MAGNET DESIGN FOR PROTON AND CARBON ION SYNCHROTRON FOR CANCER THERAPY

H. S. Suh*, Y. K. Jung, H. S. Kang#
PAL, POSTECH, Korea

Abstract

The magnets for a medical synchrotron were designed. The synchrotron is for cancer therapy with proton and carbon-iron beams. The synchrotron components are the magnetic septa, electrostatic septa, betatron core and conventional magnets. This design was carried out to satisfy the requirements made by the beam dynamics simulations. We used 3D code for the electromagnetic simulation and the optimization of magnetic structures. In this paper, the basic design process for the electromagnetic devices will be presented.

INTRODUCTION

This work concerns the proposal for the development of the synchrotron for the cancer therapy in Korea. The circumference of the synchrotron is only 60 meter, and the lattice is a FODO structure of 6 cells. Each cell has two dipole magnets with a bend angle of 30°. Figure 1 shows a schematic layout of the synchrotron in the course of design.

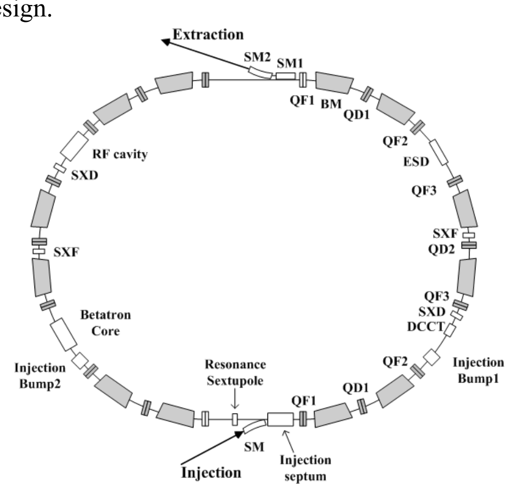

Figure 1: Layout of the synchrotron.

The beam energy from the linac is 20 MeV for proton and 7 MeV/u for carbon ion. And the extraction energy ranges are 50~250 MeV for proton, and 85~430 MeV/u for carbon. The conventional magnet system is composed of 12 bending magnets, 18 quadrupoles, 4 sextupoles and 1 resonance sextupole. Their poles are shaped to minimize the integrated errors as the individual requirements. Main devices for the injection and extraction are the magnetic septa and electrostatic septa. And a betatron core increases the beam energy to be extracted with the resonant sextupole. The electromagnetic simulations are used with OPERA/ TOSCA, /ELEKTRA. A brief description of design features will be given here.

*suhhs@postech.ac.kr
#hskang@postech.ac.kr

MAGNET DESIGN

Magnetic Septa

Magnetic septa are used for injection and extraction as shown in Table 1. These septa will be dc and will only be changed when the particle species are changed. Their cores are C-type configuration and laminated. To reduce the leakage field in the adjacent bypass channel as low as possible, the pole is shallow. Figure 2 shows the FEM model of injection magnetic septum.

Table 1: Characteristics of Magnetic Septa

	Injection Septum	Extraction Thin Septum	Extraction Thick Septum
Effective length [m]	0.450	0.680	1.024
Yoke length [m]	0.413	0.641	0.978
Maximum field [T]	0.426	0.489	0.973
Deflection angle [mrad]	250	50	150
Temperature rise [℃]	5	9	12

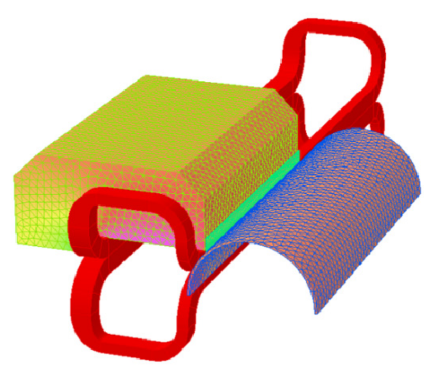

Figure 2: FEM 1/4 model of injection septum.

A field shield plate will be used to drop the field off at the stored chamber. The vertical magnetic field of the injection septum on the midplane is plotted in Figure 3.

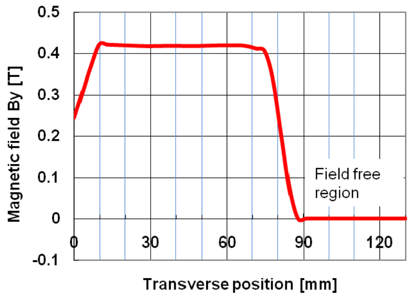

Figure 3: Magnetic field distribution of the injection septum on the midplane.

Electrostatic Septa

An electrostatic injection septum deflects the beam from the linac at the angle of 60 mrad. Another electrostatic septum deflector (ESD in Figure 1) is used for beam extraction with the betatron core. Table 2 shows the difference of the electrostatic septa.

Table 2: Electrostatic Septa

	Injection ES	Extraction ES
Effective length [m]	0.6	1.0
Max. electric field [MV/m]	2.8	8.6
Deflection angle [mrad]	60	5.9

From the equation of the motion, we can estimate the required electric field being followed.

$$m\frac{d^2x}{dt^2} = qB_x$$

$$\int m\frac{d^2x}{dt^2}dl = \int qB_x dl$$

$$\int mv^2\frac{d^2x}{dl^2}dl = \int qB_x dl$$

$$mv^2\theta = qB_x L_{eff}$$

$$B_x = \frac{mv^2\theta}{qL_{eff}} = \frac{B\rho v\theta}{L_{eff}}$$

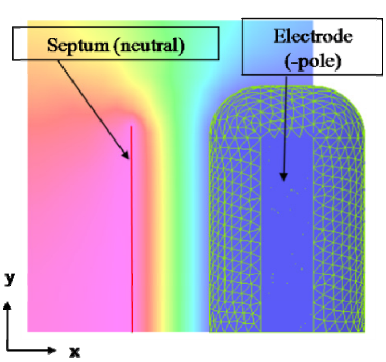

Figure 4: Potential contours of the electrostatic extraction septum.

For the extraction septum, the magnetic rigidity for carbon ion of 430 MeV/u is 6.65 Tm, the bending angle of 5.9 mrad, the effective length of 1.0 m, so the required electric field is 8.6 MV/m. The potential contours of the electrostatic extraction septum based on FEM are shown in Figure 4.

Betatron Core

A change in magnetic flux makes electromagnetic induction. Using this a betatron core increases beam energy to extract smoothly. The spill rate can be adjusted by the betatron. We should elaborately calculate the magnetic flux change including the eddy current and the nonlinear effects. The equations of the betatron are followed. The variation of kinetic energy by the betatron is: $\Delta E = Ze\, d\Phi/dt$, where Φ is the magnetic flux. Figure 5 shows the schematic view of the betatron and Figure 6 shows the magnetic flux lines inside core.

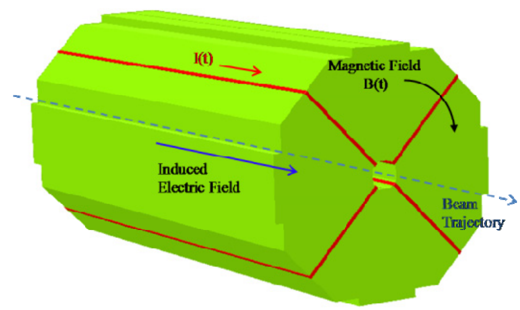

Figure 5: Schematic view of the betatron core.

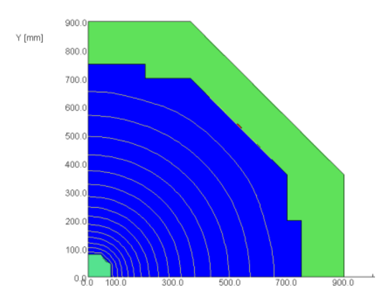

Figure 6: Flux lines inside betatron core.

Dipole Magnet

Yoke shape of the dipole magnet is H type for good field uniformity and curved to reduce a volume. The nominal magnetic field is 1.5 T and the gap height is 70 mm. The poles have been optimized to reach the required homogeneity. The FEM model of the magnet is given in Figure 7, the homogeneity of the field (< ±2x10-4 for x: ±60 mm) is presented in Figure 8. The main parameters are summarized in Table 3.

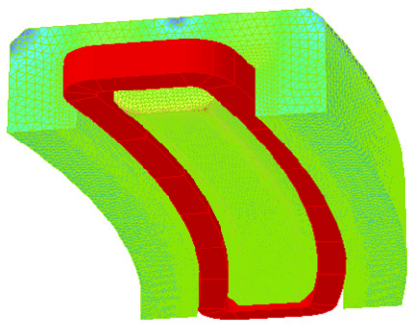

Figure 7: FEM 1/2 Model of Dipole Magnet.

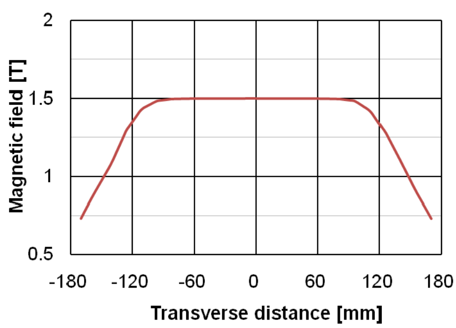

Figure 8: Field uniformity of dipole magnet.

Table 3: Dipole Magnet Parameters

Magnetic field	1.5 T
Effective length	2.2 m
Yoke length	2.074
Weight	10.5 tons
Bending angle	30°
Pole gap	70 mm
Good field region	±60 mm
Field uniformity	$< \pm 2\times10^{-4}$
Power	41 kW
Pressure drop	6.5 bar
Temperature rise	13 ℃

Sextupole Magnet

Sextupoles are required for chromaticity correction and for resonant extraction. Two kinds of the sextupoles have the same core but different coil size and turn number. Figure 9 shows FEM model and flux profile of the sextupole. And the major parameters are summarized in Table 4.

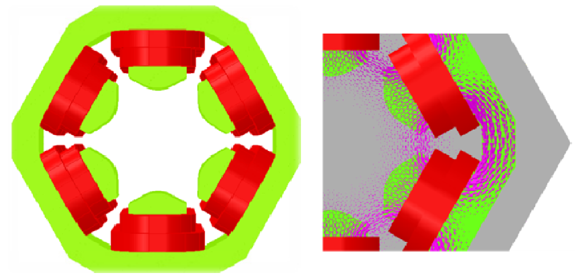

Figure 9: FEM model of sextupole and flux profile.

Table 4: Principal parameters of sextupoles

Parameters	Main Sextupole	Resonance Sextupole
Field gradient [T/m^2]	35	80
Effective length [mm]	300	300
Yoke length	172	172
Aperture radius [mm]	75	75
Good field radius [mm]	60	60
Multipole harmonic	$< \pm 4\times10^{-3}$	$< \pm 4\times10^{-3}$
Power [kW]	813	3317
Temperature rise [℃]	3	10

SUMMARY

A first conceptual design of magnets for the medical synchrotron has been performed. But we should investigate the field profile of the magnets in the cases of the low and the high energy operation. Particularly the betatron core needs many transient calculations for the constant flux change.

ACKNOWLEDGMENT

This work was supported by Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST). (Grant code: M20090062 474)

REFERENCES

[1] "Proton-Ion Medical Machine Study (PIMMS)", Accelerator Complex Study Group, CERN/PS 99-010

[2] H. S. Kang, J. Y. Huang, J. H. Choi, "Lattice Design of a Carbon-Ion Synchrotron for Cancer Therapy", Journal of the Korea Physical Society, Vol. 53, No. 2, August 2008

[3] H. S. Kang and H. S. Suh, "Lattice Design of a Carbon-Ion Synchrotron for Cancer Therapy" EPAC'08, Genoa, 2008

[4] Jack T. Tanabe, "Iron Dominated Electromagnets"