A COMBINED FUNCTION MAGNET FOR A COMPACT SYNCHROTRON

M. Tadokoro, J.I. Hirota, K. Hiramoto, M. Umezawa, S. Kakiuchi,
Hitachi, Ltd. Hitachi shi, Ibaraki 317, Japan
Y. Iwashita, A. Noda, T. Shirai and M. Inoue
Institute for Chemical Research, Kyoto University, Uji shi, Kyoto 611, Japan

Abstract

At Kyoto University, a compact proton synchrotron with combined function lattice has been proposed for cancer therapy facility, KUMPF (Kyoto University Medical Proton Facility). KUMPF provides proton beam in the energy range of 70-250 MeV with average current of about 10 nA. The synchrotron consists of six identical combined function magnets, each of which deflects the proton beam 60 degrees. The magnet has an FDF structure where focusing (F) and defocusing (D) sectors deflect the beam 15 and 30 degrees, respectively. In order to realize the tune value of (1.75, 1.75), n-values of -5.856 and 6.164 are required for F and D sectors, respectively. In the present paper, the detailed design of the combined function magnet will be presented.

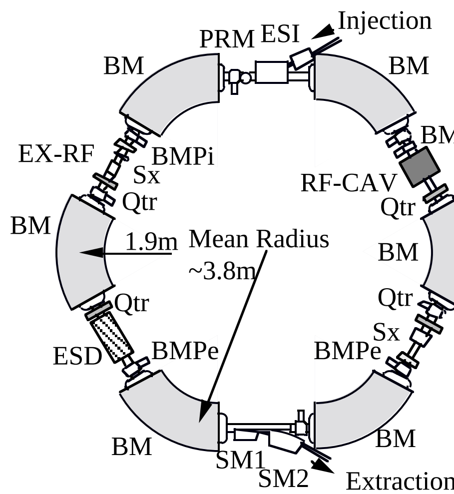
1. INTRODUCTION

At present, a particle therapy using protons and heavy ions has been recognized as a powerful tool to treat malignant tumor due to the Bragg peak effect which serves a sharp dose distribution in human body. From this effect, the particle therapy is also expected to satisfy the requirement for keeping the shape and function of the human body from the point of view of the QOL(Quality Of Life) of the patients. A medical accelerator, however, system should be able to be operated easily and acceptable in size in public hospitals.

Based on this conditions, a compact proton synchrotron dedicated for medical use composed of combined function magnets with circumference of about 23m had been proposed for KUMPF(Kyoto University Medical Proton Facility) [1][2]. To realize clinical beam energy from 70 to 250MeV for therapy in compact size, the bending field is required from 0.2 to 1.28T and the necessary focus and defocus quadrupole field are 1.71 and -1.62(1/m^2) at 1.28T, respectively. Construction of such a combined function magnet with high K-values are not so easy. A new design method to introduce vacant portions in the magnet core so as to improve a shape of the magnetic field in the combined function bending magnet has been developed. An outline of the compact synchrotron for KUMPF and a design principle of the combined function bending magnet are described in section 2 and 3, respectively.

2. OUTLINE OF THE COMPACT SYNCHROTRON

Figure 1 shows the compact synchrotron with combined function lattice in KUMPF. And typical operation parameters are shown in Table 1.



BM : Combined Function Bending Magnet
BMP : Bump Magnet
ESD : Electrostatic Deflector
ESI : Electrostatic Inflector
EX-RF : RF Electrode for Extraction
Qtr : Trim Quadrupole Magnet
PRM : Profile Monitor
RF-CAV :Untuned type RF Cavity
SM1,SM2 : Septum Magnets
Sx : Resonance Exciter Sextupole Magnet

Fig.1 Structure of the Combined-Function Synchrotron

A proton beam is injected from a linac with 7MeV. The injection energy was chosen to reduce an effect of the space charge force. The proton beam is accelerated up to 70-250MeV and extracted to the treatment room. This operation is conducted in repetition rate of 0.5 Hz. The mean radius and the circumference of the synchrotron are 3.8m, 23.9m, respectively. The combined function magnet consisting of an FDF structure was adopted for the merit of easy operation. Especially no need of tracking procedure between dipole and quadrupole magnets is a large merit. In this structure, F and D denote focus and defocus sectors in horizontal direction, respectively.

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The radius of curvature and the bending angle of the combined function bending magnet is 1.9m, and 60 degrees, respectively. The maximum field is 1.28T at the central orbit.

Moreover, an untuned type RF cavity using ferro-magnetic material named FINEMET with multiple power feeding[3] and the constant separatrix extraction with broad band RF noise are also adopted in this compact synchrotron[4].

Table1 Kyoto University synchrotron operation parameters

particle	proton
Beam Energy (MeV) Injection Extraction	 7 70-250
Repetition Rate (Hz)	0.5
Dose Rate (Maximum)	5 Gy per min
Circumference (m)	23.9
Tune horizontal υx vertical υy	 1.75 1.75

3. THE COMBINED FUNCTION BENDING MAGNET

Figure 2 shows the schematic view of the combined function bending magnet for KUMPF. The present bending magnet is an FDF type. The deflection angles of F and D sections are 15 and 30 degrees, respectively. The curvature radius is 1.9m. Then, the maximum magnetic field on the design orbit is 1.28T for 250MeV. Figure 3 and 4 show the cross sectional view of the magnet poles of the F and D regions, respectively. As shown in the figures, the gap height of both the sections is 67mm on the design orbit. This value has been determined based on the analysis of the beam size in the synchrotron. The n-values of the F and D regions are -5.865 and 6.1641, respectively. The specifications of the present bending magnet are listed in Table 2. In order to adjust the field gradient integrated along the design orbit, the one turn correction coil with air cooling is applied. This correction coil is twisted in the transition regions between the F and D sectors. A few percents of the integrated field gradient can be tuned by using the present correction coil .

The present bending magnet is designed in such a way as there are some vacant portions, hereafter called the air slots, in the magnet poles. The magnetic susceptibility of the air slots in the magnet poles is much lower than that of the iron core. This results in an increase of the magnetic flux in the iron region. In the present combined function bending magnet, the air slots in the larger gap section makes the magnetic flux in the larger gap region increase and the characteristics of the magnetic field distribution is improved. Accordingly, by adjusting the position, shape and volume of the air slots, the maximum magnetic field , that is, the beam energy range of the synchrotron is increased with keeping the size of the synchrotron constant. It is expected that the air slots in the magnet pole are also effective for the control of the magnetic field distribution in the usual dipole bending magnet as well as the combined function magnets. An intensive study to apply this effect to a conventional type bending magnet is now carried out.

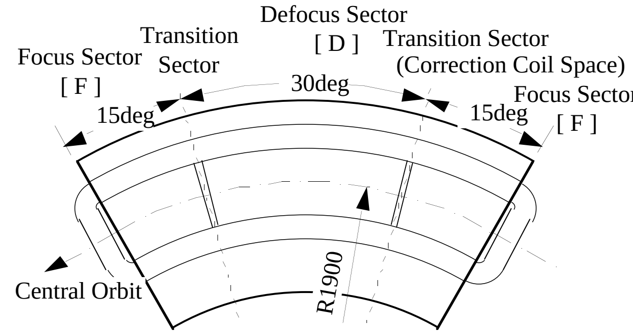

Fig.2 Top View of the Unit Magnet

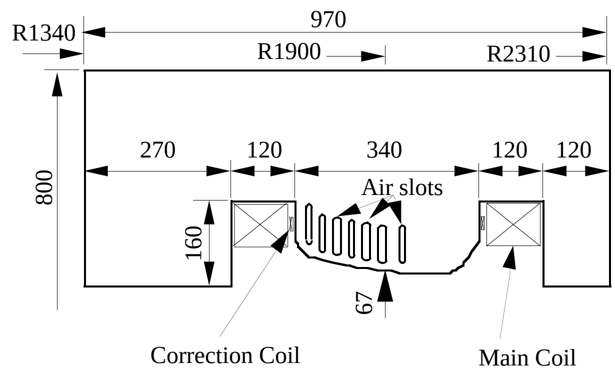

Fig.3 Cross-sectional View of the Focus Sector

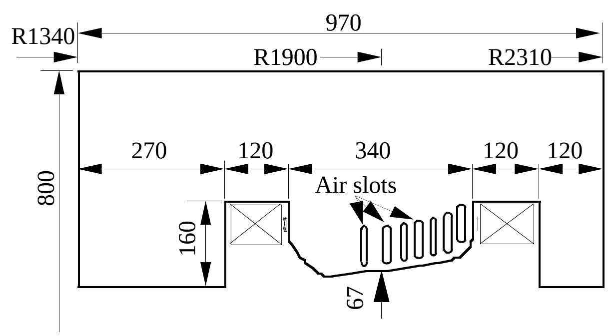

Fig.4 Cross-sectional View of the Defocus Sector

The shape of the magnet pole has been determined by the following equation.

$$y(1+b_1 x)-\frac{1}{6}\frac{b_1}{\rho}y^3=y_0-\frac{1}{6}\frac{b_1}{\rho}y_0^3 \qquad (1)$$

b_1 : quadrupole component (1/m)

ρ : curvature radius(m)

y_0 : half gap height on the design orbit(m)

Table 2 Specifications for the Bending Magnet

Bending Angle	60deg (15deg[F]-30deg[D]-15deg[F])
Radius of Curvature	1.9m
Center Gap Height	67mm
Magnetic Field Strength (at the central orbit)	0.2T (7MeV) to 1.28T (250MeV)
n-value D sector	6.1641
F sector	-5.8560

Figure 5 shows the two dimensional magnetic field distribution obtained by numerical analysis. The horizontal axis shows the radial distance from the design orbit and the vertical axis shows the deviation of the magnetic field strength from the design value. As shown in the figure, the difference between the calculated and design values is smaller than 0.02% at even the magnetic field of 1.35T for the horizontal width of 120mm. Since the curvature radius of the present bending magnet is 1.9m, the proton beam can be accelerated up to about 275 MeV.

For the comparison, the two dimensional magnetic field distribution of the conventional combined function magnet without air slots is shown in Fig. 6.

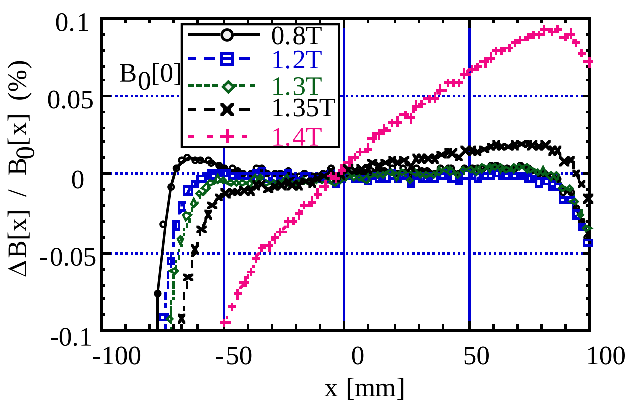

Fig.5 Two dimensional magnetic field distribution of the present combined function magnet. (D Sector)

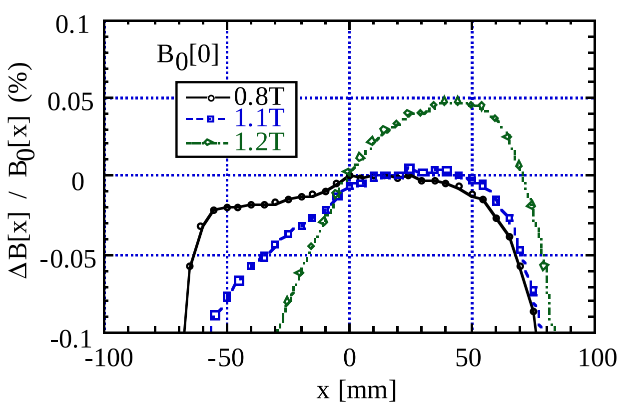

Fig.6 Two dimensional magnetic field distribution of the conventional combined function magnet.

In the conventional combined function bending magnet, the saturation effect of the magnet pole in the narrower gap region deforms the magnetic filed distribution. This effect limits the maximum magnetic field used in the synchrotron. As shown in the figure, although the good field region of 120mm width is obtained up to the magnetic field of 0.8T, the widths of the good field region are rapidly decreases to 40mm for 1.1T and to about 20mm for 1.2T.

4. CONCLUSION

The combined function bending magnet for the proton synchrotron of KUMPF has been presented. The circumference of the synchrotron is 23.9m. The acceleration of the proton beam to 250 MeV requires the maximum magnetic field and n-values to be 1.28T and -5.8560 for F, 6.1641 for D sectors respectively. A new magnet pole in which there are some vacant portions has been applied to realize the needed n-values up to the designed magnetic field. The results of the numerical analysis showed that the sufficiently good field region is obtained at 1.28T and the present bending magnet can be applied to the magnetic field up to 1.35T.

ACKNOWLEDGMENTS

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