Design of the Very High-Field Short-Pulse Dipole magnet

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Abstract

Design of a short-pulse dipole magnet for a compact proton synchrotron dedicated for cancer therapy is presented. Numerical analysis is applied for design of coil geometry of the dipole magnet. Its acceleration time and maximum magnetic field are 3.5 [ms] and 4 [T], respectively. At middle part of aperture in beam direction in the dipole magnet, the value of sextupole coefficient is reduced to 3×10^{-4} (24 [T/m^2]) at 4 [T] by the optimization of the magnet geometry, which is estimated to be sufficiently small for beam acceleration. Even considering influence of the field at the magnet ends, the value of sextupole coefficient is within $|1\times10^{-3}|$. B-constant shape rather than Rogowski's curve is adopted at the end of the magnet.

1. INTRODUCTION

For wide spread use of proton radiation therapy, which is mild for patients suffering from cancer, proton synchrotrons are required to be decreased in size of total system or to be reduced in its cost. To attain a sufficient energy for cancer therapy in a very compact scale, the magnetic field of the normal-conductive bending magnet have to be excited up to 3 - 5 [T]. Proton synchrotron using pulsed high field magnet (5 [T]) was proposed by BINP [1], and component development had been made [2]. However, field distortion (especially sextupole component) of dipole magnets remained to be improved. Pecardi et al. [3] proposed the magnet with magnetic field of 4 [T] (referred as STAC magnet hereafter). Recently the design of dipole magnet with magnetic field of 3 [T] was proposed by K. Endo et al. (KEK) [4], and good possibility to realize a very small synchrotron was suggested. Starting from parameters of STAC magnet, we tried to design very high-field, short pulse dipole magnet for compact proton synchrotron dedicated for medical use.

2. MAIN PARAMETERS OF THE SYNCHROTRON AND ITS DIPOLE MAGNET

A compact 200 [MeV] proton synchrotron with the injection energy of 3 [MeV] has been developed. Four bending magnets and two quadrupole magnets form the basic lattice. As the outer dimension is about 2.3 [m], it can be transported to hospitals after the assembly and tuning in the factory. Main parameters of synchrotron and its dipole magnet are listed in Table 1.

Table 1: Main parameters of the synchrotron and its dipole magnet

Item	Value
Maximum energy	200 [MeV]
Injection energy	3 [MeV]
Circumferences	6.193 [m]
Average radius	0.986 [m]
Tune, ν_x/ν_y	1.38 / 0.43
Rf frequency	3.86 - 27.4 [MHz]
Accumulated protons	1.0×10^{10}
Bending radius	0.54 [m]
Bending angle	90 [deg]
Max. bending field	4 [T]
Max. current	200 [kA]
Acceleration	3.5 [ms]
Inductance	0.4 [mH]
Voltage	40 [V]
Number of turn	1 [turn/coil]
Gap height/width	0.052 / 0.020 [m]

3 DIPOLE MAGNET DESIGN

3.1 Estimation method of field distortion

Figure 1 shows the shape of the dipole magnet. Magnetic fields were analysed using a 3 dimensional, time dependent code "JMAG" [5]. The excited current pattern of the dipole magnet is a quarter wave length of a sine curve.

Magnetic field in the dipole magnet is expanded as follows.

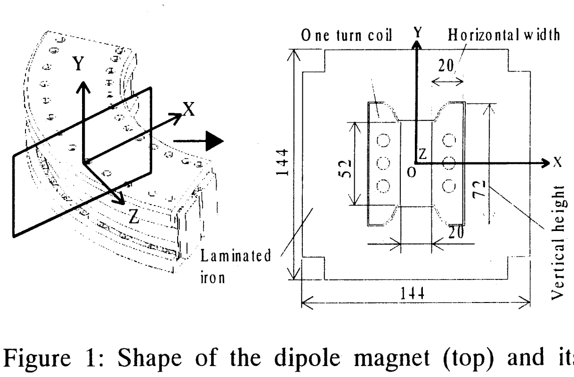

Figure 1: Shape of the dipole magnet (top) and its cross-section (bottom)

$$B_y = B_0 \Sigma_{n=0} (r/r_0)^n \{a_n \cos(n\theta) + b_n \sin(n\theta)\}$$

Where By is y component of the field, and B_0 the field at the center of the magnet. The a_n and b_n are normal and skew 2(n+1)-pole coefficients, and r_0 is a radius of reference circle (In this study, r_0 is 10 [mm]). Considering the symmetry of the magnet, b_n is always zero if we neglect fabricated error. In generally, sextupole component can be expressed as follows.

$$\frac{1}{B_0 \cdot \rho} \cdot \frac{\partial^2 B}{\partial x^2}$$

Where ρ is bending radius of dipole magnet. For example, sextupole component on X axis can be expressed by $2a_2/(\rho r_0^2)$.

In order to keep enough size of dynamic aperture during acceleration, the sextupole coefficient ($|a_2|$) must be controlled at least under $2\text{x}10^{-3}$ [3].

3.2 Reduction of multipole coefficients

As this dipole magnet is normal-conductive magnet, the magnetic core begin to be saturated at approximately 2 [T] (about 1 [ms]). Therefore the field distortion can not be reduced by improving the shape of magnetic pole. Instead, considering the penetration into the coil, we reduced the field distortion by changing vertical height of the coil geometry. Detailed explanation about improving coil geometry was reported in the previous report [6]. Figure 2a shows several design cases of coil geometry, and 2b shows time evolution of a_2 on each coil geometry at middle part in the beam direction. Increasing vertical height of coil geometry according to current penetration (Figure 2a: case2 - 4), optimal geometry with the sextupole coefficient of $3\text{x}10^{-4}$ was obtained. As shown in Figure 3, the size of dynamic aperture which was

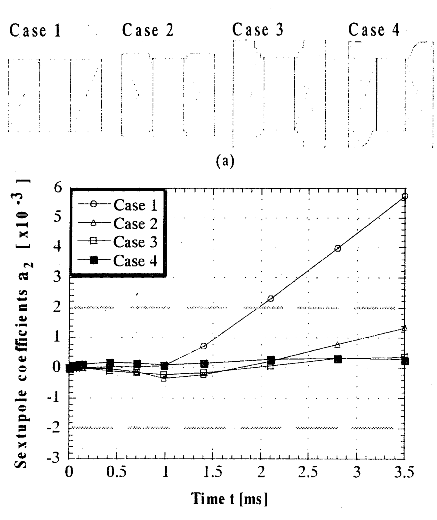

Figure 2: Coil geometry on several design cases (a), and time evolution of sextupole coefficient on each coil geometry (b).

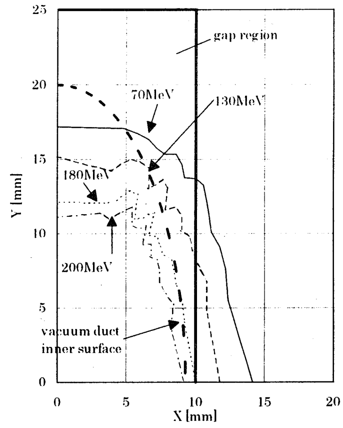

Figure 3: Energy evolution of dynamic aperture

calculated using the optimal value of a_2 and a_4 (case4) is kept during acceleration. Detailed consideration about lattice design or dynamic aperture were reported in the previous report [7].

3.3 Effect of the field at magnet end

Time evolution of field distribution in the longitudinal direction around magnet end is shown in Figure 4. In the figure, vertical axis shows field strength at the center of aperture. The figure indicates that there is leakage field outside the magnet. In order to study field distortion including the influence of the field at magnet end, field distortion is estimated using following value.

$$(B \cdot L) = \int B(l) \cdot dl$$

The case 1 in figure 5 shows time evolution of sextupole coefficients considering the influence of the magnet-end field. The figure indicates that the value of $|a_2|$ increases to $1\text{x}10^{-3}$, though the value of $|a_2|$ at middle part in the beam direction is $3\text{x}10^{-4}$ (case 2, not considering the influence of magnet-end field). The main reason for increasing the distortion is that the change of current route at the magnet end. Here, case 3 shows time

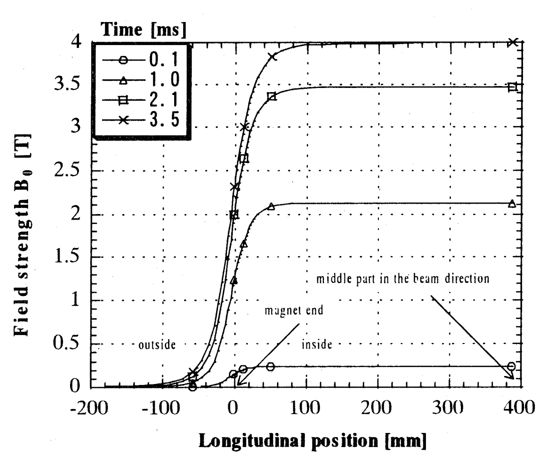

Figure 4: Time evolution of longitudinal field distribution on magnet end

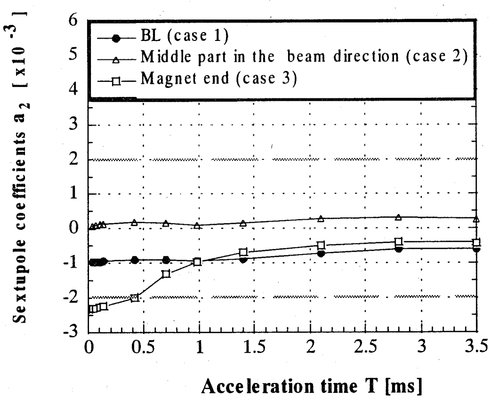

Figure 5: Time evolution of sextupole coefficients at different region.

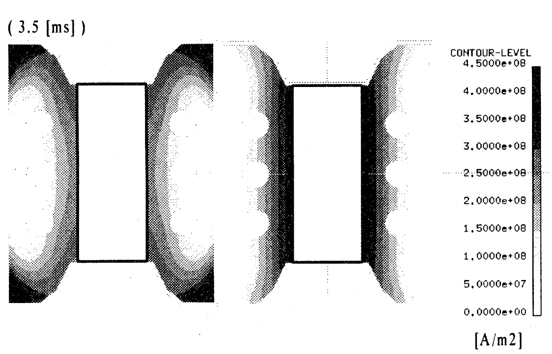

Figure 6: Current density distribution contour of the coil cross-section at different position in the beam direction. (left: magnet end, right: middle part in the beam direction)

evolution of the a_2 considering the field only at the magnet end. This result shows that the field distortion become worse at the magnet end, due to changing the current density distribution at magnet end (Figure 6).

3.4 Effective length

Figure 7 shows the time variation of the effective length at the center of the aperture for different longitudinal edge shapes. Before improving the magnet end (rectangular shape), there is considerable change of the effective length until 1[ms], while there is only a slight increase after 1[ms]. In case of the Rogowski curve end, the time variation does not become small. On the other hand, as the magnet ends are cut stepwise along the constant magnetic flux density contour (B-constant shape), the longitudinal edge shape gives smaller time variation of the effective length.

4 CONCLUSIONS

Very high-field, short pulse dipole magnet was designed.

To reduce multipole field components, coil shape was designed by increasing vertical height of coil geometry

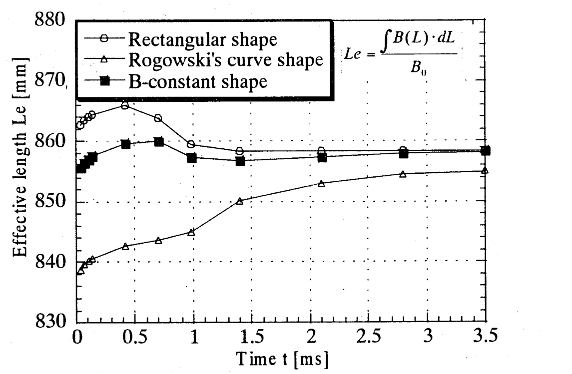

Figure 7: Time variation of the effective length at the center of the aperture

according to current penetration into the coil. Using this coil geometry, the sextupole coefficient $|a_2|$ can be controlled within $3x10^{-4}$ (24 [T/m^2]) at 4 [T], so that enough dynamic aperture can be kept during acceleration. Even considering the influence of magnet-end field, the sextupole coefficient $|a_2|$ can be controlled within $1x10^{-3}$. Besides, to diminish the time variation of the effective length, the shape of magnet ends in beam direction should be shaped along the constant magnetic flux density contour. Smaller time variation of the effective length can be obtained.

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