FIELD MODELING FOR THE CESR-C SUPERCONDUCTING WIGGLER MAGNETS *

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Abstract

Superconducting wiggler magnets for operation of the CESR electron-storage ring at energies as low as 1.5 GeV have been designed, built and installed in the years 2000 to 2004. Finite-element models of field quality have been developed and various sources of field errors have been investigated and compared to field measurements. Minimization algorithms providing accurate analytic representations of the wiggler fields have been established. We present quantitative descriptions of field modeling, of measured field quality and of the accuracy achieved in the analytic functions of the field.

INTRODUCTION

Since the 2003 PAC, CESR-c [1] has begun operation, increasing the world data sample on charm decays by more than an order of magnitude. The introduction of novel wide-aperture wiggler magnets [2][3][4][5] has proved essential to the optics. Twelve 1.3-m long 8-pole wiggler magnets are now in operation, providing the primary source of damping in the damping-dominated lattice design. We describe the modeling work which identified the primary source of field errors, and the analytic modeling which enabled accurate implementation of the wiggler transfer functions in the lattice design and development.

FIELD MODELING

The wiggler magnets are 1.3 m long, 23.8 cm wide, with a vertical gap of 7.62 cm, accommodating a beam pipe with horizontal and vertical apertures of 9 and 5 cm. The horizontal uniformity of 2×10^{-3} in the vertical field component over ±4 cm is obtained via 6-cm-wide rectangular cutouts in the pole faces with depths ranging from 3.5 mm to 5.5 mm depending on the pole length and its field strength. Two 7-pole wigglers with slightly different coil types and fourteen 8-pole wigglers have been built and tested. CESR-c presently operates with twelve 8-pole wiggler magnets.

The longitudinal anti-symmetry of the 8-pole design ensures zero kick on axis to within construction tolerances. Trim coils in the end poles allow adjustment of the second field integral, which determines the exit offset of trajectories with perpendicular incidence. The wiggler field calculations [4][6] were performed using the MERMAID 3D package and the magnetostatics portion of the OPERA (version 8.5 size 3) [7] software package.

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MEASURED AND CALCULATED FIELD ERRORS

Detailed field map measurements providing information on field uniformity at a level better than 10 G for the vertical field component were obtained using a motor-driven Hall probe. Flip-coil measurements [8] were used to obtain accurate information on the horizontal and vertical field components integrated along straight lines over the length of the wiggler.

The flip-coil measurements also quantified the residual integral of the horizontal field component, which has the effect of a skew quadrupole field in the case of a linear horizontal dependence. Figure 1 shows the measurement for the tenth production wiggler, which exhibited a skew quadrupole-type gradient of 1.2 gauss-m/cm.

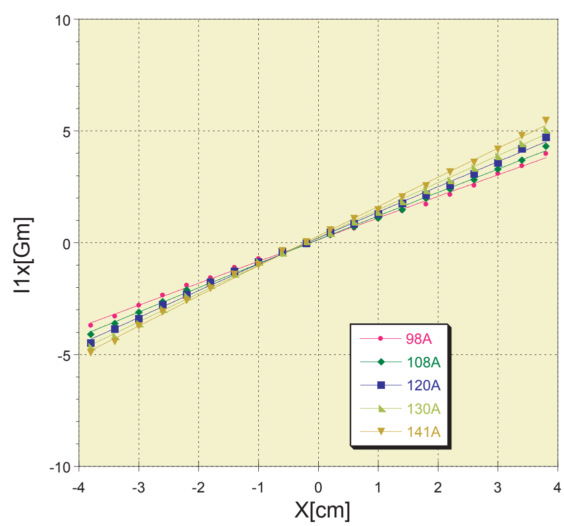

Figure 1: Flip-coil measurements of the integral of the horizontal field component in the tenth production wiggler as a function of horizontal position.

Prior to PAC2003, a variety of types of coil deformations had been considered as candidate sources for this field error, but only left/right unsymmetrical ones, which were shown via modeling not to produce the linear dependence exhibited in Fig. 1. It wasn't until late 2003 that it was realized that a left/right symmetric coil widening would produce the observed effect if the widening was different for upper and lower coils. Since half of the peak field is contributed by the current sources, its shape is appreciably sensitive to the current distribution within the coils. While the fabrication tolerances on the longitudinal dimension of the coils were strict, the gluing jig allowed distortions of the wire positions at the extreme transverse ends of the 29-cm-wide coils at the sub-millimeter level during the epoxy-curing phase. Figure 2 shows the example of

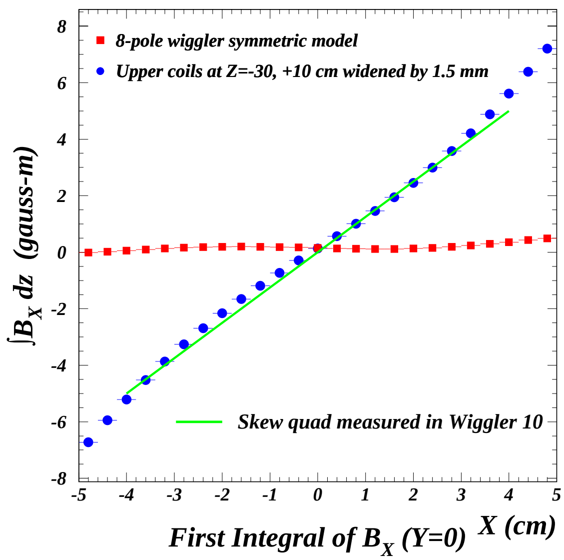

Figure 2: Comparison of the integral of the horizontal field component along the length of the wiggler for a model with two of eight upper coils widened by 1.5 mm to the symmetric model. Such coil deformations produce the same strength of skew quadrupole component measured in the tenth wiggler constructed.

a field calculation for two 1.5-mm widenings, one in each of two alternate upper 20-cm coils.Such coil deformations were thus found to be sufficient to produce the skew quad component measured in Wiggler 10. Quality control field measurements on individual coils [9] following their production limited such deformations to widenings of less than about 0.25 mm, so an unfortunate coincidence of a number of such coil deformations among the sixteen coils could result in the fluctuating skew quadrupole components which were observed in the flip-coil measurements on the wigglers. Coil fabrication had been completed by this time, but by sorting coils into categories with similar deformations and pairing them up/down in the wiggler construction, we were able to reduce this field error in the remaining wigglers to a level less than 0.2 Gauss-m/cm.

ANALYTIC WIGGLER MODEL

Once the field errors had been reduced to such a level, it was possible to use an assumption of 3-fold symmetry to speed the calculation of the field, using a 1/8 model. The final accuracy of the calculation was obtained by integrating the contributions from all current and magnetization sources, as provide for in OPERA post-processor. The peak field in these superferric wiggler magnets includes approximately equal contributions from the current and magnetization sources.

One measure of the accuracy of the calculation is the degree of consistency achieved with an analytic description of the field which obeys Maxwell's equations by construction. A further important advantage of such an analytic description is its application in tracking algorithms which can provide large gains in computing time. The CESR tracking software employs symplectic integration for constructing transfer maps, requiring such an analytic description of the field [6]. A minimization procedure based on the CERN MINUIT package [10] achieved a satisfactory level of accuracy. A two-dimensional Fourier transform served as the starting point of the iterative minimization algorithm. For 19248 field points in a volume extending 80 cm longitudinally, 2.8 cm horizontally, and 1 cm vertically, RMS residual differences from the 134-term analytic function composed of products of hyperbolic trigonometric functions (see [6] for details) were 0.324 Gauss per point, consisting of 0.076, 0.246 and 0.197 Gauss for the horizontal, vertical, and longitudinal field components, respectively. The RMS residual on the horizontal mid-plane was 0.15 Gauss. Figures 3 and 4 characterize the residual differences obtained for the horizontal and vertical field components along lines passing through a point at the extreme transverse corner of the volume at X=2.8 cm, Y=1 cm, at the Z position of peak vertical field, Z=10 cm. The difference between the integrals of the longitudinal component in the field map and the analytic description was less than 0.004 Gauss-m within in this volume, as shown in Fig. 5, which compares the results for the 1.9 T and 2.1 T models. The integrals of the other two components are zero due to the assumed symmetry in the model.

This method of field map calculation and minimization to obtain transfer maps for symplectic integration has recently been employed for the case of a 22-pole, 4.1-m-long, 1.7 T wiggler magnet designed for the purposes of a damping ring at the International Linear Collider [11] [12].

CONCLUSIONS

Sixteen 1.3-m-long wiggler magnets of 2.1 T peak field have been designed, constructed, tested and commissioned for use in the CESR-c upgrade. Twelve 8-pole wigglers have been in operation since the summer of 2004. The dominant field error was found to be an effective skew quadrupole component arising from coil deformations at the sub-millimeter level. Stringent quality control and judicious sorting of the coils resulted in limiting the strength of these errors to the level of 0.2 Gauss-m/cm. Such construction tolerance permitted the use of three-fold symmetry in the field modeling used for tracking purposes during lattice design. An analytic model with sub-Gauss accuracy including fringe fields was developed, allowing the implementation of a symplectic integration algorithm with attendant improvement in computing speed. This modeling

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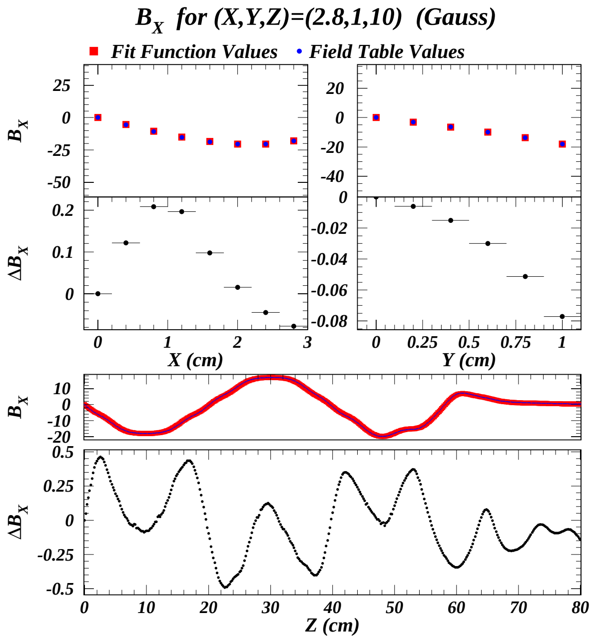

Figure 3: Residuals of the analytic description of the horizontal component of the wiggler field.

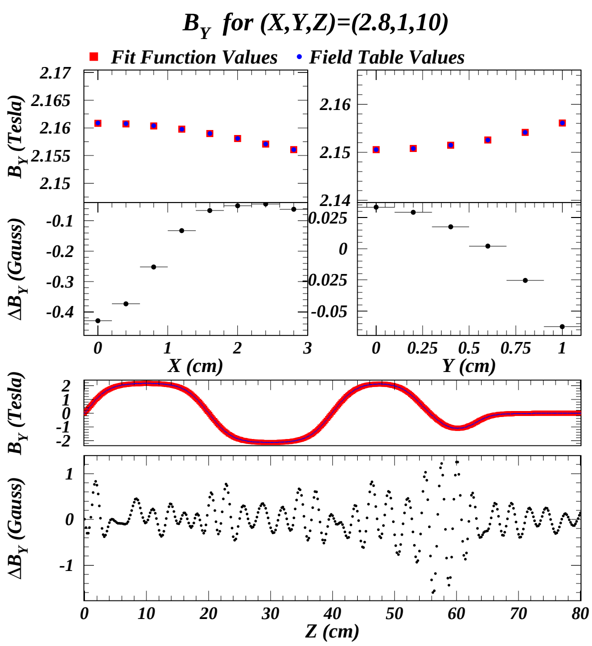

Figure 4: Residuals of the analytic description of the vertical component of the wiggler field.

algorithm has been recently applied to 22-pole 4.1-m-long models of CESR-type wiggler magnets in design considerations for an International Linear Collider damping ring.

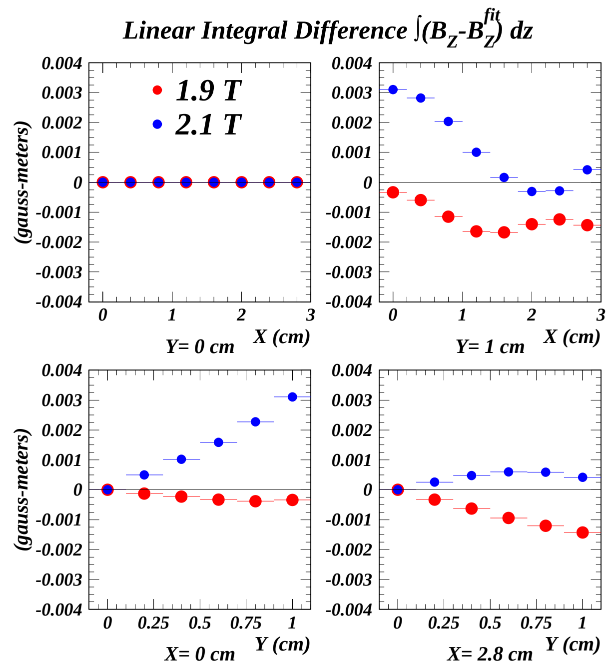

Figure 5: Difference in the integral of the longitudinal field component along the length of the magnet between the discrete field map and the analytic description of the field. Results for the 1.9 T and 2.1 T models are compared.

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