R&D COLLABORATION ON SUPERCONDUCTING INSERTION DEVICES BETWEEN KIT AND BABCOCK NOELL

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Abstract

Superconducting undulators show, with respect to permanent magnet undulators, a larger magnetic field strength for the same gap and period length, being able to generate a harder X-ray spectrum and higher brilliance X-ray beams. The worldwide first short period length superconducting undulator is in operation since 2005 at the synchrotron light source ANKA in Karlsruhe. To further drive the development in this field a research and development program has been defined. SCU15 a 1.5 m long superconducting undulator with a period length of 15 mm is planned to be installed in ANKA at the end of 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 and a phase error smaller than 3.5 degrees. The coils will be cooled using cryocoolers and should have a capability of withstanding a 4 W beam heat load at 4 K. Here we describe the main features of the 1.5 m long superconducting undulator, the test results of the coils in liquid helium, and the test results of a switchable period length prototype device.

INTRODUCTION

At ANKA is ongoing an R&D program of superconducting (SC) insertion devices (IDs) in collaboration with Babcock Noell GmbH. The aim is to develop, manufacture, and test superconducting undulator technology enabling to realize high brilliance ID beamlines at ANKA and the next generation SC undulators for low emittance synchrotrons.

A SC UNDULATOR FOR ANKA

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].

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 [2].

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Table 1: SCU15 Specifications

	Units	Value
Period length	mm	15
Number of full periods		100.5
Field on axis with 5mm mag. gap	T	1.43
Max field in the coils	T	2.4
Average current density	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 5mm gap		>2

Electromagnetic Design and Prototyping

In order to attain the specified minimum K-value, 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 0.34 mm by 0.54 mm NbTi insulated rectangular wire meets these demands when an overall packing factor of 100% is achieved in the coils. The expected load line of the magnet compared to the critical current of the conductor at 4.2 K is shown in Fig. 1. The operating field is achieved with a current of 175 A corresponding to an engineering current density in the winding packages of 950 A/mm^2. Such a value was exceeded by two 3-periods prototypes tested in LHe at the ANKA CASPER facility, one of which reached consistently 240 A with a ramp rate of 240 A/minute.

These prototypes allowed qualifying the manufacturing process of the yoke and the performance of the wire which reached a value close to the measured short sample critical limit. An additional 15-periods undulator demonstrator, consisting of two coils, was successfully fabricated with test results discussed in [3]. During the manufacturing of this unit, an improved room temperature impregnation procedure was applied aiming to the minimization of the overall dimensional yoke tolerances.

Magnet Fabrication

Simulations performed using Radia [4] demonstrated 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 in the order of 3.5 degrees [3].

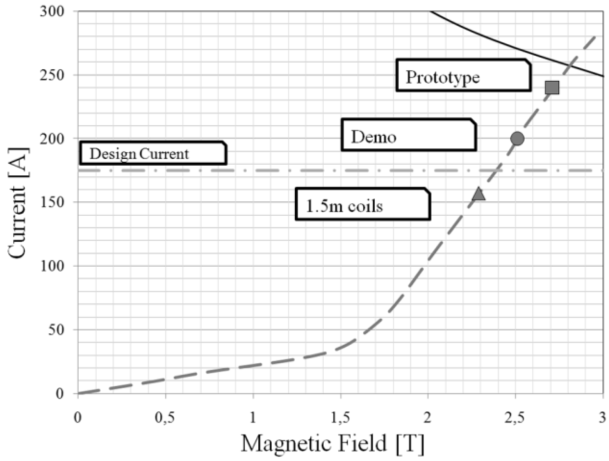

Figure 1: Load line of the magnet. The dashed curve is the load line of the magnet which is iron dominated at low fields. The dot-dashed line represents the operating current of the magnet. The square indicates the maximum operating current of a 3-periods prototype, the circle indicates the maximum current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

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 [3]. The installation of such coils requires a minimal shifting of the main coils with respect to the magnet axis leading to a negligible overall reduction of field performance.

On the other hand each of them require a separate power supply and for this reason have been restricted to a maximum number of 10. Affecting the manufacturing process is also the special cobalt-iron alloy (27% cobalt) used to fabricate the yoke which enables to reach higher saturation fields but it is harder to machine and requires a long procurement time. For these reasons, in order to reach the requested dimensional accuracy while reducing machining risks, the yokes have been produced out of plates, which have been later stapled together and compressed by stainless steel rods. This solution allowed to obtain a good control on machining accuracy, but introduced additional errors in positioning during the assembly process. In order to keep the final accuracy under control, several measurement steps have been established during the manufacturing process.

Amongst the specified parameters, the planarity of the pole heights within the yokes was the hardest to achieve.

In order to characterize the system, such measurement was performed between several manufacturing steps and repeated after a thermal cycle between room temperature and 2K demonstrating that the poles of the magnets lay within a 50 μm tolerance band. The achieved maximum deviation of the pole positioning along the length 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 while the maximum measured relative shift in positioning of the poles in the two yokes is ~50 μm.

SCU15 Test Results

The two SCU15 1.5 m coils, before installation in the final horizontal conduction-cooled 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 3 breakdowns which required a repair 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. 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. An additional cool down has been then performed, during which the magnet reached a plateau at 157 A, quenching always in the same region. The damaged region is being inspected at the moment in order to identify the failure. As a result of the tests a reasonable maximum working point at 4.4K for the magnet is expected to be 150A, corresponding to 90% of the field on axis needed to reach the specifications.

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 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. 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 procedure can be used to shim fixed gap undulators.

The field comparison shown in Fig. 3 demonstrates that this undulator coils outperform the competing technologies [5] and furthermore they improved with respect to the first demonstrator installed in the ANKA storage ring since 2005 [6].

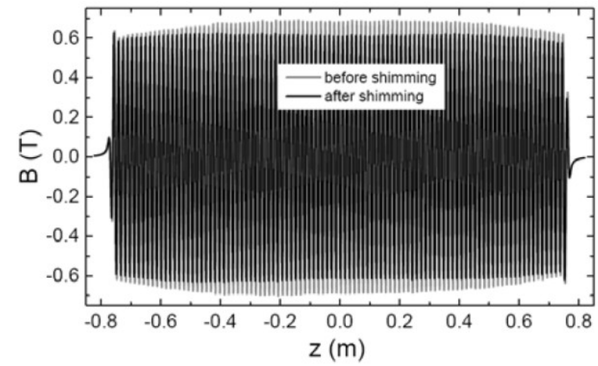

Fig. 2: Field profile measured at 135 A before (g = 7.75 mm, grey) and after mechanical shimming (g = 8.25 mm, black).

According to Radia simulations, which include the accuracy measured at room temperature of pole height and half period length (~ 50μm), a r.m.s phase error of 5.6^o is reached along 186 poles. The use of mechanical shims to reduce the bending effect of the support structure, applicable to fixed gap undulators, together with a planarity further reduced to 40 µm would make it possible to reach the specified phase error without additional correction coils. The measured field shows, after mechanical shimming, a r.m.s. phase error of 7.4^o on 106 poles, over a length of 0.795 m.

A SC UNDULATOR/WIGGLER

A superconductive undulator/wiggler device (SCUW) is foreseen for the planned IMAGE beamline at ANKA. The SCUW will allow to use in one device the high brilliance of an undulator from 6 to 15 keV for imaging, and a wiggler mode for higher photon energies to perform phase contrast tomography. These requirements can be fulfilled by tripling the period length of an undulator with 15mm period length to 45mm.

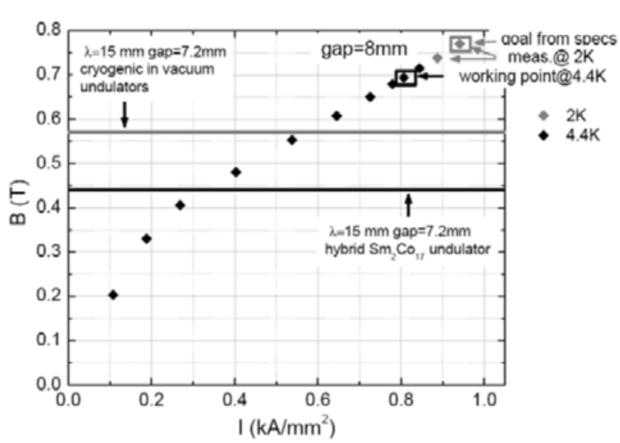

Fig. 3: Measured peak field at 7.75 mm and 8.25 mm as a function of engineering current density rescaled to the 8 mm gap.

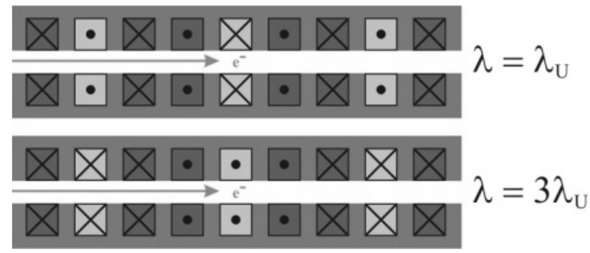

Fig. 4: Winding scheme for period tripling of the SCUW.

A scheme on how to obtain a switching period device is shown in Fig. 4 [7]. Different current circuits are indicated by the colours light and dark grey, points and crosses indicate the current directions.

To verify the feasibility of period switching, a 70mm mock-up has been designed and produced. The two modes can be exchanged by inverting the current direction in the light grey circuit.

The mock-up is one coil consisting of 10 plates with 10 poles and 9 grooves fully wound. This arrangement corresponds to 4.5 undulator and 1.5 wiggler periods respectively.

As yoke material C10 steel is used and clamping of the plates is done by two end plates pressed together by stud bolts. Before clamping, the plates were aligned on the straight side. The grooves are wound with round NbTi insulated wire of 1.05mm diameter and a copper to superconductor ratio of 1.4.

Test Results

During the first test attempt without impregnation we only checked the undulator mode since in this case the highest current was expected. The maximum current after 13 quenches was 955A which corresponds to 876A/mm² engineering current density in the groove. After this it seemed reasonable to impregnate the coil to better stabilize the wire and to test the switching of the period length.

The training after impregnation was performed with the two circuits soldered at the magnet splice and powered by only one power supply. With this solution, switching is possible only after warming up, modifying the circuit and cooling down again. During test we had the first quench at 510A in undulator mode and 849A in the wiggler mode respectively. After a few more quenches we reached 1147A and 1055A for undulator and wiggler corresponding to engineering current densities in the grooves of 1052A/mm^2 and 968A/mm^2. The highest ramp rate was 350A/min in both modes. The current density in the conductor (1.05mm diameter, A=0.866mm²) resulting from the above currents are 1324 A/mm² in the undulator mode and 1218 A/mm² in the wiggler mode.

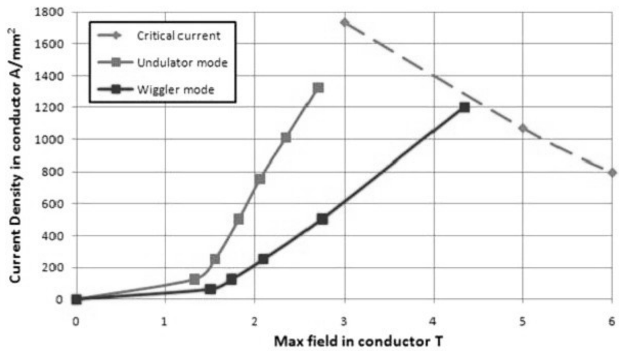

Fig. 5: Loadline of the SCUW mock-up for both undulator and wiggler mode.

These are shown as the end points of the solid curves in Fig. 5 which displays the calculated loadlines of the magnet for the two modes (undulator mode grey, wiggler mode black) together with the critical current density of the conductor at 4.2K (dashed line). In both cases the loadline is iron dominated at low fields. During training, the coil shows in the wiggler mode a stable behaviour almost up to the critical current of the conductor. As an operation current in the wiggler mode only 765A corresponding to 883A/mm² is foreseen. According to Fig. 5 this results in a performance margin of 42% for the conductor when operating as a wiggler. With the planned current of 1100A and 1270A/mm² current density in the conductor in the undulator mode the margin to the critical current during operation will be 38%.

Essential for the operation of a SCUW device is to demonstrate that the period switching works without going through a thermal cycle. To show this, we connected one power supply with 1500A maximum current to each of the circuits and ramped them simultaneously.

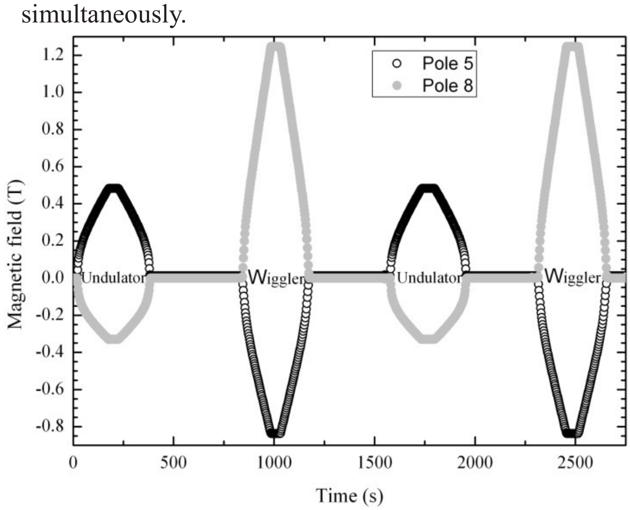

Fig. 6: Measured local field at selected poles with opposite field directions with time.

A change from one mode to the other was accomplished by inverting the current leads of one power supply and hence the polarity in the circuit. Following such procedure the time between ramping in the two different modes is about 5 minutes.

The measurement sequence was started by ramping to 1100A and down to zero in the undulator mode continuing with a sweep to 1000A in the wiggler mode both with a ramp rate of 422A/min (Fig. 6). This yields to engineering current densities in the winding packages of 1007A/mm^2 and 915A/mm^2 respectively.

The two curves in Fig. 6 present the change of the field in direction and amplitude for the two modes at pole 5 (open circles) and 8 (grey dots) measured by Hall probes. This test proved that it is possible to switch the period length, without need of training the magnet again after each switch.

CONCLUSIONS

A broad R&D program on SC undulators has been started at ANKA in collaboration with Babcock Noell GmbH. A 1.5 m long magnet has been fabricated and tested in LHe achieving a maximum field of 0.7 T on the axis with a magnetic gap of 8 mm. This value over performs the competing technologies for the same geometry.

Furthermore, it was 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. In addition a test of a short prototype demonstrated that it is possible to build a tripling period undulator/wiggler device capable of being switched when cold without training effects.

REFERENCES

[1] J. A. Clarke, The science and technology of undulators and wigglers, 2004.

[2] C. Boffo et al., IEEE Trans. Applied superconductivity, vol. 19, issue 3, part 2, p.p. 1324-1327, 2009.

[3] S. Casalbuoni et al., Status and R&D of superconducting insertion devices at ANKA, in Proc. SRI09, 2009.

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

[5] S. Casalbuoni et al., Training and magnetic field measurements of the ANKA superconducting undulator, in Proc. ASC 2010.

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

[7] A. Bernhard et al., in Proc. of EPAC´08, June 2008, Genoa, Italy, pp. 3574 - 3576.