# Magnetic Measurements of the West Wiggler in CESR

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Recent machine studies [4] found that the magnetic field of the CHESS west wiggler [5] causes substantial perturbation of the electron and positron beams during high energy physics running. In the crossing angle configuration that will be used for phase II of the CESR upgrade, the beams will be more than 1 cm off axis and the perturbation is expected to get much worse. Additionally, there is a large change in the perturbing field depending on whether the wiggler gap is opened or closed. We have found it essential to open the wiggler during injection in order to reduce the emittance of the beam, and then close it for luminosity conditions. While it is in principle possible to compensate some lower order components using auxiliary magnets near the wiggler, such corrections are made more difficult to implement because the size of the perturbation is a strongly nonlinear function of the gap field. Higher order moments are virtually impossible to compensate.

Hall probe measurements of the wiggler field were made previously [6] and included the net integrated normal dipole component of the field, but not other integrated multipole moments. Measurements of the effects of the wiggler field on the beams were done for both the east and the west wiggler and clearly show normal dipole, quadrupole, and sextupole perturbations. No coupling measurements are reported.

The west wiggler was removed from CESR for approximately six weeks to make room for an undulator for a special dedicated CHESS run. We took advantage of this opportunity and made a complete study of the integrated field multipoles on the west wiggler. Tests of asymmetric insertion devices [1],[2] have shown a significant advantage in the magnetic field quality over symmetric devices and led us to change to a 24 pole configuration. This change made a dramatic improvement in the magnetic field quality. The results of our measurements are discussed in detail in this paper.

# 1 Technique

The rotating coil used for magnetic measurements was borrowed from the APS[3]. The technique involved stretching a coil made up of a single turn of a fine ten strand wire along the gap where the beam goes. The strands were soldered together in such a way as to make a ten turn coil. The flux change was integrated every 90 degrees as the coil was rotated 360 degrees by two independent stepper motor driven rotary stages. The integrated flux provided an estimate of the average magnetic field at the coil axis. The skew fields were measured in the same manner as the normal fields except the reference angle was 90 degrees away. Multipole moments were obtained by successively moving the coil axis typically 2 or 3 millimeters and repeating the measurement of the average field. The gradient and higher derivatives were obtained by fitting to the average fields as a function of the horizontal position. The noise and sensitivity of the technique were quite good with an RMS noise of 2-3 G-cm.

Alignment was done by first leveling the wiggler using a transit. A horizontal datum surface was defined by the two lower pole pieces at opposite ends of the wiggler – assumed to be coplanar. The coil alignment was done using a theodolite and a precision level. Error in the datum horizontal plane angle relative to the coil causes the normal components to be rotated into skew moments. It turns out that the measured skew moments are of comparable magnitude to the measured normal moments so such alignment errors are totally neglible.

Stray magnetic fields in the vicinity of the wiggler during the measurement were about 2 G. These will add to the dipole measurements in some manner which is not exactly known, but could produce a systematic integrated dipole field errors of the order of a few G-m, for both normal and skew dipoles. Otherwise the local magnetic field errors are not expected to influence the results.

A wiggler field differs substantial from more commonly used magnetic elements in storage ring in that the field has large alternating longitudinal components. Such fields *cannot* be described by a transverse two dimensional harmonic field expansion such as

$$B_y + iB_x = \sum_j (b_j + ia_j)(x + iy)^j$$

as is commonly used for conventional magnets. This brings into question whether multipole coefficients $b_n$, $a_n$, have any meaning when applied to wigglers or undulators? We are indebted to Glen Decker and John Galayda for pointing out that the *integral* of the magnetic field along a path going completely through the wiggler does in fact satisfy the two dimensional laplace equation We therefore can interpret the multipole coefficients as applying to the integral of the transverse fields. [1].

# 2 Results

Though dozens of measurements were made, we report here only the results for three basic configurations, each with two different gap settings. The first is the wiggler as it was removed from CESR, aside from local dipole fields.

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[1]A brief derivation may be made by using the fact that the curl operator can be expressed as $\nabla = \nabla_t + \frac{\partial}{\partial z}\mathbf{e}_z$ where the subscript $t$ refers to only transverse coordinates and the $z$ coordinate is the coordinate along which the beam passes and the integral is performed. Since $\nabla \times B = 0$ in the region of integration we have

$$\begin{aligned}
\int_1^2 (\nabla \times B)dz &= 0 \\
&= \int_1^2 [\nabla_t \times B + \frac{\partial}{\partial z}(\mathbf{e}_z \times B)]dz \\
&= \int_1^2 (\nabla_t \times B)dz + \mathbf{e}_z \times B|_1^2
\end{aligned}$$

If the integration end points are taken to be where $B$ is zero (outside the magnet) then it follows that

$$\begin{aligned}
0 &= \int_1^2 \nabla_t \times B dz \\
&= \nabla_t \times \int_1^2 B dz
\end{aligned}$$

Therefore the integral of the field is a two dimensional harmonic function (2-D curl is zero) and can be expanded using the usual harmonic multipole coefficients.

Table 1: Measurements of normal multipoles $b_n$ and skew multipoles $a_n$ are given for the West wiggler in various configurations. The maximum allowed values are determined by the estimated effect on the beams.

| Configuration | Gap [cm] | $b_0$ [G-cm] | $b_1$ [G] | $b_2$ [G/cm] | $b_3$ [G/cm$^2$] |
|---|---|---|---|---|---|
| Max allowed | | 1000 | 160 | 16 | |
| 25 pole, sym | 4 | 100.5 ±1.0 | 138.4±1.8 | −277.6±0.8 | −2.7±1.0 |
| | 10 | 3584±1 | 77.5±1.1 | −63.5±0.5 | −0.44±0.64 |
| 24 pole, asym | 4 | −69.6±0.7 | 87.5±1.3 | −2.8±0.6 | −0.64±0.8 |
| | 10 | 53±1 | 39.3±1.2 | −7.2±0.6 | −0.54±0.7 |
| Final 24 pole | 4 | −79.0±0.6 | 46.2±0.7 | −1.8±0.2 | −2.0±0.2 |
| | 10 | 73.5±0.7 | 28.1±0.8 | −7.9±0.2 | 0.04±0.2 |
| | | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
| Max allowed | | 1000 | 23 | 2 | |
| 25 pole, sym | 4 | 48.9±1.4 | 63.5±2.4 | 53.2±1.1 | 15.8±1.4 |
| | 10 | 127.9±1.5 | 66.8±2.7 | −0.9±1.2 | 1.7±1.5 |
| 24 pole, asym | 4 | 235±0.7 | 61.2±1.3 | 37.2±0.6 | 15.0±0.7 |
| | 10 | 56.0±0.4 | 87.6±0.7 | −1.1±0.3 | 0.04±0.4 |
| Final 24 pole | 4 | −448±1.8 | 57.1±2.0 | −6.1±0.6 | 12.4±0.5 |
| | 10 | −364±0.7 | 87±0.8 | 0.05±0.2 | −0.3±0.2 |

For the second configuration the wiggler was converted from a 'symmetric' 25 pole wiggler to an 'asymmetric' 24 pole wiggler. In asymmetric configuration the field perturbations from positive and negative poles should cancel more completely. In the last arrangement, we made some changes to the transverse position of the poles in order to reduce the skew sextupole moment. This is the configuration that is being put back into CESR as of November 1993. These results are summarize in the tables below. Further discussion and plots of the fields are in the next few sections.

The following caveats apply to the data in the table:

- dipole terms $b_0$, $a_0$ are not accurate to a few G-m because of local stray and earths' magnetic fields. The error should be about the same for all data sets at the same gap settings.

- beam dynamical effects are not taken into account and can be significant [7]
- All data was arbitrarily fit to a third order polynomial.

## 2.1 25 Pole, symmetric, as it was in CESR

The magnetic measurement of west wiggler in the configuration "as it was", showed good agreement with previous determination of the normal multipoles from beam measurements [4], but also big skew magnetic fields, which were previous unmeasured. Principle problems with the field quality are: the large normal dipole with gap open, the very large normal sextupole, and the large skew fields. The dipole causes at 3.5 mm orbit error when the gap was opened. The normal sextupole term causes a large tonality (difference in tune between two separated beams). The skew fields cause unwanted coupling. A plot of the measured integrated fields is given in figure 1.

In the 25 pole configuration there are 23 full strength poles of alternating sign and two half strength poles of the same sign at each end. For 22 of the full strength poles there is an opposite full strength pole to cancel its effect on the beam. However, the two half strength poles have to cancel one full strength pole. This latter cancelation does not work very well because the half strength poles are at the ends of the wiggler where the field is quite distorted by the end effects. Also, even if the cancelation is done for the dipole field for one gap setting (as it was tuned originally) it will not be correct for any other gap setting or for other multipoles.

## 2.2 24 Pole, asymmetric

An alternate pole arrangement uses 22 full strength poles and two half strength poles of *opposite sign* at the ends. That way for each pole there is a corresponding pole which cancels its effect on the beam. Only imperfections in geometry and magnetization will contribute to the integrated field, which was not the case in the 25 pole configuration. There will be an offset the horizontal closed orbit of beam of about 0.1 millimeters (the wiggle amplitude) in this configuration that does not occur for the 25 pole configuration. We converted the wiggler to the 24 pole geometry and with no further changes made the measurements which are presented in the table. Plots of the fields are given in figure 2.

One can see that with the gap closed the normal sextupole component is reduced by a factor of 100. The gap dependence of the dipole and other multipoles is virtually eliminated. The skew components, though mostly reduced, were not greatly affected by this change.

## 2.3 Final 24 Pole

After changing to 24 poles we were left with the problem of the large skew sextupole moment $a_2$ which causes a large differential coupling error for separated beams. To reduce this moment we shifted two opposing pole pieces in opposite transverse direction approximately $\pm 1.2$ millimeters. This change resulted in a reduction of the skew sextupole component by about a factor of 10. At this level, the measurement accuracy is comparable with the reproducibility. A second pair of opposing pole pieces was likewise shifted a few tenths of a millimeter and the final results, with measurement extending horizontally to $\pm 24$ mm are given in the table. The field plots are given in figure 3.

# 3 Evaluation

Let us summarize the result. Comparing parameters for open and closed gaps we see the following: The changes of dipole moments are about 1 G-m in the vertical and horizontal directions. This means one can expect less than 0.1 mm of closed orbit displacement caused by the change of wiggler's gap. The betatron tune shift caused by the change of normal quadrupole moment should be less than 100 Hz. The changes of the skew quadrupole moment corresponds to 60 c.u. (computer units) change of standard skew lens. The wiggler's addition to tonality, i.e., to the betatron tune difference in the event that the closed orbits are displaced by $\pm 12.5$ mm, will be 60 Hz in closed gap and 240 Hz with the gap open. The local coupling difference caused by skew sextuple moment should by less than 0.02 for closed gap and practically zero for an open gap.

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# References


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[6] Memo from Ken Finkelstein to M. Billing, D. Rice, and D. Rubin, October 23, 1992

[7] *Effect of Wigglers and Undulators on Beam Dynamics* Lloyd Smith, ESG NOTE-24 1/9/86

Figure 1: Normal and skew (horizontal) magnetic fields measured on the midplane as a function of horizontal position for the west wiggler in the 25 pole symmetric configuration as it was installed in CESR previous to November 1993. The upper plot is for the normal 4 cm gap and the lower plot is for a 10 cm gap.

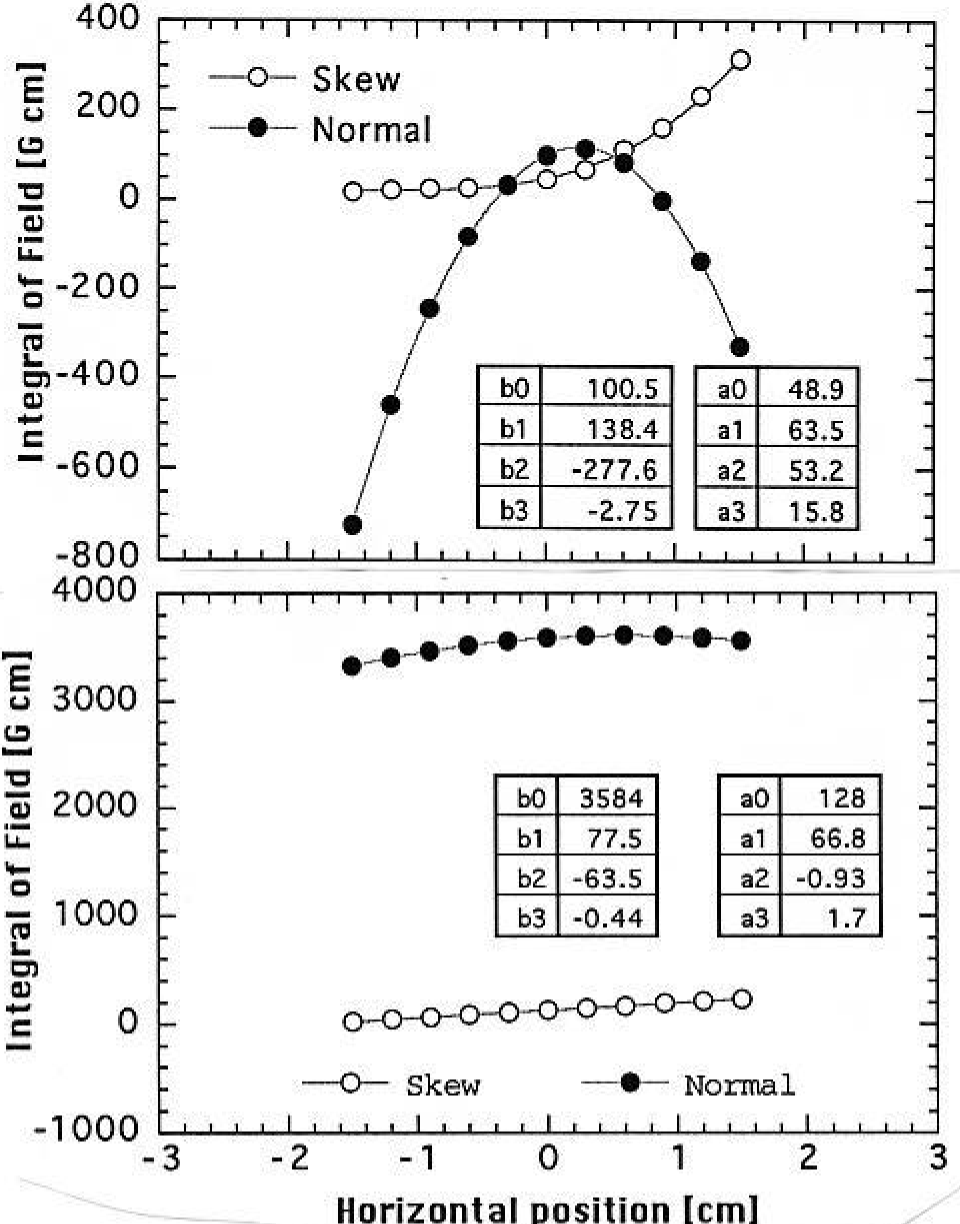

Figure 2: Normal and skew (horizontal) magnetic fields measured on the midplane as a function of horizontal position for the west wiggler after it was converted from the symmetric 25 pole configuration to the asymmetric 24 pole configuration. The upper plot is for the normal 4 cm gap and the lower plot is for a 10 cm gap.

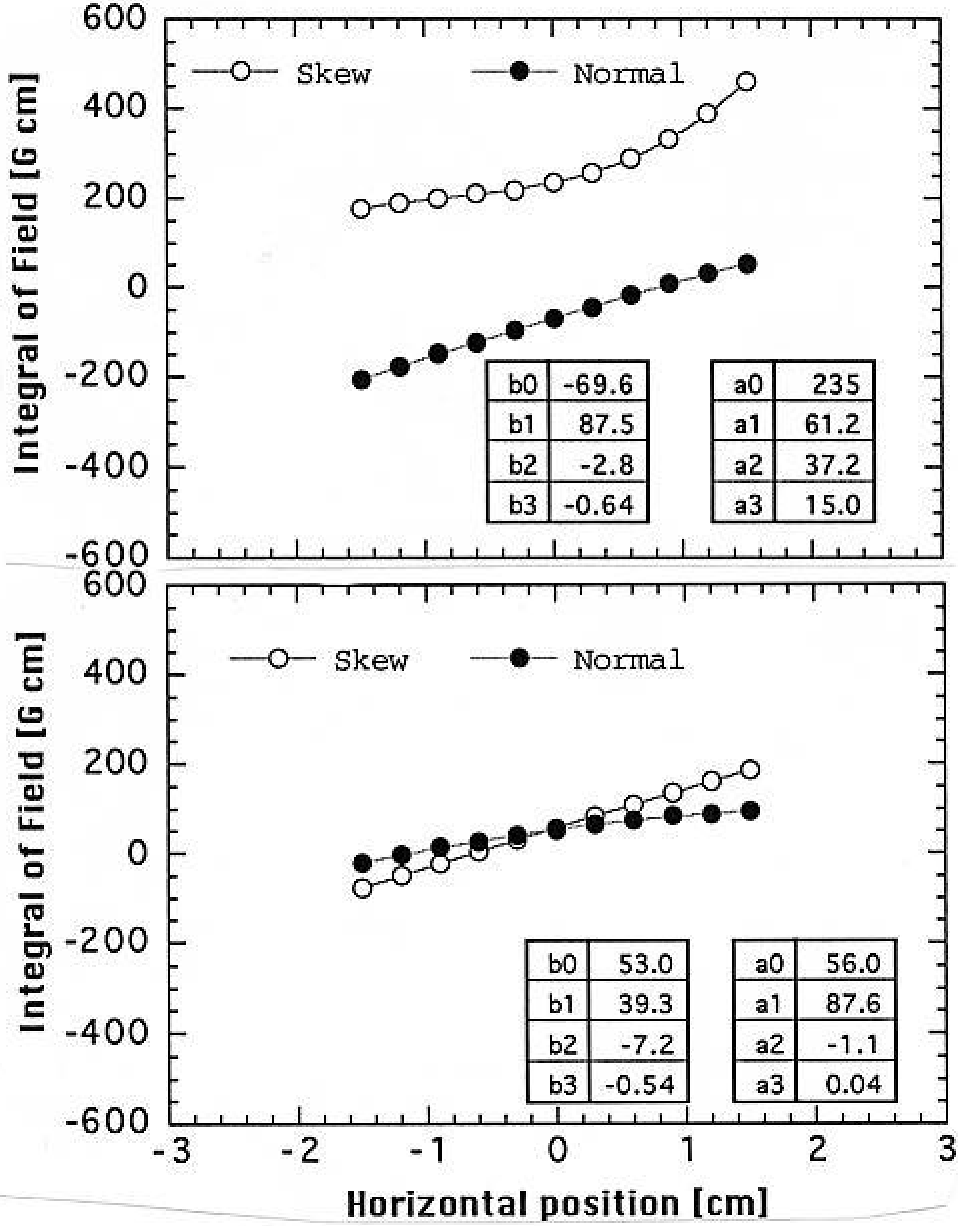

Figure 3: Normal and skew (horizontal) magnetic fields measured on the midplane as a function of horizontal position for the west wiggler in the final configuration as it will be reinstalled back into CESR in November 1993. The upper plot is for the normal 4 cm gap and the lower plot is for a 10 cm gap.