Performance of Quadrupole and Sextupole Magnets for the Advanced Photon Source Storage Ring

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Abstract—From the magnetic measurement data of several production quadrupole and sextupole magnets for the storage ring of the Advanced Photon Source, the excitation efficiencies and systematic and random multipole coefficients of the magnets are summarized. The designs of the magnets, which are constrained due to the geometry of the vacuum chamber, have rotation symmetries of 180° and 120°. The production data meet the allowed tolerances of a few parts in 10⁻⁴ for the storage ring.

I. INTRODUCTION

The 7-GeV Advanced Photon Source (APS), which is under construction at Argonne National Laboratory is a national facility dedicated to providing highly-brilliant synchrotron radiation beams [1]. The storage ring (SR) has a circumference of 1104.0 m with a 40-sector Chasman-Green lattice to achieve a beam emittance less than 8.2×10^{-9} m-rad. The ring requires 400 normal quadrupole (quad) and 280 sextupole (sext) magnets for the control of the betatron oscillations and chromaticity of the positron beam. The required beam stay-clear aperture is $x = \pm 35$ mm and $y = \pm 25$ mm.

Listed in Table 1 and Table 2 are the design parameters of

have the same magnetic length. These magnets are excited by independent DC power supplies.

In spite of the conventional nature of the magnets, the designs of the magnet cross sections are severely constrained by the need to accommodate the vacuum chamber. Because of this requirement, rotation symmetries of 180° and 120° have been chosen for the quad and sext magnets, respectively, in order to minimize the undesired multipole field components. The design of the magnets and magnetic measurement data are described below. The allowed tolerances for the quad and sext are a few parts in 10⁻⁴ and 10⁻³, respectively.

TABLE 2
 MAIN PARAMETERS FOR THE SR SEXT MAGNETS

	S ₁	S ₂	S _D	S _F
# Magnet	80	80	80	40
ℓ (m)	0.2527	0.2527	0.2527	0.2527
B' (T/m)	185.07	-359.59	-415.0	192.62
B'' (T/m)	44.72	-86.30	-99.59	46.23
I (A)	64	135	160	67

For all sext magnets: Turns/coil = 42, L = 17.2 mH, R = 107.5 mΩ,
 Steel Mass/Magnet = 405 kg.

TABLE 1
 MAIN PARAMETERS FOR THE SR QUAD MAGNETS

	Q ₁	Q ₂	Q ₃	Q ₄	Q ₅
# Magnet	80	80	80	80	80
ℓ (m)	0.50	0.80	0.50	0.50	0.60
B' (T/m)	-10.84	15.79	-10.59	-18.90	18.25
B'' (T)	-5.42	-12.63	-5.29	-9.45	10.95
I (A)	215	312	210	386	370
L (mH)	7.9	12.7	7.9	7.9	9.5
R (mΩ)	29.5	44.0	29.5	29.5	34.0
Steel Mass (kg)	1549	942	942	1144	

the conventional resistive quad and sext magnets for the SR. The 400 quads consist of five families with three different magnetic lengths; the four families of the 280 sext magnets

II. DESCRIPTION OF THE MAGNETS

All the quads have the same 2-D geometry and a bore radius of 40.0 mm. The four sext families are the same design with a bore radius of 49.0 mm. The magnet coils are water-cooled copper conductor insulated with fiberglass or a pre-applied polyimide/polyester/glass film and vacuum-impregnated epoxy. The cores of the magnets use 1.52-mm-thick laminations of low-carbon steel, coated on both sides with "C5" or a 13-μm-thick "B-stage" epoxy.

A. Quadrupole Magnet

The cross section of the quad with the vacuum chamber is shown in Fig. 1. The top and bottom halves of the quad are not connected with flux-return yokes; they are connected mechanically with aluminum spacers between the halves. Each of the top and bottom halves consists of two welded quadrant stacks. The weld joints have weld-relief grooves to reduce the effects of weld shrinkage. Two fiducial bases for "CERN balls" are welded on top of the magnet. The magnet

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cores have alignment notches used for the attachment of a removable alignment fixture used for measurements of the magnetic axis and for the survey of the magnets in the SR.

In order to maximize the excitation efficiency, the pole root ends are asymmetrically widened 22 mm towards the vertical plane of the magnet as shown in Fig. 1. By asymmetrically widening the poles, the efficiency for the 7-GeV operation is greater than 95%. The magnet has pole-end bevels of 9.6 mm x 17.4 mm and pole chamfers of 16.5 mm [2]. The shims at both edges of the hyperbolic pole face have 6-mm-straight contours perpendicular to each other, and are used as the reference surfaces for stacking the laminations.

Fig. 1. Cross section of the SR quad with the vacuum chamber.

B. Sextupole Magnet

The cross section of the sext with the vacuum chamber is shown in Fig. 2. The magnet core is assembled from three identical stacks of laminations, each with two poles and a flux-return path joining them. The vacuum chamber extends into in one of the 102-mm air gaps between neighboring stacks. At each end 12.7-mm-thick stainless steel plates hold the core sections in position; they are pinned and bolted to the core sections with an assembly fixture. The assembly of the magnet using the stainless steel plates is designed so that the upper two poles of the magnet core can be moved for

installation of the vacuum chamber. A fixture with two fiducial bases is installed on top of the magnet.

Since the length of the magnet core is relatively short compared to the dimensions of the cross section of the magnet, extensive magnetic field computations were carried out for the 2-D as well as 3-D geometries using the codes PE2D and TOSCA [3]. The computed data for the 18-pole coefficient b_8 , defined in the following section, agree with the measurements within 0.5×10^{-4} .

Fig. 2. Cross section of the SR sext with the vacuum chamber. A removable fiducial ball base is shown on top of the magnet.

III. MAGNETIC MEASUREMENTS

The integrated and 2-D fields, and multipole coefficients are measured using a rotating coil technique. The probe coil consists of "radial" and "tangential" coils on the same cylinder [4]. The 2-D "body" fields are measured using "short" tangential coils. The normal and skew multipole field coefficients, b_n and a_n , for a 2-D magnetic field, $B = B_y + iB_x$, are defined

$$B\ell = B_0\ell \sum_{n=0}^{\infty} (b_n + i a_n) [(x + i y)/r_0]^n,$$

where l is the magnetic length for an integral measurement and the reference radius r_0 is 25 mm. The coefficients are defined as $b_1 = 1.0$ and $a_1 = 0$ for a quad, and $b_2 = 1.0$ and $a_2 = 0$ for a sext magnet.

The axis of the rotating coil is aligned to the magnetic axis by adjusting the magnet position to where the dipole and quad field components of the quad and sext magnets, respectively, vanish. Prior to this procedure, for the quad magnet only, the bore axis of the quad is aligned to the axis of the two air-bearings defining the axis of the rotating coil by the following method. A laser beam unit is installed and aligned with the axis of the air-bearing. A photo-quadrant detector is placed at the bore axis of the magnet aperture. After detecting the beam position along the bore axis, the magnet position is adjusted to align the bore axis to the laser beam. This procedure not only ensures parallelism between the bore and magnetic axes to at least ± 0.2 mrad, but it also enables measurement of the offset of the two axes.

In Fig. 3 the integrated and 2-D "body" field-gradients, normalized to the values at 160 A, are plotted against the excitation current. The data show that the efficiencies up to the excitation current of 380 A are higher than 95%, and the difference between the values of the integrated and 2-D gradients are approximately 1%.

Similarly, the efficiency for the sext is plotted in Fig. 4. The 2-D data are taken using a 0.1-m-long tangential coil. At 150 A, the efficiency for the integrated sext strength is 97% and its 2-D value is 1% higher.

Fig. 3. The integral and 2-D excitation efficiencies of the SR quad. The data at 160 A are used as 100% efficiency.

Fig. 4. The integral and 2-D excitation efficiencies of the SR sext. The data at 60 A are used as 100% efficiency.

Plotted in Fig. 5 are the systematic (average) and random (rms) multipole coefficients for the first 20 production quads. Coefficients less than 1×10^{-4} are included in the figure. Variations of the systematic coefficients at the three excitation currents less than 1×10^{-4} are due to the ambient field and field saturation at the poles. Similarly, the systematic and random coefficients for the first six sexts are shown in Fig. 6.

Fig. 5. Systematic at three excitation current, and random multipole coefficients for the first 20 production quads at three excitation currents. Multipole index 2a stands for the skew sextupole coefficient. The random coefficients are independent of the currents.

Fig. 6. Systematic at three excitation currents and random multipole coefficients for the first six production sexts at three excitation currents. Multipole index 3a stands for the skew octupole coefficient.

IV. SUMMARY

The data of the magnetic performances, measured from the first 20 quad and 6 sext production magnets, meet the allowed tolerances and are summarized in Table 3. The random multipole coefficients for the 20 quads are less than 1.5×10^{-4} , which indicates that the assembly procedure for the quad is relatively consistent. In spite of the design constraints of the magnets, the efficiencies for 7-GeV operation are higher than 95%.

TABLE 3
TOLERANCE AND MEASURED RMS FOR THE SR QUAD
AND SEXT MAGNETS

		Allowed Tolerance	Measured rms
Quad	$\langle \Delta B'/B' \rangle$	5.0×10^{-4}	$3.0 \times 10^{-4} *$
	b_2	2.5×10^{-4}	1.3×10^{-4}
	b_3	3.1×10^{-4}	1.2×10^{-4}
Sext	$\langle \Delta B''/B'' \rangle$	2.5×10^{-3}	$1.0 \times 10^{-3} *$
	b_3	3.1×10^{-3}	2.6×10^{-4}

*Accuracies for individual magnet measurements.

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