A CONCEPT ON ELECTRIC FIELD ERROR COMPENSATION FOR THE ANKA SUPERCONDUCTIVE UNDULATOR

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Abstract

In April 2005 a superconductive undulator test device, the so-called SCU14 (period length 14 mm, 100 periods) was installed at ANKA. Before installation, the magnetic field was measured and documented. This was the first test of a superconductive undulator in a storage ring and the dominating questions to be answered were related to the interaction of the undulator with the beam. The field quality was of lower importance and will be improved by a modified mechanical fabrication technique at the next superconductive undulators. Nevertheless, after finishing the fundamental beam tests the question was discussed how one would improve the field quality (minimize the phase error) of the existing undulator by local correction devices. The concepts could be used later in a weaker form for local field corrections at future undulators, if necessary.

INTRODUCTION

Undulators are producing the most brilliant X-ray beams. The undulators in use are almost exclusively based on permanent magnets [1]. The maximum achievable field strength of these undulators is limited by the magnetic properties of the used materials. In order to overcome these limitations first considerations on replacing the permanent magnets with superconductive wires started in the early 90's followed by small test devices [2, 3]. After several intermediate steps the first superconductive undulator with a period length of 14 mm and 100 periods was installed in ANKA in April 2005 [4, 5].
In an undulator, the electrons continuously emit white light into a narrow cone around the forward direction (z-axis). These cones overlap and the photons emitted by a single electron interfere. Due to this interference the undulator emits a line spectrum described by

$$\lambda_L = \frac{\lambda_u}{2k\gamma^2}\left(1+\frac{K^2}{2}\right). \tag{1}$$

λ_u is the period length of the undulator, γ the relative beam energy and k the harmonic number of the emitted radiation ($k = 1, 3, 5, ...$). The deflection parameter is defined as $K = 0.0934 \cdot \lambda_u[mm] \cdot \tilde{B}[T]$, with $\tilde{B}$ the amplitude of the magnetic field on the beam axis.
In order to obtain the maximum brilliance the photons must superpose with a constant phase. A phase slip between the electron and the photon would cause a broadening and intensity reduction of the emission lines.
Therefore field errors of undulators have to be corrected [1]. In contrast to room temperature permanent magnet undulators, where measurement and correction of the field can be performed iteratively with almost no interruption, the situation for superconductive and cooled undulators is more complicated: the field has to be measured first, afterwards the magnet has to be warmed up, the field has to be corrected and the undulator has to be cooled down again for a new measurement.
This complication created the idea to study correction techniques different to the standard. For instance, the electrical shimming technique was first proposed for a single undulator period and experimentally verified [6, 7]. Recently these concepts were expanded to the whole undulator [8, 9].

PHASE ERROR CALCULATION

The evaluation of the phase error used in this paper is based on fig. 1. The variation of the period length λ_u or the amplitude of the magnetic field $\tilde{B}$ causes a slip between the electron phase and the photon phase. Fig. 1 assumes that the electron moves along the z- axis. This is a clear simplification.
In this case the phase difference between photon and electron for the period i ($i = 1, 2, ...n$) of an undulator with n periods, derived from the equations of motion of an electron, is

$$\Phi_i = \frac{2\pi}{\lambda_u}\left(\frac{2(\frac{e}{m_e c})^2 J_i - K^2 \Delta z_i}{2+K^2}\right), \tag{2}$$

with

$$J_i = \int_{z_{i-1}}^{z_i}\left(\int_{z_{i-1}}^{z} B_y(z')dz'\right)^2 dz.$$

$B_y(z)$ is the y-component of the magnetic field along the z-axis. The phase error can then be calculated as

$$\Phi_{error} = \sqrt{\frac{\sum_{i=1}^{n}(\Phi_i)^2}{n}}. \tag{3}$$

SIMULATION OF AN UNDULATOR WITH MECHANICAL DEVIATIONS

Fig. 2 shows the magnetic field along the beam axis of the SCU14, measured with a Hall probe in liquide Helium.

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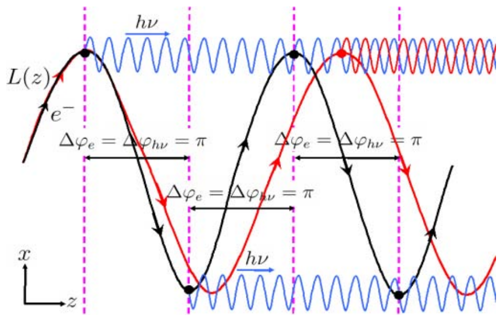

Figure 1: The variation of the period length or the amplitude of the magnetic field causes a slip between the electron phase and photon phase. In the worst case this leads to destructive interference.

The measurements show field distortions at both ends of the undulator, smaller periodic deviations and statistical deviations along the whole device. The first two distortions are caused by mechanical deviations of the undulator coils.
Based on the magnetic field data a mathematical model of a superconductive undulator with mechanical deviations was developed. Fig. 3 depicts schematically and strongly exaggerated the two types of systematic mechanical deviations exhibited by the SCU14 field - (I) bending and (II) periodical distortion of the coils - and the combination of both (III). The bending (I) at the end of each coil is 0.25 mm. With the above discussed definition, the phase error is $\Phi_{error} = 3.9°$.
The periodic distortion (II) causes a maximum variation of the pole position of 0.025 mm. The phase error caused by this perturbation is $\Phi_{error} = 1.44°$.
The phase error calculated for the model with the combination of both mechanical deviations (III) is $\Phi_{error} = 3.94°$.

EVALUATION OF THE REQUIRED CORRECTIONS

To correct the phase error, the undulator model was equipped with 4 correction coils per groove, placed onto the top of the existing main coil. Fig. 4 shows the allocation

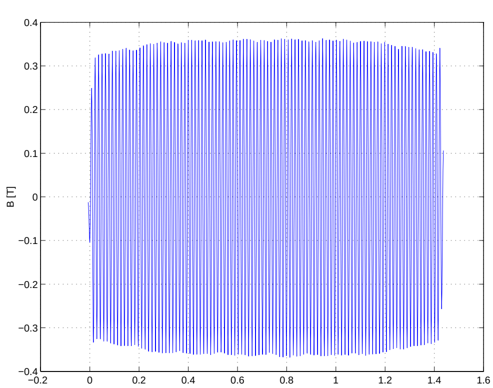

Figure 2: Magnetic field of the SCU14 installed at ANKA. The measurement was performed with a Hall-probe in a liquid helium bath [5]. The undulator parameters are: $n = 100$, $g = 8$ mm, $\lambda_u = 14$mm and $J_U = 500$ A/mm^2.

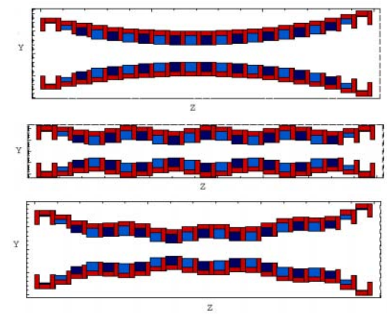

Figure 3: Schematic and strongly exaggerated drawing of the systematic mechanical distortions added to the Radia [10] model of a superconductive undulator: (I) bending (top), (II) periodic distortion (center) and (III) combination of both (bottom) [5].

of the 16 correction wires to the four correction coils of one period. The current direction in each correction wire refers to the current direction in the corresponding main coil. The additional wires have a cross-section of $1.25 \times 0.8\,\mathrm{mm}^2$. The current in period i ($i = 1...100$) and correction coil j ($j = 1...4$) is given as $J_{c,j}^{(i)}$.

Individual Correction Currents in Each Period

In a first step a correction currents for each period were calculated according to

$$J_c^{(i)} = c_0 \Delta B_y^{(i)} + c_1 \left(\Delta B_y^{(i)}\right)^2 + c_2 \left(\Delta B_y^{(i)}\right)^3 \qquad (4)$$

with

$$\Delta B_y^{(i)} = \left[\tilde{B}_{ideal}^{(i)} - \tilde{B}_{real}^{(i)}\right].$$

The constants c_0, c_1 and c_2 were determined by simulation. Applying these current densities to the correction coils, the phase error of the undulator model (I) was reduced to $\Phi_{error} = 0.39°$. For the undulator model (II) a phase error of $\Phi_{error} = 0.39°$ and for model (III) of $\Phi_{error} = 0.50°$ was achieved.
Fig. 5 shows the comparison of the maximum/minimum field values for the undulator model (III) before and after the correction.

Correction With Four Fixed Currents

For real applications the concept described in the previous section would require at least 50 additional power

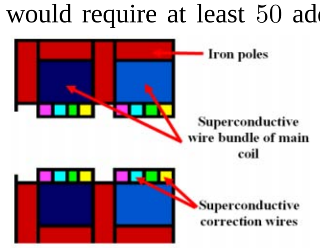

Figure 4: Wire allocation to the four correction coils in one period: Correction coil one (purple) with the current density $J_{c,1}$, correction coil two (turquoise) with the current density $J_{c,2}$, correction coil three (green) with the current density $J_{c,3}$ and correction coil four (yellow) with the current density $J_{c,4}$.

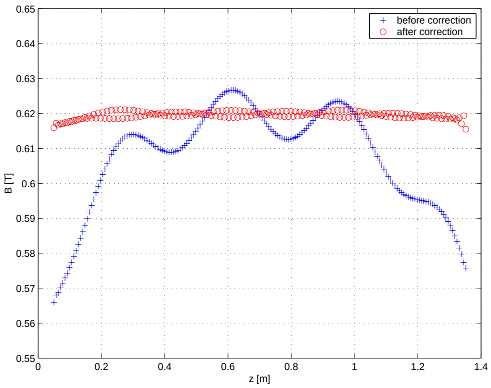

Figure 5: Maximum/minimum field values of the SCU model (III) with correction coils before and after correction with individual correction currents per period. The undulator model parameters are: $n = 100$, $g = 8$ mm, $\lambda_u = 14$ mm and $J_U = 900$ A/mm^2.

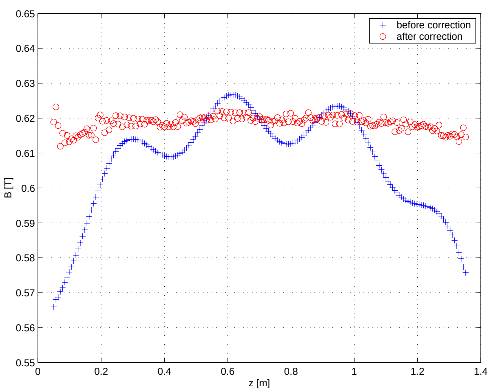

Figure 6: Maximum/minimum field values of the SCU model (III) with correction coils powered with four fixed currents before and after correction. The undulator model parameters are: $n = 100$, $g = 8$ mm, $\lambda_u = 14$ mm and $J_U = 900$ A/mm^2.

supplies and is therefore impractical. To avoid this, only four power supplies with currents of 250, 100, 50 and 10 A were added. Each correction coil is either connected to one of the four power supplies or not connected at all. Powering the four correction coils per period with the appropriate combination of these four fixed currents leads to correction currents as close as possible to the individual currents $J_c^{(i)}$, calculated in the previous section.
With this shimming concept the phase error of the undulator model (III) was reduced to $\Phi_{error} = 0.83°$. Fig. 6 shows the comparison of the field maxima before and after shimming. It can be seen that the bending and the periodical distortion of the coils is corrected in an acceptable manner.

Therefore, electrical shimming with correction coils powered by four fixed currents seems to be a sufficient concept for phase error correction of superconductive undulators with mechanical deviations.

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