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SUPERCONDUCTING UNDULATOR COILS WITH PERIOD LENGTH DOUBLING*

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Abstract

Only since few years it has been demonstrated experimentally that NbTi based superconducting undulators (SCUs) have a higher peak field on axis for the same gap and period length in operation with electron beam with respect to permanent magnet undulators (even the ones in vacuum and cooled to cryogenic temperatures). Another advantage of NbTi based SCUs with respect to permanent magnet devices is radiation hardness, widely demonstrated for NbTi magnets, which is and will become an increasingly important issue with the small gaps in the newest machines as round beam storage rings and FELs.

Moreover, SCU technology allows switching of the period length by changing the current direction in one of separately powered subset of winding packages of the superconducting coils. This feature further broadens the energy range of the emitted photons, required by the different beamlines. To this end a 0.41 m long superconducting undulator coil with switchable period length between 17 mm and 34 mm has been developed. In this contribution we describe the design and report on the quench tests, as well as on the magnetic field measurements.

INTRODUCTION

Technical working concepts for superconducting undulators have been explored in the past [1]. Short period superconducting undulators and are now successfully operated in the Karlsruhe Institute of Technology (KIT) synchrotron [2] and in the APS storage ring [3].

The Institute for Beam Physics and Technology (IBPT) at KIT is the institute within the Helmholtz Association which has driven the development of superconducting undulators in close cooperation with its industrial partner Bilfinger Noell during the past ten years. The partners have developed and successfully tested a superconducting undulator with 20 mm period length with electron beam at the KIT synchrotron. This is the first commercially available product worldwide: a robust device, with reasonable delivery time, easy handling during installation and operation [4].

Over the past 10 years unique instrumentation for the characterization of the magnetic fields and field integrals of full-scale superconducting insertion devices, necessary for their R&D, has been developed at KIT [5].

To broaden the energy of the emitted photons, several light sources apply non in-vacuum permanent magnet undulators with switchable period length called revolvers, which different magnetic structures are rotated [6].

Superconducting undulator technology allows a more elegant solution using the same magnetic structure to switch the period length. This is performed by changing the current direction in one of separately powered subset of winding packages of the superconducting coils (see Fig. 1).

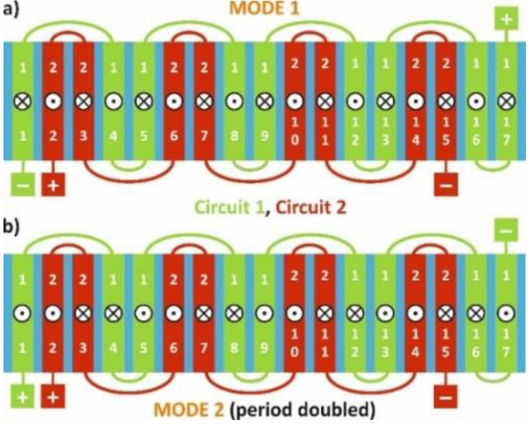

Figure 1: Scheme of period length doubling for a superconducting undulator coil by changing the current direction in one subset of windings. a) The circuits are powered to have the smallest period. b) The current direction of circuit 1 is changed to obtain period doubling [7].

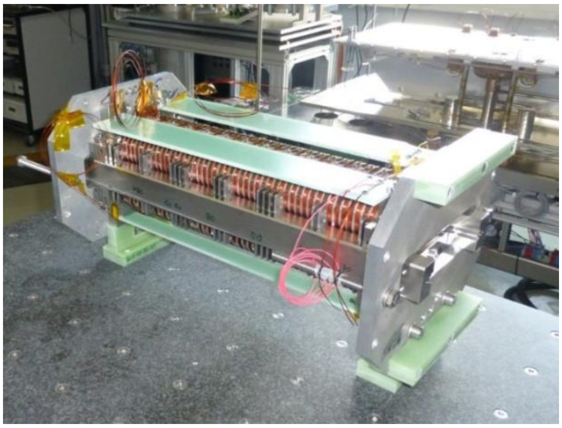

Figure 2: Superconducting undulator coils with switchable period length (between 17 and 34 mm) and a magnetic length of 0.41 m.

With the completion, testing and installation of a superconducting undulator with 20 mm period length (SCU20), which is in operation at the KIT synchrotron since January 2018, the SCU technology reached the milestone of a commercial available product. The aim is to transfer this achievement to switchable period length devices. To this end the first worldwide superconducting undulator coils with switchable period length have been designed, manufactured and tested in liquid helium.

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In the following, we present the layout of such coils with switchable doubling of the period length from 17 mm (SCU17) to 34 mm (SCU34) to operate at a magnetic gap of 6 mm (vacuum gap 5 mm). The first results from tests in a liquid helium bath of the 0.41 m long undulator coils (see Fig. 2) are also described.

LAYOUT OF THE UNDULATOR COILS

Simulations with the software FEMM [8] have been performed to optimize the geometry (pole width, groove width, and height). Taking into account the application of such an undulator in a low emittance light source a vacuum gap of 5 mm has been considered. Since the SCUs developed by KIT-Noell have a difference between magnetic gap and vacuum gap of 1 mm, we chose a magnetic gap of 6 mm.

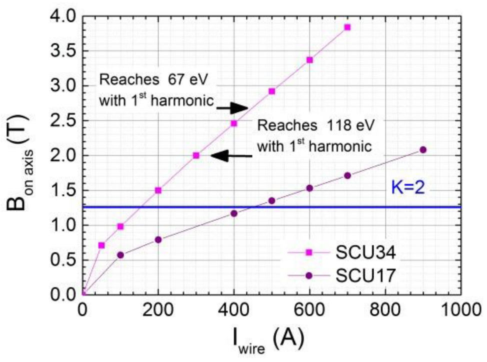

Figure 3: Simulated performance comparison of the two operations modes of a superconducting insertion device with period length doubling from 17 to 34 mm at 6 mm magnetic gap in an electron storage ring with 3 GeV electron beam energy. The peak magnetic field on axis is reported as a function of the current in the conductor. The blue line indicates the field at wich K=2 is reached for 17 mm period length.

The half period length of the smaller period of 17 mm is split into 5.6 mm groove width and 2.9 mm pole width. Each groove is wound with 60 turns within 12 winding layers of a rectangular NbTi superconductor, 56 filaments, and a bare cross section of 1 mm x 0.5 mm (1.08 mm x 0.58 mm including Formvar insulation) [7]. Figure 3 shows the simulated peak field on axis as a function of the current in the wire for the described geometry.

In order to reach K=2 with SCU17, which means superposition of the first and third harmonic with no gap to the accessible energies above the first harmonic, a current of 450 A in the wire is required. With 450 A in the SCU34, a photon energy as low as 67 eV with the first harmonic can be reached for an electron beam energy of 3 GeV, i.e., all M-edges of Cu and few of Fe are accessible. According to the loadlines simulated with FEMM and shown in Fig. 4, an operation current of 450 A allows, for both periods, a thermal margin of approximately 2 K with a working temperature of 4.2 K.

Each coil consists of 3 low carbon steel (C10E) blocks acting as a support for plates, which in turn serve as poles and grooves. The length of the middle assembled part is 138.9 mm. This is the building block for longer units, reaching 1-2 m in length. The length of the side blocks is 136 mm. Such blocks are tightened together by screws and fitting sleeves to match the required overall length. To avoid electrical shortcuts from the wire to the yoke, the bottom of each groove is capped with a 1 mm thick 3D synthetic printed piece. For the sides of the pole plates, a 100 µm thick Kapton foil was punched to the correct shape and glued to the plates [7].

Each circuit is wound with a single wire, and the current direction in consecutive grooves is changed by turning the winding direction on the side of the yoke opposite to the one looking at the electron beam. This winding scheme was successfully tested first on 6 grooves, and then with a last test coil 150 mm long. Without impregnation the 150 mm test coil achieved a maximum current of 400 A with period doubling (34 mm) and 600 A with 17 mm period length. After vacuum impregnation the test coil achieved 730 A for SCU17 and 500 A for SCU34.

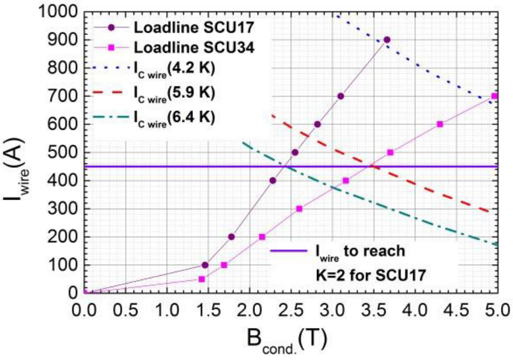

Figure 4: Loadlines of the superconducting undulator working with 17 and 34 mm period length. The current in the wire is reported as a function of the magnetic field in the conductor.

The final undulator consists of two coils, 410 mm long and held together by a support structure with a spacer keeping the distance between the coils at 6.00 ± 0.02 mm. In the mechanical design, special care has been taken to reach high mechanical accuracies, needed to be kept in cold conditions in order to maximize the brilliance of the undulator radiation. The following mechanical accuracies were reached: ±1 µm deviation for the half-period length, ±35 µm deviation for the pole height, and ±35 µm for the winding height. The measurements were performed with a coordinate measurement machine (CMM). It was shown that it is possible to mechanically and precisely manufacture the yoke for SCU coils out of plates, and that excellent mechanical accuracies of the winding heights can be reached with the chosen rectangular wire. The end field design to minimize the second field integral is shown in Fig. 5. Leaving in the end grooves only 20 turns of the main coil and using a thinner round NbTi wire with 0.254 mm diameter, it is possible to minimize the second field integral for both period lengths (17 and 34 mm). FEMM simulations show that a current of about 13 A is needed in the correction coil for both operating modes: for 17 mm it should be in the same direction as the one in the 20 turns of the main coil, while for 34 mm in the opposite. Upstream and downstream Helmholtz coils are needed to minimize the first field integral.

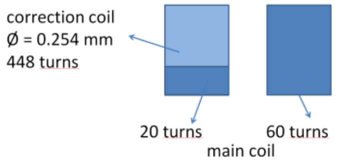

Figure 5: End field design to minimize the second field integral for both operation modes: 17 and 34 mm.

FIRST RESULTS

Before vacuum impregnation, the long coils were tested in CASPER I [9], a vertical test stand where the coils are immersed in a LHe bath. The precision of the Hall probe position is 1 µm and the accuracy of the calibrated Hall probe used is ± 0.1 mT. The maximum current reached with 17 mm period length was 562 A, and 371 A with 34 mm period length. The maximum current is expected to increase after vacuum impregnation. A vacuum impregnated test coil about 130 mm long reached 749 A with 17 mm period length and 555 A with 34 mm. Period switching was successfully shown on the same test coil, switching between 480 A for both periods.

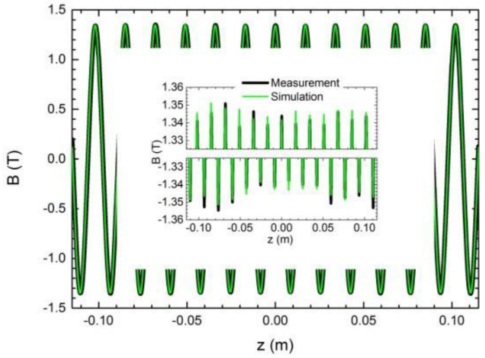

Figure 6: Magnetic field measurement along the magnetic axis z with a Hall sample of the undulator operating with 17 mm period length and a current of 500 A in the main coils (black line). They are compared to the simulated field with FEMM (green line), taking into account the mechanical accuracies measured at room temperature.

Magnetic field measurements were performed at different currents operating with both period lengths. For this first test without impregnation all grooves are fully wound, i.e. the vertical field integrals are not minimized. Figure 6 and Fig. 7 show the comparison, in the central part of the coil, of the on axis magnetic field measurements and of the simulated field for SCU17 with 500 A current and for SCU34 with 370 A. The uncompensated end field configuration causes a constant magnetic field all along the coils length on the magnetic field axis, due to the presence of iron all along the coils. This constant magnetic field component is removed from the measured values and from the simulations performed with FEMM [5] shown in Figs. 6 and 7. The simulations take into account the mechanical accuracies measured at room temperature with a CMM. The difference between the measured and simulated peak field values is < 5 mT (<10 mT) for the 17 mm (34 mm) period length.

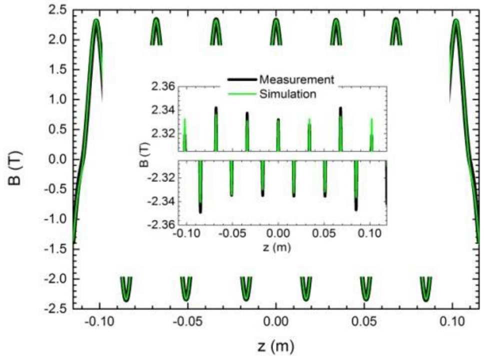

Figure 7: Magnetic field measurement along the magnetic axis z with a Hall sample of the undulator operating with 34 mm period length and a current of 370 A in the main coils (black line). They are compared to the simulated field with FEMM (green line), taking into account the mechanical accuracies measured at room temperature.

CONCLUSION

In this contribution the design and testing of superconducting undulator coils with switchable period length is presented, together with magnetic measurements. The good agreement between measurements and simulations shows that the mechanical accuracies reached at room temperature are kept in cold conditions, producing a magnetic field on axis of high quality. Next, the end field correction scheme presented will be implemented and the coils will be vacuum impregnated. Afterwards the magnetic the measurements will be repeated.

ACKNOWLEDGMENTS

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