Magnetic Measurements of the Wedge-Pole Prototype Undulator

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1. INTRODUCTION

The Advanced Photon Source (APS), a 7-GeV positron storage ring, will have as many as 34 straight sections available for installation of multiple insertion devices (IDs). The size and the taper of the gap of the IDs will be able to be varied to tune the energy of the emitted radiation to the experiments. The IDs must not affect the particle beam motion. Therefore, the disturbances should be kept within tight boundaries to assure that the ring performance parameters are maintained and that the emitted radiation shows little degradation from an ideal device. These requirements are derived from the stability criteria of the beam to be stable within 10% of the emittance [1]. The requirements cannot be met without using closed loop orbit compensation. With such a system installed, it is reasonable to relax the requirements on the ID magnetic field performance. These relaxed requirements are listed in Table 1 for integrated multipole moments.

Table 1. Integrated Multipole Moments

<u>Multipole n</u>	<u>Normal component (b_n)</u>	<u>Skew component (a_n)</u>
1(Quadrupole)	50 Gauss	50 Gauss
2(Sextupole)	200 Gauss/cm	100 Gauss/cm
3(Octupole)	300 Gauss/cm ²	50 Gauss/cm ²

We use the common definition of the multipole moments:

$$\int (B_y + iB_x)dz = \sum (b_n + ia_n)(x + iy)^n,$$

where x and y are transverse horizontal and vertical space coordinates; B_x and B_y are the horizontal and vertical magnetic fields, respectively; b_n and a_n are the normal and skew components of the integrated multipole moments of the field; and z corresponds to the longitudinal direction of the undulator.

It is impossible to use scanning along the y -direction due to a small gap size. Therefore, we chose to scan along the x -direction in the median plane ($y=0$). From the above expression, we obtain equations for determination of normal and skew components of the integrated multipole moments of the field in this case :

$$\int_{-\infty}^{\infty} d_z B_y = \sum_0^N b_n x^n$$

$$\int_{-\infty}^{\infty} d_z B_x = \sum_0^N a_n x^n$$

Polynomial fitting to the measured data of the integrated fields up to the 3rd order (N=3) as a function of x results in multipole coefficients a_n and b_n , as well as their errors (see, e.g., [2]). Scanning was done in the required "good field" region (± 5 mm in the x-direction).

The first vertical and horizontal field integrals are required to be ≤ 100 Gauss-cm. The second vertical and horizontal field integrals are required to be $\leq 100,000$ Gauss-cm². Currently, magnetic measurement tests have been performed on a wedge-pole undulator to examine the quality of the undulator prototype and to test the magnetic measurement facility.

Two types of undulators were examined. The symmetric undulator has an integer number of periods and both end poles of equal strength. The antisymmetric undulator has a half-integer number of periods, and the downstream and upstream end strengths are of opposite sign. The magnetic measurement facility is described in detail in [1].

The first and second field integrals are defined:

$$J_1(l) = \int_{-\infty}^l B(z) dz$$

$$J_2(l) = \int_{-\infty}^l J_1(z) dz,$$

where $B(z)$ is the horizontal or vertical magnetic field for the horizontal or vertical field integrals, respectively.

2. Magnetic Measurement Technique

There are two types of magnetic sensors available for the magnetic measurement system, the Hall sensor and the moving search coils.

2.1 Hall Probe Sensor

A Hall probe (model MPT-141) from Group3 is currently used. The Hall probe is miniature sized with a temperature sensor built into the probe head. The probe has the overall dimensions of 5 x 14 x 2 mm with a sensitive area of 1 x 0.5 mm encapsulated in epoxy and mounted on a reference surface made of ceramic. The probe is connected to a Hall probe interface (HPI) with a low thermal drift.

The Hall probe also has a low thermal drift and was accurately calibrated at given temperatures to provide a calibration chart of its voltage response to the strength of the magnetic field. The measured voltage is converted to a magnetic field using a fitting function based on the calibration table.

2.2 Search Coils

Four coils have been used in the characterization of the wedge-pole ID (see Table 2 for coil parameters).

Table 2

Coil #	Measured field	length m m	width m m	# of turns
1	Vertical	33.	10.	100
2	Vertical	510.	7.	170
3	Horizontal	16.5	4.	400
4	Horizontal	165.	4.	400

3. Performance Evaluation of the Wedge-Pole Undulator

The wedge-pole undulator is a planar insertion device with a period length of 3.3 cm and 25 full-strength magnetic periods (the same period length as Undulator A). The magnetic field reaches a maximum of 0.7 Tesla at the minimum gap of 11.5 mm. The transition to the antisymmetric end pole configuration was implemented by making a half-integer number of magnetic periods (24.5, e.g.), that corresponds to an even number of poles.

3.1 Hall Probe Measurements

The miniature Group3 Hall probe and Hall probe interface (HPI) were used for magnetic tests of the wedge-pole undulator. The first results were obtained for the regular symmetric-end-pole undulator.

The wedge-pole magnetic field and first and second vertical field integrals were measured. The accuracy of the Hall probe system was investigated with respect to the required specifications based on analysis of these scans.

The main factor limiting the accuracy of the Hall probe measurements is the noise of the HPI system. The dependence of the Hall probe noise level on the integration time is shown in Fig. 1 (for integration times of 100 ms, 33 ms, and 7 ms). For most of the

Hall probe measurements, an integration time of 33 ms was chosen as a compromise between measuring time and noise level.

A second important factor for the accuracy of Hall probe measurement is the temperature instability. The vendor data show the variation of .5 Gauss/°C. Our measurements in a free space out of magnetic field show the temperature dependence of the first field integral equal to 15 G-cm/°C at a distance 80 cm, thus less than $\pm .1$ °C temperature stability is required so that the value of the systematic errors in the measurements are comparable to the statistical RMS errors.

A set of Hall probe measurements was performed to estimate the value of the integrated multipole moments of the wedge-pole undulator (normal components). For this purpose, we investigated the first vertical field integral dependence on the x-coordinate in the median plane. The result is shown in Fig. 2 for a gap of 11.5 mm.

The results of a third order polynomial fit are shown in Table 3 for the regular symmetric-end-pole undulator. Only the dipole component does not satisfy the requirement of being less than 100 G-cm. Many different techniques were attempted in this set of the measurements to bring the first and second field integrals to the desired values. One possible solution is shimming the end poles in order to zero the first field integral for the chosen gap, but the difference in the first field integrals for all ranges of gaps is rather large, approximately equal to 200 Gauss-cm. A transition to antisymmetric-end-pole geometry sufficiently decreases this value.

Table 3. Integrated Multipole Moments

Multipole n	Normal Component (b_n)
0 (dipole)	360 G-cm $\pm$ 9
1 (quadrupole)	-1.5 G $\pm$ 4.8
2 (sextupole)	-5 G/cm $\pm$ 6.6
3 (octupole)	-43 G/cm ² $\pm$ 24.8

The results of measurements of the gap dependence for the first vertical field integral in both cases are shown in Fig. 3. Curves A and B correspond to different shimming in the symmetric case. The results of measurements of the first and second vertical field integral dependence on the gap for (x,y)=(0,0) in the antisymmetric case are shown in Table 4.

Table 4. Antisymmetric End Pole Results (23.5 periods)

Gap (mm)	J_1 (Gauss-cm)	J_2 (Gauss-cm ²)
50.	28	-20000
35.	26	-18800
28.	46	-14360
20.	37	-5070
15.5	46	6820
13.5	59	15320
11.5	87	25000

Results for the first field integral in the antisymmetric case are rather satisfactory. Second field integral values for the undulator with a length of 2.4 m could be extrapolated roughly by multiplying these values by a factor of three, and they are very close to the requirements. The results of typical field map measurements in the antisymmetric and symmetric configurations are shown in Figs. 4-6.

The Hall probe data were obtained with RMS errors equal to 2-5 Gauss-cm. The latest improvements in measurement technique decreased the average RMS errors up to 2 G-cm. This accuracy was obtained when no zero-field measurements were performed before each scan. The Hall probe zero value was determined once before each set of measurements by averaging over the time equal to the usual measurement time. (Hall probe zero drift time is much larger than measurement time.)

The next set of Hall probe measurements was of the integrated multipole moments for different wedge-pole gap settings in the antisymmetric configuration. The results of a third order polynomial fit are shown in Table 5.

Table 5. Integrated Multipole Moments (Normal Components)

gap(mm)	b_0 (G-cm)	b_1 (G)	b_2 (G/cm)	b_3 (G/cm ²)
11.5	119.±.55	25.5±3.	-20.4±4.1	-32.7±15.4
14.5	106.±1.4	8.1±7.4	-21.7±10.3	-28.7±38.3
20.	72.4±1.2	-7.±6.4	-18.5±8.9	23.6±33.
27.	54.±.9	-4.5±5.1	-2.95±7.1	-3.±26.4
35.	38.5±.9	-18.9±5.	3.66±7.1	9.49±26.5
51.	36.8±1.5	-33.±10.	7.2±14.	13.2±69.1

The RMS error values of the measurements cannot be explained solely by statistical errors and the HPI-produced noise. If they could, the accuracy would improve by increasing the measurement

time. But it does not, indicating the existence of some systematic errors. The cause of such errors is not clear and should be investigated. It certainly is not a result of temperature fluctuations, because this dependence was too small to produce such values. But the current accuracy is good enough to obtain all the necessary results with a Hall probe.

Field map measurements were performed away from the wedge-pole undulator to separate the effects of Hall probe measurement errors and other sources. The results are shown in Fig. 7. The typical time between consecutive measurements is approximately one day.

3.2 Coil Measurements

Different coils were used for the first set of wedge-pole measurements, see Section 2.2 for coil descriptions. B_y coils were used for the first vertical field integral measurements to check the results of Hall probe measurements. B_x coils were used for the first horizontal field integral measurements. The B_x coil was also used to study the dependence of the first horizontal field integral on the horizontal coordinate. In contrast to the Hall probe system, the integrator is fully linear but has a rather large zero drift. Zero drift integrator fluctuations were adjusted carefully before each measurement. In order to increase measurement accuracy, a special technique was used [3]. Integrator zero drift values were measured before and after each measurement. The results were then interpolated to zero drift. The maximum available bench platform speed of 200 mm/sec was used for coil measurements to decrease the influence of integrator zero drift.

A third order polynomial fit yields the results shown in Table 6 and Fig. 8 for the skew components of the integrated multipole moments (for an ID gap of 11.5 mm and for the symmetrical case).

Table 6. Integrated Multipole Moments

Multipole n	Skew Component (a_n)
0 (dipole)	-28 G-cm $\pm$ 1.4
1 (quadrupole)	24 G $\pm$ 5.1
2 (sextupole)	8.6 G/cm $\pm$ 5.
3 (octupole)	-17.2 G/cm ² $\pm$ 12.6

The next set of measurements were performed to obtain skew components of the integrated multipole moments for all range of gaps in the antisymmetric case. A typical horizontal field map measured with B_x -coil #4 is shown in Fig. 9. A third order polynomial fit yields the results of skew component measurements, which are shown in Table 7.

Table 7. Integrated Multipole Moments (Skew Components)

gap(mm)	a ₀ (G-cm)	a ₁ (G)	a ₂ (G/cm)	a ₃ (G/cm ²)
11.5	-16.±.76	35.±4.2	-3.2±6.2	-56.4±23.6
14.5	-4.4±.47	6.3±2.6	.05±3.8	-13.5±14.4
20.	-6.9±.5	-2.1±2.7	-3.2±3.8	-26.4±14.1
27.	-9.5±.76	-26.7±4.1	4.47±5.7	22.3.±21.4
35.	-10.4±.7	-32.6±3.7	8.0±5.2	-2.45±19.4
51.	-7.1±.5	-32.±2.7	-7.7±3.7	4.9±13.9

These results fully satisfy the requirements of Table 1 for integrated skew components.

Typical RMS errors with B_x-coil #4 for the first field integral measurements were 1-3 G-cm.

Coil measurement accuracy strongly depends on the correct choice of the integrator range and on accurate adjustment of the integrator zero drift.

4. Conclusion

Included here are some general remarks about the wedge-pole measurements taken. First, no adjustments were made to the end poles when the gap was changed. Also, the measurement results show that, in this case, we do not need end clamps. We shall not have any magnetic materials placed closer than 300 mm to the undulator, that is, in the region where the undulator might produce an influence on an external device (the fringing field at a distance of 100 mm from the end pole is about 2 Gauss). In our case the antisymmetric configuration allows us to satisfy the requirements for the both J_1 and J_2 simultaneously.

References

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Figure 1. Hall probe noise vs integration time

Figure 2. First Vertical Field Integral vs. X

Figure 3. First Vertical Field Integral (Gs-cm)
vs. Gap (mm) for Symmetric (A and B) and
Antisymmetric Cases

Figure 4. Vertical Field Map for the Antisymmetric Configuration, 15.5 mm Gap

Figure 5. First (1) and Second Vertical Field Integrals
for the Antisymmetric Configuration, 15.5 mm Gap

Figure 6. Vertical Field Map for Symmetric Configuration

a) field; b) first field integral; c) second field integral

Figure 7. Zero Drift Measurements (G) vs Time.
Each Point is the Average of 12,000 Measurements

Figure 8. First Horizontal Field Integral vs X

Figure 9. Horizontal Field Map (T) vs Z (mm)