Permanent Magnet-based Dipole for a Small Storage Ring *

Firas Putris and Wayne Vernon
Physics Department, University of California at San Diego
and
Intercampus Institute for Research at Particle Accelerators
B-019, UCSD, La Jolla, CA 92093

Abstract

We designed and constructed a small dipole magnet driven by NdBFe permanent magnet material with iron for field shaping. The gap is 1.5 inches high and 4 inches wide; the magnet length is 8 inches. A central field value of 0.422 T has been measured and a computer prediction for a long magnet predicted 0.6 T. The central field is quite uniform in the horizontal midplane and field integrals have been measured and are plotted.

I. Introduction

We wish to study small, inexpensive bend magnets for a small storage ring; the advent of low cost, high energy density permanent magnet material (NdBFe) makes possible new, compact designs. The storage ring design [1] is part of a study to evaluate the use of Compton back-scattered x-rays (CBX) in protein crystallography, and the bend magnets are a critical component in that design. This permanent magnet material, NdBFe, is very useful both because it should result in much lower system costs, and because it allows the individual magnets to be more compact than in conventional copper winding designs. In particular, the magnet faces are almost flush when permanent magnets are used, rather than being recessed behind the windings as in the case of conventional electromagnets.

The field strength of the dipole is not as high as one would have at first expected because we need to have a very uniform field, but we expect that a longer magnet (40 cm instead of 20 cm) would result in a considerably higher field strength. The present prototype has a large part of the flux located in the fringe field, and the length of the magnet is too short to approximate the asymptotic, long magnet case. Horizontal and vertical aperture were chosen to allow for fairly large beams in this low energy (80 to 125 MeV) electron storage ring, and there is a need for a high quality region (2 cm high by 4 cm wide) which must be somewhat smaller than the full aperture.

II. Magnet Design

We began the design with computer simulation using POISSON [2] in a Physics special projects course. The solution to the uniform magnet field requirement is shown in Figure 1 for one quadrant of the magnet. Permanent magnet material has been allocated in two regions so that the ratio of the quantity in the two regions can be changed in order to minimize the horizontal gradient of the vertical magnetic field component. It is also possible to predict the magnetic field value for a very long magnet even though the program only produces solutions in two dimensions. The NdBFe material has a high remnant field as well as a high energy density (about 30 Megagauss-Oersted for our samples), and the program predicted a 6 kG field for the long case. The short prototype was all that we could afford (about

$ 8000 for the permanent magnet material), and the 8 inch length is much too short to be in the "very long" regime. However, the predictions for the uniformity of the magnetic field seem to hold for this short prototype.

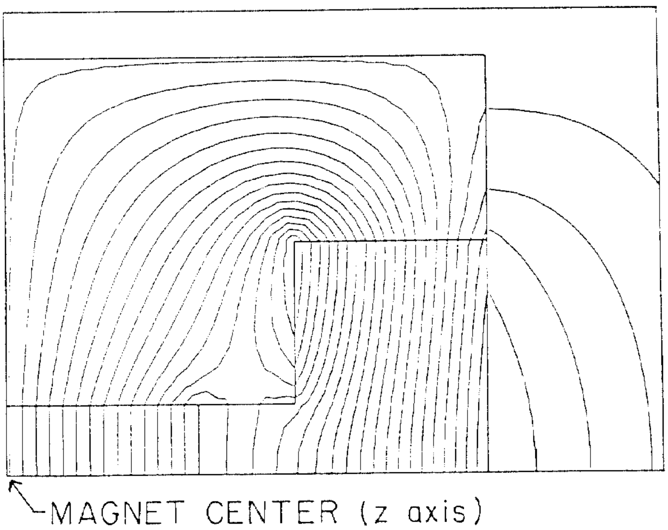

Figure 1. Cross section of one quadrant of the magnet with field lines from computer (POISSON) prediction.

We also did some computer runs to verify that the stray fields to the side of the magnet could be contained by placing a vertical iron plate along the side of the magnet, a few cm away. It is necessary to have some kind of isolation from the outside; random iron and steel objects anywhere in the vicinity of the permanent magnet will otherwise cause a reduction in the central magnetic field. These computer simulations also indicated that the central field intensity could be varied by making adjustments in the reluctance of this external flux path. It appeared to be easy to accomplish the required 20% field variation by simply moving the plate in or out, but a more sophisticated scheme would be used in a real system. We also wish to vary the field by having an outside current loop; computer simulations indicated that a few percent change ought to be possible with modest power levels.

III. Fabrication

Permanent magnet material was acquired in blocks with $1 \times 2 \times \frac{1}{2}$ inch dimensions and magnetized along the short direction. Since the cost of this material is dominated by licensing fees, it might pay to try to negotiate special purchases for research applications; the price which was paid for these pieces ($43 each) ought to include those fees. An earlier purchase of a few pieces at a considerably lower price was probably from a source who was not paying the fees. We have not painted or coated the pieces, and they do rust in the humid environment where we work. However, there is no obvious deterioration in the magnetic field properties of the blocks as their surfaces become rust coated.

Iron for the body of the magnet was cut from "run of the mill" soft iron bar (12-15 low carbon steel, 0.23 % max. carbon) of 8×2 inch cross-section. The pieces were then ground

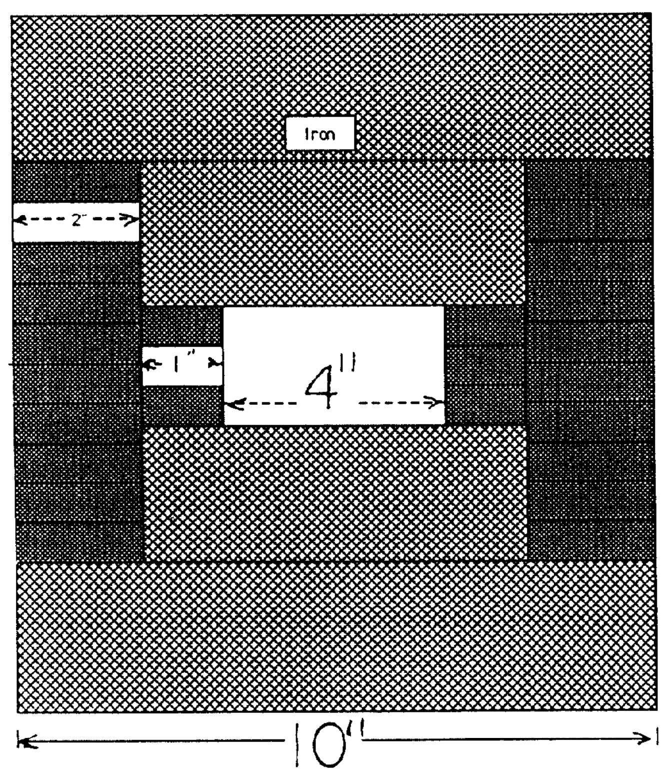

Figure 2. Full cross section of magnet with dimensions. The darker rectangles are the permanent magnet blocks.

flat and bolted together to make the assembly shown in Figure 2. Aluminum bars and threaded brass rods (not shown in Figure 2) were mounted around the sides of the structure to hold the permanent magnet blocks in place. Although the forces needed for restraining the pieces are modest, some external constraint is necessary to keep them in position.

Assembly of the permanent magnet blocks into the desired geometry required strong hands, considerable strategy and a particular type of leather glove which is tough, but resilient, so that individual blocks can be edged into place. The iron pieces were positioned with an external frame which permitted the gap to be adjusted during assembly.

IV. Measurements of Magnet Properties

The magnetic field in the vertical direction was measured along several parallel axes every 0.05 inch for 8 inches, starting 4 inches in front of the magnet face. These axes approximate the beam trajectories which the magnet should bend. The central field was 4220 Gauss (0.422 T).

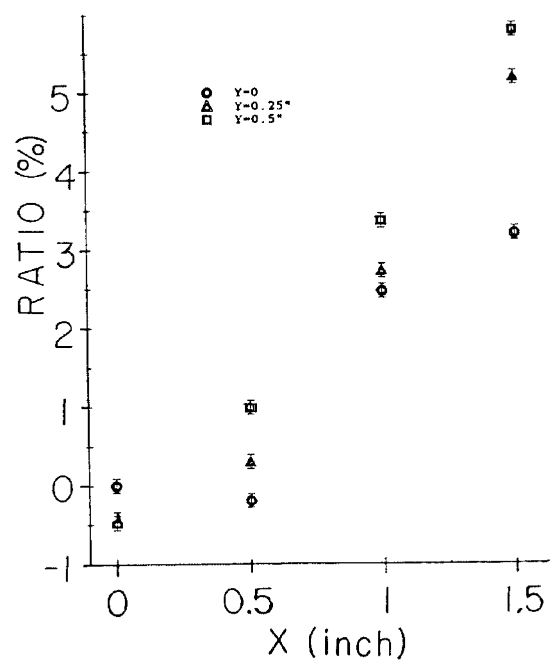

Figure 3. Plots of twelve of the ratios ($r_{i,j}$ in the text) of magnetic field (B_z) integrals along z. Circles are y=0, triangles are y=0.25" and squares are y=0.5".

In order to check the variability of the field integrals

$$I_{j,k} \; = \; \int_{-8}^{8} B_y(x_i, y_j, z)\; dz$$

we plot the difference ratio $r_{i,j} = (I_{i,j} - I_{0,0})/I_{0,0}$ in Figure 3 for the 12 axes in one quadrant. The central region of about 2 cm on either side of center, horizontally is quite good, for up to 1 cm up or down. For larger distances from the axis the integrals are changing because of the end effects of the permanent magnet material, and some pole shape correction is probably needed.

We note that the integrals have a value (0.108 T-m) which is equivalent to assigning the magnet an effective length of 10.1 inches; the iron is 8 inches long. A few hundred turns of copper wire were wound around the outside of the magnet structure and the variation of central field was observed to be $\Delta B/B$ (%) = (3.4×10^{-3})H when H is Amp-turns. We also checked the sensitivity to placing external iron plates near both sides of the magnet. Pieces with dimensions of $6 \times 8 \times \frac{1}{2}$ inches were placed two inches away and caused the field to decrease by 4%. This is consistent with predictions of the computer program. Changes in field integral were different than changes in the central field value, sometimes by as much as 20%, in both the coil and the iron plate method of changing the field.

We wish to thank Everett Stauffer and Richard Lansky for their many contributions to the early part of this project.

V. References

[1] P. Kiefer and W. Vernon, these proceedings.

[2] "Reference Manual for the POISSON/ SUPERFISH Group of Codes," Los Alamos National Lab, LA-UR-87-126 (1987).

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