BENDING MAGNET OF THE HIMAC HEAVY-ION SYNCHROTRON

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Abstract

The HIMAC is a heavy-ion medical accelerator for cancer therapy at Chiba NIRS. The machine is designed for ion beams from He to Si(Ar) of up to 800Mev/u at a charge to mass ratio of q/A=0.5, corresponding to a magnetic rigidity of Brho=9.75Tm.

The main dipole magnet system of the synchrotron ring is composed of 12 dipole magnets with maximum field strength of 1.5T. The magnets have curvature equal to bending radius and are of sector type. The yokes are fabricated from silicon steel stamped laminations, 0.5mm in thickness. The gap height is 66mm and the core length is 3400mm, the cross section being of H type. The bending angle is 30 degrees.

Demountable pole end pieces made of glued stack of laminated silicon steel are attached to the magnet ends for the adjustment of magnetic field length.

Field properties of the magnets are measured by using a temperature stabilized Hall probe which moved in the magnet on a curved 4m long support. The results are compared with field calculation.

Introduction

At NIRS, the construction of heavy-ion synchrotron accelerator facility HIMAC was started in 1987. It is a first accelerator facility for tumor therapy in a hospital environment in Japan. Synchrotron ring is of a separated function type with a strong FODO focusing structure with a six fold symmetry. Schematic layout of the ring is shown in Fig.1. Further detail of the HIMAC ring is given elsewhere[1].

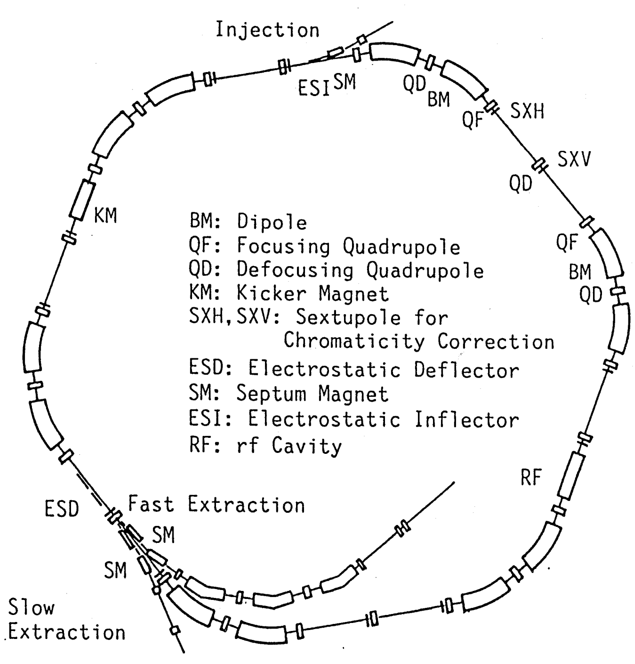

Fig. 1 Schematic Layout of HIMAC Synchrotron Ring.

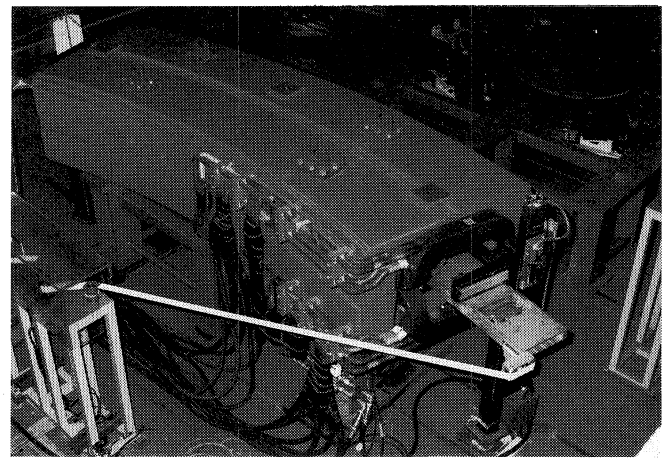

Fig.2 Photograph of the Dipole Magnet.

The main dipole magnet system of the synchrotron ring is composed of 12 dipole magnets with maximum field strength of 1.5T. The yokes were made with a radius of curvature equal to bending radius to suppress a sagitta. A sector type dipole magnet is chosen to suppress a change of betatron function of the synchrotron lattice with tune around the operation point. A H-gap design of the dipole with saddle shape coil configuration is adopted to obtain a wide good field region. Beam apertures in the dipole at injection are ±94mm horizontally and ±25mm vertically. Allowance for the closed orbit distortion is taken into account(16mm H and 5.1mm V for 3 sigma). Useful horizontal beam aperture required for extraction is ±105mm. The vacuum chamber in the dipole is 0.3mm-thick stiffened by ribs and is 200° C bakable. The gap height is 66mm and the core length is 3400mm. The bending angle is 30 degrees. Figure 2 shows a photograph of a HIMAC dipole magnet. Specifications of the dipole are summarized in Table 1.

Table 1.
Specifications of the dipole magnets.

Number/ring	12+1
Required field(T)	1.5
Magnet length(mm)	3400
Magnet type	Sector type
Good field region(mm) Hor/Ver	210 / 50
Vertical gap(mm)	66
Field flatness dB/B	$\pm 2\times10^{-4}$
Bending angle(deg)	30
Field rise(T/s)	2
Magnet yoke size(mm)	1170Wx680Hx3400L
Material	Laminated silicon steel Nippon steel corp., 50A600
Lamination thickness(mm)	0.5
Number of coil-turns	40
Current(A)	2070
Magnet weight(ton)	24

*One dipole is used for on-line field monitoring and a generation of B-clock for rf acceleration.

Demountable pole end pieces made of glued stack of laminated silicon steel are attached to the magnet ends. This method facilitates a shimming control of magnetic length of the dipoles by adding or omitting laminated sheets between the poles and the end pieces.

In the present paper the field calculations of the dipole magnet are described and the results of the magnetic field measurement by Hall probe are presented.

Magnetic Field Calculation of the Dipole Magnet

As the ring is designed to accelerate particle beams at a rate of dB/dt=2T/s for the dipoles, the yokes are made of stamped laminated steel of 0.5mm thickness to reduce eddy current effect. The steel used is laminated silicon steel 50A600 of Nippon steel corporation. Coercitivity Hc is 65.30±2.28 A/m. Magnetic induction field B_{50} at 5000 A/m of magnetic field strength is 1.680±0.003T.

The shape of the pole face was determined by the use of computer code LINDA. The pole width is 460mm to ensure homogeneity of the magnetic field over the required useful aperture of 210mm. Thickness of the end shim is 0.84mm. Outer sides of the pole has B constant shape[2]. Fig.3 shows the cross section of the pole. Fig.8 shows the calculated normalized field excitation (B/I vs. I) of the magnet. Fig.4 shows the calculated radial field distribution. Packing factor was assumed to be 97 %. The calculation does not include the effect of remanent field.

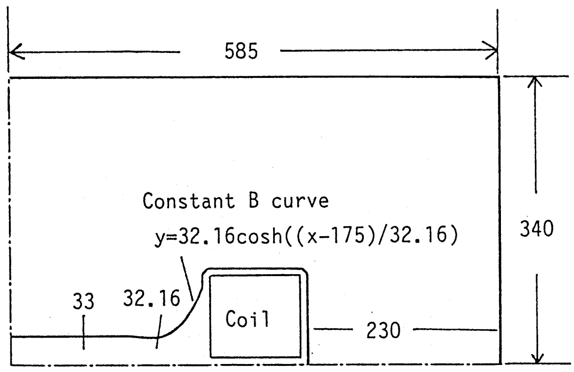

Fig.3 Cross Section of the Magnet Pole.

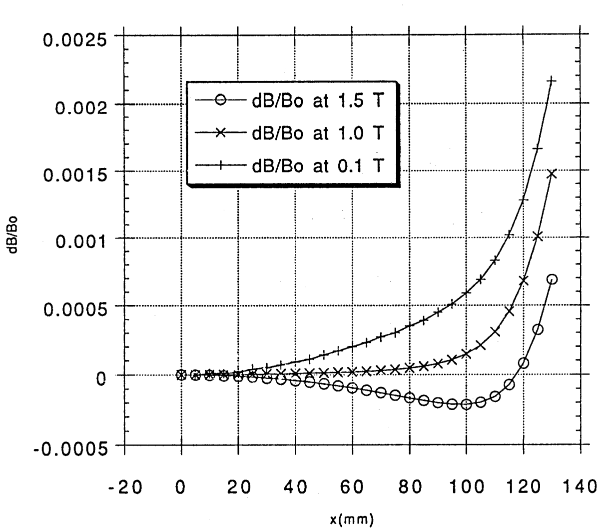

Fig.4 Calculated Radial Field Distribution.

The pole ends are shaped according to Rogowski's profile[3] by approximating the exponential curve by five straight cuts. Fig.5 shows the pole end piece attaching to the yoke by screw bolts.

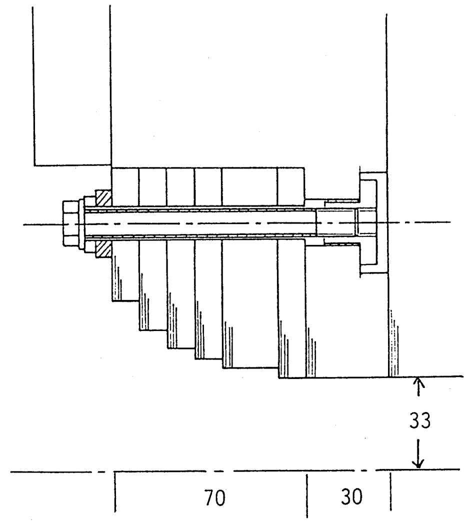

Fig.5 Demountable Pole End Piece.

To make a yoke with a radius of curvature equal to bending radius and with sector edges, 12 lamination sheets with different sizes were made as liners from full size stamped lamination sheets. Fig.6 shows these laminations. These lamination sheets were stacked on a curved bed to form a curved yoke. The 100mm long outer parts of the yoke and the end pieces with Rogowski's profile are glued respectively and have a rectangular shape. So the magnet has actually a small edge angle of 0.8825 degree.

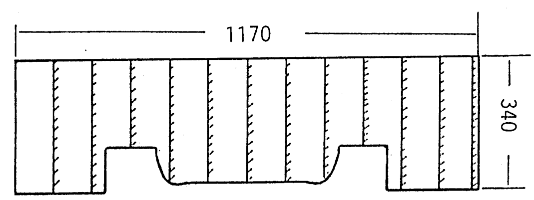

Fig.6 Stamped Lamination Sheets for Liners.

Field Measurement of Magnet

To measure the magnetic field distributions of the HIMAC dipoles, a computer controlled 4m-long curved table was used to map the whole area of the magnetic field(Fig.2). For field mapping, a Hall probe was used, temperature being stabilized within ±0.1 degree. The absolute calibration of the system was done comparing the Hall probe to a NMR.

In Fig.7, a measured excitation of the magnet is shown(B vs. I). In Fig.8, the same results are presented in a normalized form(B/I vs. I). The results are compared with field calculation by LINDA. The discrepancy at low current comes from the effect of remanent field. Remanent field at zero excitation current was measured to be 16 gauss after initialization up to 1.6 T. The effect of remanent field was included to correct the cal-

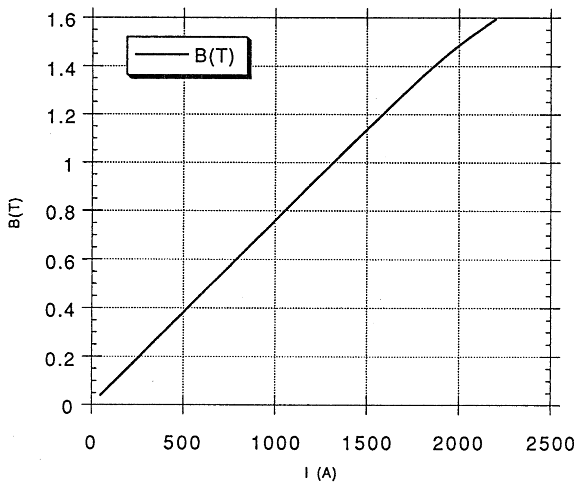

Fig.7 Measured Excitation of Magnet.

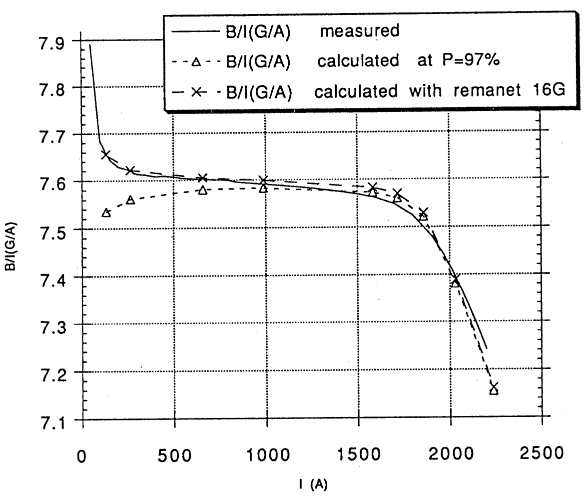

Fig.8 Normalized Excitation of Magnet

culated excitation curve and is also shown in Fig.8. The result shows a good agreement at whole current region. In Fig.9, radial field distributions for different excitations are shown. At 0.1T, an effect of remanent field is observed. Asymmetry in the distribution is qualitatively now under investigation. The effect comes from the sector shape of the magnet. Fig.10 shows a field mapping along a reference orbit. Magnetic length was estimated to be 3452mm at 1 T.

Adjustment of Magnetic Lengths of Dipole Magnets.

To adjust the magnetic field lengths of 12 dipoles, two sets of calibrated measuring coil system with equal geometry are designed. Each coil system consists of 4 single search coils which approximate the reference orbit. Series dipole is powered in series with reference magnet and the difference between the two dipoles can be determined. Then the shimming control of the magnetic length can be performed to each series magnet by adding or omitting laminated sheets between the poles and the end pieces.

References

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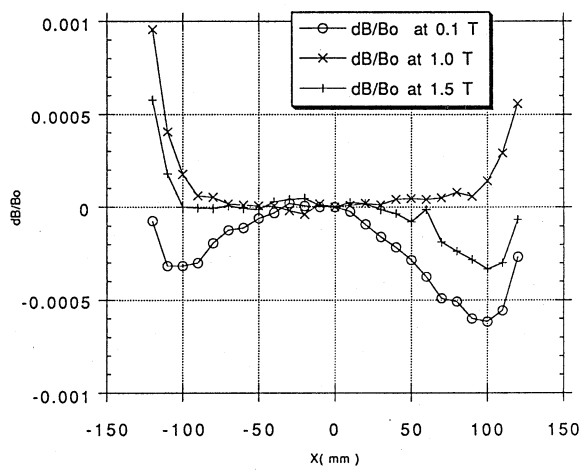

Fig.9 Measured Radial Field Distribution.

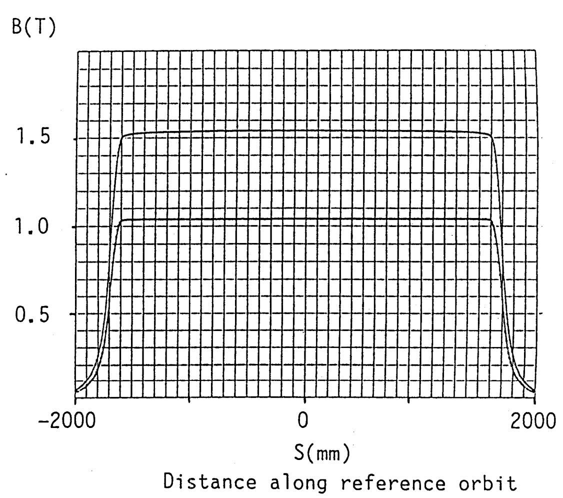

Fig.10 Field Mapping along a Reference Orbit.