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FIELD PROPERTIES FOR A 4-GeV MICROTRON SECTOR MAGNET*

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Summary

The central magnetic field uniformity and field edge shapes have been investigated for a 609 metric ton sector magnet designed for the 4-GeV Electron Microtron (GEM)⁸ at Argonne National Laboratory. The effect of a Purcell¹ filter on the central field uniformity was studied using the 2D magnetostatic computer program, TRIM.² The effects on the shape of the edge field were studied for various geometries of endguard, pole tip shim, shield plate, pole edge shape, and coil. Both 2D and 3D programs were used for these latter studies and all results showed that the proposed design would produce acceptable field qualities.

Introduction

There are several major technical aspects that were addressed during the preliminary design phase of GEM in order to verify the feasibility of the proposed accelerator, the hexatron. The one that will be discussed in this paper concerns the properties of the magnetic field of the hexatron sector magnet.

Two views and two sections of the sector magnet are shown in Fig. 1. The high energy region is on the right end of the plan view and the low energy end is shown containing 14 steps along the edge of the pole. These steps are used to reduce the dipole edge angle for the low energy orbits.

Fig. 1 The Sector Magnet for GEM.

The electron beam has been successfully transported through the entire hexatron for a low energy edge angle of 0° and a high energy angle of -60° (no steps). The central field was assumed to be uniform and the field profile in a direction perpendicular to the pole edges was assumed to be the Enge "short-tail" shape.³ The calculations of the field properties were done to verify that: 1) the central field shape is sufficiently uniform to be corrected by the pole face coils located along individual orbits, 2) the edge field falls off at least as sharply as an Enge short-tail, and 3) the angle of the effective field edge is within ±5° of the design value (this small a deviation can be easily corrected by adjacent beam line elements).

To obtain the required edge field shape the magnet contains the following elements: 1) a steel

endguard which wraps around the main coil, 2) steel plates which extend across the midplane between the tips of the endguards and shield the adjacent external beam from the edge of the field from the neighboring step, 3) pole tip shims, and 4) pole face correction coils.

Central Field Uniformity

The 2D magnetostatic field program named TRIM² was used to study the central field uniformity. An average section through the proposed sector magnet, section A-A in Fig. 1, was used for these calculations. Figure 2 shows a typical geometry and the resulting flux lines. A double precision version

Fig. 2 The Flux Lines Calculated with TRIM for an Average Section of the Sector Magnet.

of TRIM allowed the convergence of the calculations to 1×10^{-7} and gives values of field uniformity that will change less than 1×10^{-5} when further converged. Figure 3 contains a plot of the results of the reference (no Purcell gap) calculation showing the field change across the useful part of the pole to be about 4.5×10^{-3} ($\pm 2.2 \times 10^{-3}$ uniformity).

To reduce this, a Purcell filter¹ was placed between the pole piece and the magnet yoke and is shown in Figs. 1 and 2.

The effect of this gap was investigated for gap heights of from 0.25 cm to 1.0 cm and with it located as shown and also at a place 3 cm lower. In this lower position the endguard is connected to the yoke, rather than the pole.

The Purcell gap must be kept small to minimize the ampere-turns of the main coils and it must be large enough to homogenize the field. A compromise height of 0.30 cm gap was chosen and it was located above the endguard. There are several reasons to locate the gap here: 1) a 0.3 cm gap here produces a more uniform field than a 0.75 cm gap located 3 cm lower, 2) the mechanical design of the pole is greatly simplified, and 3) the coil used to drive the gap (the auxiliary coil) can provide the additional ampere-turns needed to control the flux in the endguard structures. Figure 3 contains a plot of the resulting central field for this gap geometry showing a uniformity of $\pm 4 \times 10^{-4}$.

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Fig. 3 Plots of the TRIM Results Across an Average Pole Width.

Edge Field Shape

High Energy Edge

After the Purcell gap was sized and located, attention was given to the details of the pole edge, coil, and endguard geometries as shown in Fig. 4. The thickness of the endguard was 2 cm for these calculations. With no current in the auxiliary coil there is a field of -300 G in the region between points A and B in Fig. 4 (the central field is positive). The corresponding maximum flux density in the endguard was 17.5 kG. When 13% of the current was transferred from the main coil into the auxiliary coil the field at points A and B is 33 G and -19 G respectively, and the maximum flux density in the endguard was 15.3 kG. This was selected as the current distribution for succeeding calculations.

Fig. 4. The Flux Lines Calculated with TRIM in the Region at the Edge of the Sector Magnet.

Figure 5 shows a plot of the field perpendicular to the pole edge at the high energy end of the magnet. Also shown is a plot of an Edge short-tail for reference. Here the magnetic fields are normalized to the corresponding central field values and the abscissa is represented in terms of the number of half-gap heights from the step edge.

Low Energy Edge

The stepped edge field at the low energy end of the sector magnet is too complex to be properly modeled with a two dimensional program like TRIM. As a result two 3D programs were used to calculate the magnetic fields in the vicinity of one of the steps along this edge. One program,⁴ written at Argonne, performs magnetostatic calculations for geometries with steel elements of infinite permeability. It can

Fig. 5. Plots of Edge Fields for Calculations and Measurements.

define smaller details in the steel geometry than other presently available 3D programs, and the resulting edge field shapes represent those that can be achieved in a real magnet for the geometry used. This program was used to calculate a single step in the low energy end of the magnet. A plan view of the pole surface geometry used for the calculation is shown in Fig. 6. This does not include pole tip shims

Fig. 6. Sketch of the Pole Tip Geometry used in a 3D, Infinite Permeability, Field Calculation.

which could be used to further sharpen the edge but it does include a shield plate which is shown in section A-A in Fig. 6. The field shape along the beam direction shown in Fig. 6 is plotted in Fig. 5. The experimental measurements of this field shape⁵ for a magnet with the same pole edge geometry but different central field geometry are also included in Fig. 5. The effective edge was also calculated for several paths across the step edge showing it to be oriented at an angle of 4.3° of the design position.

The low energy edge field profiles have also been calculated using TOSCA, a program developed at the Rutherford Appleton Laboratories by the members of the Computing Applications Group.^{6,7} It is a finite

element program for solving magnetostatic and electrostatic fields in three dimensions. For magnetostatic problems, it solves for two scalar potentials, namely the total scalar potential within magnetic regions and the reduced scalar potential in regions where source currents are present.

An interactive pre-processor program called SCARPIA helps the user construct a finite element mesh suitable for solution by the batch program SOLVE. An interactive post-processor program, POSTOSCA, enables the user to examine the output graphically.

Since most three-dimensional objects can be divided into a series of planes which have similar cross-sectional geometries, then it is possible to perform the reverse process, namely, defining a two-dimensional geometric profile of the object and extending it in the third dimension. This is the method used in SCARPIA. The topology must be continuous from plane to plane. Figure 7 is an expanded view of the block layers for the steel elements of the hexatron magnet in the "step" region. In the first block layer only the magnet yoke and shield plates are steel. The second block layer contains the yoke, pole, and endguard. The third and fourth layers contain the main coil surrounded by an endguard, and the sixth layer contains the auxiliary coil that reduces the flux through the endguard and shield plate.

Each of the large elements shown is further subdivided into smaller elements. The total number of nodes must be less than 10,000 (for 8 node elements) or 4,000 (for 20 node elements). This problem used 20 node elements in the region of interest, i.e., along a particle beam path, and 8 node elements elsewhere. The total was 5670 nodes in 2304 elements.

For constant permeable steel elements, only one iteration is needed to find the scalar potentials at each node. Output meshes are defined by the user, where the field, potential, or permeability are calculated and printed. For variable permeability, about 10 to 20 iterations are required to find a "converged" solution of the scalar potentials. A B-H table for fully annealed AISI 1010 steel has been used in these calculations.

The field shape along a line perpendicular to the "step" is included in Fig. 5. It can be seen that this agrees very well with other calculations and measurements. The location of the effective edge has also been calculated at two points across the step edge and it was found to be within 2° of the design orientation.

Conclusions

The results of the calculations described here have shown:

1. The central field is uniform enough to provide B_{d1} values that are easily within $\pm 4 \times 10^{-5}$ of the design values (excluding the edge effects). The pole face correction coils will be able to compensate for errors as large as $\pm 2 \times 10^{-2}$. The central field has, therefore, been shown to be acceptable.
2. The field, perpendicular to the pole edge, falls off more sharply than the Engle short-tail in every calculation performed and agreement between the calculations and the actual measurements of a model magnet agree to within a few percent.
3. The effective edge is parallel to the steel pole edge to within $\pm 5\%$.

Fig. 7. Expanded View of the Block Layers used in the TOSCA Calculation.

There are still details to be considered before a final optimum design is established. It has been shown, however, that all calculations and measurements of model magnets done so far provide firm evidence that the required field properties can be achieved for a real and practical sector magnet design.

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