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Variable-Field Permanent-Magnet Dipole*

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Abstract — A new concept for a variable-field permanent-magnet dipole (VFPM) has been designed, fabricated, and tested at Los Alamos. The VFPM is a C-shaped sector magnet with iron poles separated by a large block of magnet material (SmCo). The central field can be continuously varied from 0.07 T to 0.3 T by moving an iron shunt closer or further away from the back of the magnet. The shunt is specially shaped to make the dependence of the dipole field strength on the shunt position as linear as possible. The dipole has a 2.8 cm high by 8 cm wide aperture with ~10 cm long poles.

I. INTRODUCTION

A variable-field permanent-magnet dipole (VFPM) has been designed, fabricated, and tested for use on the Los Alamos Advanced Free-Electron Laser (AFEL) experiment [1]. This project requires many beam optics and diagnostic elements to be located in a limited area. The AFEL requires high-quality optics to prevent emittance growth in the beam which reduces the FEL lasing efficiency. During the design of the AFEL it was determined that variable-field permanent-magnet dipoles and quadrupoles would meet the required field quality and field range, while occupying less space than comparable electromagnets. The AFEL variable-field permanent-magnet quadrupoles are described in [2], and the design, fabrication, and testing of the VFPM is described in this report. The VFPM is a C-shaped sector magnet with a 2.8 cm-high by 8 cm-wide aperture with ~10 cm-long poles. The central field can be continuously varied from 0.07 T to 0.3 T by adjusting the location of an iron shunt.

II. MAGNETIC DESIGN

The basic design of the VFPM is a C-shaped sector dipole made of iron poles separated by a large block of magnet material. A schematic is shown in Fig. 1. The dipole field is varied, or tuned, by adjusting the location of an iron shunt at the back of the magnet. Special care was taken in the design of the shunt. A flat shunt results in a steep non-linear tuning curve. This is because little flux is shunted away at shunt gap distances greater than the dipole gap. However as the separation distance approaches the width of the dipole gap there is a sudden increase in the amount of flux diverted from the gap. To overcome this problem a special C-shaped shunt

has been designed. This shunt has tapered tips which become saturated as the shunt is moved towards the magnet, limiting the amount of flux that can be shunted in proportion to the cross section of the saturated tips. As the shunt is moved closer to the magnet the cross section of the tips increases allowing more flux to be diverted through the shunt. The amount of shunt travel needed to produce a given field variation can be controlled by adjusting the taper of the shunt

Fig. 1 Schematic of the magnetic design of the VFPM. The iron is indicated by the shaded areas and the permanent magnet material and its orientation is indicated with arrows.

Fig. 2 Two-dimensional calculation of the central field (B_0) vs the shunt gap for a flat shunt (dashed curve) and a C-shaped shunt (solid curve). Both curves have been normalized to one at the maximum.

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tips. Fig. 2 shows the results of magnetic field calculations that show the difference between tuning curves of a flat shunt and the C-shaped shunt used for this magnet. These results were calculated in two-dimensions using the FLUX2D magnet-design code[3]. The C-shaped shunt yields a much more linear tuning curve and greatly extends the range of travel. This not only relaxes the precision with which the shunt must be moved but also reduces the magnetic force on the shunt which in turn simplifies the mechanical design. Besides determining the optimum shape of the shunt, the two-dimensional model was used to determine the geometry of the iron pole tips and size of the magnet block. Low carbon steel (C-1006) and samarium cobalt ($\text{Sm}_2\text{Co}_{17}$) with a remanent field of 1.05 T were used in the design. An 8 cm-wide aperture was found to meet the field-uniformity specification of 1 part in 1000 across the 2.8 cm width of the beam pipe without shims at the edges. The final design was modeled in three-dimensions using the TOSCA magnet design code[4].

III. MECHANICAL DESIGN

A side view of the mechanical assembly for the VFPM is shown in Fig. 3. The shunt is moved by a lead screw driven by a small stepper motor through a 100:1 gear-reduction unit. All linkages in the shunt drive system are designed for minimum backlash, although this is not strictly required since the drive system is always pre loaded against the pull of the shunt. Not shown in Fig. 3 are the guide rods used to maintain the horizontal alignment of the shunt with respect to the dipole. The vertical alignment is maintained by a pair of rollers on the top and bottom. An electric brake on the drive shaft locks the shunt position once it has been set. Micro-switches limit the range of travel and define a reference point for the position readout. The position of the shunt can be determined by either the motor or encoder step count from either of the limit switches. The entire assembly is mounted on a 3-point mount to expedite the installation and alignment of the magnet on the beam line.

Fig. 3 Schematic of the mechanical assembly.

IV. TEST AND MEASUREMENT RESULTS

A series of point maps were taken of one of the dipoles to characterize the general performance of the set of magnets. A Hall probe was used to measure the central field vs shunt position, shown in Fig. 4, and the field distribution across the width of the aperture shown in Fig. 5. Also shown in Figs. 4 and 5 are the results of the two-dimensional field calculations of the same quantities. The coordinate system referred to in Figs. 4, 5 and 6 has the z-axis along the beam direction, the x-axis in the direction of the bend, and the y-axis orthogonal to the z and x-axes. Since the two-dimensional model does not include the effect of fringe-field loss in the third dimension, it over estimated the central field by about

Fig. 4 Measured (points) and calculated (curve) central field (B_0) vs the shunt position. The calculated results have been normalized to fit the data at the maximum field value.

Fig. 5 Measured (dots) and calculated (smooth curve) dipole field (B_y) across the width of the aperture (x-axis). The magnet is set at maximum field. The calculated results have been normalized to fit the data.

40%. Therefore the results calculated from the two-dimensional model shown here were normalized to fit the data. Finally Fig. 6 shows the results of point map made along the z-axis of the magnet through the center of the dipole gap. Included in Fig. 6 are the results of a three-dimensional calculation for the same configuration. After the point maps were complete a NMR probe was used to calibrate each magnet's central field vs shunt position. The NMR measurements determined that the dipole field was reproducible to better than 0.1%.

Fig. 6 Measured (dots) and calculated (smooth curve) dipole field (B_y) along the z-axis of the dipole. The magnet is set at maximum field.

V. CONCLUSIONS

Three variable-field permanent-magnet dipoles have been designed, fabricated, and tested. The magnets have been installed and are currently in use on the AFEL project at Los Alamos. The VFPMd achieved the design goal of being compact, high-quality, dipoles, with a large tuning range and excellent reproducibility. The fabrication cost of these magnets was approximately 20% less than the cost of comparable electromagnets with their accompanying power supplies and coolant systems, with none of the operational cost associated with electromagnets. In addition the stepper motor control of the field setting is quite amenable to most control systems, simplifying the task of remotely controlling the magnets and setting the field. The use of variable-field permanent-magnets can further simplify control systems by eliminating interlocks, such as water flow, over temperature, over voltage, and ground fault, that are typically found on electromagnets.

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