MAGNETIC MEASUREMENTS OF THE 1.5 M COILS OF THE ANKA SUPERCONDUCTING UNDULATOR

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Abstract

A 1.5 m long superconducting undulator with a period length of 15mm is planned to be installed in ANKA end 2010 to be the light source of the new beamline NANO for high resolution X-ray diffraction. The key specifications of the system are an undulator parameter K higher than 2 (for a magnetic gap of 5mm) and a phase error smaller than 3.5 degrees. In order to characterize the magnetic field properties of the superconducting coils local field measurements have been performed by moving a set of Hall probes on a sledge in a liquid helium bath: the results are reported.

INTRODUCTION

In order to produce synchrotron radiation of highest brilliance, third generation synchrotron sources make use of insertion devices (IDs). The state of the art available today for IDs is the permanent magnet technology with magnet blocks placed inside the vacuum of the storage ring. Following an initial proposal at SPRING8 [1], the concept of Cryogenic Permanent Magnet Undulators (CPMU) is presently considered as a possible future evolution of in-vacuum undulators [2]. Superconducting undulators can reach, for the same gap and period length, higher fields even with respect to CPMU devices, allowing to increase the spectral range and the brilliance. Efforts to develop superconducting undulators have been performed at ESRF [3] and are ongoing at the APS [4]. At ANKA we are running a research and development program on superconducting insertion devices (SCIDs). Our industrial partner Babcock Noell GmbH designed and is about to complete the fabrication of a 1.5 m long superconducting undulator for ANKA [5]. The period length of the device is 15 mm for a total of 100.5 full periods plus an additional matching period at each end. The key specifications of the system are: a K-value higher than 2 for a magnetic gap of 5 mm, the capability of withstanding a 4 W beam heat load, and a r.m.s phase error smaller than 3.5 degrees. This superconducting undulator is planned to be installed in ANKA at the end of 2010 in the storage ring. It will be operated at a magnetic gap of 8 mm to reach a magnetic field of 0.77 T. In this contribution we report on the training and local field measurements of the 1.5 m long superconducting undulator coils performed in a liquid helium cryostat at CERN.

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EXPERIMENTAL SETUP

The coils are fabricated using a commercially available NbTi superconductor with a cross section of 0.54 x 0.34 mm (including insulation). The rectangular shape allows to maximize the engineering current density. The expected operational current of 175 A corresponds to an overall density in the winding package of 950 A/mm^2. The first and second end winding packages have 21 (7 single turns x 3 layers) and 63 (7 single turns x 9 layers) turns, respectively. The yoke is fabricated out of high magnetic field saturation cobalt-iron alloy plates, consisting of a pole and a winding groove. The plates are aligned and pressed to each other by two stainless steel rods. The coils are vacuum pressure impregnated to assure stability during operations and are mounted in a stainless steel support structure, which fixes the magnetic gap at room temperature to 8 ± 0.01 mm. On each coil 21 voltage taps have been installed, dividing it in 20 parts monitorable during the training. The training of the magnet has been performed using a power supply and a fast acquisition system for quench detection both provided by CERN. The local field measurements have been performed by moving a set of Hall probes mounted on a brass sledge. Fifteen Hall probes have been mounted on 5 rows spaced 30 cm. On each row are placed 3 Hall probes spaced 2 cm one from the other. The Hall probes have been calibrated at the Institute of Technical Physics (KIT) in a liquid helium bath. The field generated by a solenoid has been varied from -3T to +3T in a region with a field homogeneity better then 10^{-4}. The local phase error induced by the precision achieved in the calibration of the Hall probes $\Delta B < 1$ mT is

$$\Delta\Phi = \frac{K^2}{1+K^2}\frac{\Delta B}{B}360^\circ < 0.35^\circ,$$

where $K = 93.37\lambda_u B = 1.08$, with an undulator period length $\lambda_u = 0.015$ m and maximum field on axis $B = 0.77$ T.

RESULTS

Training

During the first training (blue triangles in Fig. 1) the magnet quenched always in different regions. The undulator coils achieved 82% of the current needed to reach the specifications. After the last quench a resistive behaviour has been measured in one of the twenty parts in which the magnet is divided. Additional 12 voltage taps have been installed after warming up the coils in order to localize the region to be repaired. During debugging, the damaged region where the superconducting wire was burned (over a length smaller than .5 mm) was identified and successfully repaired. The test after repair (black circles) is indicated in Fig. 1 as second cool down. The training is much faster then after the first cool down, then a plateau at 140 A is reached at a ramp rate of 42 A/min. At plateau, the quench happened always in the same region, so that we decided to install 12 additional voltage taps. During the third cool down the magnet reached the 140 A plateau after a first quench at 80 A, confirming the memory effect observed also after the first thermal cycle. The performance of the coils did not improve in comparison with the previous test and the quench happened in the same region as before. In order to investigate if the limitation was due to an electrical defect, the magnet has been cooled down to 2 K. As expected in case of an electrical defect, the coils reached a higher current and a constant plateau with the quench happening always in the same region. The maximum current reached by the magnet at 2K is 175 A, which is the value needed to achieve the specified magnetic field on axis of 1.43 T (0.77 T) for 5 mm (8 mm) magnetic gap and K=2 (K=1.08). The magnet has been then successfully repaired a second time and tested up to a maximum current of 145 A. The magnet has been ramped up to 145 A and down to 0 A with 42 A/min. The stability at 145 A has been tested for 3 hours.

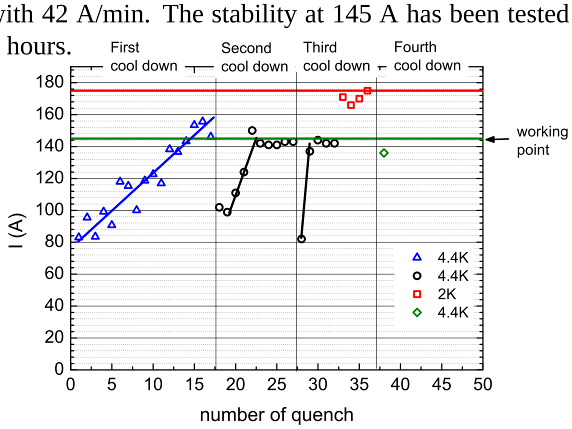

Figure 1: Training of the magnet.

Field measurements

Local field measurements have been performed at several currents between 20 A and 145 A at 4.4 K and with 165 A at 2 K, moving the Hall probes along the undulator axis in the middle of the magnetic gap in steps of 50 μm. Due to the thermal contraction of the stainless steel support structure, the gap is reduced at low temperatures from 8 mm to 7.75 mm. The measured field at 135 A with a gap of 7.75 mm in the middle of the undulator coils is reported in Fig. 2, see red line. The bending of the field, believed to be due to the different thermal contraction between the stainless steel support structure and the cobalt-iron yoke, has been compensated applying mechanical shims along the support structure that increased the gap to 8.25 mm. This is demonstrated in Fig. 2, see blue line. This procedure can be used to shim fixed gap undulators.

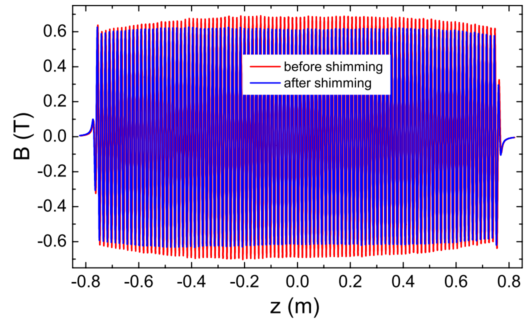

Figure 2: Field profile measured at 135 A before (g = 7.75 mm, red) and after mechanical shimming (g = 8.25 mm, blue).

The peak field values measured at different currents have been rescaled to 8 mm gap and are reported in Fig. 3. In Fig. 3 we report the value $B = 0.44$ T of the field of a hybrid permanent magnet undulator using Sm_2Co_{17} ($B_r = 1.05$ T) obtained by rescaling the value of $B = 0.57$ T reported in Ref. [3] for a period length of $\lambda_u = 15$ mm and a magnetic gap $g = 6.2$ mm, to $g = 7.2$ mm using [8]

$$B \propto \exp\left(-5.08g/\lambda_u + 1.54(g/\lambda_u)^2\right)$$

The value of the field $B = 0.57$ T shown for CPMU's (magenta solid line) in Fig. 3 has been obtained by rescaling the value of $B = 0.72$ T given in Ref. [3] for a period length of $\lambda_u = 15$ mm and a gap $g = 6.2$ mm, to $g = 7.2$ mm using

$$B \propto \exp\left(-4.06g/\lambda_u + 0.63(g/\lambda_u)^2\right)$$

obtained by fitting the simulations reported in Ref. [1] and valid in the range $0.3 < g/\lambda_u < 0.7$. The field comparison shown in Fig. 3 demonstrates that this undulator coils outperform the competing technologies. Furthermore this undulator coils improved with respect to the first demonstrator installed in the ANKA storage ring since 2005 [9]. The corrected field profile measured at 135 A (blue line) is compared in Fig. 4 with the ideal one (black line) and with the simulations performed with Radia [7] (red line). From the Radia simulations, which include the accuracy measured at room temperature of pole height and half period length ($\sim 50\mu$m) [5], a r.m.s phase error of 5.6° is reached along 186 poles. The measured field shows, after mechanical shimming, a r.m.s. phase error of 7.4° on 106 poles, over a length of 0.795 m.

The photon flux produced by an electron beam wiggling in the three field profiles in a straight section of the ANKA storage ring (with the following parameters: beam energy $E = 2.5$ GeV, beam current $I = 200$ mA, energy spread $\Delta E/E = 0.1\%$, horizontal $\epsilon_x = 41$nm rad and vertical $\epsilon_y = 0.3$nm rad emittance, horizontal $\beta_x = 14.7$ m and vertical $\beta_y = 1.9$ m beta function) at 10 m distance

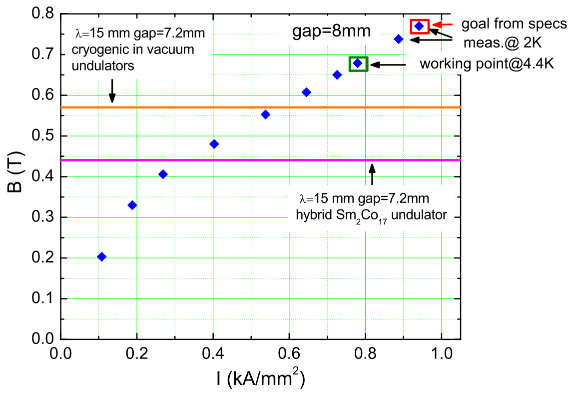

Figure 3: Measured peak field at 7.75 mm and 8.25 mm as a function of engineering current density rescaled to the 8 mm gap.

from the middle of the undulator through a slit of 1mm x 1mm, is reported as a function of photon energy in Fig. 4. There is no appreciable difference between the one calculated from the ideal field and from the one obtained by the simulations with Radia which consider the mechanical accuracies measured at room temperature. A decrease in the intensity of about 25% and a broadening is observed in the first harmonic of the measured field, when compared with the ideal case. Both effects are slightly more pronounced for the higher harmonics. The first and second field integrals of the field at maximum operating current 145 A are $I_1 < 2 \times 10^{-3}$ Tm and $I_2 < 2 \times 10^{-3}$ Tm^2, respectively. For all currents it is possible to correct the first and second field integrals by means of two pair of Helmoltz coils, that will be installed inside the cryostat at 58 mm from the beginning and 86 mm to the end of the undulator coils. The Helmoltz coils can compensate for the following values of the first and second field integrals: $I_1 = 1.5 \times 10^{-2}$ Tm and $I_2 = 3 \times 10^{-2}$ Tm^2.

CONCLUSIONS AND OUTLOOK

The undulator coils achieved a maximum field of 0.68 T for an undulator with 15 mm period length and a magnetic gap of 8 mm. This value overperforms the competing technologies for the same geometry. We have proved that coils wound with single length wire can be repaired without rewinding the whole coil. Furthermore, we have demonstrated for the first time that it is possible to build superconducting undulator coils with a phase error of 7.4 degrees over a length of 0.795 m, obtained by a simple mechanical shim, which is easily applicable to fixed gap devices.

The thin rectangular wire used will be replaced in the next devices by a round thicker wire and for the yoke normal steel will be used.

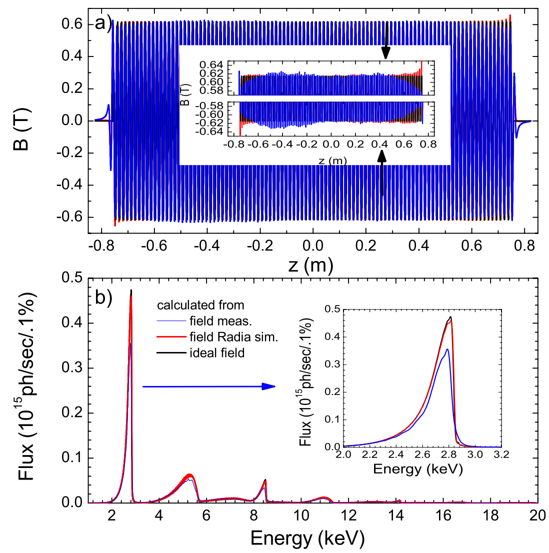

Figure 4: a) Field profile measured at 135A and gap=8.25 mm (blue), simulated with Radia with the pole heights and half period lengths measured on the magnet at room temperature (red), and ideal (black). In the inset are shown the positive and negative field peaks along the magnet. b) Flux calculated with B2E [6] using the three above fields through a slit of 1mm x 1mm at 10 m distance from the middle of the undulator. In the inset the first harmonic is zoomed.

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REFERENCES

[1] T. Hara et al., *Phys. Rev. ST Accel. Beams* **7**, 050702 (2004).

[2] C. Kitegi et al., Proc. EPAC 2006, Edinburgh, Scotland 2006; T. Tanabe et al., Proc. PAC07, Albuquerque, New Mexico, USA 2007; C. Benabderrahmane et al., Proc. EPAC08, Genoa, Italy 2008; J. Chavanne et al., Proc. EPAC08, Genoa, Italy 2008.

[3] E. Wallén, J. Chavanne and P. Elleaume, *Nucl. Instr. and Meth. A* **541** 630 (2005)

[4] Y. Ivanyushenkov et al., Proc. PAC09, Vancouver, Canada, 2009.

[5] C. Boffo et al., this Proceedings.

[6] P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)

[7] O. Chubar, P. Elleaume, J. Chavanne, J. Synchrotron Rad. **5**, 481 (1998).

[8] ANL-87-15-ANNEX, May 1988.

[9] S. Casalbuoni et al., *Phys. Rev. ST Accel. Beams* **9**, 010702 (2006).