EFFECTS OF GEOMETRICAL ERRORS ON THE FIELD QUALITY IN A PLANAR SUPERCONDUCTING UNDULATOR*

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Abstract

Short-period superconducting undulators are being developed at the Advanced Photon Source (APS). A 21-period undulator prototype is being fabricated. Later, the short coil will be replaced with a longer one using the same cryostat. A high quality magnetic field with a phase error of 2 degrees rms was achieved in the prototype magnets due to accurate winding of the superconducting coils on the precisely machined formers. Manufacturing meterslong undulator magnetic structures is a challenging task. A detailed understanding of the impact of geometric tolerances on the spectral performance is essential and appropriate manufacturing techniques have to be applied. The magnetic fingerprints of positioning errors of the superconducting windings in a planar structure are derived. Using these data the field profile of a long non-ideal undulator magnet is then built and analyzed with respect to phase errors. The spectral performance degradation due to random and systematic geometric errors is presented.

INTRODUCTION

Within the APS-upgrade project [1] several superconducting undulators (SCUs) are foreseen. Currently, a 42-pole NbTi-based undulatorprototype SCU0 is being built and magnetically characterized at the APS. The installation into the APS 7GeV-storage ring is planned for 2012. The magnetic design is not yet pushed to the limits (superconductor operates at about 70% of a short sample critical current). The purpose of the undulator prototype is rather a serious testing of the key components under realistic conditions, including the thermosyphon based cooling concept, the cryostat, the actively cooled 20K vacuum chamber and the magnetic measurement facility consisting of a Hall probe system and a rotating coil system [2].

Conventional shimming techniques using Fe-shims or permanent magnets cannot be applied to a SCU. Furthermore, the crosstalk between poles and, thus, the range of field errors can be rather large (several ten cm). It is intended to minimize field errors already during fabrication to avoid extensive shimming. As long as the Fe-yoke is not saturated, the field errors are determined by the mechanic tolerances of the yoke. At maximum excitation currents the impact of coil winding errors increases. Apart from these random errors systematic errors such as longitudinal gap taper or Fe-yoke bending degrade the spectral performance.

Bobbs et al. demonstrated a strong correlation of the spectral performance and the phase errors whereas the correlation with the field errors is rather poor [3]. The correlation of the spectral performance and the phase error is described by [4]:

$$R = ((1 - \exp(-i\sigma_\varphi^2)\, M) + \exp(-i\sigma_\varphi^2)\, M^2)/M^2 \quad (1)$$

where R is the reduction factor of harmonic i, M is the number of poles and σ_φ is the phase error. For large pole numbers the expression converges to $R = \exp\,(-i\sigma_\varphi^2)$. In the following we will evaluate the dependence of the phase error on various geometric errors.

SIMULATION METHOD

The APS SCU-0, -1, -2 employ period numbers of 21, 72 and 144. The evaluation of small field errors of these devices requires an accurate field simulation strategy. Usual magnetic field codes provide a sufficiently high accuracy only for a small number of periods and cannot be used for full length devices. Instead, we developed a FORTRAN code which synthesizes a periodic undulator with arbitrary length adding field errors later on. The periodic field is derived from the half period field of a RADIA [5-6] simulation.

Random errors were extracted from small periodic model simulations with and without a specific geometrical error. The magnetic error signatures which are quite different for different types of errors are added randomly across the poles of the full length periodic field. The error strength and sign varies randomly from pole to pole. We assume a flat error strength distribution in a hard edge interval. The size of the interval is varied for different runs. For better statistics we averaged over 100 simulations with different seeds for each case (given error type and fixed error interval). Electrons were tracked through these fields and phase errors were derived.

Systematic phase errors were introduced by multiplying the periodic field with polynomials up to the 4th order.

ERROR MODELS

Random Errors

Random errors originate either from machining errors of the Fe-yoke or winding errors of the coil. In the following we study the consequences of vertical field errors and concentrate on two typical errors: i) local positioning error of an Fe-yoke groove (machining error) and, thus, longitudinal displacement of one winding; ii)

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vertical displacement of one winding caused by a wrong groove depth or by a geometric error during the gluing process. The 1st error produces a symmetric pattern which extends far into the structure (Figure 1). For small currents the individual poles are visible. With higher currents the poles saturate and the pole structure disappears. Nevertheless, the return flux still penetrates far into the yoke where the material is not saturated at all. A RADIA model of 10 periods still does not reproduce the complete range of the error (Figure 1). The on-axis field integral is dominated by the flux leakage in 3D at the truncated structure. Using this field error pattern would cause unrealistic trajectory kicks and in consequence large phase errors. Assuming a pure 2-dimensional structure (wide poles) the on-axis field integral of an infinite long undulator must be zero. Hence, we use the periodic part from the RADIA simulations and apply an exponential extension of the field such that the total field integral gets zero (Figure 1, dotted lines).

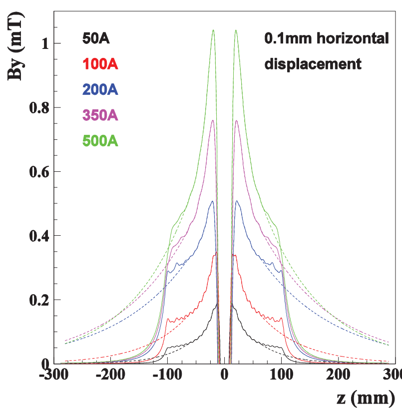

Figure 1: Error distribution for a 0.1mm longitudinal positioning error of one Fe-yoke groove / winding evaluated for various excitation currents. The drop of the solid lines is due to the finite RADIA model. In the simulation an exponential extension is used (dotted lines).

The 2nd error has an asymmetric fingerprint (Figure 2). The error pattern is localized and the on-axis field integral derived from the 10-period model is zero due to symmetry.

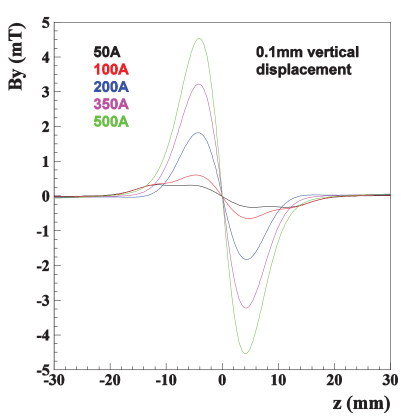

Figure 2: Error distribution for a 0.1mm height error of one winding for various excitation currents.

Systematic Errors

Apart from random errors systematic errors can deteriorate the spectral performance. Typical systematic errors are: i) longitudinal gap variation (taper) due to inaccurate positioning; ii) girder bending caused by magnetic forces or thermal gradients; iii) gap variation due to fabrication errors. We parametrize this class of field errors with the 4th order magnetic field correction function of the form:

$$B(z) = B^{ideal}(z) \cdot (1 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4) \quad (2)$$

where z is the longitudinal coordinate. Higher order terms are not considered.

RESULTS

Random Errors

For both error types the phase errors have been evaluated for error amplitude bands of ±100μm, ±50μm, ±25μm and for undulator lengths of 21, 44, 72 and 144 periods, a period length of 16mm and an excitation current of 500A (Figure 3).

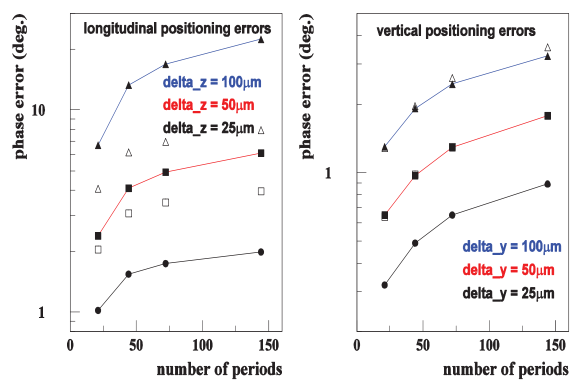

Figure 3: Phase error dependence upon error amplitude and undulator length for the two errors as depicted in Figures 1 (left) and 2 (right). Filled symbols: evaluated errors, open symbols: linear extrapolation from small error values; ±delta_z and ±delta_y are the hard edge intervals for the random error distribution.

For a detailed understanding it is helpful to separate the phase error into two terms [7]. The 1st term is an integral over the product of two integrals, one over the ideal field and one over the field errors (residuals). The 2nd term is an integral over the product of two identical integrals over the residuals. The first term describes a linear dependence of the phase error upon the error amplitude. It dominates for small errors and short devices. The 2nd term adds a positive contribution to the phase error which grows quadratically with the error amplitude and which increases monotonically with the length of the device. The contribution of both terms can be observed in Figure 3: i) a linear dependence on the error distribution amplitude is clearly seen for the vertical positioning errors (Figure 3 right). Though the error amplitude of a

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vertical displacement exceeds that of a longitudinal displacement (Figures 1-2) the sum over all vertical errors is small due to the small error distribution range; ii) in case of longitudinal positioning errors both phase error terms contribute equally and the scaling with amplitude is between linear and quadratic depending on the undulator length and the error amplitude (Figure 3 left).

For a given field error range the phase error scales with the square root of the undulator length. This reflects the random walk of the electrons through an undulator with random errors.

Systematic Errors

All systematic field variations have been evaluated for a full gap modulation of 20µm. The corresponding field variations were derived from $\Delta B = \exp\left(-\pi \cdot \Delta gap/\lambda_0\right)$ with λ_0 being a period length. The various contributions in Eq.2 have been studied individually, where lower order terms have been added such that the field modulations fill the given error band (Figure 4 top). The data are given for a 144 period device with a period length of 16mm (APS SCU-2) and a current of 500A (Figure 4 bottom).

The data of Figure 4 can be scaled linearly over a wide range of field amplitudes, though, the proportionality factors are different for error polynomials of different order. Only for larger errors, which are not present in storage ring undulators a deviation from linearity is observed (Figure 5). In contrast to the case of random errors the spectral perfomance is dominated by the 1st phase error term in the relevant regime.

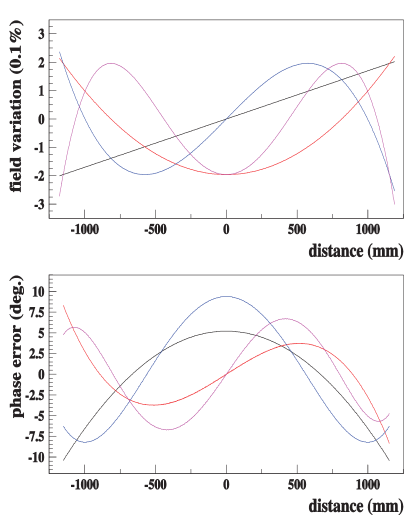

Figure 4: Top: field modulation in 0.1% over the full length according to Eq.2 up to 1st order (black), 2nd order (red), 3rd order (blue), 4th order (magenta). Bottom: phase errors associated with the field errors of Figure 4 top (same colour code). A straight line has been subtracted from the phase error for minimization.

Applying the error distribution of Figure 4 top to devices of different lengths we scaled the distribution along the undulator axis with the factor S while keeping the amount of the error modulation constant:

$$B(\bar{z}) = B^{ideal}(z) \cdot (1 + \bar{a}_1\bar{z} + \bar{a}_2\bar{z}^2 + \bar{a}_3\bar{z}^3 + \bar{a}_4\bar{z}^4) \quad (3)$$

with $\bar{z} = S \cdot z$ and $\bar{a}_i = a_i/S^i$. The phase error can be evaluated analytically using the error function of Eq.3. The contributions of the polynomial expansion add linearly to the phase error and can be treated individually. The highest order phase error term of the error field contribution $\bar{a}_i\bar{z}^i$ is proportional to $\bar{a}_i\bar{z}^{i+1}$ and, thus, proportional to S. The linear dependence upon the undulator length L (Figure 6) is valid as long as $2\pi N \gg 1$ with $k = 2\pi/\lambda_0$ and N = number of periods.

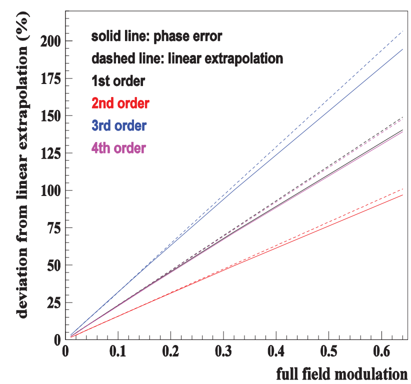

Figure 5: Deviation from linear dependence of phase errors upon error amplitude (colour code as in Figure 4).

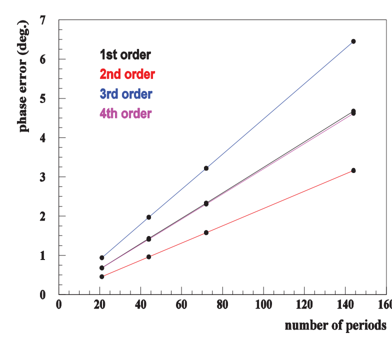

Figure 6: Linear dependence of phase errors based on systematic errors upon undulator length.

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