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著者	HONMA Toshihiro
journal or publication title	The science reports of the Tohoku University. Ser. 8, Physics and astronomy
volume	17
number	1
page range	143-144
year	1996-07-25
URL	http://hdl.handle.net/10097/25913

Study of A Permanent-Magnet Dipole with Variable Field Strength and Polarity

Toshihiro HONMA

Cyclotron and Radioisotope Center, Tohoku University

A proto-type dipole magnet employing permanent-magnet rods has been designed and constructed. The magnet is able to change the magnetic field strength continuously as well as the polarity of the field direction by rotating the rods. The magnet has a special advantage of high-field production within a small open space available. The magnet of this type will be used for beam steering at an extraction channel for a planned negative-ion acceleration in our cyclotron. The first important objective at the exit channel is to steer the beam extracted from the cyclotron by some dipole magnet onto the optical axis of a new beam line to be constructed. This is not a trivial task because available open space is too small to install a coil-type magnet. One of the selections is to use a permanent-magnet dipole because such a magnet is expected to provide a very high field in a small space when compared with a coil-type magnet. A proto-type permanent-magnet dipole (PMD) with variable field strength and polarity has been designed and constructed for such a purpose.

The PMD consists of six-cylindrical permanent-magnet (PM) rods magnetized transversally, a window frame type pure iron return yoke, pure iron shims to obtain uniformity of the field strength in the required region, and a driving mechanism to rotate the PM rods. The permanent-magnet material is commercially available NdBFe, which has an energy product of $(BH)_{max}$= 42 MG·Oe. The two-dimensional code PANDIRA and POISSON were used to investigate magnetic properties. The field strength change at the center of PMD is quite similar both for the calculated and the measured results as a function of the form $B(\vartheta) = B_{max} \cdot \sin\vartheta$, where ϑ is the rotation angle of the rod and B_{max} is the maximum magnetic field strength of 2.4 kG (measured value).

To estimate the total torque T working on the six PM rods the total magnetic energy stored in the PMD was calculated for various rotation angle ϑ of the rods. The code PANDIRA, however, can not calculate this energy for a permanent-magnet problem. Instead we calculated the energy with the method of equivalent surface-current given by $\vec{i}_{eq} = (\vec{M}_0 \times \vec{n}) \cdot \delta_S$,where $\vec{M}_0$ is the magnetization of the rod, $\vec{n}$ is the outward unit vector normal to the boundary and δ_S is the one-dimensional delta function with its singularity concentrated on the surface. Owing to this equivalence we can calculate the magnetic energy W(POI) by means of the $\vec{B}$-field by using POISSON. On the other hand the magnetic energy density within the PM can be represented as $w_{in} = \frac{\mu_0}{2}(\vec{H}_{in})^2$ by means of $\vec{H}$-field, where $\vec{H}_{in}$ is the magnetic field intensity in the PM which is calculated by the relation of $\vec{B}_{in} = \mu_0 \cdot \vec{H}_{in} + \vec{M}$. Then the total magnetic energy of PMD, W(PMD), can be obtained in the following way.

$$W(\mathrm{PMD}) = W(\mathrm{POI}) + \left[\int_{in} \frac{\mu_0}{2}\left(\vec{H}_{in}\right)^2 \mathrm{dV} - \int_{in} \frac{1}{2\mu_0}\left(\vec{B}_{in}\right)^2 \mathrm{dV}\right](\mathrm{PAN}),$$

where $\int_{in}$ denotes integration within the six PM rods. In Fig.1 both W(PMD) and W(POI) are plotted together with the torque T calculated by numerical differentiation. The dependence on ϑ of both W(PMD) and W(POI) are seen to be well described by a function $W(\vartheta) = a + b \cdot \cos 2\vartheta$. Also, the maximum value of $|T|$ is thus predicted to be $T_{cal}(\max) = 46$ N·m at $\vartheta = \pm$ 45 deg.. The calculated torque was in fair agreement with the measurement, where the mechanical transmission efficiency of the worm-gear systems was taken into account.

The present PMD type of magnet can also be used elsewhere in beam handling systems. Due to its advantage it is particularly useful for a limited available space, and can be applied to instruments with a negligible electric power without cooling system.

I would like to a make special mention of the fact that the discussions with Prof. M. Fujioka, my co-worker, proved to be very significant throughout the entire course of this work.

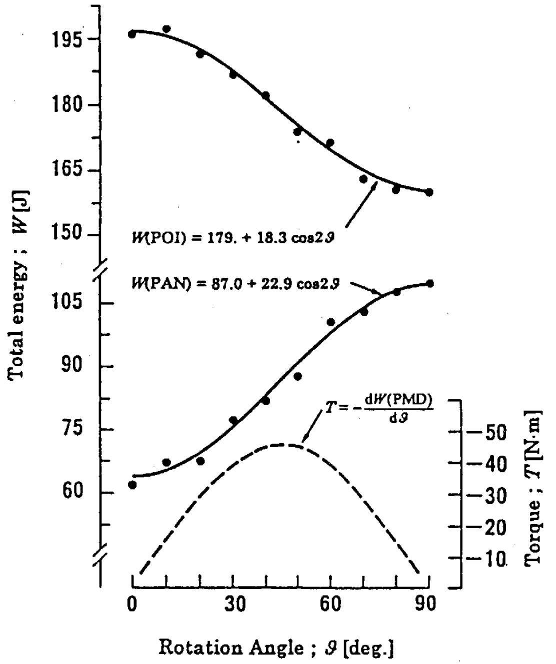

Fig. 1. Calculated total energies W(POI) and W(PMD) as a function of rotation angle ϑ. Calculated torque T using the curve W(PMD) is also shown by a broken curve.