A NEW CONCEPT FOR REDUCING PHASE ERRORS IN SUPERCONDUCTIVE UNDULATORS: INDUCTION-SHIMMING

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Abstract

Undulators are the most advanced sources for the generation of synchrotron radiation. The photons generated by a single electron add up coherently along the electron trajectory. In order to do so the oscillatory motion of the electron has to be in phase with the emitted photons along the whole undulator. Small magnetic errors can cause unwanted destructive interferences. In standard permanent magnet undulators the magnetic errors are reduced by applying shimming techniques. Superconductive undulators have higher magnetic fields than permanent magnet undulators but shimming is more complex. In this paper it is shown that coupled superconductive loops installed along the surface of the superconductive undulator coil can significantly reduce the destructive effect of the field errors. This new idea might allow the building of undulators with a superior field quality.

INTRODUCTION

Undulators are the most effective sources for brilliant X-rays in storage rings. Up to now undulators are mainly made from permanent magnets. This technique was optimized over many years. The maximum magnetic field strength of permanent magnet undulators is limited by the material properties of the permanent magnets [1, 2]. Two new concepts tried to overcome these limitations.

The first one was the development of in-vacuum permanent magnet undulators with a smaller magnetic gap and higher on axis field strengths [3, 4].

A second concept consisted of replacing the permanent magnets by superconductive wires. This development started in the early 1990's [5, 6], and after several intermediate steps a 100 period superconductive undulator with a period-length of $14\,\mathrm{mm}$ was installed in the storage ring ANKA in April 2005 [7, 8].

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 along the z-axis:

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

λ_L is the wavelength of the photons, 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 K is $K = 0.0934\cdot\lambda_u[mm]\cdot\tilde{B}[T]$, with $\tilde{B}$ the amplitude of the magnetic field on the beam axis. In order to obtain the maximum brilliance the photons must add up constructively. A phase slip between the electron and the photon would cause a line broadening and intensity reduction of the emitted lines. A measure for the deviation between electron and photon phase is the so-called phase error [2].

In permanent magnet undulators field errors are caused by a variation of pole-strength and finite mechanical tolerances of the poles [1, 2]. In superconductive undulators field deviations can only be caused by finite mechanical tolerances. The poles and wire-bundles have statistically distributed distances to the beam axis and the period-length varies around a certain value. Therefore, by ensuring tight mechanical tolerances and by applying mechanical measurements it is possible to reduce the expected phase errors significantly. In addition electrical shimming concepts have been proposed and verified for single undulator periods [9, 10]. These have subsequently been extended to whole undulators [11, 12].

For both types of undulators shimming is an iterative and time consuming process of measuring, applying shims or shim coils and verifying the improved field quality.

This provided the stimulation to think about concepts for superconductive undulators where field errors are compensated automatically without additional steps of shimming.

INDUCTION-SHIMMING

The induction-shimming concept for superconductive undulators is based on Faraday's law of induction

$$\oint_C \vec{\mathbf{E}}d\vec{l} = -\frac{d}{dt}\int_S \vec{\mathbf{B}}d\vec{A}, \tag{2}$$

where $\vec{\mathbf{B}}$ is the magnetic flux density over the area S with the contour C, $\vec{\mathbf{E}}$ is the electrical field strength and $d\vec{A}$ is the surface element. The line integral of the electric field strength $\vec{\mathbf{E}}$ along C is equal to the negative time derivative of the integral of the magnetic flux density $\vec{\mathbf{B}}$ over the area S, which is confined by the contour C.

Using an ideal conductor along the contour, for instance a superconductive closed-loop, equation (2) is reduced to

$$0 = \frac{d}{dt}\int_S \vec{\mathbf{B}}d\vec{A}. \tag{3}$$

In other words, a change of the magnetic flux through the closed loop is compensated by the magnetic flux produced by the induced current.

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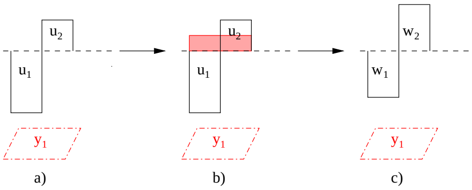

Figure 1: Influence of a superconductive closed-loop installed at the undulator surface. The loop covers a single undulator period. Without the induced current in the loop (a) the magnetic flux in the two half periods is different. For the sake of simplicity it is assumed that the flux has a rectangular shape. When the loop is installed, the induced current produces a correction flux (red - b) and equalizes the field strength according to equation (3) (c).

The idea is to use closed superconductive loops for phase error compensation. These closed-loops must be arranged in such a way that for an ideal undulator the magnetic flux enclosed by one loop is equal to zero. This is the case when the loop covers integer multiples of undulator periods.

In the following a superconductive closed-loop is considered, which is installed on the undulator surface and covers a full period (see figure 1). Furtheron it is assumed that the magnetic flux in each half period is different. For the sake of simplicity it is assumed that the flux in each half period has a rectangular shape. The magnetic flux enclosed by the superconductive loop is not zero (see figure 1a).

The magnetic flux in the first and second half period u_1 and u_2 and the flux y_1 produced by the loop superpose to zero

$$y_1 + u_1 + u_2 = 0. \tag{4}$$

The flux w_1 and w_2 in each half-period is changed to

$$w_1 = u_1 + \frac{1}{2} y_1 \tag{5}$$

$$w_2 = u_2 + \frac{1}{2} y_1. \tag{6}$$

Equations (5), (6) and (4) yield

$$w_2 = -w_1 = w. \tag{7}$$

Equation (5) and (6) can be rewritten and solved for w

$$w = \frac{-u_1 + u_2}{2}. \tag{8}$$

The current in the loop equalizes the field strength according to equation (3). This is shown in figure 1c.

An induction-shimming scheme with n overlapping closed-loops is shown in figure 2. Extending equation (8) to this system yields

$$w = \frac{\pm u_1 \mp u_2 \pm \ldots \pm u_n \mp u_{n+1}}{n+1}, \tag{9}$$

with the resulting flux w and the magnetic flux u_n in the n-th half period. As with the one loop system described before, the system of n overlapping closed-loops adjusts the absolute values of the magnetic flux in each half period to the same level.

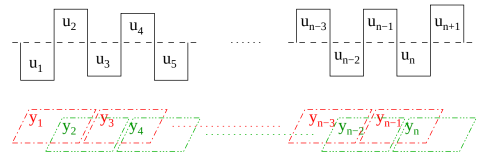

Figure 2: Rectangular flux with n+1 half periods and n overlapping closed-loops

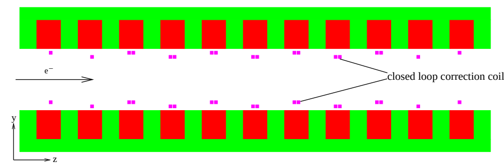

Figure 3: Cross section of an undulator with the main coils (green: iron; red: superconductive wire-bundles) and overlapping closed-loops for correction (magenta) placed close to the main coils.

SIMULATIONS WITH BIOT-SAVART CLOSED-LOOPS

In the following the concept is extended to sinusodial fields and the field produced by the current in the loops is described by the law of Biot-Savart. Amplitude and period-length can be varied in each half period.

For the sake of simplicity the closed-loops are considered to consist of ideally superconductive long straight wires perpendicular to the beam direction (z-axis). The loop parts parallel to the e-beam direction can be neglected due to their large distance from the e-beam. The mid-plane of the superconductive closed-loops is considered to be $1\,\mathrm{mm}$ away from the source (main coil) and $2.5\,\mathrm{mm}$ from the beam plane. The undisturbed field amplitude on axis is $1\,\mathrm{T}$. Such an arrangement is shown in figure 3.

Faraday's law of induction (see equation (2)) for a system of overlapping closed-loops can then be written as

$$\Phi_i = L \left(\sum_{j \neq i} M_{ij} I_j - I_i \right). \tag{10}$$

Φ_i is the magnetic flux enclosed by loop i and I_i is the current induced into loop i. The self-inductance L and the mutual inductances M_{ij} are defined by the geometrical arrangement and the design of the closed-loops.

Correction of a Single Field-error

For a first simulation a three period undulator has been modelled with a 10% too high second maximum. A single pole, which is closer to the beam than the others would cause this error. The field plot along the beam axis with and without induction-shimming is shown in figure 4. The second maximum was reduced by about 70% from $1.1\,\mathrm{T}$ to $1.03\,\mathrm{T}$. The absolute values of the neighbouring minima were increased to $1.025\,\mathrm{T}$ and the first maximum was increased to $1.015\,\mathrm{T}$. The changes in the third maximum and

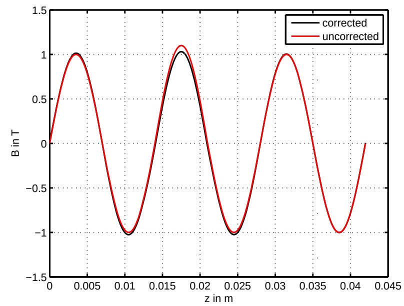

Figure 4: Comparison of the magnetic field along the beam axis with (black) and without (red) induction-shimming.

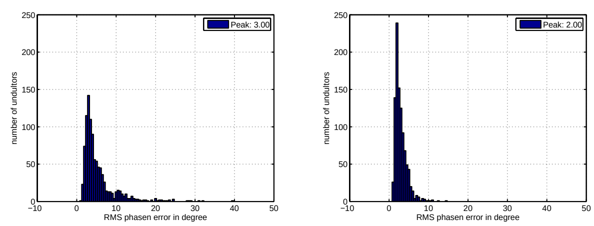

Figure 5: Phase-error distribution for 1000 50-period undulators without (left) and with (right) induction-shimming; $\sigma_{\frac{\Delta B}{B},coil} = \sigma_{\frac{\Delta B}{B},pole} = 3 \cdot 10^{-3}$

minimum were negligible. The error previously localized in one half period was distributed over two periods.

Comparing these results with those obtained in chapter two with rectangular fields shows that the method with coupled Biot-Savart loops is somewhat less effective. This is due to the fact that in the rectangular field model the field is assumed to be confined inside the loop. But in reality the field generated by a loop expands to some extent into the space outside the loop and reduces the efficiency of the method. This reduction in efficiency can be partly compensated by using a different arrangement of the loops: loops covering two or more periods instead of one.

Monte-Carlo Simulations

In a superconductive undulator statistically distributed mechanical deviations are the main reasons for phase errors. Figure 5 shows the phase error distribution calculated for 1000 undulators with and without induction-shimming. The undulators consist of 50 periods. Normally distributed variations of the wire-bundle y-positions (anti-symmetric field deviation) and pole y-positions (single field distortion at one extremum), both with $\sigma_{\frac{\Delta B}{B}} = 3 \cdot 10^{-3}$, were assumed. The width of the phase-error distribution with induction-shimming is significantly lower and the tail of the distribution is shorter (see table 1).

CONCLUSION

A new shimming-concept for superconductive undulators is described. The simulations showed that the phase error significantly is reduced.

Table 1: Comparison of the confidence-levels in the phase-error distributions with and without induction-shimming (ind.-shim.).

	without ind.-shim.	with ind.-shim.
peak of the distribution	3.0°	2.0°
50%-level	3.9°	2.5°
99.7%-level	29°	11°

The efficiency of the correction can be increased by using different loop arrangements: loops covering two or more periods instead of one.

A first induction-shimming test device has been produced and will be tested experimentally with an undulator mock-up coil in the near future.

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