FABRICATION OF THE NEW SUPERCONDUCTING UNDULATOR FOR THE ANKA SYNCHROTRON LIGHT SOURCE

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Abstract

Superconducting insertion devices (IDs) are very attractive for synchrotron light sources since they allow increasing the flux and/or the photon energy with respect to permanent magnet IDs. Babcock Noell GmbH (BNG) is completing the fabrication of a 1.5 m long unit for ANKA at KIT. The period length of the device (SCU15) 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 phase error smaller than 3.5 degrees. The field performance of the magnet has been qualified in liquid helium and vertical configuration. As a result of this test the magnet is, at the moment, being inserted in the final cryostat. This paper describes the main features of the system and the manufacturing process followed to achieve the required magnetic performance.

INTRODUCTION

The SCU15 is a 15 mm period length, 100.5 full periods long cryogen-free superconducting undulator with one matching period at each end to adjust the field distribution according to a scheme similar to the one adopted in permanent magnet systems [1].

This should be an improved version of the existing SCU14 installed in ANKA since 2005 [2] and is part of a broader R&D program ongoing at ANKA in collaboration with BNG. At the end of 2010, SCU15 will be installed in the ANKA ring as light source for the new beamline NANO for high X-ray diffraction.

Table 1: SCU 15 Specifications

	Units	Value
Period length	mm	15
Number of full periods		100.5
Max field on axis with 5 mm mag. gap	T	1.43
Max field in the coils	T	2.4
Average current density in the winding	A/mm^2	950
Minimum magnetic gap	mm	5
Operating magnetic gap	mm	8
Gap at beam injection	mm	16
Beam heat load	W	4
Maximum r.m.s. phase error	°	3.5
K at 5 mm gap		>2

The specifications of the unit are shown in Table 1. The two critical features for such a magnet are: the need for high engineering current density within the winding package (K-value requirement) and the requirement for high precision machining in order to reach an r.m.s. phase error smaller than 3.5 degrees. In order to achieve performance, during the design phase, special attention was paid to the cryogenic scheme and during manufacturing to the quality assurance process [3].

ELECTROMAGNETIC PERFORMANCE

In order to attain the specified minimum K-value of 2 at a gap of 5 mm with a period length of 15 mm, a peak magnetic field of 1.43 T on the undulator axis is needed. This, given the chosen design, corresponds to a calculated peak field in the superconducting coils of ~2.4 T. A commercially available 0.3 mm by 0.5 mm NbTi rectangular wire met the demands. The expected load line of the magnet compared to the critical surface of the conductor at 4.2 K is shown in Fig. 1.

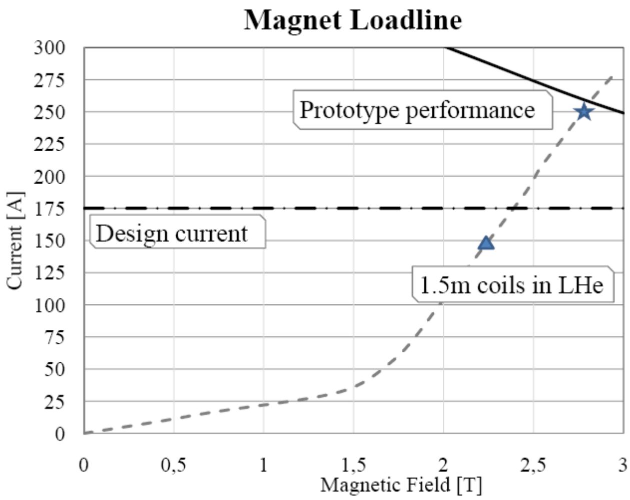

Figure 1: Load line of the magnet. The dashed curve is the load line of the magnet which is iron dominated at low fields. The dot-dashed line represents the operating current of the magnet. The star indicates the maximum operating current of a 3-periods prototype and the triangle indicates the maximum current of the 1.5 m long coils tested in LHe at CERN.

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According to simulations, the expected operating current of the magnet should have been 186 A. Never the less, during the qualification tests, it was discovered that the magnetic properties of the cobalt-iron yoke at cryogenic temperature outperform the reference values at room temperature provided by the manufacturer. As a result, the current necessary to achieve the operating field is reduced to 175 A. Such a value was exceeded by two 3-periods prototypes tested in LHe at ANKA which reached consistently 250 A with a ramp rate of 250 A/minute.

These prototypes allowed qualifying the manufacturing process of the yoke and the performance of the wire. An additional 15-periods undulator demonstrator, consisting of two coils, was successfully fabricated with test results discussed in [4].

The two SCU15 1.5 m coils, before installation in the final horizontal cryostat, have been tested in vertical configuration and in LHe at CERN. The goals of the test, reported in [5], were the training of the superconducting system and the mapping of the magnetic field along the beam axis of the undulator in order to quantify phase error and field integrals. During training, the magnet suffered from 2 breakdowns which required two repairs of the damaged winding packages. In the first case, the magnet was damaged by a quench at 146 A. During the repair, the quench spot was identified and replaced. The most likely explanation for the failure was an excessive bending of the wire in the transition between two winding packages. In the second case, after a quench at 155 A, the magnet was restricted in performance to 140 A. Also in this case the damaged area has been identified and replaced. The explanation for the failure was a defect in the order of about 50 μm in the winding groove, visible using a microscope, which caused a partial burn of the wire after the quench, thus limiting its possibility of carrying current. Thus a larger wire with less sensibility to mechanical stress and to handling will be employed in future units. As a result of the two repairs it was decided to set the maximum current in the magnet to 145 A corresponding to a maximum field at the undulator axis of ~1.3 T with a magnetic gap of 5 mm.

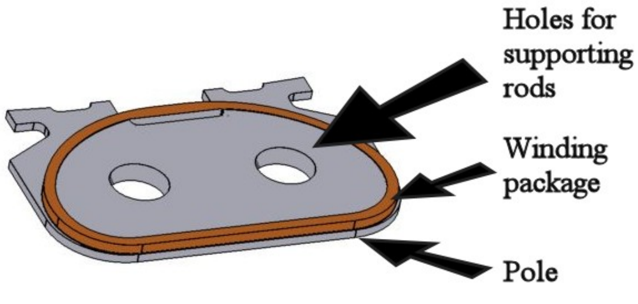

Fig. 2. 3D model of one of the 408 plates constituting the two magnet yokes. Each plate is half period which includes a pole and a superconducting coil winding.

This value exceeds what is reachable by units with the same geometrical characteristics built using competing technologies such as in-vacuum and cryogenic permanent magnet undulators [5]. Furthermore this magnet outperforms other existing superconducting units of this length and its design will be improved to achieve even higher fields in the future. Thanks to this experience, BNG developed and successfully applied a procedure enabling to fix a damaged coil by replacing single winding packages. This solution demonstrates that undulators wound with single length wire do not require to rewind the full magnet in case of localized damage.

MAGNET FABRICATION

Simulations performed using Radia [6], as the one shown in Fig. 3, demonstrate that a local variation of 140 μm in the gap between the coils (pole height) generates a peak field deviation corresponding to a local phase error of 3.5 degrees.

SCU15 has been designed and manufactured to meet this geometrical requirement. In order to correct local inaccuracies we have designed and experimentally demonstrated that thin racetrack coils can be positioned between poles on top of the main coils allowing to correct up to 1.6% of the main magnetic field [4].

A special cobalt-iron alloy (37% cobalt) enables to reach higher saturation fields in the magnet yokes but it is harder to machine and requires a long procurement time. For these reasons, in order to reach the requested manufacturing accuracy while reducing machining risks, the yokes have been produced out of plates, Fig.2, which have been later stapled together and compressed by steel rods. This solution allowed a good control on machining accuracy, but introduced additional errors in positioning during the assembly process. In order to keep the final tolerances under control, several measurement steps have been established during the manufacturing process. The results of these measurements are described in the next sections.

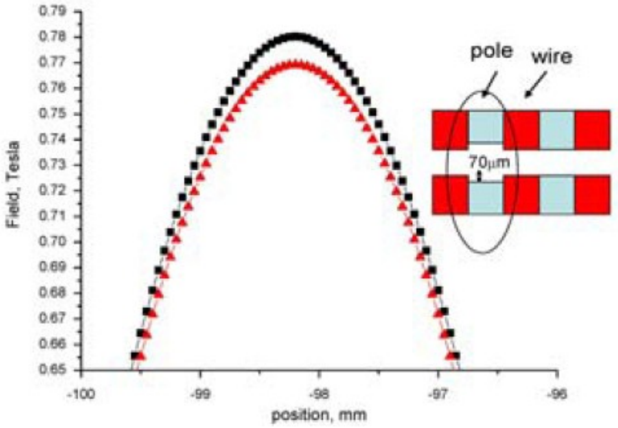

Fig. 3. Simulated difference in peak field between the ideal geometry (black dots) and a case where the gap at one pole is increased by 140 μm (red) leading to the local phase error of 3.5°.

Winding Positioning

The positioning error of the winding packages is mainly correlated to the dimensional accuracy of the superconducting wire (3 µm). The coils consist of 91 turns in 13 layers leading to a maximum dimensional accuracy of ~40 µm. Since a rectangular wire is used, the winding package is very compact with minimal deviation between the single coils.

Period Length

The thickness of the plates, corresponding to half period length of the undulator, has been monitored during the production process. The maximum deviation from the ideal thickness of all the 408 plates is 5 µm. This value was achieved with minimal rejection rate. Before stapling and pressing, the plates have been sorted to minimize the accumulation of the manufacturing inaccuracies. This process is important to minimize the misalignment of the poles between the two yokes. The achieved maximum deviation of the pole positioning within one yoke with respect to the ideal case is 30 µm. The length difference between the two yokes after winding and impregnation is ~20 µm over a total of 1542 mm.

Pole Height

Within the specified parameters, the planarity of the pole heights within the yokes is the hardest to achieve, but also the most influent on the phase error. In the cryostat, the two yokes are supported by stiff stainless steel strongbacks but during manufacturing these supports had to be removed in several occasions. In order to characterize the system, the planarity was measured between several manufacturing steps. Furthermore this measurement was repeated after a thermal cycle between room temperature and 2K. Results for yoke 2 shown in Fig. 4 demonstrate that the poles of the magnets lay within a 50 µm tolerance band.

Support Structure for the Vertical Test

In order to achieve the required field quality, not only the yokes have to be precise, but also their relative positioning must be accurate. For the vertical test, a stainless steel support structure has been fabricated, which allowed to reach, at room temperature, a precision in the relative planarity between the two yokes of 10 µm. This value was also achieved after dismounting the structure several times and after thermal cycles. The longitudinal positioning of the coils was precise and reproducible within 50 µm, even after each thermal cycle.

Accuracy of the Assembly and Phase Error

The phase error calculated by Radia when including the planarity of the yokes and the longitudinal relative position of the poles between the magnets, measured at room temperature, is 5.4°. At 4.4K, a deformation due the differential contraction between yoke and support structure materials, allowed to reach a value of 7.4° in the inner 106 poles after mechanical shimming [5].

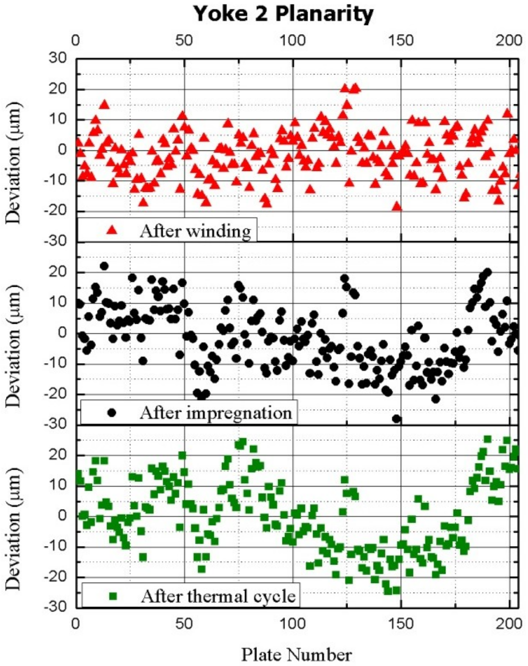

Fig. 4. Pole height planarity of coil 2 at different manufacturing steps. From the top: after winding, after impregnation and after thermal cycle to 2K.

The use of mechanical shims to reduce the bimetallic effect, applicable to fixed gap undulators, together with a planarity further reduced to 40 µm (red curve in Fig. 4) would make it possible to reach the specified phase error without additional correction coils.

CONCLUSION

A new superconducting undulator has been designed and fabricated by Babcock Noell GmbH for ANKA at KIT. The superconducting coils have been tested in LHe at CERN by KIT reaching a maximum field of 0.68 T for a magnetic gap of 8 mm. A procedure to locally repair damaged winding packages has been implemented and a mechanical shim technique allowed to reach for the first time a r.m.s. phase error of 7.4° over a length of 795 mm.

AKNOWLEDGEMENTS

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