TEST OF A SHORT PROTOTYPE OF A SUPERCONDUCTING UNDULATOR FOR THE ANKA SYNCHROTRON LIGHT SOURCE

E. Mashkina#, N. Vassiljev, A. Magerl, University of Erlangen-Nürnberg, Germany
A. Grau, S. Casalbuoni, M. Hagelstein, D. Saez de Jauregui, T. Baumbach, Institute for Synchrotron Radiation, Research Center Karlsruhe, Germany
C. Boffo, M. Borlein, W. Walter, Babcock Noell GmbH, Würzburg, Germany

Abstract

A 15 mm period and 1.5 m long planar undulator is being fabricated by Babcock Noell GmbH (BNG) for the ANKA synchrotron light source [1]. A short prototype has been fabricated to qualify the production process, the magnetic field quality, and the magnetic field correction system. The prototype has been tested in liquid helium at 4.2 K in vertical configuration in the CASPER facility at ANKA.

We report here on the mock-up design, fabrication, field shimming and performance tests using a Hall-probe mapping system.

INTRODUCTION

Superconducting undulators may play an important role for existing and future synchrotron light sources. To drive the development in this field we have set up a R&D program for superconducting insertion devices at the synchrotron light source ANKA [2].

The required longitudinal coherence of the x-ray radiation from an undulator demands a high degree of accuracy of the field parameters. For this reason high demand is put on the mechanical tolerances of both the windings and the yoke material. To compensate for possible mechanical deviations in the period length, the pole height and the position of the superconducting coils an active shimming concept [3-7] has been proposed. The basic idea consists in adding an additional layer of superconducting wire on top of the main coils in order to provide a field perturbation that can correct the field errors. Active shimming with NbTi racetrack coils has already been tested [4, 6, 7] and a correction of > 1% [4], 3% [6] and 7% [7] on the field strength was achieved.

With the aim to develop a 1.5 m magnetic length superconducting undulator with a K-value larger than 2, a period length of 15 mm and an optical phase error of less then 3.5°, a NbTi mock-up has been built to verify the design, the magnetic field performance and the efficiency of active local field correction coils.

ELECTROMAGNETIC DESIGN

A NbTi superconducting undulator mock-up was produced by Babcock Noell GmbH. It has 15.5 periods including end matching sections with a period length of 15 mm and 3.68 mm pole width. The main coil configuration consists of 91 turns organized in 13 layers. The end-poles have 21 (7 single turns x 3 layers) and 63 (7 single turns x 9 layers) turns for the first and the second end poles, respectively. For this prototype a commercially available NbTi superconductor with a cross section of 0.54 x 0.34 mm (including insulation) has been chosen. The rectangular shape allows to minimize the difference between wire current density and winding package current density. The expected operational current of 186 A corresponds to an overall density in the winding package of ~ 1000 A/mm^2.

The yoke is fabricated out of high magnetic field saturation steel HyperCo27. In order to reduce the consequences of a failure in machining, the yoke is built from plates which are produced individually. Each plate is a pole and a winding groove. The plates are aligned and pressed to each other by two threaded rods.

The coils were vacuum pressure impregnated to assure stability during operations.

Racetrack active shimming coils were applied for pole numbers 11 and 17 of one of the magnets.

MAGNETIC MEASUREMENT SYSTEM

In order to establish the performance of an undulator, it is necessary to measure the magnetic field distribution along the undulator beam axis and to calculate from this information the phase errors. The field distribution is usually obtained by moving magnetic sensors like Hall probes through the undulator driven by an actuation stage with a high mechanical precision.

A device for magnetic measurements of superconductive coils CASPER (**Ch**ar**a**cterization **S**et-u**p** for Field **E**rror **R**eduction) built at ANKA is described in [8].

MECHANICAL DEVIATIONS AND MAGNETIC FIELD MEASUREMENTS

The mechanical deviations of the pole heights of the constructed magnet were measured. Due to the impregnation process at 180°C the pole height profile along the beam axes deviates from the ideal flat behaviour showing a parabola-like shape with maximum of about 200 μm for one coil and about 400 μm for the other (see right plot in Fig. 3). This problem has been solved meanwhile by using an alternative impregnation

#Elena.Mashkina@iss.fzk.de

procedure at room temperature that has been tested on a smaller mock-up of 3 periods [1].

The magnet was subjected to quench tests. An operational current of 186 A was reached with a ramping rate of 40 A/min after three subsequent quenches at 143 A, 157 A and 180 A. The stability of the operational current of 186 A was longer than 15 hours. Magnetic field profiles were measured at different currents. Later we concentrate on the measurements at the highest current of 186 A shown in Fig.1, above. The peak magnetic field reached in the middle of the magnet is 0.73 T. This value is lower than the expected field B =0.78 T for 8 mm gap. The difference is due to the larger gap of 8.57 mm in the middle of the magnet caused by the mechanical deviations of the pole height described above. The magnetic field profile along the beam axis was simulated with programs RADIA [9] which have been confirmed by simulations with the program ANSYS. Data are compared with the simulated ideal magnetic field without mechanical deviations and the ones simulated with the real geometry (Fig. 1, below).

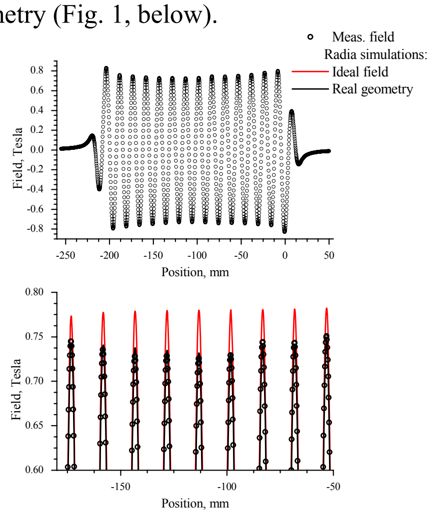

Figure 1: Above: Measured field along the central axis of the undulator with a current of 186 A.

Below: Comparison with simulated ideal magnetic field without mechanical deviations and ones simulated with a real geometry.

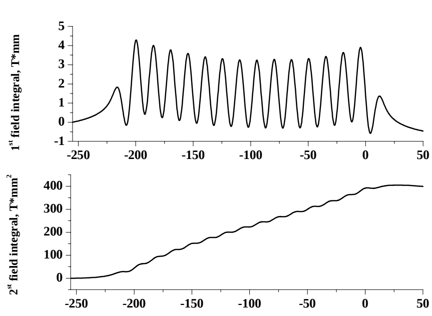

Figure 2: 1st and 2nd field integrals calculated from measured magnetic field at 186 A.

The uncorrected first and the second field integrals are shown in Fig. 2. Two correction coils at the beginning and at the end of the magnet would be needed to correct the electron beam. These large deviations will be consistently improved with the new impregnation procedure [1].

PHASE ERROR

The phase error quantifies the deviation from perfect matching in phase between the trajectory of an individual electron and its emitted radiation between two poles. The phase function is by the formula [10, 11]:

$$\Phi(z)=\frac{S(z)}{\lambda_r}=k_u\left[\frac{1}{1+\frac{K^2}{2}}\left(z+\frac{e^2}{m^2c^4}J(z)\right)-z\right] \quad (1)$$

where

$$S(z)=\int_0^z\left(\frac{1}{2\gamma^2}+\frac{1}{2}x'^2(z)\right)dz \quad \text{is a slippage} \quad (2)$$

$$x'(z)=\frac{e}{m_e\gamma}I_1(z),$$

$$k_u=\frac{2\pi}{\lambda_u},\ \lambda_r\cong\frac{\lambda_u}{2\gamma^2}(1+\frac{K^2}{2}),\ J(z)=\int_0^z I_1^2dz, \quad (3)$$

$$I_1(z)=\int_0^z B_y(z)dz$$

with I_1 being the first field integral.

The optical phase error is calculated by subtracting from the phase function (Eq. 1), corrected for the trajectory, the ideal phase [11] at each pole and shown in Fig. 3 (circles). The mechanical measurements have shown that the largest error is the pole height deviation from the ideal value. The variation in the period length is small (less than 30 µm), thus the local phase error between two adjacent poles can be defined as the deviation from the ideal *B* value [10] and shown on Fig. 3 (squares):

$$\Delta\Phi(z_i-z_{i-1})=\frac{K^2}{(1+\frac{K^2}{2})}\frac{\Delta B}{B}\cdot 360° \quad (4)$$

The relative pole heights of both coils were measured with respect to the end poles. The result is shown in Fig. 3 together with the associated phase errors calculated with the two different approaches described above. These data show that mechanical deviations less than 100 µm are needed for the calculated phase error of 3.5°. This result is in fair agreement with magnetic field simulations. In Fig. 4 we show the difference in the peak field for one pole between the simulated ideal field and the case where the pole height is decreased on both sides of the magnet by 70 µm. The corresponding phase error is 3.5°.

CORRECTION COILS

Two racetrack shims were applied around the pole 11 and 17 on one side of the magnet. The tests of two racetracks were performed with 186 A in the main coil. Hall probe

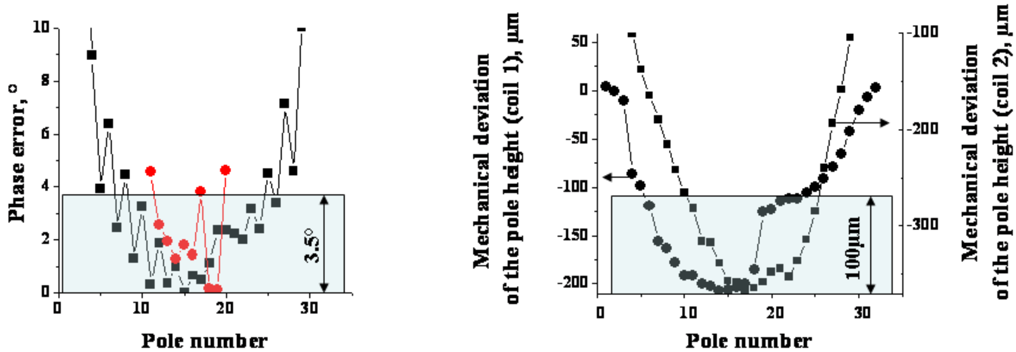

Figure 3: Left: Undulator mock-up phase errors calculated with eq. (4) (squares) and with phase function corrected for the trajectory (circles) [11] vs. number of pole at 8 mm gap. Right: measured mechanical deviations of the pole height of both coils. Two periods at both ends of the undulator are omitted.

scans were performed to detect the perturbation to the main field generated by the shimming coils.
The difference ΔB_{sh}, defined as

$$\Delta B_{sh} = B_{max}^{shimm} - B_{max} \tag{5}$$

where B_{max}^{shimm} corresponds to the maximum magnetic field with shimming correction and B_{max} to the maximum magnetic field without shimming, is shown in Fig. 5. The racetrack is compensating the field locally and $\Delta B_{sh}/B_{max}$ for 186 A current in the main coil is 1.3% and 1.6% for the pole 11 and 17, respectively. The distance from the poles 11 and 17 to the Hall probe is different due to the pole height deviations. Thus the measured magnetic field intensity B_{max} and the calculated generated field from correction coils ΔB_{sh} differ for two poles by applying two identical racetrack coils.

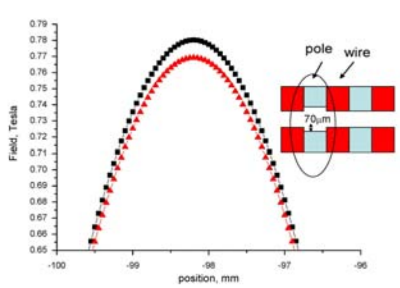

Figure 4: The difference in the peak field for one pole between the simulated ideal field (black dots) and simulated case where the pole height is decreased on both sides of the magnet by 70 µm (red) leading to the local phase error of 3.5°.

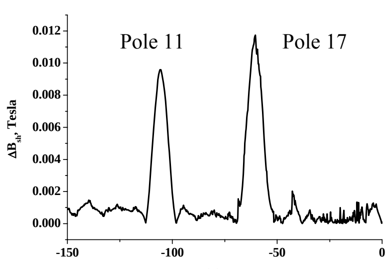

Figure 5: Correction field generated by the racetrack coils on top of the background field from the main coil operated at 186 A.

CONCLUSION

A superconducting test undulator with 15.5 periods was constructed. Its field quality was evaluated and a shimming concept was tested in a liquid helium bath cryostat by measuring the magnetic field with Hall probes. The results show that if the deviations in the period length and winding package are below 30 µm and the variation in the pole height is within a 70 µm band, a phase error of 3.5° can be reached.
An active shimming concept can compensate deviations of the magnetic field at maximum specified current of 186 A in the undulator of up to 1.6% which allows to correct up to 4° of the phase error.

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