Combined Function Magnet for Compact Proton Synchrotron

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Abstract

For a charged particle cancer therapy, low construction cost and easy handling in daily operation are required for the accelerator. To satisfy these requirement, the compact proton synchrotron with combined function magnets is proposed.

In order to make a reference design of the combined function magnet to be used without adjustment, we developed its design with the help of three-dimensional field calculation and constructed the model magnet to verify the feasibility of the design by measuring its magnetic field distribution.

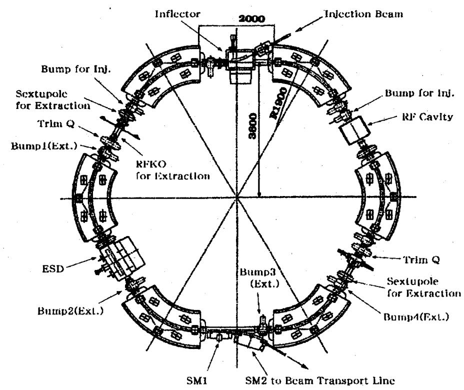

Fig. 1 Overview of our ring

1 Introduction

Recently cancer therapy by charged ion irradiation has been paid attention because it can preserve function and shape of human body and fairly light load to a patient compared with the other therapy.

From the needs of popularizing these therapy, low construction cost, compactness, and easy handling in daily operation is required for the accelerator. As the accelerator achieving such requirement, the compact proton synchrotron with combined function magnets is proposed [1]. The merit of using combined function magnet is easy operation by rigidity of its operation condition and low construction cost. The magnet design, however,should be accurate enough to be used without adjustment.

Thus we developed a reference design of the combined function magnet with the help of three-dimensional magnetic field calculation code TOSCA. In this paper, we describe the outline of our magnet system design and the measurement results of the model magnet.

2 Design Flow

Our synchrotron ring [2][3] is shown in Fig.1. The ring circumference is 23.9m and the ring has six fold rotation symmetry. Each cell of the ring has 2m drift space and 60 degree bending magnet whose curvature radius is 1.9m. The bending magnet is combination of three n-indexed bending sector magnets. And its focusing structure is Focusing-Defocusing-Focusing. The bending angles of F and D sector are 15 and 30 degrees, respectively. The horizontal tune ν_h and the vertical tune ν_v are designed 1.75 and 1.75, respectively. To achieve designed tune values, the n-value of F and D sector are to be -5.8560 and 6.1641, respectively.

Checking the operating condition and brushing up the design, we calculate the three-dimensional magnetic field distribution using TOSCA. The tune value and the beta function are extracted by reconstructing transfer matrix from a set of betatron oscillating orbits which is calculated by the particle tracking. [4]

The first design gives the tune value $(\nu_h, \nu_v) \sim (1.64, 1.86)$, which deviates far from the designed value $(1.75, 1.75)$.

There are two major methods for correction of tune value. One is modifying the n-values of the bending magnet. The other is adjusting the ratio of the bending angle of F to D sectors. In order to minimize a change of the machining schedule, we selected the method to adjust bending angle ratio. This adjustment means local n-value change and the change of the tune values are predicted by the tune shift formula, $(\triangle\nu_h, \triangle\nu_v) \sim (\frac{-1}{4\pi}\oint_C \frac{\triangle n}{\rho^2}\beta_h ds, \frac{1}{4\pi}\oint_C \frac{\triangle n}{\rho^2}\beta_v ds)$. From

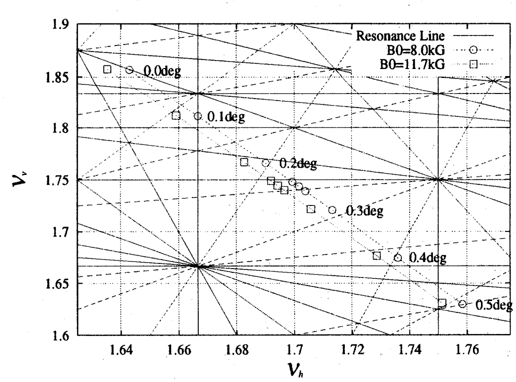

Fig. 2 the dependence of the tune value on bending angle modulation $\triangle\theta$ with resonance lines up to 6th order. $\triangle\theta$ shows increase of bending angle of F sector.

the adjustable line of the tune values shown in Fig.2, we selected operation point $(1.70, 1.75)$ avoiding up to

6th order resonance lines. Finally, the bending angle of F and D sectors are adjusted to be 15.25 and 29.5 degree, respectively.

3 Measurement of Model Magnet

To verify the magnetic field distribution evaluated in the design stage, we constructed the model magnet which are made of the laminated iron sheets whose thickness are 0.5mm.

Considering the symmetry, we measured the half of the sectored area of the magnet using the three-axis Hall-probe [1] (see Fig.3). To keep a movable range for the probe, the edge of the magnet is tilted 15 degree from the axis of the XYZ stage. The measurement has been performed with 5mm spacing in radial direction from 1.84m to 2m and 1 degree spacing in azimuthal direction from the center of D sector to outside of magnet with 43 points.

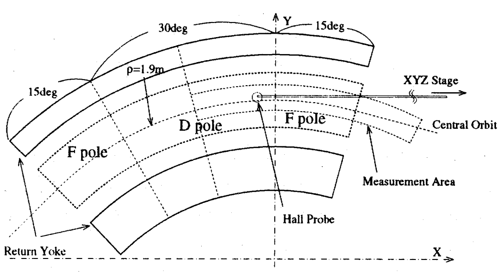

Fig. 3 Measurement setup

From the mirror symmetry between upper and lower poles, the magnetic field flux is perpendicular to the median plain. Therefore the horizontal components of the magnetic field are zero at the median plain. The measured horizontal components, however, are not zero, because of the miss-alignment of the probe axis and the offset of the median plain. Because it is very difficult to know the exact direction of the Hall-probe, we consider that the origin of these horizontal component error is the miss-alignment between the model magnet and the probe axis. Thus we correct the miss-alignment of the probe axis by rotating the measured magnetic field vectors to minimize the sum of the square of the horizontal components.

4 Results and Discussion

In the comparison of the measured magnetic field with the calculated one, we use the vertical component of the magnetic field B_z and the n-value on the line whose curvature radius is 1.9m as the characteristic parameter. The global shapes of B_z and n-value distribution shown in Fig.4 and Fig.5 have good agreement between the measured magnetic filed and calculated one. These results, however, are slightly different in detail. Particularly, the difference of the n-value modulates the tune value directly. The n-value predicted from TOSCA results has the flat top in the center of each sector shown in Fig.5. The n-value of the measured field, however, contain some deviations and these deviation are lager than the deviation predicted from the precision of the measured value. Furthermore we cannot find the correlation such deviation with the coordinates. Therefore the origin of these deviations is considered as the problem of the measurement system.

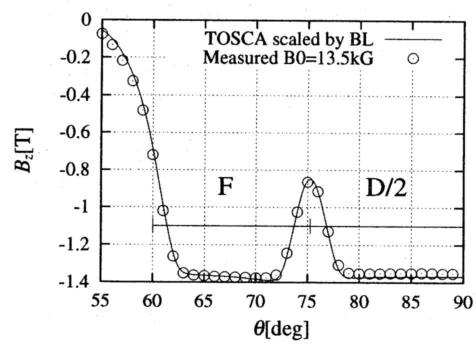

Fig. 4 B_z on the magnet center line

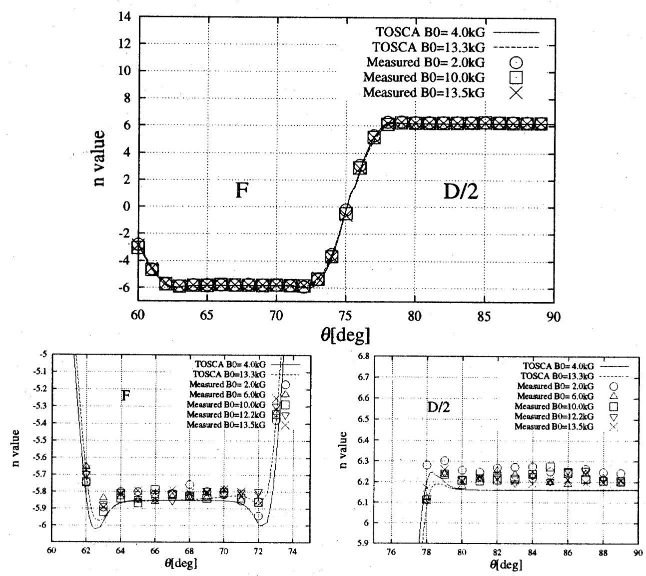

Fig. 5 n-value on the magnet center line

In order to evaluate n-values in quantitative way and to measure more detail in the azimuthal direction, we are preparing more precise measurement.

References

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