Octupole Magnet for Expansion of Irradiation Area

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Abstract

An octupole magnet for experiments is designed to prove a scheme for expanding beam irradiation area with good flatness. The length and maximum strength of the octupole field $\frac{1}{3!}B'''$ are 0.6m and 4000T/m^3, respectively.

1 Introduction

In charged particle radiotherapy for cancer, a wide and uniform irradiation area is required. To make wide irradiation areas, the beam should be expanded. But a beam expansion by quadrupole magnetic field is linear, which means that the structure of the expanded beam is similar to that of the original one. Because the beam structures have neither sharp edges nor uniform distributions, an expansion field must have nonlinearity to modify the beam structures. A leading component of the magnetic field nonlinearity that is required to deform a gaussian beam structure is an octupole field[1].

A proof of principle experiment of this method in the HIMAC beam line is scheduled. Figure 1 shows the experimental beam line configuration. Specifications of an octupole magnet designed for the experiment are listed in Table 1.

Table 1
Specifications of an octupole magnet

magnet length	0.6m
bore radius	52mm
octupole strength $\frac{1}{3!}B'''$	4000T/m^3

2 Basic Consideration

Constraints of the octupole magnet which were determined from experimental requirements and resource availabilities were as follows:

- Bore Radius: 52mm
- $B_3L = 2.4 \times 10^3$T/m^2
- Power Source Limitation: 42V 390A
- Maximum Pole Thickness: 40mm
- Available Hollow Conductors: 6mm × 6mm (with 3mm ϕ for cooling channel), $7\times7(4\times4)$, $8\times8(4\times4)$

where pole thickness is indicated in Fig. 2, L is magnet length, and B_n is weight of r^n component in $\boldsymbol{B}(x,y)$.

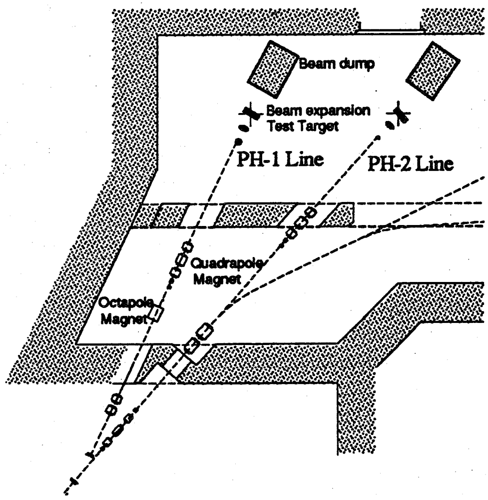

Fig. 1 Experimental beam line configuration in HIMAC

This B_n notation is given from a general form of $\boldsymbol{B}(x,y)$ in bore:

$$B_x(x,y) - iB_y(x,y) = \sum_n (A_n + iB_n)(x+iy)^n.$$

Considering the symmetries of an octupole, we can select x-axis to eliminate $B_x(x,0)$, and write down $B_y(x,0)$ in simple form: $B_y(x,0) = -\sum_n B_n x^n$. Further the rotational symmetry for an octupole gives $B_n = 0$ at $n \neq 3 \bmod 8$. Thus main components of an octupole is $B_3 = \frac{1}{3!}B'''$, and distortion components are B_{11}, B_{19},....

The necessary excitation current NI is given by

$$\frac{1}{\mu_0}\int_0^{r_0} B_3 r^3 dr = \frac{1}{4\mu_0} B_3 r_0^4,$$

where μ_0 and r_0 are vacuum permeability and bore radius, respectively. Then, the lower limit NIL_{min} calculated from B_3L becomes 3.5×10^3Am. NIL_{min}, and power source limitation determines the selection of conductors.

At first, in order to make full use of the power source we shall use coil impedance R_{coil} of $V_{max}/(8I_{max})[\Omega/coil]$, where V_{max} and I_{max} are maximum rating of the available power supply. The coil length becomes greater than $2NL$ where N are the number of coil turns per pole. Thus the upper limit of NIL is

$$NL_{max}I_{max} = \frac{1}{2}R_{coil}\left(\frac{S}{\sigma}\right)^{-1} I_{max} = \frac{1}{16}\frac{\sigma}{S}V_{max},$$

where σ and S are the conductivity of the coil and conductor cross section, respectively. Table 2 shows this upper limit of hollow conductors with series connection. These values do not include return connection at both ends, coil leadout, and design margin. For example the upper limit of NIL is reduced 10 percents by a condition: return connection length at both ends 40mm, $L = 400$mm. To make enough margin, we should use hollow conductors of 8 × 8(4 × 4).

Table 2
The upper limit of NIL

Conductor[mm]	$S/\sigma[\Omega/\mathrm{m}]$	NIL_{max}[Am]
$6 \times 6(3\phi)$	7.3×10^{-4}	3.6×10^3
$7 \times 7(4 \times 4)$	6.4×10^{-4}	4.1×10^3
$8 \times 8(4 \times 4)$	4.4×10^{-4}	6.0×10^3

The short distance between adjacent poles makes large leakage flux. Considering the Ampère's low, the current should be concentrated around the pole top as high as possible. Large leakage flux pushs up the maximum magnetic field in the pole center plane, B_{max}. In case iron poles are saturated with magnetic-flux, L shuld be elongated for smaller B_3.

To sum up, we should use hollow conductors of 8 × 8(4 × 4) to satisfy $NIL_{min} = 3.5 \times 10^3$Am with enough margins. Pole design should be determined compromising iron saturation with magnet length.

3 Practical Design

We use circular poles to reduce machining costs. Pole shapes are represented by 4 parameters–R, w, l_1, l_2– which are shown in Fig. 2.

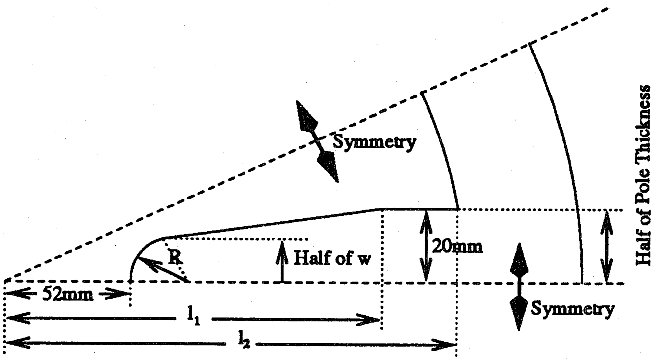

Fig. 2 Tapered circular pole and its parameters

The design optimization principles are as follows:

- make enough coil spaces
- prevent iron saturation
- suppress distortion components :$B_{11}, B_{19}, ...$

Parameters l_1 and l_2 have strong dependence on coil spaces; then two parameters R and w are optimized preventing pole saturation and suppressing B_{11}/B_3.

Firstly we assume that the coil sapce can be filled by conductors without dead-space to consentrate the current around the pole tip. The magnet length L, strength B_3, and excitation current NI are 0.6m, 4000T/m^3, and 5833A, respectively. To make 10 percent margin for power line drop, and same margin for magnetic resistance of poles, we needed 18 turns per pole, namely $S_{coil}\ \mathrm{min} = 18 \times 8^2 \sim 1728\mathrm{mm}^2$. From this condition w, l_1, and l_2 are determined as 20mm, 117mm, 117mm, respectively.

Figure 3 shows a dependence of B_{11}/B_3 on parameters R and w. Figure 4 shows a relation between B_{max} and B_{11}/B_3 in above conditions. There is a trade-off between B_{11}/B_3 and B_{max}.

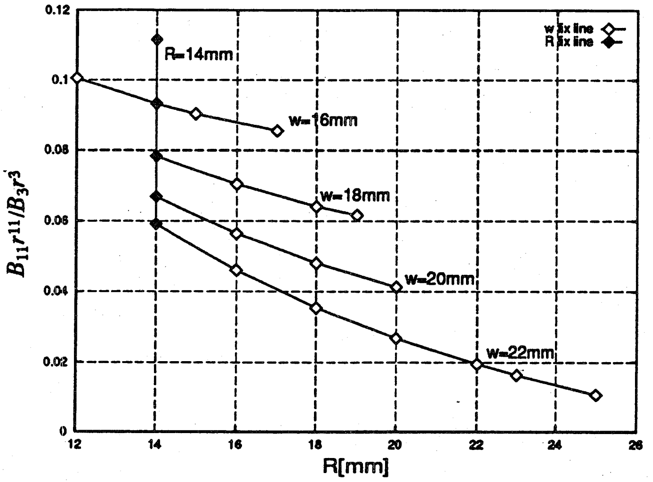

Fig. 3 R dependence of $B_{11}r^{11}/B_3r^3(r = 47\mathrm{mm})$ in several w. Condition: $l_1 = l_2 = 117$mm, $B(r = 50\mathrm{mm}) = 5$kG

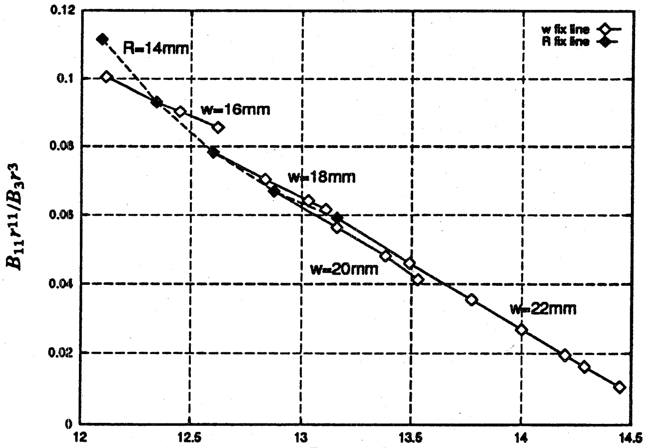

Fig. 4 $B_{max} - B_{11}r^{11}/B_3r^3(r = 47\mathrm{mm})$ relation in several (R, w). Condition: $l_1 = l_2 = 117$mm, $B(r = 50\mathrm{mm}) = 5$kG

Because real magnet coils with hollow conductors have winding dead-space between conductors, the coil space has to be expanded. Then the currenent spreads out and the leakage flux increases, which makes B_{max} increase.

In order to reduce the winding dead-space of coils, we selected a convenient parameter set:

$$R = 27\text{mm}, w = 23\text{mm}, l_1 = 138\text{mm}, l_2 = 160\text{mm}.$$

Figure 5 shows a pole shape and a magnetic-flux calculated by POISSON, where the hollow conductors are approximated by 10mm squares. POISSON calculation gives $B_{max} = 17.8$kG, $B_{11}r^{11}/B_3r^3(r = 47\text{mm}) = -7.0 \times 10^{-4}$, and $B_{19}r^{19}/B_3r^3(r = 47\text{mm}) = -1.7 \times 10^{-2}$. Figure 6 shows errors between POISSON calculation and pure octupole in bore. Table 3 shows the final magnet specifications which is shown Fig. 7.

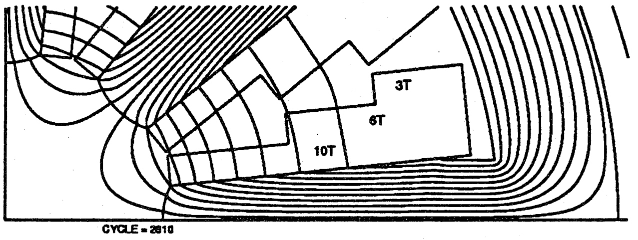

Fig. 5 Final pole design and a magnetic-flux calculated by POISSON. Condition: $R = 27\text{mm}, w = 23\text{mm}, l_1 = 138\text{mm}, l_2^* = 162\text{mm}$, $N = 19\text{turn}, B(r = 50\text{mm}) = 5\text{kG}$

$^*l_2$ was modified from 160mm to avoid mesh problems

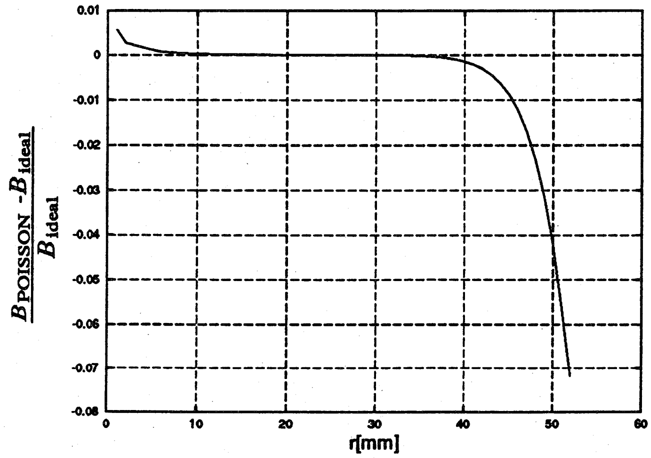

Fig. 6 Error of B between POISSON calculation and pure octupole.

4 Discussion

Design of octupole magnets has serious saturation problem by leakage flux. In order to verify an effect of the tapered pole, we compared similar scale poles at the same excitation. One is shown in Fig. 5(case A). The other is a pole without both taper and dead-spaces of coil(case B). In case B, thickness and l_2 are 40mm and 170mm, respectively. And the pole tip shape of case B is given by $r^4 \cos 4\theta = r_0^4$ which is used in early design. The difference of pole tip shape should not be essential for pole saturation ploblem.

At an excitation B_3 of 4000T/m^3, B_{max} for case A was 17.8kG and that of case B was 21.8kG. This result means that tapered pole is effective to prevent pole saturation.

Table 3
Final specifications of an octupole magnet

magnet length	0.6m
bore radius	52mm
octupole strength B_3	4000T/m^3
hollow conductors	8mm × 8mm(4mm × 4mm)
turn number N^*	20turn/1coil
maximum current	360A
weight	650kg

$^*N$ = 19turn/1coil used in design calculatioon by POISSON

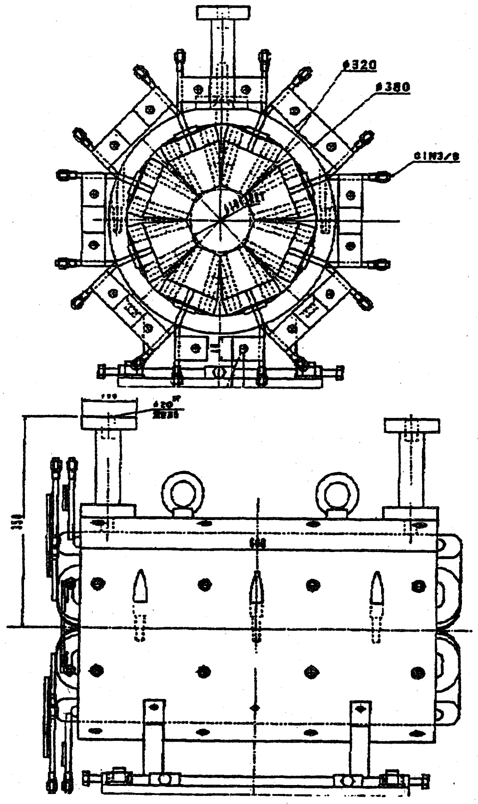

Fig. 7 Final design plan of an octupole magnet

References

[1] Kazuo HIRAMOTO, et al., "A Compact Proton Synchrotron with a Combined Function Lattice Dedicated for Medical Use", Bulletin of the Institute for Chemical Reserch, Kyoto University, Vol. 73, No. 1, 1995