COMPUTATION OF A QUADRUPOLE MAGNET
FOR THE APS STORAGE RING*

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Abstract - The storage ring of the Advanced Photon Source will include 400 quadrupole magnets for focusing the beam. A prototype quadrupole has been designed, constructed, and measured. This paper describes the two- and three-dimensional (2-D and 3-D) field computations performed for this design.

INTRODUCTION

The Advanced Photon Source (APS) is now under construction at Argonne National Laboratory (ANL). This 7 GeV positron storage ring will provide x-ray beams for material science, biology, medicine and other research. A site view of the APS is shown in Figure 1. Because the positron beam in the APS storage ring must have a lifetime of ten hours or more, the magnets must be designed, constructed, and installed with high precision. An end view of the quadrupole magnet is shown in Fig. 2.

To achieve the vacuum needed for a long beam lifetime, and to facilitate the extraction of the photon beam, the APS vacuum chamber, seen in the center of the quadrupole in Fig. 2, has two chambers. This vacuum chamber complicates the design of the ring magnets. In particular, there can be no magnetic yoke connecting the top and bottom halves of the magnet.

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Also the long narrow poles that keep the magnet coils from interfering with the vacuum chamber tend to saturate at the high field gradients at which the quadrupoles will operate. Although the nominal energy of the APS is 7 GeV, the quadrupole magnet design is to be optimized for 7 GeV (field gradients of 10.6 to 18.9 T/m), but with the option of going to 7.7 GeV (maximum field gradient of 20.8 T/m).

Other features of the quadrupole design that had to be included in the computation were:

1. Each magnet pole has two 90° notches for alignment and a hole for a tie rod through the laminations.
2. At the ends of the magnet, the sides of the poles are bevelled to reduce the overall magnet length by making the coils fit more closely there.
3. At the ends, the pole tips are also bevelled to improve field quality.

DATA ANALYSIS: MULTIPOLE COMPONENTS

The multipole components provide a simple numerical expression for the field quality. In polar coordinates (r, θ) the vector potential A_z can be expressed (the so-called CERN Convention) as

$$A_z = a_0 + \sum a_n (r/R)^n \sin n\theta \quad (1)$$

where $R=25$ mm is the reference radius and a_n the n th multipole coefficient.

The quantity of interest is the ratio of the n th multipole field to the quadrupole field. As the

Fig. 1. Site view of the APS.

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Fig. 2. Design for the APS ring quadrupole magnet.

fields are derivatives of the potential, the field ratio of the n th multipole to the quadrupole at the reference radius $R=25$ mm is given by $n a_n / 2 a_2$. To minimize the effect of round-off error, in practice Eq (2) is fit at a larger radius, 35 mm, then scaled to 25 mm.

In 3-D analysis, the total scalar potential is fit to a series of cosines and sines for odd and even multipoles, but otherwise the analysis is much the same. The field ratios are found at different z positions, and also the ratios are found for integrals of the field over z .

2-D COMPUTATIONS

The earliest computations of the quadrupole were done with the 2-D finite difference code POISSON. It uses only linear elements, corresponding to constant magnetic field within each element. In analyzing quadrupole magnets with POISSON, typically the quadrupole geometry is transformed to a dipole geometry through conformal mapping before solving the magnet. This process can give a surprisingly good approximation, even for variable permeability μ . On the other hand, the process restricts the choices that can be made. For example, the hyperbolic shims on the APS quadrupole magnet are a consequence of the initial POISSON design [1].

Later computations were done with PE2D. PE2D was developed at the Rutherford Appleton Laboratory (RAL), and is marketed by Vector Fields. It uses the finite element (FE) method and employs the one component vector potential A_z as solution variable. This choice requires only one variable per node while avoiding the problem of multiple values characteristic of magnetic scalar potential. It permits either linear or quadratic finite elements.

Quadratic elements are well suited to the solution of a quadrupole magnet, in which the field varies linearly in the aperture.

Figure 3 shows one quadrant of the quadrupole geometry, with iron and current regions shown, but not air regions. Note the notches on the pole. Note also that there is an iron flux return yoke between the left and right halves of the magnet, but not between the top and bottom halves. The figure also shows the computed flux lines.

In an ideal quadrupole magnet, the four pole tips would be in the shape of hyperbolas. For a real quadrupole, the hyperbola must terminate to provide room for the coils. Cutting off the hyperbola distorts the field, and the pole must be shimmed to correct the field pattern. There is some freedom in the choice of the size, shape, and location of the shims. This is used to promote accessibility and ease of manufacture.

A computation over 45° suffices to determine the shape of the pole and the effect of notches and hole. To determine effects of the asymmetric yoke requires a 90° region. Effects of manufacturing variation require a full 360° computation.

Fig. 3. 2-D Computation of the quadrupole magnet

2-D RESULTS

Neither the 11.125 mm diameter hole for bolting the laminations together nor the alignment notches changed the ratio of 12-pole field to quadrupole field by more than 0.2×10^{-4} at 25 mm; higher multipoles changed much less.

Magnetic iron connects the right and left sides of the magnet yoke, but not the top and bottom. Computation shows this asymmetry to introduce negligible multipole field components for the corresponding values ($n=4, 8, 12, \dots$). The field ratios at 25 mm radius are all less than 0.1×10^{-4} .

The effects of variations in the core geometry arising during core assembly were modeled by displacements of the poles. These results are reported elsewhere [2].

There are three more or less independent, saturation effects that can be seen in comparing computations with the linear case (constant value of $\mu = 10000$) and the nonlinear case (specified BH curve). The linear case corresponds to low excitation currents and extrapolation from low currents. The first effect is that the multipoles differ. Second, the field for a given excitation current is reduced below what would be predicted by extrapolation from low currents. In both 2-D and 3-D computations, the central field gradient is reduced, and in the 3-D computation, the integral of the field gradient is further reduced.

The ratio of the $n=6$ to $n=2$ (quadrupole) field at 25 mm drops by 0.55×10^{-4} as the excitation current rises from low values to its 7.7 GeV value and by 0.33×10^{-4} to 7.0 GeV. This change is acceptable, but could be reduced through a change in the shim geometry. With a shim that is flat and parallel to the shim on the neighboring pole, as shown in Fig 4b, the multipole ratio drops only 0.31×10^{-4} from low excitation to 7.7 GeV. The peak field computed on the shim at 7.7 GeV also drops from 2.2 T to about 1.8 T.

Likewise, the field gradient at 7.7 GeV is only 90.3% of the value extrapolated from low excitation, and at 7.0 GeV, 94.0%. This effect increases power consumption slightly, but is otherwise acceptable. Nonetheless, it could be reduced by increasing the width of the magnet pole. With a pole increased by a 6° rotation about the top of the notch on one side, the ratio of computed to extrapolated field gradient increases to 93.3% at 7.7 GeV and to 97.6% at 7.0 GeV.

Fig. 4. Shims on the pole.

- a. Original hyperbolic shim
- b. Modified flat shim

3-D COMPUTATIONS

Most 3-D analysis of the APS accelerator magnets has been done with TOSCA, developed at RAL and marketed by Vector Fields. With TOSCA, the solution variable in each region is either the total or reduced scalar potential. Because of the computer time and memory demands of a 3-D code, only a single 45° half-pole region was modeled; the 2-D results justify this simplification. For the same reason, the notches and hole in the pole were ignored.

A major part of the computational effort went into finding a cross-sectional mesh that gave good values for the potential and field and yet was economical in mesh points. This was done by using a pseudo 2-D geometry, with only one mesh step in the z direction, and a no flux crossing boundary condition ($\partial V / \partial n = 0$) imposed on the faces at $z = 0$ and $z = 5$ cm. The cross-sectional geometry and mesh are shown in Fig. 5. Elements are concentrated near the bore region.

Fig. 5. Mesh for 3-D Quadrupole Magnet Computation.

1. Air, total scalar potential, quadratic elements
2. Air, reduced scalar potential, quadratic elements.
3. Steel, total scalar potential, linear elements.
4. Steel, total scalar potential, quadratic elements.
5. Same as 4, with 45° bevel to accommodate coil.
6. Same as 4, with 45° bevel to reduce multipoles.

The choice of steel or air, total or reduced scalar potential, and linear or quadratic elements in Fig. 5 was made as follows. First, TOSCA demands three conditions.

1. All iron regions must be total scalar potential.
2. All regions containing coils must be reduced scalar potential.
3. A multiply-connected group of total scalar potential regions must not link a net current, because in such a situation, the total scalar potential is multiple-valued.

The "bridge" of reduced scalar potential connecting the coil region to the 45° boundary and separating the total scalar potential regions of the iron from that of the bore is to satisfy the third condition. (The current region and its reflection about the 45° boundary have opposite signs.) Empirically it was found that all regions should be quadratic except the steel return yoke.

A quadrupole magnet of steel length 0.5 m was modeled; end effects for the 0.6 m and 0.8 m magnets should be the same. The model included half the length and 45° of the cross section. The steel extended from $z=0$ to $z=250$ mm. Beyond that, the same geometry, but all air, extended to $z=500$ mm. Elements 10 mm long were used from $z=200$ mm to $z=300$ mm; elsewhere elements were 50 mm long. (Runs with shorter elements shows that these were short enough.)

The design includes a 45° bevel on the pole tip to reduce multipole field components and a 45° bevel over much of the side of the pole to make the coil fit more closely around the pole. This was accomplished by changing the z coordinates of points

in the $z=250$ mm plane. Neighboring points were also moved to keep the quadrilateral elements of reasonable shape.

Early 3-D computations showed that the field quality suffered if the coil bevel extended all the way to the pole tips, so removable pole caps were added with pole bevel but no coil bevel.

3-D RESULTS

Figure 6 shows a plot of B_y vs. z , the beam coordinate, for an iron half length of 250 mm, computed for nonlinear (variable μ) iron. The x and y coordinates are (10,0), so the plot represents the field gradient. Observe that the field amplitude begins to decrease far from the end of the iron. This is a saturation effect; the computation with linear iron does not show this fall off.

Table 2 shows the effective length (L_e) and the multipole field components for the reference design, and also for some other cases in order to show the effects of design choices. The effective length is the integral of the quadrupole field component divided by the central value of that component. The undesired components, $n=6, 10, \dots$ have both a body contribution and an end contribution. The body contribution is taken from the PE2D computations. The end contribution is taken as the value from the TOSCA computations, with the TOSCA body contribution subtracted. Table 2 shows both the TOSCA end part, marked E, and the sum of the TOSCA end part and the PE2D body part, marked T.

Because nonlinear computations are time-consuming and expensive, only two are included in Table 2. It can be seen that the reference design, with pole bevel, coil bevel, and pole caps, is similar to the case with pole bevel alone. On the other hand, the case with the coil bevel extending all the way to the pole has a very large $n=6$ component. These first three cases in Table 2 show the value of the end cap.

The last four cases show that by varying the pole bevel, the total $n=6$ component can be changed between -6.3×10^{-4} and $+3.7 \times 10^{-4}$. Thus the pole bevel may be changed empirically to fine tune the field quality after the magnets are built and measured.

CONCLUSIONS

The magnet as designed meets the specifications of the APS. Design modifications may be made to reduce saturation effects and thus to permit operation of the APS under extended conditions that may be proposed later.

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Fig. 6. Field B_y (or field gradient) vs. z .

Table 1.
APS Ring Quadrupole Magnet
3-D Computations with TOSCA

Description	Coil Bevel (mm x mm)	Pole Bevel (mm x mm)	Linear/ Nonlinear	Effective Length mm	Multipole Ratio ^(a)		
					$n=6$	$n=10$	$n=14$
Reference Design	20x20 ^(b)	10x10	N	534.2	E ^(c) -0.66	-0.22	0.02
					T -0.26	-0.72	-0.07
No Coil Bevel, reference pole bevel	No	10x10	N	532.6	E -1.04	-0.19	0.02
					T -0.64	-0.69	-0.07
Coil Bevel extends to end	20x20	10x10	L	529.8	E -14.55	-0.45	0.06
					T -14.15	-0.95	-0.03
No Pole Bevel	No	No	L	543.4	E -6.69	0.10	-0.01
					T -6.29	-0.40	-0.10
Reference Design	20x20 ^(b)	10x10	L	535.2	E 0.62	-0.19	0.02
					T 1.02	-0.69	-0.07
Reference Pole Bevel, no coil bevel	No	10x10	L	536.0	E 0.73	-0.18	0.02
					T 1.13	-0.68	-0.07
Larger Pole Bevel	No	10x17.32	L	531.6	E 4.08	-0.25	-0.02
					T 3.68	-0.78	-0.11

(a) Multipole Field ratio $a_n/2a_2$, units 10^{-4} at $R=25$ mm.

(b) Pole cap: Coil bevel does not extend to pole tip.

(c) E = end contribution (body contribution from 3-D computation subtracted) T = total (body contribution from 2-D computation added, $n=6$: 0.40, $n=10$: -0.50, $n=14$: -0.09).