EXPERIMENTAL DEMONSTRATION OF THE INDUCTION SHIMMING CONCEPT IN SUPERCONDUCTIVE UNDULATORS*

D. Wollmann†, A. Bernhard, P. Peiffer, T. Baumbach, University of Karlsruhe, Germany
E. Mashkina, University of Erlangen-Nürnberg, Germany
A. Grau, R. Rossmanith, Forschungszentrum Karlsruhe, Germany

Abstract

Recently a novel shimming concept for superconductive undulators was proposed, which automatically reduces magnetic field errors. According to this proposal the field errors are compensated by an array of coupled high temperature superconductor (HTSC) loops attached to the surface of the superconductive undulator. The field errors induce currents in the coupled type II-superconducting loops and, as a result, the magnetic field generated by these currents minimizes the field errors. In this paper the results of a first successful experimental test of this concept are described.

INTRODUCTION

Undulators are the photon sources in synchrotron light sources and Free Electron Lasers [1, 2]. The wavelength of the emitted light is related to the undulator period length λ_u by the equation

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right). \quad (1)$$

Where $K = 0.0934 \cdot \lambda_u[mm] \cdot \tilde{B}[T]$, $n = 1, 3, 5, ...$ is the harmonic number and $\tilde{B}$ is the peak magnetic field. Deviations in $\tilde{B}$ and λ_u due to mechanical tolerances can influence the trajectory of the particles and thereby disturb the constructive interference of the photons. Therefore mechanical tolerances limit the achievable brightness of the undulator radiation. This is especially true for higher harmonics. The measure for the field variations is the so-called phase error [1]. In permanent magnet undulators the phase error is minimized by mechanical or magnetic shimming systems [1, 2]. In superconductive undulators additional superconductive correction coils can be used for phase error correction [3, 4, 5, 6].

Recently a novel concept called *induction-shimming* was proposed, in which the field errors for superconductive undulators are automatically minimized by an array of HTSC loops [7, 8]. In this paper the first experimental results are reported [9, 10].

INDUCTION SHIMMING

The idea of induction-shimming is sketched in Fig. 1. The induction-shimming system consists of a set of overlapping closed loops each covering two adjacent magnet poles. The array of high temperature superconductor

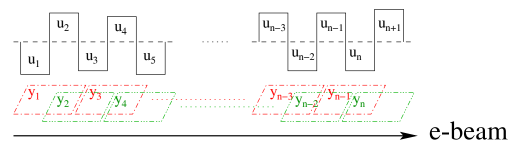

Figure 1: Concept of induction-shimming. The sinusoidal field in one of the undulator-halves is approximated for the sake of simplicity by a rectangular shape. Due to minor field errors caused by finite tolerances the amplitude of the field varies slightly. This variation is compensated by HTSC loops (red and green). The length of one loop in the beam direction is exactly one ideal period length.

(HTSC) loops is attached to the surface of the undulator. Each loop covers one full period and is electrically isolated from all other loops. For an ideal undulator field the flux through one loop is zero. In case of deviations each half-wave has a slightly different field integral. For the sake of simplicity the sinusoidal magnetic field in each half period of the undulator is approximated by a rectangular shape. Each rectangle u_1, u_2, ... represents the integrated field of a half period.

The behaviour of one closed loop can then be described by Faraday's law

$$\oint_C \tilde{\mathbf{E}} d\vec{l} = -\frac{d}{dt}\int_S \tilde{\mathbf{B}} d\vec{A}, \quad (2)$$

where $\tilde{\mathbf{B}}$ is the magnetic flux density over the area S with the contour C, $\tilde{\mathbf{E}}$ is the electrical field strength and $d\vec{A}$ is the surface element. If the conductor along the contour C is a superconductive closed loop equation (2) is reduced to

$$0 = \frac{d}{dt}\int_S \tilde{\mathbf{B}} d\vec{A}. \quad (3)$$

If the externally produced magnetic flux through the loop changes by the amount of $\Delta\Phi$ a current is induced. The current produces a magnetic flux $-\Delta\Phi$ which compensates the change of the external magnetic flux. Due to the coupling, the field amplitude in each period is leveled to the same value. This idea is the base of the induction-shimming concept for undulators and is explained in detail in [7, 8, 10].

EXPERIMENT

In order to perform a first experimental test of this concept an existing superconductive undulator mock-up was

* Work supported by the Carl-Zeiss-Stiftung, Germany
† daniel.wollmann@cern.ch

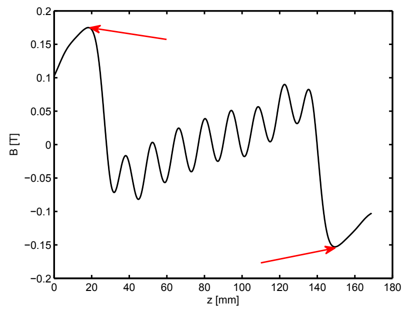

Figure 2: The distorted magnetic field strength of an undulator mock-up before applying the induction shimming concept. The field is significantly deformed by the end plates (red arrows).

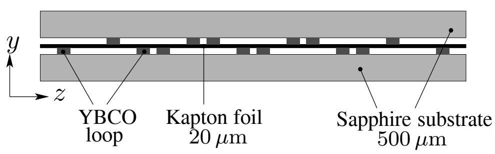

Figure 3: Cut through the stacked induction-shimming structure with the substrate. The YBCO loops are arranged on a $500\,\mu\mathrm{m}$ thick sapphire substrate. The thickness of the YBCO layer is $330\,\mathrm{nm}$. The period of the mock-up is $14\,\mathrm{mm}$.

used. The period of the undulator mock-up is $14\,\mathrm{mm}$. Each groove is filled with 28 round NbTi wires with a diameter of $0.8\,\mathrm{mm}$. The cross-section of the wire is $0.5\,\mathrm{mm}^2$. From former measurements it was known that this mock-up has a rather deformed field (Fig. 2) mainly due to massive magnetic iron plates at the beginning and the end of the mock-up. This deformed field is well suited to study the induction shimming concept. In order to reduce the field error seven $YBa_2Cu_3O_{7-x}$ (YBCO) loops (see Fig. 3) were placed at one millimetre distance from the undulator surface. The seven loops were installed in the center of the mock-up. The arrangement of the loops is shown schematically in Fig. 3 and a photo is shown in Fig. 4. The field was measured in a Helium bath cryostat - CASPER I - a field measuring device for short superconductive undulators described in detail in [11]. The result of the measurements is shown in Fig. 5. The field was measured with a Hall probe which was moved at a distance of $7.15 \pm 0.1\,\mathrm{mm}$ from the undulator surface. The position of the YBCO closed loop system is shown at the bottom of Fig. 5. The measurement was performed for several currents through the undulator: $I_{main} = 30\,\mathrm{A}$, $70\,\mathrm{A}$, $100\,\mathrm{A}$, $150\,\mathrm{A}$, $200\,\mathrm{A}$ and $250\,\mathrm{A}$.
The upper plot of Fig. 5 shows that the YBCO loops flatten the field amplitudes significantly at $I_{main} = 30\,\mathrm{A}$ and $I_{main} = 70\,\mathrm{A}$. With increasing undulator current this effect is reduced. The difference between the fields measured with and without the YBCO loop system is shown in the lower plot of Fig. 5. The compensating field is positive at the left hand side and negative at the right hand side as

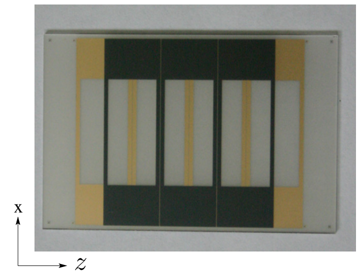

Figure 4: Photograph of the set of seven correction loops. Two $500\,\mu\mathrm{m}$ thick sapphire substrates are sputtered with four and three YBCO loops with a thickness of $330\,\mathrm{nm}$, covered with a $200\,\mathrm{nm}$ thick gold layer. Dimensions of the loops: $14\,\mathrm{mm} \times 44\,\mathrm{mm}$. The two substrates are stacked and mounted at a distance of $1\,\mathrm{mm}$ from the surface of the undulator.

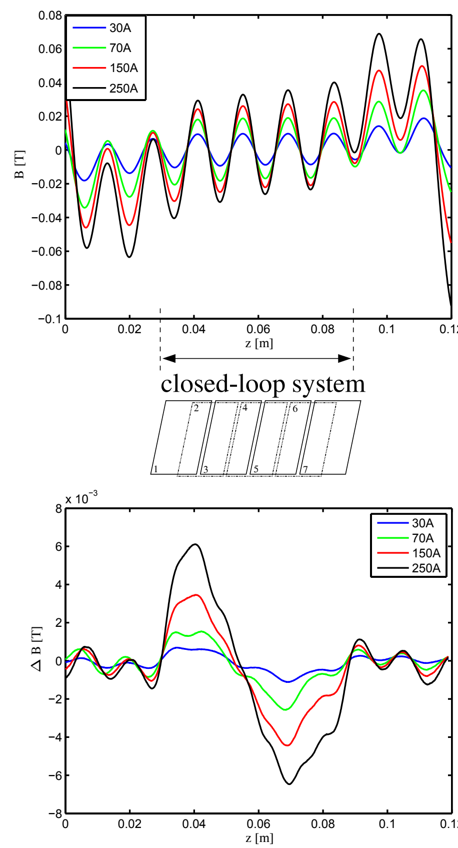

Figure 5: The influence of the YBCO closed loop system on the field shown in Fig. 2 for various undulator currents (above) and the difference of the field measurements with and without the YBCO loops system (below). The YBCO loop system tries to compensate the field which increases from left to right in Fig. 2.

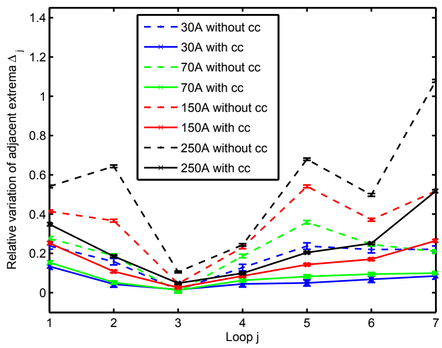

Figure 6: Ratio of the absolute values of adjacent extrema with and without the YBCO loop system for different currents I_{main}. The values at the beginning and the end are higher due to the finite length of the induction-shimming system.

one would expect from the distorted field (see Fig. 2). It also shows that both peaks change the form as the current increases.

The efficiency of the system is shown in Fig. 6 for the different currents through the undulator. The ratio of adjacent extrema covered by the loop j are compared:

$$\Delta_j = \left| 1 - \left| \frac{A_{j,max}}{A_{j,min}} \right| \right|. \quad (4)$$

The data are taken from the measurements shown in Fig. 5 and corresponding measurements without the induction-shimming system. The efficiency is lowest at the first loop, which suffers from a fabrication error in the YBCO layer. The dashed curves show the ratio before compensation, the solid lines after compensation. The values of the solid lines increase towards both ends of the area covered with YBCO loops especially for currents above $I_{main} = 150\,\mathrm{A}$. This is caused by two effects: 1) The induced currents reach the saturation current, in the right loops for $150\,\mathrm{A} \leq I_{main} \leq 250\,\mathrm{A}$ and in the first loop at the left-hand side at $I_{main} \gtrsim 70\,\mathrm{A}$ due to a fabrication error. 2) At both ends of the loop system the values in Fig. 6 are higher since the outmost loops have no partner due to the finite length of the induction-shimming system (see Fig. 3 and 4).

CONCLUSION

This demonstration experiment shows that the phase error in superconductive undulators can be significantly reduced by an array of coupled HTSC closed loops. The measured correction field of the loop system was about $6\,\mathrm{mT}$ at a distance of $7.15 \pm 0.1\,\mathrm{mm}$. Typically an undulator with a period length of $14\,\mathrm{mm}$ has a gap of $5\,\mathrm{mm}$, resulting in a maximum on axis field of $1.5\,\mathrm{T}$. In that case the loop system will only be $2.5\,\mathrm{mm}$ away from the beam trajectory. The correction field scales with $1/r$ and therefore the available correction field will be about $17\,\mathrm{mT}$. In a real superconductive undulator the field error should not exceed $1\,\%$, i.e. $15\,\mathrm{mT}$ for the example mentioned above. With correction loops on both undulator coils the available correction field is $34\,\mathrm{mT}$ and sufficient for a good correction. The YBCO loops with a thickness of $330\,\mathrm{nm}$ are sufficient for most superconductive undulators.

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