INDUCTIVE SHIMMING OF SUPERCONDUCTIVE UNDULATORS: PREPARATIONS FOR A REALISTIC TEST

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Abstract

The monochromaticity and intensity of synchrotron light emitted by undulators strongly depend on the undulator field quality. For the particular case of superconductive undulators it was shown recently that their field quality can be significantly improved by an array of coupled high temperature superconductor loops attached to the surface of the superconductive undulator. Local field errors induce currents in the coupled closed superconducting loops and, as a result, the hereby generated magnetic field minimises the field errors. In previous papers the concept was described theoretically and a proof-of-principle experiment was reported. This paper reports on a preparation experiment for the first quantitative measurement of the phase error reduction in a 13-period short model undulator equipped with a full-scale induction shimming system.

INTRODUCTION

Undulators generate highly brilliant radiation in a narrow energy band due to constructive interference of the photons emitted by each single electron along its undulating trajectory. The condition for constructive interference, i.e. the phase relation between the electron motion and the electromagnetic wave needs to be maintained through all periods of the undulator which requires a high quality of the magnetic field [1].

Both accurately measuring and correcting the field particularly of superconductive undulators is a technical challenge. The requirement of liquid Helium temperature severely complicates the control of systematic effects from alignment and calibration errors and makes iterative correction procedures cost-intensive and time-consuming. Passive, self-adjusting field correction schemes for superconductive undulators therefore would be a very attractive solution.

A possible passive field correction scheme based on induction in closed superconducting loops was recently proposed [2]. The basic idea is schematically shown in Fig. 1: A chain of coupled closed superconducting loops is placed on top of the undulator coils, each loop covering one undulator period. In case of field deviations a current is induced in each loop levelling the field integral over the area enclosed by the loop. By coupling the loops e.g. through a half-period overlap the field integrals is levelled globally to a certain extent, depending on the coupling strength, and thereby the rms phase error is reduced.

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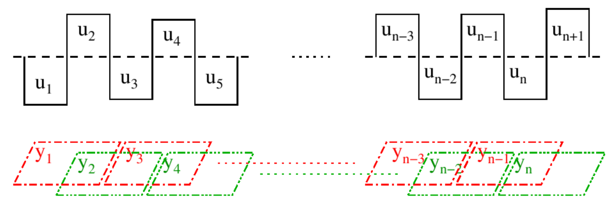

Figure 1: Concept of induction shimming. The sinusoidal field is approximated for the sake of simplicity by a rectangular shape. Because finite tolerances, the amplitude of the field varies slightly. This variation is compensated by HTSC loops arranged in the way shown in this picture.

It was shown in a demonstration experiment with a short, 4-period inductive shim loop system that the idea works [3]. Starting from this result a detailed experimental and theoretical evaluation of the concept is under way which will be followed by R&D on the technical implementation of induction shimming in full-scale superconductive undulators.

The following first steps in this direction were taken:

- test and characterisation of the first of two short model coils
- test and characterisation of the experimental setup, in particular with respect to systematic errors, which have to be very small in order to resolve the reduction of small phase errors on a significant level
- decision on the shim configuration, in particular on the question how many poles in the matching region have to be excluded from being covered by the shims

From the point of view of global error reduction, covering as many periods as possible might be preferable. However, in the period(s) closest to the matching periods at the ends of the undulator rather large local field integrals can occur which may drive some shim loops into saturation and thereby cause unwanted field distortions and hysteresis effects.

EXPERIMENTAL SETUP

The experiments were carried out in the cryogenic magnetic measurement facility CASPER at the Karlsruhe Institute of Technology [4]. The setup is shown in Fig. 2.

The main parameters of the short model undulator coil used are summarised in Tab. 1.

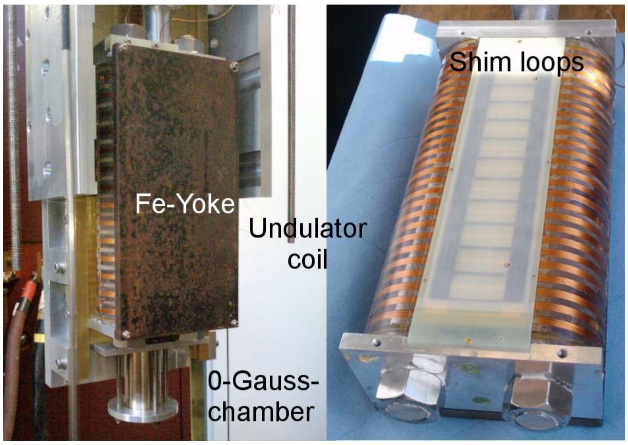

Figure 2: The measurement setup submersed in the liquid Helium bath at CASPER (left) and short model coil with induction shim loop system applied (right)

Table 1: Basic Parameters of the Short Model Undulator Coil

period length	15 mm
full periods	13
matching configuration	2 coils (1/4,3/4 filled)
conductor	NbTi multifil., 0.77×0.51 mm^2
max. current density	1380 $\mathrm{A/mm}^2$
$\tilde{B}_y$ @500 A, 3 mm dist.	600 mT

Figure 2 (rhs) shows the short model coil equipped with the shim loop system. The shimming system employed consists of two identical arrays of 12 closed YBCO-loops deposited on sapphire substrates of 0.5 mm thickness, fabricated by THEVA Dünnschichttechnik GmbH, Germany. Each loop covers an area of $15 \times 41\,\mathrm{mm}^2$ and has a thickness of $300\,\mathrm{nm}$ corresponding a conductor cross section of $3 \cdot 10^{-4}\,\mathrm{mm}^2$ in the narrow conductor paths oriented parallel to the undulator coil windings and $3 \cdot 10^{-3}\,\mathrm{mm}^2$ in the broad conductor paths crossing the undulator iron poles, respectively. The YBCO loops are covered by 200 nm Gold layers. The two loop arrays are shifted by one half undulator period length with respect to each other and mounted on top of the pole surface, enclosing the poles 1...25 of the 26 poles constituting the 13 full periods of the undulator.

The Hall probe carriage can be moved into a zero-Gauss chamber attached to the lower end of the bearings. The chamber was employed in order to reduce systematic errors due to unknown offset voltages of the Hall probes. The chamber consists of two concentric CRYOPERM10®-cylinders and screens the magnetic stray fields to a level of $2.5 \cdot 10^{-5}\,\mathrm{T}$ according to finite-element-simulations [5].

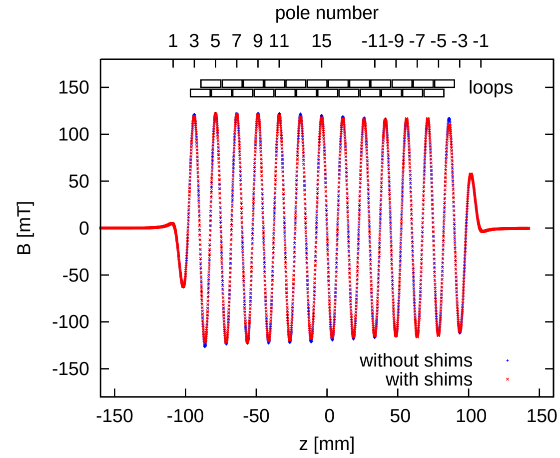

Figure 3: Field maps at 50 A operation current with and without shims

RESULTS

Test of the Zero-Gauss-Chamber

The performance of the zero-Gauss chamber was tested during the initial quench training of the short model coil with the hall probes parked in the screened volume. No field increase was detected indicating that the field is effectively shielded to a level below the resolution of the Hall probes. During the whole campaign the Hall probe scans were started in the zero-Gauss chamber and exhibited a considerable long-term drift of the Hall voltage offset, especially after thermally cycling the setup. The measurements were corrected for this zero drift.

Field Maps and Setup Alignment

Figure 3 shows the measured field map along the beam axis for $I_{\mathrm{main}} = 50\,\mathrm{A}$. The field amplitude decreases with increasing z. This decrease indicates that the sliding system is slightly inclined with respect to the undulator. Using the Maxwell-conform representation of the field of a half undulator

$$B_y(y,z) = B_{y0}\left(\cosh(k_u y) - \sinh(k_u y)\right)\cos k_u z \quad (1)$$

with $y = y_0 + az$ the inclination can be estimated to be in the order of $a = 1\,\mathrm{mrad}$. Moreover, it can be concluded from the data that the deviation from the correct alignment is not identical for the two series of measurements with and without the shim loops applied. The effect of the different inclinations is considerably larger than the expected difference of the field amplitudes with and without induction shimming. Therefore a direct comparison of shimmed and unshimmed fields would — even if path-corrected — have a high degree of arbitrariness and is omitted here.

An adjustment technique for the setup improved both in terms of absolute accuracy and reproducibility is currently under development.

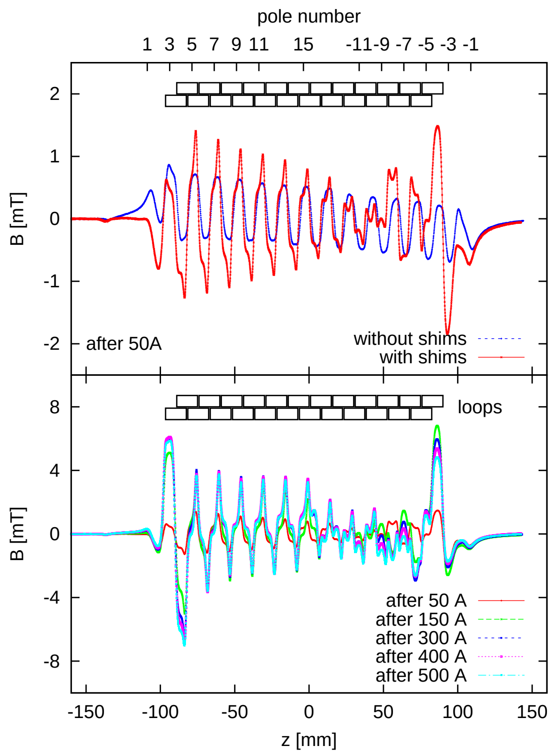

Figure 4: Field maps generated by persistent currents in the loop system after operating the magnet at 50 A (top) and different currents (bottom)

Influence of End Fields on the Induction Loops

The series of Hall probe scans with and without shims applied were performed in the following order: First, the magnet was cycled before mounting the shims. Subsequently, scans were performed at 50, 100, 150, ..., 500 A. After each scan, the magnet was ramped down again to 0 A and the remanent field was scanned.

The top graph in Fig. 4 shows the 0 A-scans with and without shims after the magnet was loaded with 50 A. Already after operating the magnet at 50 A the measured field pattern is dominated by persistent currents in the shim loops. A set of 0 A-scans after operation at different currents is shown in Fig. 4 (bottom). A similar pattern of the fields generated by persistent currents is observed in all scans.

The persistent currents are a hysteretic effect caused by a part of the shim loops reaching the critical current density and becoming resistive.

The observations indicate that on the left hand side the first two shims covering the poles no. 3 and 4, and on the right hand side the last shim covering pole no. -4 reach saturation (for the pole numbering convention refer to the figures). The saturation is caused by a comparatively large overshoot in field amplitude at poles no. 4 and -4 occurring at low operation currents.

The persistent currents in the inner periods are not due to saturation in these shims, but due to coupling to the outermost loops. The fact that pole no. 4 on the left is covered by two shims while pole no. -4 on the right by only one shim results in a different coupling behaviour determining the persistent current pattern in the inner periods: the persistent currents in the two saturated coils flow in equal sense, resulting in a long-ranged coupling with the current in all loops flowing in the same direction. In contrast, the hysteresis in only one loop on the right results in a coupling scheme with alternating current directions which is short-ranged and interferes with the long-ranged pattern around $z = 50\,\mathrm{mm}$.

To conclude, unwanted hysteresis effects in the induction shimming system can — for the given matching coil configuration — be avoided if the shim chain covers poles no. 5...-5.

CONCLUSIONS AND OUTLOOK

This paper reports intermediate experimental steps towards a detailed experimental evaluation of the concept of induction shimming. The experimental setup for the field measurements was improved with respect to the control of systematic errors due to Hall voltage offset drifts. The short model undulator to be employed was successfully tested. First tests with the shimming chain revealed that unwanted hysteretic effects due to the loops next to the matching period of the undulator reaching saturation can be avoided if the shim chain starts at the fifth pole counted from outside.

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