PROPERTIES OF A PERMANENT-MAGNET DIPOLE WITH VARIABLE FIELD STRENGTH AND POLARITY

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A new type of small dipole magnet utilizing 4-pairs of cylindrical permanent magnets has been designed. The magnet is able to change the field strength as well as the field polarity. By the use of 4-pairs of permanent magnets the anti-symmetry terms of the vertical field component in the horizontal mid-plane can be completely eliminated over the whole range of field strength, resulting in a better field uniformity as a dipole magnet.

1. Introduction

A small dipole magnet is required to steer the beam extracted from the cyclotron onto the optical axis of a suitable beam handling system in the developmental program[1] of the CYRIC 680 cyclotron. Previously we proposed and manufactured[2] a new type of permanent-magnet dipole(PMD) utilizing 3-pairs of cylindrical permanent-magnet rods for such a purpose.

Although the PMD nearly satisfied the conditions for the steering magnet, a small quantity of quadrupole component remained due to its anti-symmetry terms of vertical field distribution in the horizontal mid-plane. However, it is practically impossible to eliminate the anti-symmetry terms with the PMD consisting of 3-pairs of magnet. So, a better configuration was searched to correct the field distribution.

In this paper we present a new assembly of dipole magnet (PMDII) which have 4-pairs of cylindrical permanent-magnet rods, and discuss the field properties of the PMDII by using the two-dimensional permanent magnet code PANDIRA[3] .

2. Magnet Layout

The PMDII has been designed to have the almost same dimension as the PMD except for the rod diameter and its assembly. Hence the main parameters of the magnet are restricted by the horizontal width of 17 cm, longitudinal length of 15 cm and working area of 3 cm height × 4 cm wide. More than 3 kG of field strength is required in the working area. A cross sectional layout of the PMDII with 4-pairs (8-permanent magnets) of rods is shown in Fig.1. Each permanent magnet having a maximum energy product of $(BH)_{max} = 42$ MG·Oe ($B_r = 12.96$ kG and $H_c = -12.42$ kOe) is a cylindrical rod of 2.6 cm diameter × 15 cm length, and is magnetized transversally.

The magnetic field in the working area can be changed by rotating the rods, where each adjacent rods are rotated in the *reverse* direction to obtain the symmetric field distributions for the configuration of 4-pairs of rods.

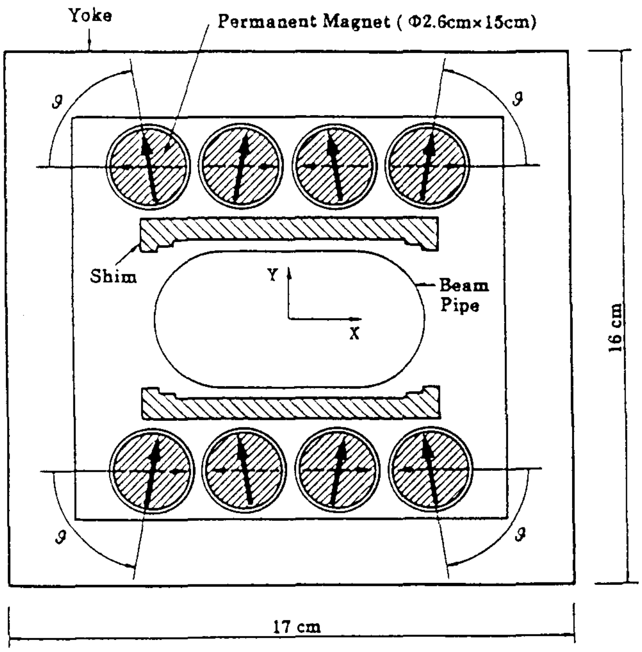

Fig.1. Cross section of permanent-magnet dipole (PMDⅡ). Solid arrows indicating direction of magnetization of permanent-magnet rods with arbitrary rotation angle of ϑ, and broken arrows show $\vartheta = 0°$.

3. Magnetic Field Properties

The magnetic field distribution in the horizontal mid-plane of ref.4 was given by

$$B_y(x_i, \vartheta) = B_S(x_i) \sin \vartheta + B_A(x_i) \cos \vartheta \,, \quad (1)$$

where the first and the second terms of right hand side represent the symmetric and the anti-symmetric fields, respectively. For the case of the newly proposed permanent-magnet dipole, PMDⅡ, the latter terms can be completely eliminated by using the 4-pairs of rods due to its symmetrical arrangement and unique combination of the rotating direction of the rods(see in Fig.1). On the other hand, the unnecessary sextupole component which produces the lack of uniformity for the dipole field from the former term is strongly coupled with the shim shape. Therefor a better field uniformity can be obtained by choosing the shim shape in finer details.

Fig.2 shows the calculated field inhomogeneity distributed in the horizontal mid-plane as a function of the rotation angle of ϑ =30°, 60° and 80.5°, where the value of ϑ=80.5° gives the maximum field strength in the PMDⅡ instead of ϑ = 90°. The vertical scale in Fig.2 represents the ratio of the field inhomogeneity, $[\{B(x) - B_c\}/B_c]$, in unit of %. As can be seen in Fig.2, symmetrical field distributions are obtained, and they do not depend strongly upon the rod rotation angles ϑ. The maximum field inhomogeneity for the present shims over the region of ± 2.0 cm amounts to 0.05 %.

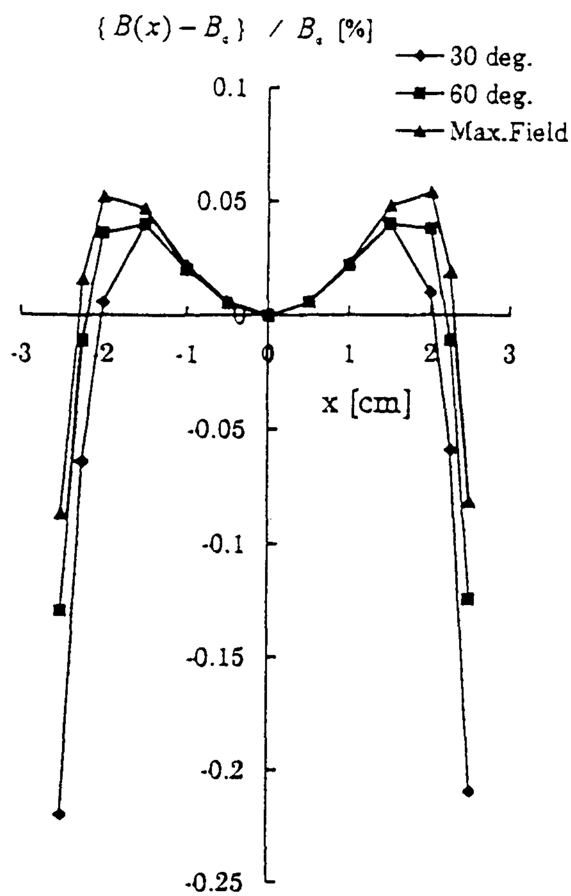

Fig.2. Distribution of magnetic field inhomogeneities in horizontal mid-plane for rotation angle of 30°and 60°, and for the condition of the maximum field strength.

Fig.3 shows the field distributions in the various planes of y =0.0 (mid-plane), 0.4, 0.8 and 1.2 cm for the rotation angle of ϑ=60°, where the field inhomogeneities are represented by the ratio of

[$\{B_y(y) - B_y(0)\}/B_y(0)$] similarly as in Fig.2. As is clear in the figure, the field distributions over the whole y-planes have a good symmetry. The maximum field inhomogeneity in the working area amounts to about 0.15 %.

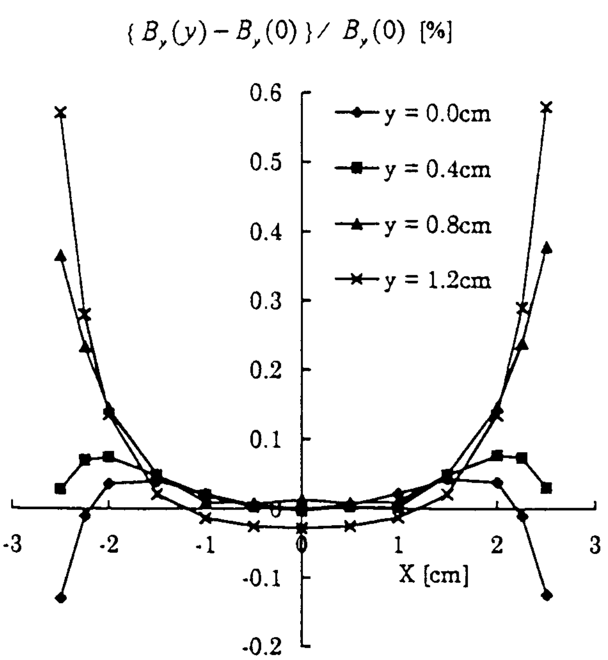

Fig.3. Distribution of field inhomogeneities on various planes perpendicular to the y-axis.

Field strength at the center of the magnet calculated by the code as a function of the rotation angle ϑ is shown in Fig.4. Maximum field strength of 3.56 kG was predicted. One should note that the maximum field strength emerges not at the rotation angle of 90° but at 80.5°. That means the minimum field strength(zero-field) also occurs not at $\vartheta = 0°$ but at $\vartheta = -9.5°$; otherwise the field strength depends upon the rotation angle of the rods, like a function of $\sin \vartheta$ (see in Fig.4). With regard to this phenomenon, we consider that the total *stored energy* of the PMDII should be maximum at $\vartheta = 80.5°$ and minimum at $\vartheta = -9.5°$,respectively having a function of $a + b\cos[2(\vartheta + 9.5°)]$.

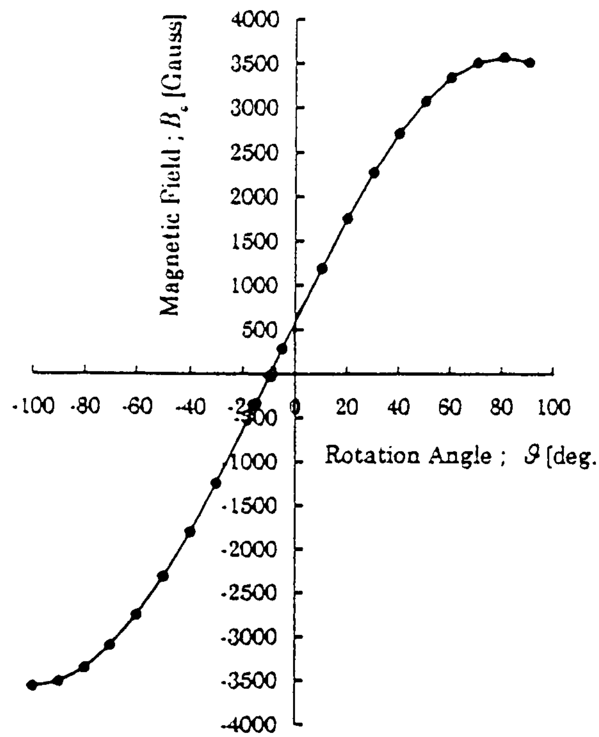

Fig.4. Calculated magnetic field strength B_c at the center of the dipole magnet as a function of rotation angle ϑ using PANDIRA. Solid circles indicate points of calculation.

4. Summary

We have designed a small dipole magnet utilizing 4-pairs of cylindrical permanent-magnet rods (PMDII) and investigated the magnetic properties with the aid of a two-dimensional code PANDIRA.

The PMDII has a special advantage of field uniformity in the vertical field distributions due to the fact that the quadrupole components over the whole range of field strength are completely eliminated by the symmetry of the configuration.

The PMDII is able to change its field strength as well as the field polarity, because the field strength depends upon the rotation angle ϑ of the permanent-magnet rods like $\sin(\vartheta + 9.5°)$. The maximum field strength amounts to 3.56 kG as predicted by the code.

This type of magnet can be used not only as a steering magnet but as a dipole magnet convenient elsewhere in beam handling systems.

5. References

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4. M.Fujioka, et al., CYRIC Ann. Rept.(1980) pp.93.