DESIGN AND TESTS OF SWITCHABLE PERIOD LENGTH SUPERCONDUCTING UNDULATOR COILS

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Abstract

Several photon beamlines in different synchrotron light sources make use of undulators with switchable period length, which offer a larger tunability of the energy of the emitted photons. Superconducting technology allows switching the period length by changing the sign of the current in separately powered subset of windings.

The single period is required for high brilliance at specific photon energies in the keV range, while period doubling or tripling offers tunability and/or to reach low photon energies in the few tenths of eV range.

We present here the design and tests performed in liquid helium with superconducting switchable period length undulator coils, where period doubling from 17 mm to 34 mm can be applied.

INTRODUCTION

Many synchrotron light sources of latest generation use insertion devices (IDs), such as undulators, to produce high brilliant synchrotron radiation. An undulator is an arrangement of dipoles with alternating direction of the magnetic field resulting in an on axis sinusoidal periodic field, along the beam direction, between two magnet halves. The spectral range of the emitted photons coverable by the harmonics of an undulator with period length λ_U and the magnetic field on axis B_y is given by the equations [1],

$$\lambda = \frac{\lambda_U}{2\,\gamma^2\,n}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{e}{2\,\pi\,m_e\,c}\lambda_U\,B_y$$

where e is the electron charge, m_e the electron mass, γ the Lorentz factor, c the speed of light and λ the wavelength of the emitted photons at the n-th harmonic. Typically for an insertion device the period length λ_U is fixed and the wavelength (energy) of the emitted photons is tuned by varying the magnetic field strength B_y. The lowest photon energy reachable with a given harmonic, is defined by the Lorentz factor γ, the undulator period length λ_U and the tuning range is determined by the achievable magnetic field.

At a synchrotron light source the demands on the energy of the emitted photons are given by the beamlines and can vary over a wide range. A way to increase the energy range of the emitted photons is to vary the period length, which, however, complicates the technical realization of the insertion devices.

The 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 (Fig. 1).

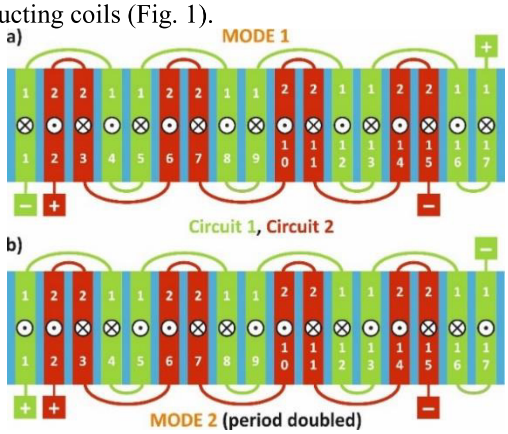

Figure 1: Sketch of period length doubling for superconducting undulators by changing the current direction in one subset of windings.

The presented case in Fig. 1 shows the case of period doubling. The colouring indicates to which circuit each winding belongs. In Fig. 1a the circuits are powered to have the smallest period, while on Fig. 1b the current direction of circuit 1 is changed to obtain period doubling.

Planar NbTi-based cryogen free SCUs with openable vacuum gap are now commercially available from the collaboration KIT-Bilfinger Noell GmbH. Series-production readiness has been demonstrated with a new full-scale superconducting undulator with 20 mm period length (SCU20), successfully operating in the KIT synchrotron since January 2018 [2]. The aim is to transfer this achievement to switchable period length devices.

In the following, we present the coil design for a superconducting insertion device 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) and the first results from tests in a liquid helium bath.

COIL DESIGN

In order to have an overlap between the first and third harmonic (K = 2) for the 17 mm period length it is needed a peak field on axis larger than 1.25 T.

Simulations with FEMM [3] have been performed to optimize the geometry (pole width, groove width and height) and to determine the engineering current density needed to choose the wire to obtain K=2 for the SCU17, and to reach high brilliance in the soft X-ray regime with

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the first harmonic of SCU34, to measure M-absorption edges of metals like V, Cr, Mn and Fe, going as low as few tens of eV, in a low emittance light source with 3 GeV electron beam energy.

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). Figure 2 shows the 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 a current of 460 A in the wire is required, while to reach 50 eV (all M-edges of Fe) with the first harmonic of SCU34 a current of 463 A is needed. These operation points allow for a thermal margin of more than 1 K.

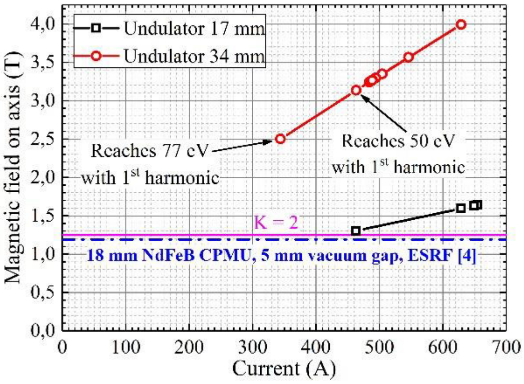

Figure 2: Simulated performance comparison of the two operations modes of a superconducting insertion device with switchable period length at 6 mm magnetic gap.

The coil, shown in Fig. 3, consists of low carbon steel (C10E) blocks acting as support for plates, which are serving as poles and grooves. The length of the shortest assembled part is 144.5 mm (8.5 periods of 17 mm). This is the building block for longer units reaching 1-2 m length. Such blocks can be tightened together by screws and fitting sleeves to match the required overall length.

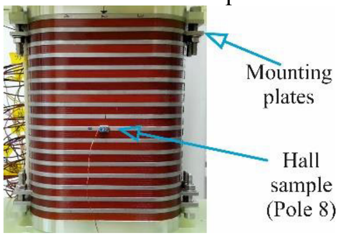

Figure 3: Shortest unit of a former block wound with rectangular NbTi superconducting wire. Hall sample placed on middle pole 8.

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 tolerances have been reached: ±3 µm deviation for the half-period length, ±30 µm deviation for the pole height, ±80 µm for the winding height counting all windings and ±60 µm excluding the two extremes. The measurements were performed with a coordinate measurement machine. After winding, additionally the winding height was measured. The measured data are shown in Fig. 4 and they prove, that it is possible to mechanically manufacture precisely the yoke for SCU coils out of plates, especially concerning the half period length and the pole height distribution. The somewhat larger deviations for the winding heights are mainly related to the accuracies of the wire dimensions, as well as to the challenge of the measurements due to the insulation layer of the wire and to the presence of several wires per groove.

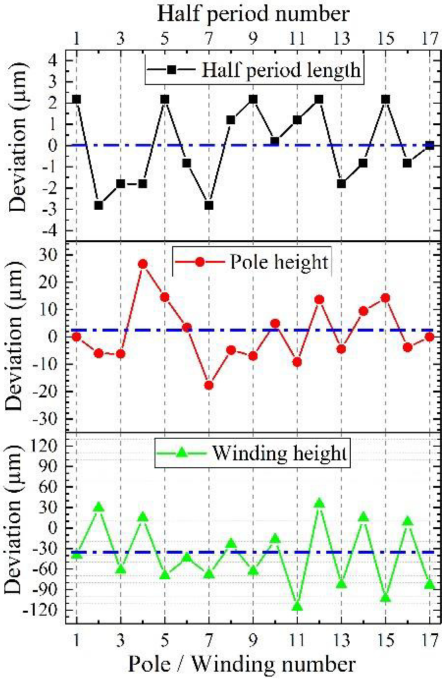

Figure 4: Results of mechanical measurement of the half period length before winding and the pole heights, and winding heights after winding.

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. To obtain the two individually powered circuits, in- and output wires of specified winding packages are connected via joints made out of copper tubes filled with Niobium and squeezed.

The two last pole plates on each side of each unit are mounting plates to fix the gap height between the two undulator halves to 6 mm, when clamped together on a precisely machined spacer bar. With the aim to test the coil in conduction cooled working conditions [5], a copper cooling bar is implemented in the coil side facing away from the beam.

MEASUREMENT SETUP

To test the current performance of the superconducting wire and the switching procedure, the coil is cooled down in CASPER I (Fig. 5), a liquid Helium bath cryostat, at the Institute for Beam Physics and Technology (IBPT) at the Karlsruhe Institute of Technology (KIT) [6]. At the test setup, two power supplies are available, whereof one has the possibility to change its polarity. Additionally it is possible to record the magnetic field via a Hall sample and an attached Keithley DAQ system to verify the period length switching.

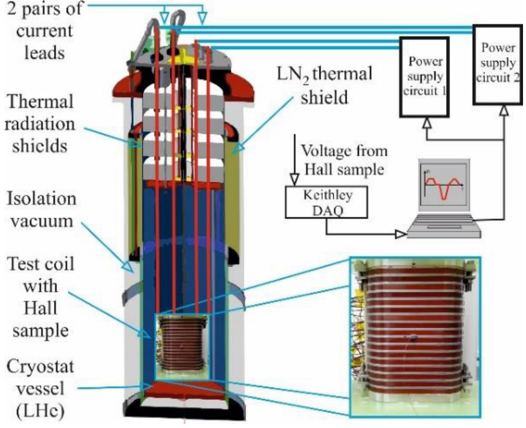

Figure 5: Test coil mounted in liquid helium bath cryostat CASPER I for superconductor performance tests and period length switching.

QUENCH TESTS AND SWITCHING

The first training was performed on the non impregnated coil with the winding packages connected by Niobium joints. Their resistances were measured while being powered, to measure the heat intake. Resistances of 10 nΩ per joint at 500 A, leading to 2.5 mW dissipated power, were measured. Keeping in mind that approximately 140 joints for a 1.5 m device with two coils are needed, a total cooling power for the joints of ~400 mW is required. This can be handled in a conduction cooled setup, reducing however the temperature margin of the operation.

The training started with a first quench at 300 A and after 10 quenches 500 A in the SCU17 mode are reached. Operating in the SCU34 mode with the doubled period length, 440 A as maximum current could be reached. Casting the superconducting wires with epoxy on the back side of the coil, increased the mechanical stability of the superconductor and the quench currents to 550 A for SCU17 and 450 A for SCU34. During the next cooldown switching of the period length was tested.

The resulting field during a two times switching procedure from 540 A in SCU17 mode to 340 A in the SCU34 mode, is shown in Fig. 6. The magnetic field was measured by a Hall sample 4 mm placed above pole 8 and the change in the field direction when changing the period length is illustrated in Fig. 1. During this procedure the period doubling was performed without any quench occurring after switching the current direction. The calculated magnetic field strength on axis with 6 mm magnetic gap for the chosen current values is shown in Fig. 2. With the applied maximum currents, energies down to 77 eV can be reached with 340 A in the SCU34 mode, and a K-value larger than 2 with 540 A in the SCU17 mode allows full superposition of the first and third harmonics.

To further improve the performance a winding procedure with no joints was conceived. The superconducting wire is directed by 3D printed pieces at the passages between neighbouring grooves.

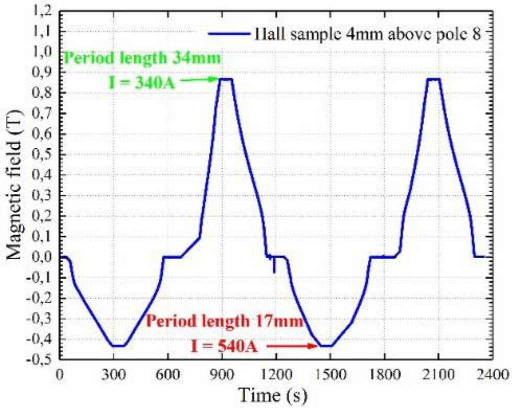

Figure 6: Magnetic field measurement with a Hall sample placed 4 mm above pole 8 during period length switching of the test coil.

A room temperature vacuum impregnation is foreseen before next tests in CASPER I. The absence of joints reduces the heat intake increasing the thermal margin during operation.

CONCLUSION

In this contribution the design and testing of superconducting undulator coils with switchable period length is presented, and the feasibility of period length doubling is demonstrated. The design and precise manufacturing of the yoke is confirmed by mechanical measurements. New tests will be performed on a similar coil without joints and vacuum impregnated at room temperature.

Two 400 mm coils are now being wound and after impregnation they will be tested in the in-house developed horizontal, conduction cooled test facility CASPER II.

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