Magnet System of the Synchrotron for Hyogo Hadron Therapy Center

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Abstract

The dipole and quadrupole magnets of the synchrotron were manufactured with good accuracy by applying adhesive coated lamination and reducing welding connection. The end parts of the pole pieces have the structures whose length or shape can be adjusted, and using these structures the difference of the magnetic field length was minimized for the dipoles and the uniformity of the magnetic field was optimized for the quadrupoles. The method of arranging the magnets in the synchrotron is also reported in order to get minimum COD and distortion of β function using the result of magnetic field measurement.

1.Introduction

The synchrotron for Hyogo Hadron Therapy Center[1,3] will provide proton, helium and carbon beams whose required intensity is 2Gy/min(aimed at 5Gy/min for the goal) at the irradiation stage. Injection energy is 5MeV/u for all the beam species. Extraction energy range are 70~230MeV/u for proton and helium, and 70~320MeV/u for carbon respectively. Corresponding range of magnetic rigidity is 0.3235~5.576Tm. A third integer resonance is used for the slow extraction. The ring has 6-fold symmetry(Fig 1); each superperiod consists of two regular FODO cells. We have designed the operating tune to be (3.75, 3.30) at the injection and (3.676, 3.28) at the extraction. Since this machine is specified for medical use, easy operation and stability are important. Generally, for the FODO lattice the stable region in the tie diagram is large.

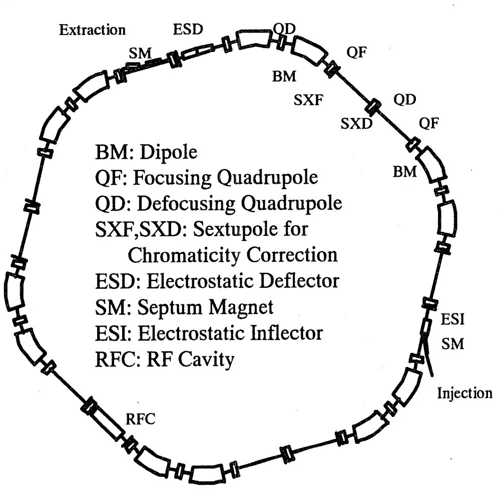

Fig. 1 Layout of the synchrotron ring

This machine is designed to be able to change the tune of about ±0.2 in both directions.

The unnormalized emittance of the beam from the injector is supposed to be 10π mm-mrad. The horizontal emittance becomes 400π mm-mrad in the synchrotron after multi-turn injection. Then the horizontal beam size is defined by the emittance of 400π mm-mrad, bucket height of 0.7% and COD of 3 sigma. We have considered the amplitude of betatron oscillation in the last 3 turns during the slow extraction as well. The vertical beam size is also defined by emittance of 10π mm-mrad and 3-sigma COD.

Specification is shown in Table 1 for dipole and quadrupole magnets.

TABLE 1
Specification of Dipole and Quadrupole Magnets

Dipole magnets	
Number	12 + 1
	(1 is used for B-Clock generation)
Maximum field strength	1.38T
Magnet length	2.15m
Bending radius	4.106m
Horizontal good field region	190mm
Magnetic field uniformity	$\pm 2\times10^{-4}$ at 1.38 T
Vertical gap	55mm
Bending angle	30 deg.
Number of coil turns	40
Maximum current	1530A
Coil resistance	12.3mΩ
Coil inductance	34mH
Weight	13,400kg
Quadrupole magnets	
Number	12 Focusing
	12 Defocusing
Maximum field gradient	6.7T/m
Magnet length	350mm
Bore diameter	162mm
Horizontal good field region	210mm
Field gradient uniformity	$\pm 2\times10^{-3}$ at 6.7 T/m
Number of coil turns / pole	18
Maximum current	980A
Coil resistance	10mΩ
Coil inductance	6.5mH
Weight	1,940kg

2.Structure of iron cores

Fig.2 shows the structure of the iron core for the dipole magnet. The core consists of 7 segments,; 5 of 5° and 2 of 2.5° which include the straight section of 100mm to attach the end shims. After stacking laminations according to the bending radius(R4106), both ends (either ends for end segments) of these laminations were cut with the angle of 2.5° to get the segments. This method of manufacturing has the merit that it is easier to stack laminations straightly in the same direction without large stacking tool, and we can get good accuracy because of machining after stacking. Actually the outlines of the return yoke does not become true circle, but the center of the core exactly corresponds to the beam orbit and sagitta is very small(0.28mm; along the outside surface of the pole at the joint of the segments). Thin adhesive layer was inserted between the segments to get insulation and firm connection. End plates and side plates are welded together with the iron cores to make sure the connection between segments, and these are welded staggered-intermittently in order to reduce the thermal distortion by welding.

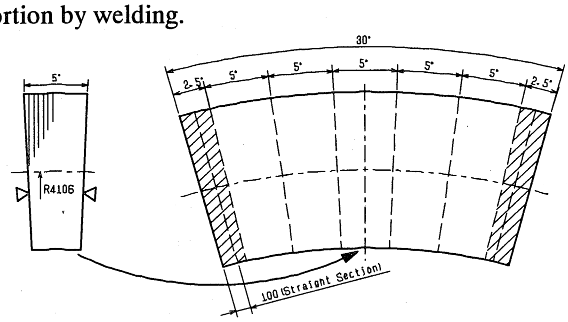

Fig. 2 Structure of the iron core for the dipole

We also applied gluing core to the quadrupoles to get good accuracy with less welding. All the other magnets including quadrupoles in the synchrotron (sextupole, bump, septum, and steering magnets) were made of gluing lamination without end plates, so more space became available for assembling and maintenance in the very crowded ring.

3.Magnetic field calculation and measurement

To determine the parameters and shape of magnets, magnetic field was analyzed using 2 dimensional code. The width of poles and yokes is wide enough as the saturation in the core does not become so severe (less than 1% saturation) at the nominal operation (B=1.38T for BM, g=6.7T/m for QM), therefore the uniformity of the magnetic field does not change so much according to the operation condition. The pole tip shape is determined as the uniform magnetic field (gradient) can be obtained in the required aperture shown in Table 1.

Especially for the quadrupole, since the core length is short compared with the bore diameter and the integral of the magnetic field along the beam line was expected to become lower at the aperture end, we applied the pole tip shape which leads to the result that the field at the aperture end is slightly higher in two dimensional calculation. Moreover, the shape of the end shim gives a great influence on the integral of the magnetic field, we applied loose laminations cut stepwise on the pole end and optimized their shape by measuring the magnetic field distribution with the long shift coil and replacing the laminations one by one(refer to Fig.3).

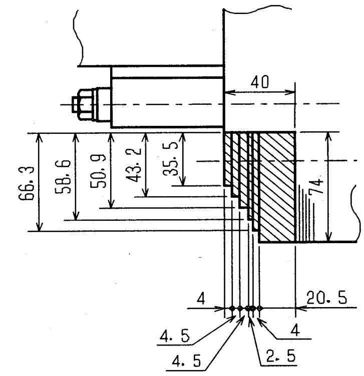

Fig. 3 Final shape of the end shim for the quadrupole

The result of the calculation is shown in Fig 4 and 5 together with the measurement result. We could get good results which satisfy the specification for both magnets.

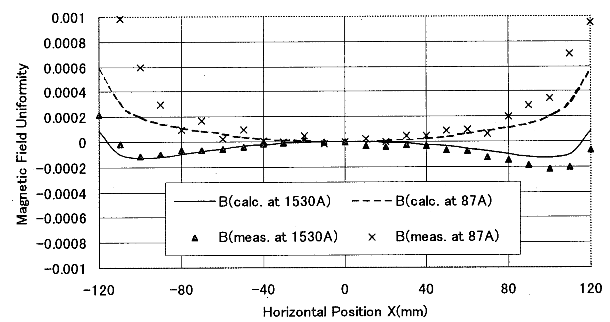

Fig.4 Field distribution of the dipole

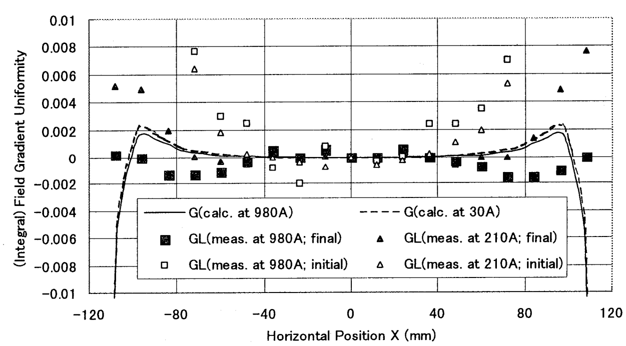

Fig. 5 Field distribution of the quadrupole

As for the dipoles, we adjusted the magnetic field length for 12 magnets installed in the synchrotron ring by long search coil, comparing with the reference (13[th]) magnet. The end shim is profiled with Rogowski curve which is affected little influence on the magnetic filed length by the excitation level and its length to the beam direction is also adjustable within ±3mm. We could adjust the magnetic field length within $2X10^{-4}$ at 1T, as is shown in Fig. 6.

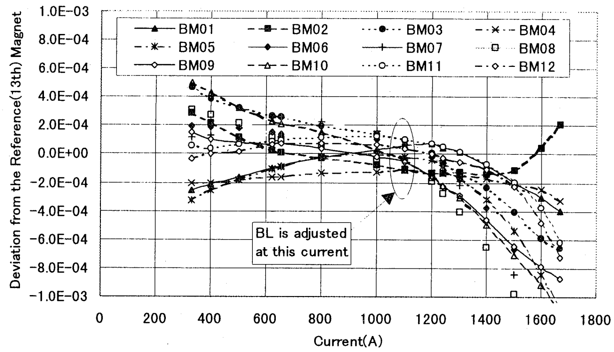

Fig. 6 Adjustment of magnetic field length for dipoles

4.Arrangement of magnets in the synchrotron ring

The horizontal COD comes from the field error of the dipoles and the alignment error of quadrupoles. Thus we have determined arrangement of dipole magnets so that horizontal COD becomes minimum. If each dipole magnet has the error $\Delta(Bl)_i$, the rms value of the horizontal COD is given by[2]

$$< \eta >_{rms} = \left[\sum_{k=-\infty}^{+\infty} \left(\frac{\nu_x^2}{\nu_x^2 - k^2} f_k \right)^2 \right]^{\frac{1}{2}} \qquad (1)$$

where

$$f_k = \sum_{i=1}^{12} \frac{\beta_i^{3/2}}{2\pi} \frac{\Delta(Bl)_i}{B\rho} e^{-ik\phi_i} \qquad (2)$$

$$\phi_i = \int_0^{s_i} \frac{2\pi}{\nu_x \beta_x(s)} ds \qquad (3)$$

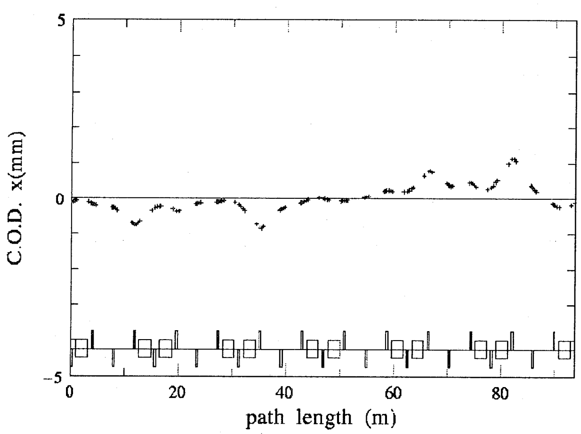

Fig. 7 Closed orbit calculated with the arrangement obtained by the minimum finding calculation.

Because of the horizontal tune, the terms of k=3 and 4 are dominant. Equation (1) has been evaluated for all the configurations of the dipole magnets (11! cases) for k=3,4 in order to find the minimum value of $<\eta>_{rms}$. We have used the data set of I=1530A which corresponds to the bending field for 320MeV/u of C^{6+} beam. Fig.7 shows the closed orbit calculated with the arrangement obtained by the minimum finding calculation. Residual COD is less than 2mm.

Quadrupole magnet arrangement is determined to minimize the distortion of the β functions. With an error of the integrated field gradient for each quadrupole Δ(gl) the distortion $\Delta\beta/\beta$ is given by[4]

$$\Delta\beta / \beta = \frac{\nu}{4\pi} \sum_p \frac{J_p e^{ip\phi_i}}{\nu^2 - (p/2)^2} \qquad (4)$$

where

$$J_p = \sum_{i=1}^{24} \beta_i \frac{\Delta(gl)_i}{B\rho} e^{-ip\phi_i} \qquad (5)$$

Since $\nu_x \sim 3.7$ and $\nu_y \sim 3.3$, we have considered for only p=6,7,8. Optimizations have been done for each direction independently i.e. $\Delta\beta/\beta$ has been calculated for the 2x11! configurations instead of 23!. The β functions are calculated using optimized arrangement. Then we found that $\Delta\beta_x/\beta_x$ and $\Delta\beta_y/\beta_y$ are less than 1% and 3% respectively.

Summary

Concerning dipole and quadrupole magnets for Hyogo synchrotron, we have reported method of manufacturing, magnetic field measurement, adjusting the magnetic property, and arrangement in the ring.

Apparatuses are now installed in the ring of Hyogo Hadron Therapy Center which is located in Nishiharima Garden City and after testing the performance of every apparatus beam commissioning will be started from the beginning of 2000.

References

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