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DEVELOPMENT OF A COMPACT STEERING MAGNET WITH EIGHT-POLE STRUCTURE

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Abstract

A compact steering magnet has been devised. The steering magnet has "eight-pole structure". The strength and its direction of the dipole field can be electrically changed. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. The effective length is measured to be 97 mm and magnetic field of 0.4 kG is achieved. The steering magnet is very useful under severe space limitation.

1. Introduction

The 7 MeV proton linac at Institute for Chemical Research, Kyoto University consists of 50 keV proton ion source, 2 MeV RFQ linac and 7 MeV Alvarez DTL. The linac system has been operated since 1992[1]. Unfortunately, the output beam from the DTL has a slight angle against the designed axis, and then the beams are deflected away by quadrupole lenses installed downstream.

A conventional steering magnet system consists of two dipole magnets whose fields are perpendicular to each other, while our facility does not have enough space for two dipole magnets between the exit of the DTL and the quadrupole magnets. Because the direction of the output beam is found to be changed with operating conditions, a short steering magnet system, which has the variable strength and the steering direction, was required. Considering these requirements, we have developed a new type of compact steering magnet which has "eight-pole structure". The main features of this steering magnet and the results of the field measurements are described in the present paper.

2. Concept of the multi-pole structure

It is well-known that a circular distribution of electric current, in which the current density is proportional to the cosine of the azimuthal angle, can produce a perfectly uniform dipole field [2][3]. In analogous way, it also can be shown that a magnet with "multi-pole structure" can produce a dipole field around the axis.

Inside the aperture r_0, where their is no electric current (ignoring the beam), the magnetic field can be expressed as the gradient of the magnetic potential ϕ, i. e.,

$$B=-\mu\nabla\phi \tag{1}$$

The magnetic potential of the perfect $2N$-pole field can be written as

$$\phi_{2N}=\frac{r_0}{N}k_{2N}\left(\frac{r}{r_0}\right)^N\sin(N\theta) \tag{2}$$

where k_{2N} is an appropriate coefficient representing the field strength and θ is the azimuthal angle relative to the horizontal direction. In order to generate the dipole field ($N = 1$) inside the radius r_0, the magnetic potential at $r = r_0$ must have the form

$$\phi_2 = r_0k_2\sin\theta \tag{3}$$

The above considerations provide us a guide line for a design of a dipole magnet with "multi-pole structure". The extension to a magnet for higher order field is straight forward.

Applying the above considerations to an actual magnet, the sinusoidal magnetic potential should be approximated by segments where the magnetic potential is constant and chosen to be proportional to the sine of the azimuthal angle. Further more, coil space should be reserved. Taking these requirements into consideration, we adopt "eight-pole structure" in which the sinusoidal magnetic potential is approximated by eight poles (See Fig. 1 and 2). The magnetic potential on the pole tips is chosen to be proportional to the sine of the azimuthal angle. In this structure, enough space is available for coils and we can get relatively large field strength.

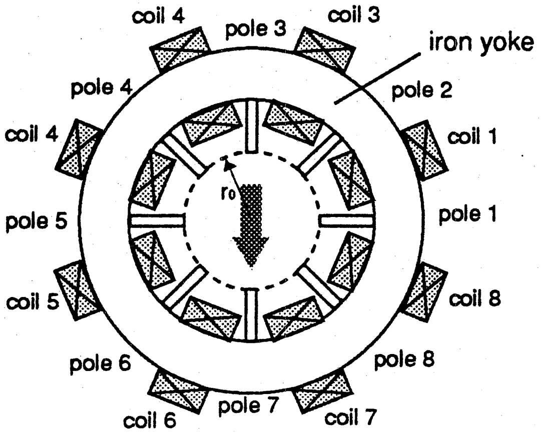

Fig. 1 Schematic view of the eight-pole structure

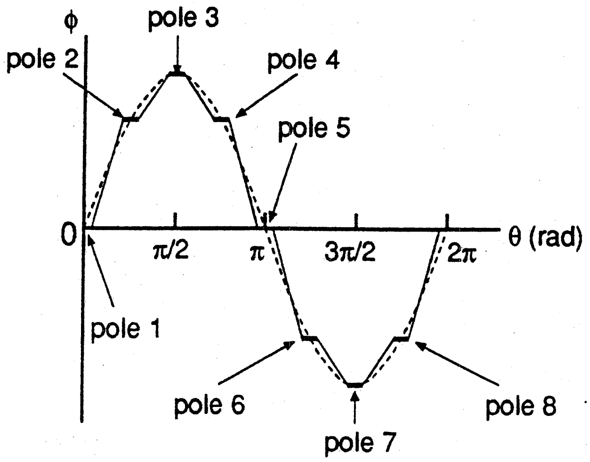

Fig. 2 Magnetic potential distribution at $r = r_0$
The magnetic potential is linearly interpolated between poles.
broken line: sine curve, solid line: generated by eight poles

We adopt thin poles to reduce leakage flux and have a good approximation of the sinusoidal magnetic potential.

It can be easily derived from eq. (1) and (3) that in eight-pole structure the field strength on the pole tips can be written as

$$B_{rn} = B_0 \cos\left(\frac{n-1}{4}\pi - \Theta\right) \qquad (n = 1, 2, 3, \ldots, 8) \tag{4}$$

where B_{rn} is the field strength on the n-th pole tip and Θ is the azimuthal angle of the dipole field relative to the horizontal direction. The azimuthal angle of the n-th pole tip measured relative to the horizontal direction is $(n-1)\pi/4$ radian (See Fig. 1). The excitation current in each coil can be written as

$$I_n = I_0\left\{\cos\left(\frac{n-1}{4}\pi-\Theta\right)-\cos\left(\frac{n}{4}\pi-\Theta\right)\right\} \qquad (n = 1, 2, 3, \ldots, 8) \tag{5}$$

where I_n is the excitation current in the n-th coil and I_0 is a coefficient representing the strength of the excitation current. N-th coil is located between the n-th and $(n+1)$-th poles (See Fig. 1).

With this structure, we can change the field strength and its direction only by changing the excitation currents and then we can steer the beam in both horizontal and vertical directions by a single element. It is very advantageous under severe space limitation.

3. Field calculation and design

The geometry of the steering magnet is shown in Fig. 3. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. In order to have long effective length, the length of the pole is longer than that of iron yoke. Its iron yoke is octangular rather than circular for simple fabrication.

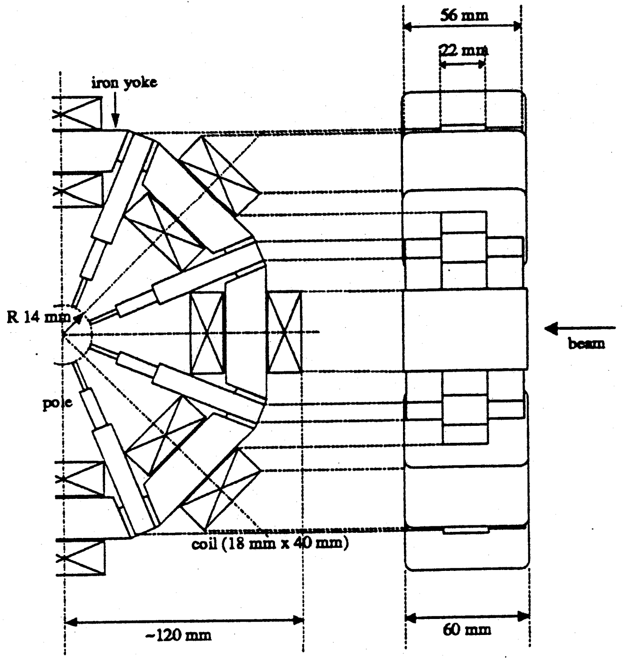

Fig. 3 Geometry of the steering magnet

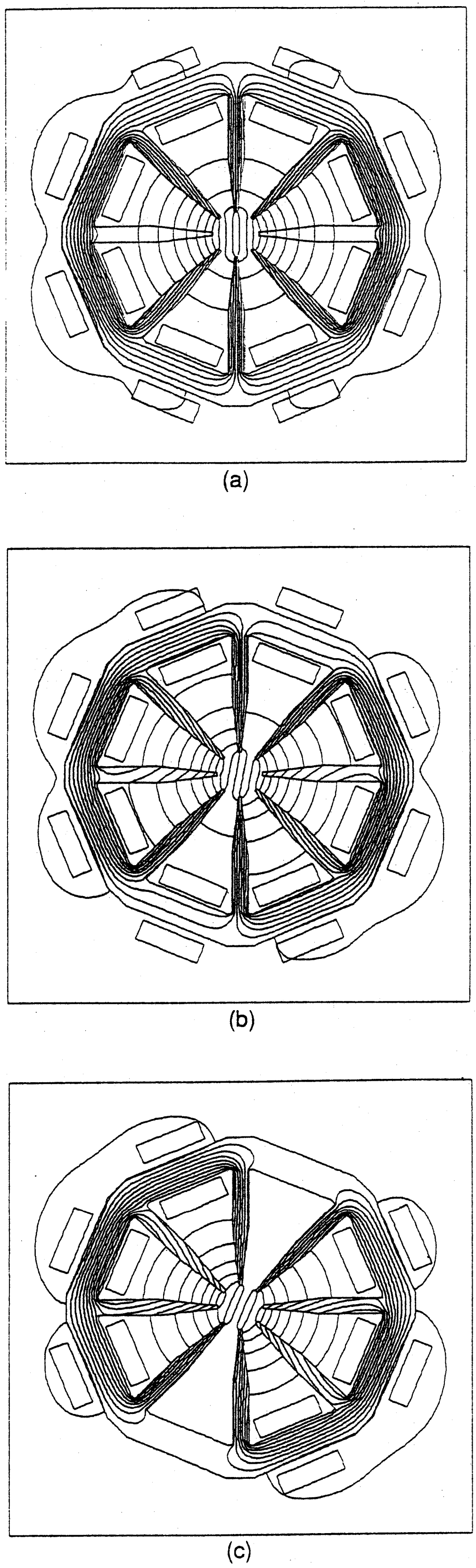

Fig. 4 Flux Plot of a eight-pole magnet
$I_0 = 2.0$ A. Mesh size is 1 mm.
(a) $\Theta = 90°$ (b) $\Theta = 78.75°$ (c) $\Theta = 67.5°$

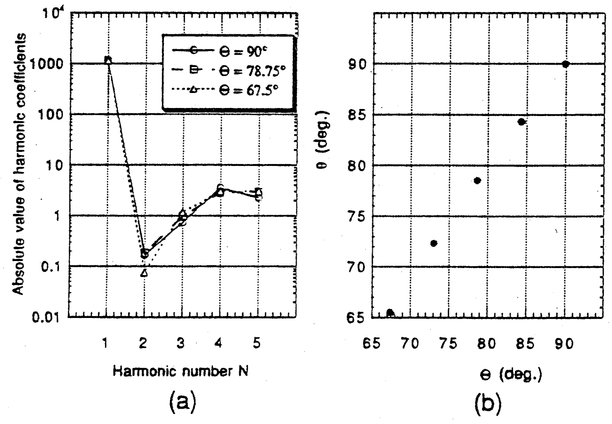

Fig. 5 Results of harmonic analysis
(a) harmonic field components
(b) azimuthal angle of the generated dipole filed θ

Table 1 Main features of the steering magnet

iron pole	number of poles	8
	bore radius	14 mm
	axial length	56 mm
iron yoke	axial length	22 mm
coil	number of coils	8
	number of turns per coil	498
	cross section	18 x 40 mm^2
	axial length	60 mm
	excitation current	< 5 A
total axial length		60 mm
effective length		97 mm
maximum field strength		> 0.4 kG

This geometry is designed by PANDIRA[4]. Some results of the calculations are shown in Fig. 4. In the calculations, we found that a steering magnet with eight-pole structure can produce sufficiently good dipole field around the axis, in which higher components of the field are negligibly small. Some results of harmonic analysis are shown in Fig. 5. The harmonic field components are normalized at 10 mm from the axis.

Four DC power supplies feed the excitation current with an accuracy of ± 1 %. Main features of the steering magnet are shown in Table 1.

4. Magnetic field measurement

The steering magnet has been fabricated and some characteristics of its magnetic field are measured. The dependence of the field strength at the magnet center on the excitation current strength I_0 is measured by a Hall probe (FWBELL 4048) (See Fig. 6). The field strength of 0.4 kG is achieved and it is strong enough for the present purpose. Above I_0 = 3 A, the field strength becomes to saturate. Judging from the results of the two-dimensional calculations with PANDIRA, the nonlinearity is mainly due to the iron saturation in the connection region of the iron pole to the yoke.

The magnetic field distribution on the beam axis is also measured with the Hall probe (See. Fig. 7). The effective length of the steering magnet is calculated to be 97 mm from the measured results, which is considerably larger than the pole length of 56 mm. It provides larger deflection angle for the beams.

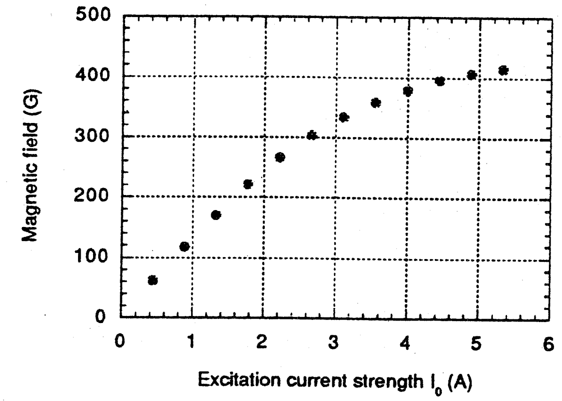

Fig. 6 Magnetic field strength as a function of the excitation current strength I_0

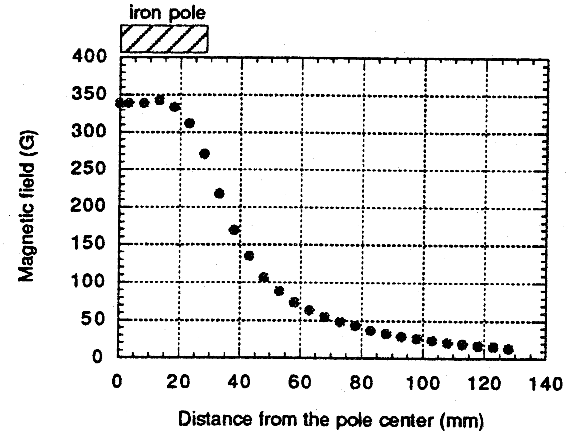

Fig. 7 Magnetic field distribution on the axis

5. Summary

A compact steering magnet with eight-pole structure, which has variable strength and field direction has been developed. It has been installed in the beam line. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. The effective length of the steering magnet is measured to be 97 mm and the magnetic field of 0.4 kG is achieved. The steering magnet with eight-pole structure is very advantageous under severe space limitation.

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