FIELD MEASUREMENT OF COMBINED FUNCTION MAGNET FOR MEDICAL PROTON SYNCHROTRON*

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Abstract

A compact proton synchrotron dedicated for cancer therapy is proposed. Using combined function magnet, compactness and easy daily operation would be achieved because of self tracking between dipole and quadrupole magnetic fields. The tuning of the operation point at the design stage, however, is more difficult than separate function magnets. In order to confirm feasibility of such a ring, we made a model magnet. The magnetic field distributions were measured by a three-axis hall probe. And we evaluated tune values.

1 INTRODUCTION

For a charged particle cancer therapy, low construction cost and easy handling in daily operation are required for the accelerator. The compact proton synchrotron with combined function magnets is satisfied these requirement. The merits of using combined function magnet are easy operation from rigidity of its operating condition and low construction cost. The magnet design, however, should be accurate enough to work without adjustment.

Thus, we developed a reference design of the combined function magnet with a help of three-dimensional magnetic field calculation code TOSCA and tune value evaluation based on the particle tracking [3]. To verify the accuracy of the three-dimensional field calculation, we made a model magnet and measured magnetic field distribution.

In the following paper, we report our measurement method and its results.

2 DESIGN OF MAGNET

The proposed ring[1][2] is shown in Fig.1. Our ring has a six-fold symmetry and one cell is constructed by 60 degree bending sector magnet and 2 meters drift-space. The radius of the design orbit is 1.9m. The maximum field strength on the design orbit is 1.28T to accelerate proton up to 250MeV. The designed horizontal and vertical tune-value are 1.7 and 1.75, respectively.

The focusing elements are embedded in the bending magnets as FDF triplet. The n-value of the magnet sectors are 6.164 for a D-sector and -5.855 for a F-sector. From the tune value evaluation by the particle tracking method based on TOSCA results, bending angles of F, D and F sector are tuned 15.25, 29.5 and 15.25 degree, respectively.

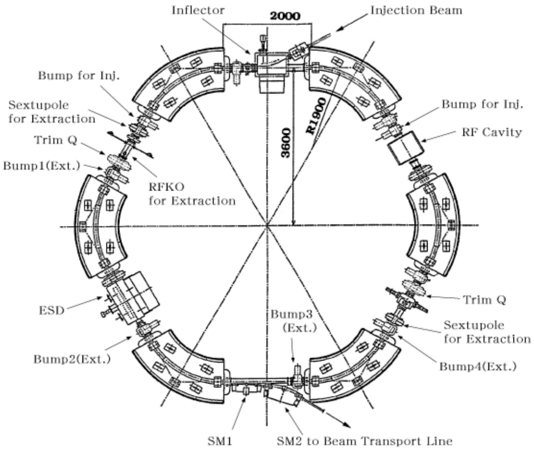

Figure 1: Structure of the synchrotron ring

3 MODEL MAGNET MEASUREMENT

3.1 Model Magnet

To verify the accuracy of the three-dimensional field calculation, we made a model magnet and measured magnetic field. Figure.2 shows the lower half of the model magnet, which made of the laminated iron sheets with thickness of 0.5mm.

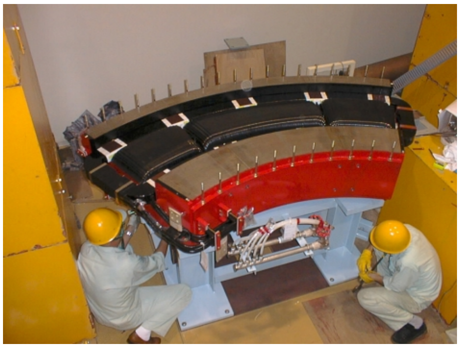

Figure 2: Lower half of the model magnet

3.2 Measurement Strategy

To evaluate tune value by tracking, we have to measure magnetic field distribution around the median plane. The hall probe alignment and median plane search are difficult, because our magnet does not have flat region. The sectored magnet shape makes a measurement of whole area difficult at one setup. Using the symmetry between upper and lower

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poles and Maxwell equation $\nabla \cdot \mathbf{B} = 0$, we can reconstruct magnetic field near median plane from major component B_z map on median plane as follows.

$$\begin{aligned} B_x(x,y,z) &= \frac{\partial B_z(x,y)}{\partial x} z + O(z^2) && (1) \\ B_y(x,y,z) &= \frac{\partial B_z(x,y)}{\partial y} z + O(z^2) && (2) \\ B_z(x,y,z) &= B_z(x,y) + O(z^2) && (3) \end{aligned}$$

Because the magnetic field flux crosses perpendicular to the median plane, the horizontal components of magnetic field should be equal to zero on the median plane.

Considering the symmetry of the lattice, we measured the half of the magnet by a three-axis hall probe fixed to a three-axis movable stage. The median plane was searched so as to be crossed whole flux with same angle.

3.3 *Measurement Geometry and Equipment*

Figure.3 shows the geometry of the measurement setup. The Cartesian coordinate grid was chosen to avoid the vibration of the probe arm. The measurement was performed by 5×5mm spacing grid. The measurement region covers the half of D sector, F sector and 10 degree fringe within the radius from 1.84m to 1.96m.

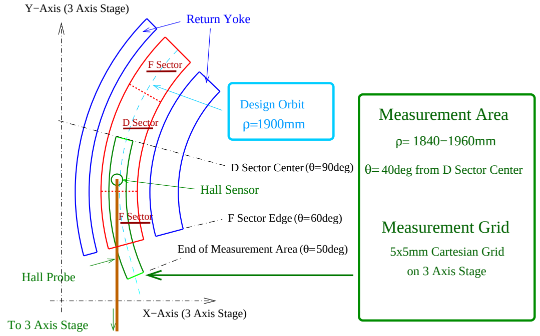

Figure 3: Geometry of measurement setup

We used F.W.BELL gauss meter model 9903 and three-axis hall probe 3X-99-216 whose temperature was controlled by 60°C thermostatic oven. Single axis gauss meter (Group3 tesla meter DTM-151 with hall probe MPT-141) measures the stability at a reference point. The stepping motor driver for three-axis stage is controlled by TUJI DENSHI four-channel pulse motor controller PM4C. All measurement device is controlled by Note PC with NI PCMCIA-GPIB card.

3.4 *Field Interpolation*

Because the raw data of magnetic field distribution are on a Cartesian grid, we have to convert them on a cylindrical grid for convenience. We use the discrete cosine transformation (DCT) to interpolate the grid. To obtain good derivative, we extrapolate non-measured grid by following method. At the first step, we apply DCT and low pass filter. At the second step, we apply inverse DCT and replace measured grid value by origin one. And then, we iterate these step until converged.

4 RESULTS AND DISCUSSION

We measured the magnetic field distribution at excitation current 197, 646, 900, 983, 1100 and 1214A, which corresponded to 0.21, 0.68, 0.95, 1.03, 1.15 and 1.25T on the design orbit, respectively. We found the n-value on design orbit $(-\frac{\rho}{B}\frac{\partial B}{\partial \rho})$ at the center of F and D sector changes about 0.25. And evaluated tune-value excursion exceed 0.1 at vertical axis. Its excursion is too larger than expectation. Figure.4 shows relationship between field strength and field gradient at flat region of D sector. In Fig.4, a discontinuity of field gradient can be seen at 1.0T. This fact suggests the breakdown of the hall probe lineality. We measured a linearity of the hall probe by NMR (ECHO ELECTRONICS EFM-2000AX). Figure.5 shows the error from linear line fitted at the region from 0.2T to 0.9T. We tried to correct the measurement data using piecewise linear function:

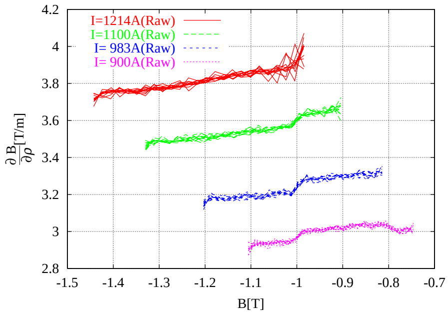

Figure 4: Relationship between field strength and field gradient at flat region of D sector

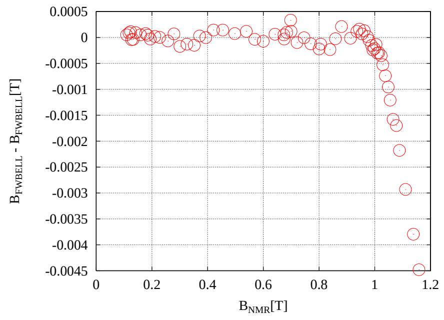

Figure 5: The error between calibration curve and linear fit at the region from 0.2T to 0.9T

$$B_{cal} = B_0 + k_0 \cdot B + k_1 \cdot |B - B_1| + k_2 \cdot |B - B_2|. \quad (4)$$

Figure.6 shows date with correction. Although the fluctuation of field gradient becomes small, the continuity is not

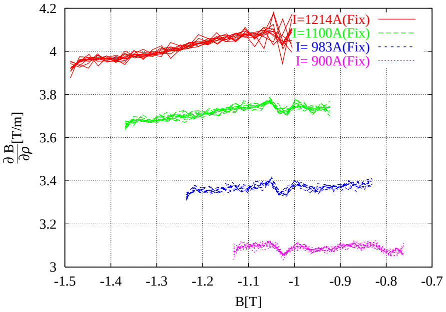

Figure 6: Relationship between field strength and field gradient at flat region of D sector with calibration

completely recovered because of the ambiguity of bending point.

Figure.7 shows θ dependence of the n-values with correction. Except the case of excitation current 1214A, the n-values at the flat region are -5.84 ± 0.02 in F sector and 6.20 ± 0.02in D sector, respectively.

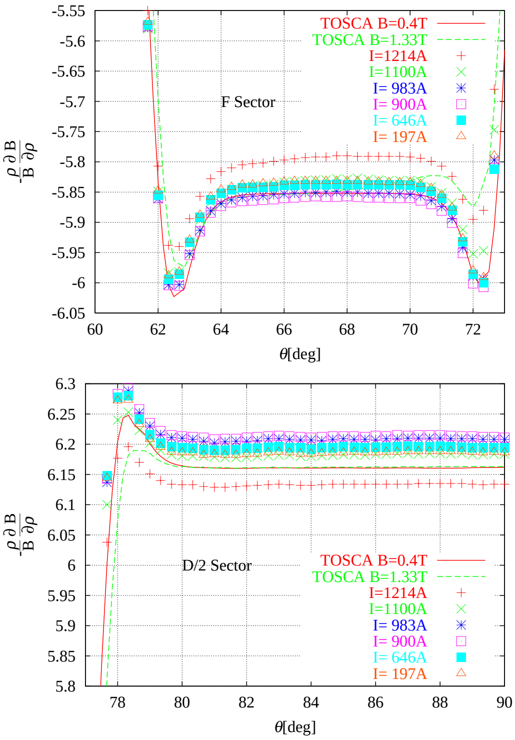

Figure 7: θ dependence of n-value

The calculated beta function and an excursion of the tune value are shown in Fig.8 and Fig.9. At the excitation current 197A, 983A and 1214A, fluctuation of tune value is very large. The excitation current 1214A is not covered by the calibration curve in Fig.5. At 983A, the discontinuity in Fig.6 sits close to the central orbit and affects the betatron oscillation. The resolution of field strength is not enough because of the low absolute value at 197A. Except such cases, the tune values stay around $(1.7, 1.71)$. The tune shift formula with the beta function shown in Fig.8 predicts that a field error propagation coefficient of the vertical tune is 2 or 3 times larger than the horizontal tune.

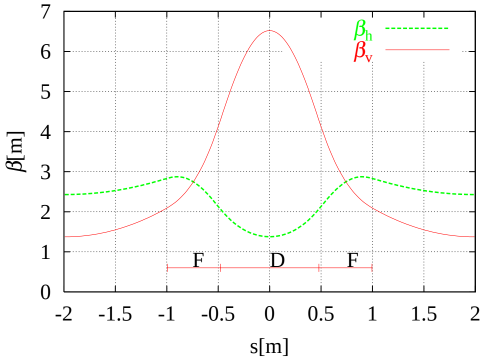

Figure 8: Beta function of cell

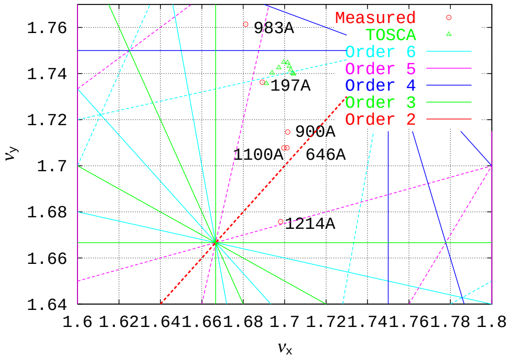

Figure 9: Tune value excursion and resonance line

In order to obtain a accurate tune values, we need a multi-axis probe with good lineality because a bend is difficult to cancel.

ACKNOWLEDGMENT

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