A Permanent-Magnet Dipole with Variable Field Strength and Polarity

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I. 14. A Permanent-Magnet Dipole with Variable Field Strength and Polarity

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Abstract

A prototype dipole magnet employing six permanent-magnet rods has been designed and constructed. The magnet is able to vary the magnetic field strength as well as the polarity of the field direction. We present some results of the design studies and measurement of the magnetic properties.

Introduction

As a part of the developmental programs of the CYRIC 680 cyclotron\(^1\), we have been studying high-current beam extraction by means of negative ion acceleration\(^2\). A positive ion beam, which is achieved by passing an accelerated negative ion beam through an appropriately positioned thin foil to strip off the electrons, is then deflected out into a suitable exit channel. The first important objective at the exit channel is to steer the beam extracted from the cyclotron onto the optical axis of a new beam line to be constructed. This is not a trivial task because the available open space is too small to install a coil-type magnet. One of the selection is a permanent-magnet dipole with adjustable field strength and polarity because such a magnet is expected to provide a very high field strength in a small space when compared with a coil-type magnet. A prototype permanent-magnet dipole (PMD) with adjustable field strength and polarity has been constructed for such a purpose. Since the original idea of such a magnet was described in the previous report\(^3\), the present work is a realization of this idea.

Magnet Design

The PMD consists of 6-cylindrical permanent-magnet rods magnetized transversally, a window-frame type pure-iron return yoke, pure-iron shims to make a uniformity of the field strength in the required region, and a drive mechanism to vary the magnetic field by rotating the permanent-magnet rods. The cross sectional layout of the PMD is given in Fig. 1. Not shown in Fig. 1 are the drive mechanism of the rods and the support stands of the
shims. The permanent-magnet material is commercially available NdBeFe(Neodymium-Iron-Boron), which was formed into a cylindrical rod of 2.5 cm diam. and 15 cm length; it was magnetized perpendicularly to the rod axis (Table I).

In the design studies, the energy product of the permanent-magnet rod of \((BH)_{\text{max}} = 40 \text{ MG}\). \(Oe(B_r = 12.5 \text{ kG} \text{ and } H_c = 12.0 \text{ kOe})\) was assumed, and 2-dimensional permanent-magnet code PANDIRA was used to calculate the magnetic field. The field strength as a function of the rotation angle calculated by the code is shown in Fig. 2. The maximum field strength of about 2.7 kG was predicted at the center of the PMD at the rotation angle of 90 deg. The typical flux line plots simulated by the code are shown in Fig. 3 for the rotation angles of 90, 60, 30 and 0 deg. From this calculation the field strength as a function of the rotation angle \(\theta\) is expected to be

\[
B(\theta) = B_{\text{max}} \cdot \sin\theta, \tag{1}
\]

where \(B(\theta)\) is the magnetic field at the center of the PMD, and \(B_{\text{max}}\) is the maximum magnetic field strength of 2.7 kG. The field inhomogeneity in the mid PMD plane amounts to 0.64 % over the region of +2.5 cm from the magnet center.

Another important problem for designing the magnet system is to estimate the mechanical moment working on the drive mechanism. This moment is calculated in the following way. The magnetic energy \(W\) is mainly stored in volume \(V\) between the shims, and when the magnetic field \(B\) changes by \(\Delta B\), the change of the energy \(\Delta W\) is given by

\[
\Delta W = \frac{V \cdot B}{\mu_0} \cdot \Delta B. \tag{2}
\]

where \(\mu_0\) is the magnetic permeability of vacuum. If we consider a small change \(\Delta \theta\) of the rotation angle of the permanent magnet rods, the amount of the moment \(F\) is given by

\[
F = \frac{\Delta W}{\Delta \theta} = \frac{V \cdot B}{\mu_0} \frac{\Delta B}{\Delta \theta} \tag{3}
\]

Using eq.(1) in eq.(3), we have

\[
F = \frac{(B_{\text{max}})^2 V}{2\mu_0} \cdot \sin 2\theta, \tag{4}
\]

which is plotted in Fig.2.
Magnetic Measurements

Firstly, we measured the field distribution of the permanent magnet rods to investigate their magnetization previously to assemble them in the PMD system. The results of measurement were in good agreement with the analytical formula\(^4\) and with the numerical results calculated by PANDIRA.

The magnetic fields of the present dipole magnet were measured with a Hall probe. The measurements were performed for variance of the field strength corresponding to various rotation angles; we measured field uniformity in the horizontal mid-plane and the field distribution along the longitudinal direction. The results of measurement except the field uniformity are plotted in Figs. 4 and 5. The maximum field strength of ±2.33 kG has been obtained at the rotation angle of ±90 deg. The measured field values as the function of the rotation angles are quite similar to the numerical calculations and Eq.(1). The reproducibility of the field for repeated rotations is quite good, the difference being about ±10 Gauss, but the realized maximum field strength is not as high as the calculated value of 2.7 kG, giving an apparent discrepancy. This fact, however, is quite understandable if we consider the stray fields from the magnet edges. The effective longitudinal length defined conventionally is 17.8 cm, whereas the actual length of the PMD is 15 cm. Thus 2.7 kG×15 cm=40.5 kG cm is nearly equals 2.33 kG×17.8 cm=41.5 kG cm, indicating a fractional difference of as small as 2.4 %.

Although the non uniformity of the central field in the horizontal mid-plane have been measured to be about a few percents, it will be possible to obtain a better uniformity by optimizing the shim shape after more detailed studies.

Results and Outlook

In this works, the studies were mainly directed to a comparison of magnetic properties of the PMD from calculation and measurement, and to the performance of the mechanical driving system. The magnetic field could be adjusted smoothly by rotating the permanent-magnet rods as the function of sinθ. The effective magnetic field rigidity=\(\int B(s)ds\) was nearly equal to the calculation. There was no serious problems in the mechanical driving and electrical control systems. In the future, it may be possible to use this type of magnet for a steering magnet with our program.

References

Table 1. Parameters of permanent-magnet rods.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Ø25mm X 150mm</td>
</tr>
<tr>
<td>Residual flux density; Br</td>
<td>12.8 - 13.3 kG</td>
</tr>
<tr>
<td>Coercive force; Hc</td>
<td>12.0 - 13.0 kOe</td>
</tr>
<tr>
<td>Relative permeability; $\mu_r$</td>
<td>1.05</td>
</tr>
<tr>
<td>Magnetic energy; (BH)$_{\text{max}}$</td>
<td>39 - 43 kG-Oe</td>
</tr>
<tr>
<td>Material</td>
<td>Neodymium-Iron-Boron (NdBFe)</td>
</tr>
</tbody>
</table>

Fig. 1. Cross section of the PMD (Perment Magnet Dipole) with the arrows indicating the direction of magnetization of the permanent magnet rods.
Fig. 2. Two-dimensional calculation of the magnetic field $B$ and the total moment $F$ as functions of the rotation angle $\theta$.

Fig. 3. Flux lines simulated by PANDIRA over the cross section of the PMD at the rotation angles of 90, 60, 30 and 0 deg.

Fig. 4. Measured magnetic field as a function of the rotation angle. The dots indicate the points of measurement.

Fig. 5. Measured magnetic field distributions along the longitudinal direction for the rotation angles of 90 and 30 deg.