QUADRUPOLE MAGNET FOR THE APS STORAGE RING*

K.M. Thompson, S.H. Kim, R.J. Lari,† L.R. Turner
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439 USA

Abstract

An asymmetric core geometry has been selected for the quadrupole magnets in the storage ring of the Advanced Photon Source (APS) in order to accommodate the vacuum chamber and photon beam pipes. The requirements of the positron beam make it necessary that the magnet be able to produce a field gradient of 20-T/m with high accuracy. The design for this magnet has been fully developed in preparation for the construction of a prototype. Some unique features included in the design are described. Design choices are being validated by extensive magnetic-field calculations in both two and three dimensions. The results of these calculations are presented.

Introduction

There are 400 quadrupoles required for the storage ring of the Advanced Photon Source (APS); they have effective field lengths of 0.5 m, 0.6 m, and 0.8 m. All have the same design except for the core and coil lengths. An end view of this magnet is shown in Fig. 1; the APS storage ring vacuum chamber,[1] now under development, is also included for reference. The geometry of this chamber assembly has been used to define the permissible geometries for the pole face, the coil, and the parts of the magnet that extend across the horizontal mid-plane. Quadrupole field gradients of up to 20 T/m are required by the positron beams; the other field harmonic coefficients must also have relative values less than 1×10^{-4}.

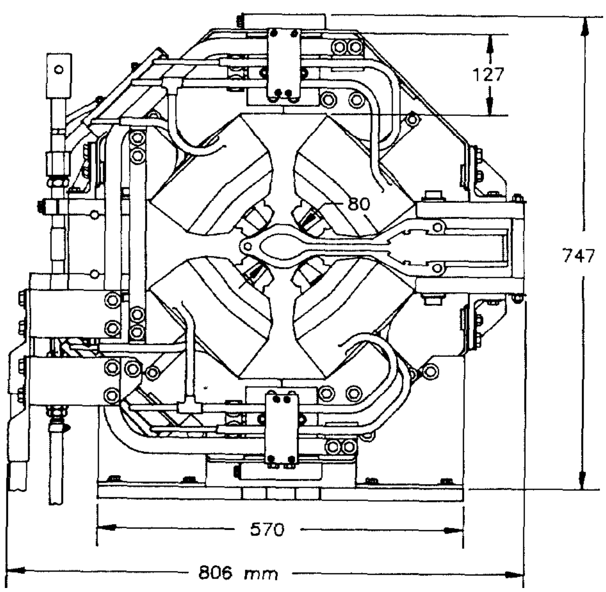

Fig. 1 End view

The prototyping plan for this quadrupole involves the construction of a 0.8-m-long magnet that produces magnetic fields with the required qualities over the required range of strengths; the longest version is being built because it is the most difficult one to make. Three major tasks are being addressed to implement this plan. The first is to build a magnet with removable end-plates; this facilitates the development of the final contours at the pole ends. The second is to build at least one magnet that is as identical as possible to those placed in the storage ring. The third task is to develop acceptable core assembly procedures and the associated tooling necessary to build magnets to the required geometrical tolerances.

The third task is included because the core assembly is the most critical phase of the construction effort; attainable, geometrical tolerances for the core parts and assemblies will be determined and actions will be identified, if necessary, to compensate for the effects of deficient tolerances. Details concerning the design of the core assembly are the major items addressed in the following sections.

This core has several unusual features, and the systematic effects of some of them on the magnetic field quality have been studied with two-dimensional field calculations. Effects of variations in the geometrical dimensions of the core that arise during manufacturing have also been studied with calculations in two dimensions. The contours on the ends of the poles are being addressed with three-dimensional field calculations. These have shown the relative effects of several geometries on the effective lengths of the integrated field and the integrated, harmonic coefficients.

Magnet Design

The design of this quadrupole has changed somewhat since it was described last.[2] The horizontal mid-plane is still kept open to clear the vacuum chamber and the photon beam pipes and to maintain 180° symmetry in the core geometry. The core is made from four quadrants, all of which are magnetically identical. Each pole is still tapered to reduce the saturation effects near the root and is still rather long. The details of the pole geometry are shown in Fig. 2. A tie rod has been added near the end of each pole

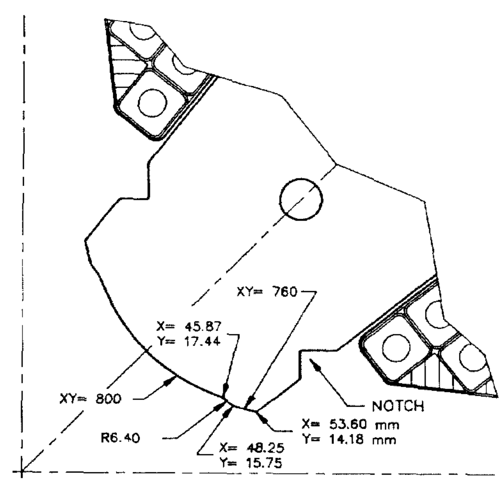

Fig. 2 Core geometry near pole tip.

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†R.J. Lari is presently with Vector Fields, Ltd., 1700 N. Farnsworth Ave., Aurora, IL 60605.

to maintain the axial compression. The shims on the pole edges have been changed to reduce the 12-pole harmonic coefficient. Small reference surfaces, called notches, have also been added to both sides of each pole near the pole face; see Fig. 2. The primary function of this unusual feature is to provide surfaces that can be measured during core assembly. Because these are located close to the pole faces, they provide a better control on the positions of the pole faces during stacking. They also allow the positions of the poles in a core assembly to be more accurately measured. The thicknesses of the yokes between the top and bottom pairs of quadrants have also been increased, keeping the flux densities here below 1.4 T. This also increases the areas of the mating surfaces of the quadrants, providing a more stable joint.

The coil design has been changed by increasing the number of turns to 33 and shifting the outside layer away from the mid-plane. The coil geometry and associated operating parameters were defined with the program, MADEST.[3] Several parameters for this magnet are listed in Table 1.

Table 1 - Quadrupole Parameters

Strength	20 T/m
Bore Diameter	80 mm
Effective Length	0.8 m
Turns/pole	33
Conductor Height	11.5 mm
Width	11.5 mm
Hole Diameter	6.3 mm
Inductance	29 mH
Resistance	45 mΩ
Current	414 A
Current Density in Coil	2.5 A/mm^2
Voltage	19 V
Power	7.9 kW
Water Flow	2.7 gal/min
Water Pressure Drop	40 psi
Water Temperature Rise	11 °C

Systematic Body Effects

Because there are three different quadrupole lengths required, the field errors in the body of the magnet are reduced to acceptable levels independently of the errors arising at the ends. The systematic effects of several geometrical features on the magnetic fields in the body of the quadrupole have been studied in two dimensions with the program PE2D.[4,5] The magnet geometry and associated field lines are shown in Fig. 3 for a typical case including as many details as possible. The geometrical features of particular interest are the pole face contour, the notches on the pole sides, the empty tie-rod hole, the shape of the edges of the coil conductors adjacent to the mid-planes of the magnet, and the asymmetric core. The systematic differences were also found for doing a given calculation with a constant permeability of 2000 or with a BH table for SAE 1010 steel and for running the final geometry at a maximum gradient of 21 T/m or a minimum of 10 T/m.

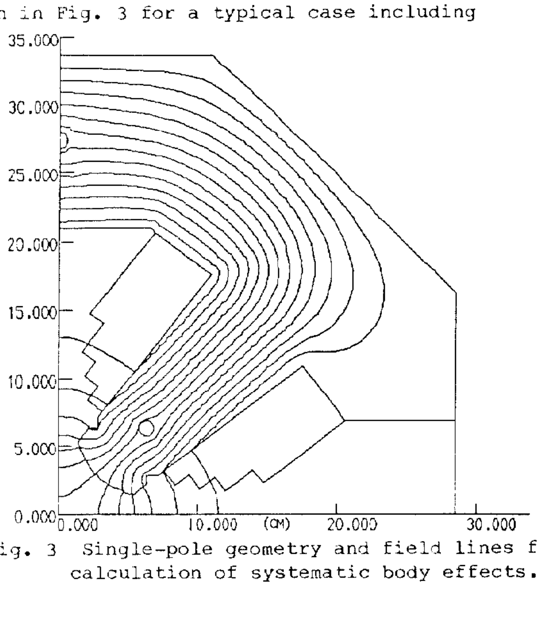

Fig. 3 Single-pole geometry and field lines for calculation of systematic body effects.

The results of the two-dimensional calculations, showing the systematic effects on the body fields, are summarized in Table 2. All cases listed, except case 1, were done with an SAE 1010 BH table. The first entry, REF, is for the final geometry, including all design features operating at the maximum, nominal gradient. The relative field harmonics at a radius of 25 mm for the following entries are listed as the amount of change from a case that was identical except for the feature of interest.

Table 2 - Systematic Effects of Body Features

Case	Description	G [T/m]	B_5 [10^{-4}]	B_9 [10^{-4}]
REF	Final Design	19.3	0.4	-0.5
			Changes	
1	Constant μ=2000	17.7	+0.2	<<+0.1
2	Asymmetric Yoke	18.5	<+0.1	<+0.1
3	Hole and Notch Near Pole Tip	18.5	<<-0.1	<<+0.1
4	Minimum Gradient	10.4	+0.3	<<+0.1
5	Maximum Gradient	21.0	-0.3	<-0.1

Effects of Construction Variations

The effects of variations in the core geometry arising during core assembly were estimated with calculations of the magnetic field in two dimensions using the program PE2D. The variations were modeled by simple displacements of only the pole face contour(s). All geometries used for this study included four quadrants; a typical geometry is shown in Fig. 4, along with the associated flux lines. A number of cases were run where the poles were intentionally displaced by various combinations of purely radial and

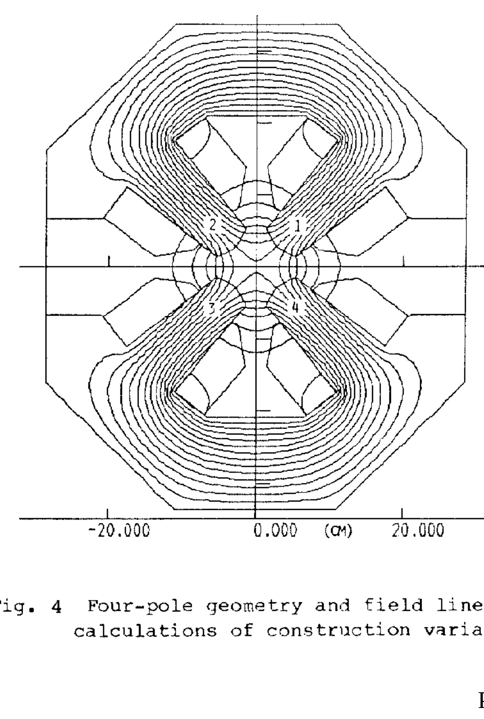

Fig. 4 Four-pole geometry and field lines for calculations of construction variations.

angular shifts of a reference pole contour. The maximum amounts of the shifts were within values considered to be achievable (0.05 mm or 0.002 in.) by conventional manufacturing techniques.

The types of variations considered are summarized in Table 3 for a number of representative cases. References here to pole numbers correspond to the numbers appearing in Fig 4.

Table 3 - Descriptions of Pole Variations

Case	Description
1	$\Delta r=-0.042$ mm on all poles
2	$\Delta x=-0.02$ mm for pole #1
3	$\Delta y=-0.013$ mm for pole #1
4	$\Delta x=-0.04$ mm for pole #1 $\Delta\phi=0.7$ mrad (CCW) for pole #1
5	$\Delta y=0.04$ mm for pole #1 $\Delta\phi=-0.7$ mrad (CW) for pole #1
6	$\Delta y=-0.04$ mm for pole #1 $\Delta\phi=+0.04$ mm for pole #3 and #4
7	$\Delta y=-0.04$ mm for pole #1 $\Delta x=+0.04$ mm for pole #3 and #4 $\Delta r=-0.042$ mm on all poles

The effects of the variations for each case are listed in Table 4. The values of the harmonic coefficients, normalized to the corresponding value of the main field, B_1, are listed only as the changes from the results for a reference case in which all the poles are exactly symmetric.

The coefficients are calculated with respect to the nominal, geometric center of the gap; therefore, the dipole coefficients are non-zero. Only those coefficients are listed that showed changes greater than or equal to 1×10^{-5} in at least one case.

Table 4 - Changes in Normalized Field Harmonics for Pole Variations

	Case (10^{-4})						
	1	2	3	4	5	6	7
B_y(Gauss)		0.8	0.2	1.7	0.2	-3.1	-4.3
B_2		-0.1	0.4	-0.1	1.3	1.5	2.8
B_3		-0.3	0.2	-0.7	0.6	0.6	1.7
B_4					0.2	0.2	0.3
B_5							-0.1
A_x(Gauss)		-0.6	-0.6	-1.3	-1.9	-2.0	-2.3
A_1		0.8	-0.5	1.6	-1.6	1.6	3.6
A_2		1.0		1.9			1.3
A_3							-0.7
A_4		-0.1		-0.2			-0.6
A_5							-0.2

Systematic End Effects

The systematic effects related to the geometry of the steel at the pole ends have been studied with calculations of the magnetic fields in three dimensions using the program, TOSCA.[5,6] The geometries used for these calculations were for one half of one pole, with the steel having an axial length of 250 mm. The end geometries of all cases included so far involve bevels. These bevels are formed by one or two planes, oriented normal to the plane of the axis of the pole. The dimensions of the resulting bevels are expressed in terms of the distances to the steel edges from the original, unbeveled apex of the pole, H- for the radial dimension and L- for the axial dimension.

The effective length of the field was also found for each case. As the bevel dimensions are increased, the effective lengths are decreased. Bevels with effective lengths less than 267.4 mm need a maximum driving current, proportionately larger than the value shown in Table 1, to provide the required value of integrated gradient. The results of several, preliminary calculations are summarized in Table 5. The values included for each case are the effective length, L_o, and the normalized, integrated harmonic coefficient, B_5, evaluated at a radius of 25 mm. The cases shown in the table have bevels with a range of sizes, extending from no bevel to one composed of two bevels at 9° and 45°. The values of B_5 for these cases straddle a value of zero, showing that there exists a geometry that would effectively eliminate the 12-pole harmonic. Procedures for extracting the harmonic coefficients from the potentials calculated by TOSCA are being developed now. These procedures will be used, along with geometries that more accurately represent the final designs of the core and coil, to define the best choice of end-shape for the poles. Other shapes, besides planar bevels, will be considered. The final shape will be defined during the magnetic-field measurements on prototype magnets.

Table 5 - Systematic Effects of End-Shapes

Bevel Size LxH [mm]	B_5 [10^{-4}]	L_0 [mm]
NO BEVEL	-4.6	271.6
20x20	-3.1	258.5
20x14	-1.7	260.4
40x20	-1.3	248.2
60x20(Double)	+10.5	248.9

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