3Qy=6 and 2Qx+2Qy=6, the working point is set to be (Qx, Qy)=(1.72, 1.13) at the injection with the phase advances per cell of 103 and 68 [degree] in the horizontal and vertical plane, respectively. The twiss parameters are shown in Fig. 2. The CODs without the correction are estimated to be about 4.5 mm for the horizontal and 1.7 mm for vertical at 2σ, respectively.

Table 1: Main parameters of the synchrotron.

Lattice Type	FODO
Maximum intensity of C^{6+}	2×10^9 pps
Cell number	6
Long straight section	3.0m×6
Circumference	61.5m
Injection energy	4 MeV/u
Extraction energy	140-400 MeV/u
Revolution frequency	0.450-3.483MHz
Emittance and Δp/p of injection beam	10 π mm mrad ±0.2%
Acceptance (after COD correction)	240/30 π mm mrad
Momentum acceptance	±0.4%
Qx /Qy	1.68-1.72/1.13
Maximum β function	11.5/13.4
transition gamma	1.72
ξx/ξy	-0.5/-1.5

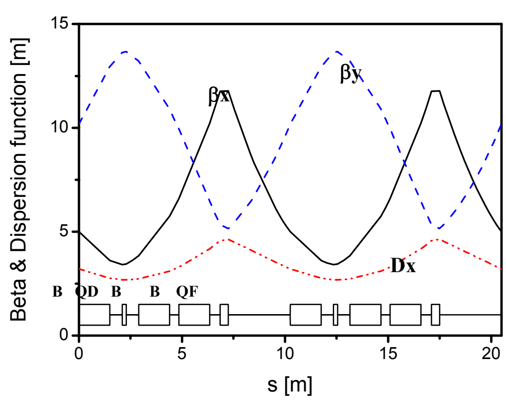

Figure 2: Beta function and dispersion function for two periods of the synchrotron lattice.

Magnet system

The laminations of 0.5 mm thickness will be stacked on an arc to suppress the sagitta of 33 mm in the rectangular dipole magnet. The window-frame type of magnet is foreseen with the maximum dipole field of 1.5 T. The field uniformity of the magnet is to be $\pm2\cdot10^{-4}$. In order to increase the duty factor toward the respiration-gated irradiation, the ramping rate is to be 3 T/s at goal. In order to reduce the unwanted field caused by the eddy currents, the vacuum chambers with 0.3 mm thickness stiffened by ribs are planed for the dipole ones. The magnet gap of 56 mm is foreseen to keep the vertical acceptance of 30 π mm mrad after the COD correction.

The quadrupole magnets will also have stacked with 0.5 mm laminations. The lengths of the magnets are 0.35 m of QF and 0.15 m of QD. The maximum field gradients are 5 and 3 T/m, respectively. The bore radius of 65 mm and the field uniformity of $\pm2\cdot10^{-3}$ are foreseen.

Injection system

The fully stripped carbon ions from the injector linac will be stored into the ring by means of the multi-turn injection method. The horizontal emittance of 200 π mm mrad is determined to obtain the injection gain of more than 15, while the emittance of the injection beam is less than 10 π mm mrad. The injection system contains two bump magnets (BMPf1,2), an electrostatic inflector (ESI) with the septum thickness of 0.5 mm, and a septum magnets (SM). The simulation of the multi-turn injection was carried out in order to optimize the related parameters. As a result, the injection gain is estimated to be 18 just after the injection period of 180 μs corresponding to 80 turns. The horizontal beta-function of the injection beam at the injection point will be set at 0.55 m. Under the injection current of 200 μA, the beam intensity of $8\cdot10^9$ ions is expected without any beam losses. In this case, the incoherent vertical tune shift is estimated to be 0.06.

Acceleration system

For acceleration, the RF cavity with the magnetic alloy core [5] is chosen because of tuned-free. The frequency ranges from 0.8 to 7.0 MHz under the harmonic number of 2. While the momentum spread of the injection beam is ±0.1 %, the maximum RF voltage of 2 kV is necessary to achieve the capture efficiency of more than 90 %. The simulation result of RF capture including the space charge effect is shown in Fig. 3. As increasing the dilution factor, the capture efficiency decreases owing to the momentum acceptance of ±0.4 %. The momentum spread at the beginning of the acceleration will be ±0.4 %, and to be ±0.03 % after the acceleration. In order to suppress the space charge effect by decreasing the maximum beam density in the bunch, the second harmonics component of the RF will be additionally employed.

Extraction system

At the HIMAC synchrotron, the RF-knockout slow extraction method [6] has been routinely used for therapy and the experiments of physics and biology. For therapy usage, the RF-knockout extraction has an advantage of the quick response within several hundred μs of beam on/off for the respiration-gated irradiation [7]. Since the beam delivery system [8] in the proposed facility also plans the layer-stacking irradiation method [9] with the respiration- gated irradiation, the RF-knockout slow-extraction should be employed. Since this method utilizes

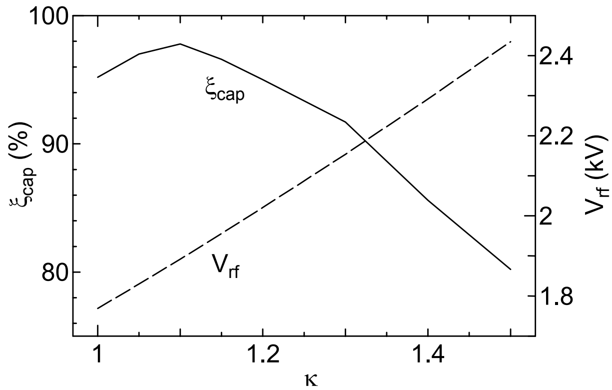

Figure 3: Capture efficiency and RF voltage as a function of dilution factor.

the constant separatrix, further, we can easily keep the extracted beam size and position constant. We can also make it possible to control the time structure [10] as a result of the study at the HIMAC synchrotron.

The extraction system contains three bump magnets (BMP1-3), two pairs of the separatrix exciter (SXFr/SXDr), the electrostatic deflector (ESD), two successive septum magnets (SM1,2), and the transverse RF kicker (RF-KO). Two pairs of the sextupoles can rotate the separatrices, while keeping the separatrix size constant. In order to enlarge the turn separation at the entrance of the septum magnet, the phase advance between ESD and SM1 is to be around 90 degree. The ESD is two successive plate of 0.8 m length with the gap of 13 mm. The maximum electric field of 100 kV/cm is foreseen. The maximum fields of the septum magnets are 0.5 and 1.5 T, respectively.

The optimized separatrices for each momentum and the trajectory of last 3 turns are shown in Fig. 4. While the turn separation at the entrance of the ESD is about 10 mm, the bump orbit is set to be (22mm, -2.8mrad) there. The separatrix for different momentum is well aligned owing to the Hardt condition [11] under the horizontal chromaticity of around –1. The area of the separatrix is 40 π mm mrad. The trajectory of the last 3 turns is well suppressed not to over the envelope of the injected beam.

SUMMARY

The conceptual design of the synchrotron ring for the compact carbon therapy facility is carried out. While the lattice is compact design with a circumference of 61.5 m, the dipole-magnet filling factor of 43 % is achieved owing to the FODO lattice structure. The ring will be able to achieve the requirement for the therapy use with the carbon ions.

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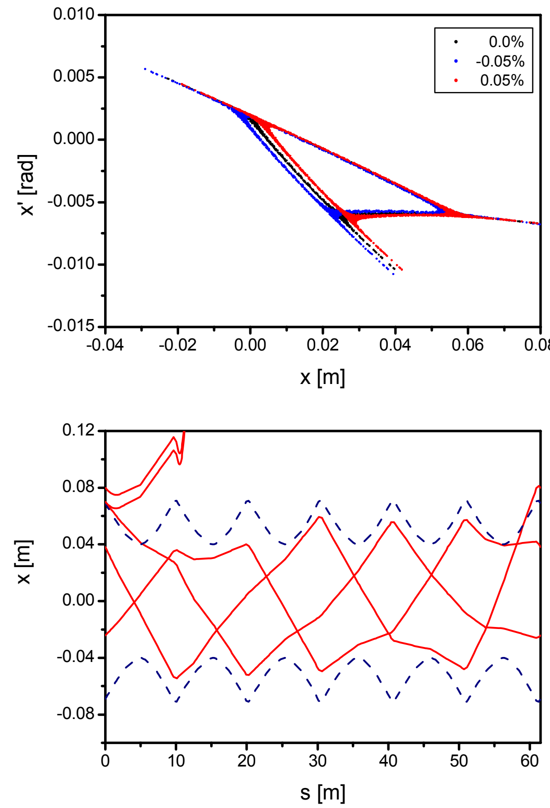

Figure 4: (a) Separatrix for each momentum of -0.05, 0.0, and 0.05 %. (b) Trajectory of last 3 turns and the extracted beam. Dashed curve represents envelope at injection including corrected COD.

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