RING MAGNETS FOR THE SYNCHROTRON X-RAY SOURCE AT ANL*

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Abstract: The designs of the bending, focusing, and correction magnets for the storage ring are described. The computer-optimized pole-tip contours of the dipole, quadrupole, and sextupole magnets and the construction and assembly techniques keep the field errors within the specified limits. Horizontal and vertical steering corrections are provided by separate magnets in addition to a steering capability included in the sextupole magnets.

Introduction

The magnets which form the lattice of the storage ring in the Advanced Photon Source (APS) include dipoles, quadrupoles, sextupoles, and correctors. The location of each of these magnets in the lattice of one sector is shown elsewhere.[1] All magnets are designed to deliver the field strengths required for a storage ring energy of 7.7 GeV and have a clearance of about 2 mm between the vacuum chamber[1] and each pole tip. All magnets allow the synchrotron radiation beam lines to exit the ring from the outside radius. The dipoles, quadrupoles, and sextupoles are assembled from low carbon (SAE 1010) steel laminations, solid, low-carbon steel end plates which are 25-mm thick, and hollow copper conductor which is insulated with fiberglass and vacuum impregnated with epoxy resin. The parameters for these magnets have been determined with the program MADEST[2] and are summarized in Table 1.

Table 1 - Main Magnet Parameters

	Dipole	Quadrupoles			Sextupole
Number Required	80	80	80	240	280
Strength at 7.7 GeV	0.66T		21T/m		540T/m^2
Effective Length (m)	3.06	0.8	0.6	0.5	0.24
Gap (mm)	60H		80 Dia.		100 Dia.
Turns/Pole	32		32		44
Inductance (mH)	51	27	20	17	36
Resistance (mΩ)	38	44	35	30	98
Current (A)	497		458		214
Voltage (V)	19.1	20.4	15.9	13.6	21.0
Power (kW)	9.5	9.3	7.3	6.2	4.5
Water Flow (gal/min)	2.9	2.8	3.2	3.4	2.4
Water Δp (psi)	100	40	40	40	100
Water ΔT (°C)	12	13	9	7	7

The choice of using laminated rather than solid steel for the cores is dictated by the requirement of producing large numbers of units with identical magnetic field shapes. The average magnetic properties of the steel in each are matched to those of all others by shuffling the laminations. Because the dipole laminations will be punched as a single piece, the effects of die errors are reduced still further by appropriate rotations of the laminations about the horizontal midplane.

Each core is held under compression by welded parts on the exterior surfaces or tie rods installed under tension and extending between the end plates. The solid steel end plates transfer the compression to the pole tips, which are located relatively far from the ties near the outside surfaces of the core. These solid plates also facilitate the machining of the con tours required to properly control the field shapes at the ends of the poles. They are also easily beveled along the pole edges allowing the coils to hug the ends of the cores thereby minimizing the overall lengths of the assembled magnets.

After all magnets have been tested and measured, they are installed around the associated section of the vacuum chamber. For the dipole magnets this installation process is accomplished in the ring. The focusing and correction magnets, on the other hand, are remotely installed onto support structures which are several meters long. These assemblies are aligned at this point and then moved as a unit into the ring where a final alignment check is made. To permit this type of installation, the focusing magnets are separated into top and bottom halves. The designs of the horizontal, midplane joints in these units permit them to be reassembled while maintaining the original geometrical alignment of the parts.

The designs appearing here are not fully optimized. They will also be verified by building of full-scale prototypes and subsequent magnetic field measurements. These will be used to develop the assembly tooling and procedures, to determine the field errors introduced when the halves are disassembled and reassembled, and to find the errors introduced at the ends of the magnets (these may be used to redefine the pole tip shapes to provide some localized error compensation in every magnet).

The magnetic field calculations have been done for each of these magnets using the program POISSON. Conformal transformations[3] of these geometries allowed the linear elements in the calculation to more accurately represent the nonlinear potentials in the gaps.

Dipole

The major components of a dipole are shown in Fig. 1 along with dimensions including those of the

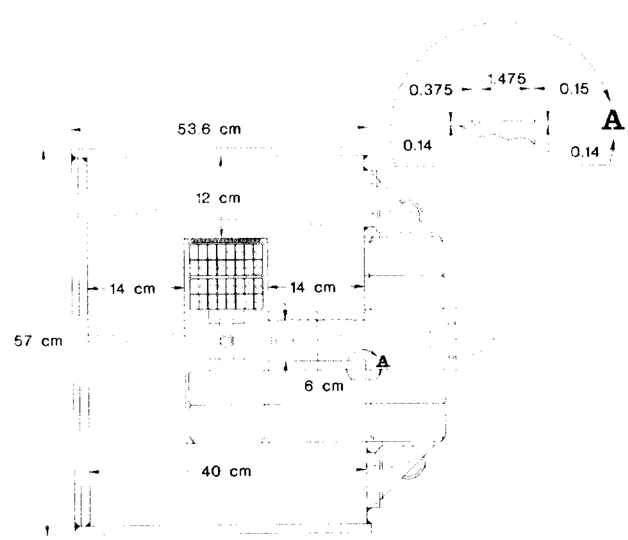

Fig. 1. End View of Dipole

*This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

pole-edge shims. These magnets have 1.5-mm thick core laminations. The height of the gap between the shims is sufficient to allow the vacuum chamber to be installed from the outside radius. The thicknesses of the yoke is sufficient to keep the vertical deflections of the poles to less than 0.025 mm.

The axis of the dipole gap is curved with a radius 38.98 m which minimizes the pole width required. The laminations and end plates are assembled as a parallel-ended stack against a curved reference surface along the outside radius (open) side. After stacking, the core is axially compressed and 12.5-mm thick steel plates are welded under tension to the end plates and laminations on the top and bottom surfaces. A 9.5-mm thick steel plate is then drawn up against the inside radius surface of the assembly and welded between the top and bottom plates. These plates form a structure which provides sufficient strength to limit vertical deflections along the length of the assembly to less than 0.025 mm.

The quality of the magnetic field produced with the pole-tip shim geometry shown in Fig. 1 has been calculated to be

$$|\Delta B/Bo| \leqslant 1.0\times10^{-4} \text{ and}$$

$$|Bn/Bo| \leqslant 0.5\times10^{-4} \text{ for } n=1\ldots10$$

in a gap width of ± 30 mm. The relative effects of moving one of the four coils by 1 mm vertically or horizontally, of removing the single conductor nearest the pole and midplane in one coil and of pole deflections of 0.025 mm have been calculated to be less than 0.5×10^{-4}.

Quadrupole

All quadrupoles in the storage ring have the same design with tapered poles except that there are three different lengths provided, 0.8 m, 0.6 m, and 0.5 m. The major components of a quad are shown in Fig. 2 along with dimensions including those for the pole-edge shims. These magnets are made with 1.5-mm

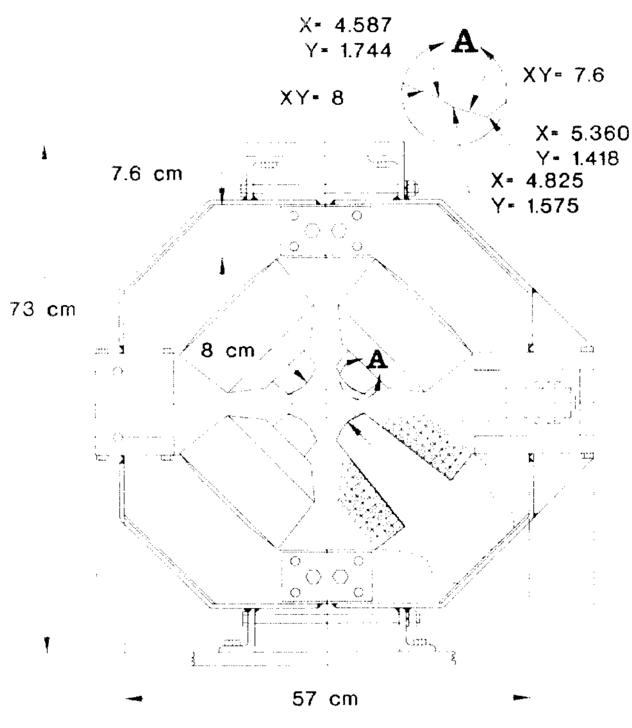

Fig. 2. End View of Quadrupoles

thick core laminations. The vacuum chamber and worst-case beam tube locations are also shown for reference. To accommodate the vacuum chamber and beam lines, the quads must be split (have no yoke) on the outside radius side of the gap. To provide 180° magnetic symmetry requires that there be no magnetic yoke on either side.

The cores of these quads contain four separate sections which permit installation of the coils around each pole. The two sections which make-up the top and bottom halves, however, are simultaneously assembled as a pair using a fixture containing precision reference surfaces. This fixture supplies a means of securely holding the laminations against reference surfaces while the stack is compressed and the dowel pins, tie rods, and bars are attached. The required welds in the assembly are applied at this stage.

The top and bottom halves are joined through stainless steel parts which extend across the midplane. On the inside radius side, these parts are solid blocks which are reproducibly located with hardened dowels between bolted flanges welded to the laminations and end plates. On the opposite side, these parts are cylindrical spacers secured between the bolted flanges. These spacers are positioned, for any specific magnet, at several locations along the length and at radii compatible with the vacuum chamber and beam pipe that must pass through it.

The quality of the magnetic field produced with the pole-tip shim geometry shown in Fig. 2 has been calculated to be

$$|\Delta B'/B'o| \leqslant 3.0\times10^{-4} \text{ and}$$

$$|Bn/B1| \leqslant 0.5\times10^{-4} \text{ for } n=6,\ 10,\ 14$$

inside a radius of 25 mm. The relative effects of moving all coils by 2 mm away from the pole tip and of removing the conductor nearest the pole tip on all poles were determined to be less than 0.5×10^{-4}.

Sextupoles

All the sextupoles in the storage ring have the same design with tapered poles. The major components of a sextupole are shown in Fig. 3 along with dimensions including those of the pole tip. The

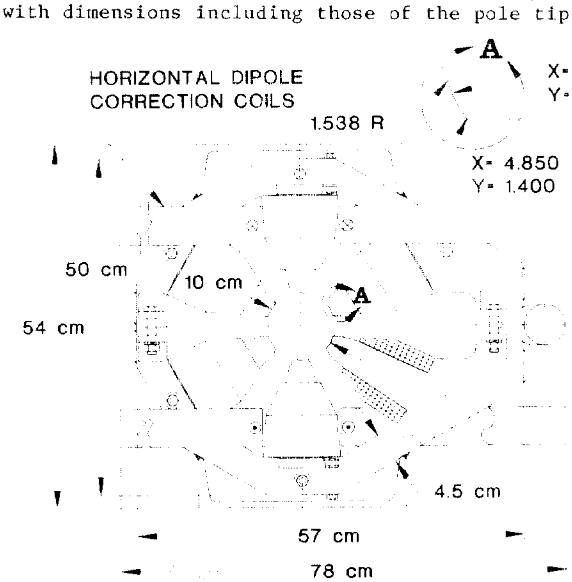

Fig. 3. End View of Sextupole

vacuum chamber and the worst-case beam tube locations are also shown for reference. For this magnet the yokes extend across the horizontal midplane. The outside radius yoke, however, is thicker to provide the same reluctance for the flux that passes through it as that for the other five, thinner and shorter yokes. This provides the required magnetic symmetry and greatly simplifies the assembly. The core laminations are 0.5mm-thick and allow the magnet to respond to frequencies up to 25 Hz.

To permit the coils to be installed around the poles, the center pole and coil in both the top and bottom halves are designed to be inserted as a separate unit. The type of joint between the center pole tips and yokes is a modified dovetail. The assembly of the laminations, end plates, and ties for each half of this magnet is done with fixtures similar to that described above for the quads. The coils are placed over the side-poles and the center pole assembly, complete with its coil, is axially moved into position and held in place with the wedge shown.

The quality of the magnetic field produced by the geometry shown in Fig. 3 has been calculated to be

$$|\Delta B''/B''o| < 1.5\times10^{-3} \text{ and}$$

$$|Bn/B2| < 2.5\times10^{-4} \text{ for } n=9,\ 15$$

inside a radius of 25 mm.

Correctors

Vertical dipole correction fields are provided with auxiliary coils in the dipole magnets and with other separate, small magnets. Horizontal dipole correction fields are provided with auxiliary coils in the sextupoles and with other small magnets. The parameters for these coils and magnets are summarized in Table 2 for operation at peak rated currents. The field quality is given at ±20 mm from the magnet axis.

Table 2 - Dipole Corrector Parameters

		Main Dipole	Sextu-pole	Verti-cal	Vert/Horiz
Dipole Field Type		V	H	V	V/H
Number		80	280	240	78
Peak Bo	(T)	0.04	0.11	0.14	0.16
|ΔB/Bo|	(%)	0.05	3	0.2	3/2
Effective L	(m)	3.06	0.28	0.22	0.20
Gap height	(mm)	60	0.1	90	11.4/13.4
Turns/Pole		18	80	480	108/150
Inductance	(mH)	16	9	570	3/30
Resistance	(mΩ)	243	187	3900	95/133
Peak Current	(A)	54	113	11	134/116
Voltage (dc)	(V)	13.0	21.1	42	12.7/15.4
Water	(gal/min)	0.2	0.6	2	0.2
Water Δp	(psi)	100	100	25	100
Water ΔT	(°C)	15	16	1	28/35

The auxiliary coils in the main dipoles are assembled with the adjacent main coil section before potting. The auxiliary coils in the sextupoles are installed after each half-magnet is assembled.

Small adjustments in the correction fields, except those in the main dipoles, are made at rates of up to 25 Hz with feedback loops from the extracted beams. This requires 0.5mm-thick core laminations for all correction magnets.

The two types of individual correction magnets are shown in Figs. 4 and 5; they have overall lengths of 0.14 m. One produces a vertical dipole field and the coils are made with solid copper conductor. The heat is removed through surface mounted water cooled heat sinks. The coils are placed 35-mm vertically away from the pole tips to allow the poles to extend further in the axial direction. This increases the effective lengths of these magnets by 55%.

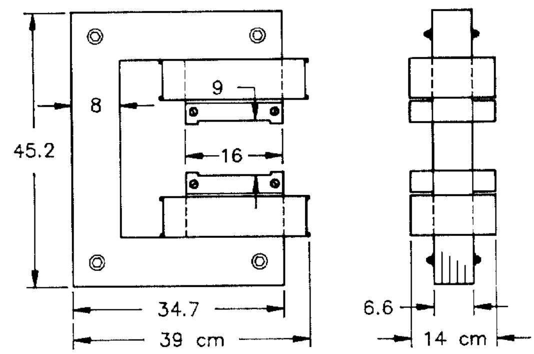

Fig. 4. Vertical Correction Magnet

The second correction magnet shown in Fig. 5 produces both horizontal and vertical dipole fields with coils wrapped around the picture-frame yokes. To give about the same field quality for both fields, all coil ends are beveled.

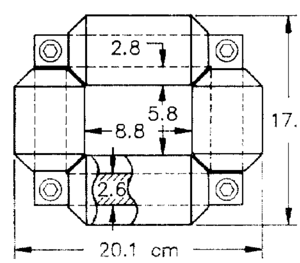

Fig. 5. Vertical/Horizontal Correction Magnet

Acknowledgments

We acknowledge the effort of R. Lari for magnetic field calculations done to determine the pole shapes of the quadrupole, sextupole, and correction magnets.

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