ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF066

PERFORMANCE OF A FULL SCALE SUPERCONDUCTING UNDULATOR WITH 20 mm PERIOD LENGTH AT THE KIT SYNCHROTRON

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Abstract

Within the collaborative effort between KIT and Bilfinger Noell GmbH the development of a full scale superconducting undulator with 20 mm period length (SCU20) has been completed. This device addresses the reliability and reproducibility aspects of the manufacturing process, allowing for the status of a commercial product. The conduction cooled 1.5 m long coils were characterized in the KIT horizontal test facility CASPER II and later assembled in the final cryostat. The system was extensively tested in the final configuration before installation in the KIT storage ring KARA (Karlsruhe Research Accelerator) to be the source of the NANO beamline in December 2017. Here we present the performance of the device.

INTRODUCTION

Undulators are used in modern synchrotron radiation sources to produce high brilliance photon beams. Superconducting technology allows to increase the flux and brilliance with respect to permanent magnet technology.

Figure 1: SCU20 installed in the storage ring KARA of the KIT synchrotron.

KIT and Bilfinger Noell GmbH (Noell) have a long-term collaboration to develop superconducting undulators. After the successful test of a full scale device with 15 mm period length in the KIT synchrotron [1] a new full scale device with 20 mm period length has been developed and installed in December 2017 in the electron storage ring KARA of the KIT synchrotron (see Fig. 1).

The collaboration focused on the development of conduction-cooled undulators wound with NbTi wire and with a UHV beam chamber (liner) with adjustable vacuum gap. SCU20 is more compact and the manufacturing process has been optimized to be more reliable and efficient as compared to the previous undulator [2].

After a short description of the layout, a summary of different tests performed before the installation in the storage ring is presented. Then, the first results of SCU20 performance in the storage ring are reported followed by conclusions.

LAYOUT

The main parameters of SCU20 are listed in Table 1. Each of the undulator coils consists of eleven blocks of low carbon steel approximately 0.15 m long and wound with a NbTi round wire with 0.76 mm diameter (including insulation).

Table 1: Key Parameters of SCU20

Period length	20 mm
Maximum peak field on axis	1.18 T
Number of fully wound periods	74.5
Magnetic length	1.554 m
Vacuum gap closed (open)	7 (15) mm

Four pairs of correctors, placed in the cryostat to compensate the vertical field integrals, are wound with a much thinner NbTi wire [2, 3]. Two pairs of auxiliary coils are wound in the first and last groove of each yoke (AUX1) and other 2 pairs on top of the windings of the second and second to last grooves which are filled with 23 of 113 turns of the main windings. The third and third to last grooves are filled with 53 turns of the main windings. Two pairs of Helmholtz coils are placed upstream and downstream (HH DS) with respect to the main undulator coils. The required vertical field integrals are reached using only AUX1 and HH DS [3]. To compensate the horizontal field integrals, 2 normal conducting correctors are placed out of the cryostat upstream and downstream.

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The device is cooled with 4 Sumitomo cryocoolers RDK415D [4] each providing 1.5 W at 4.2 K (second stage) and 35 W at 50 K (first stage) and is designed for a beam heat load of 4 W.

The adjustable liner, which allows changing the vacuum gap from 7 mm to 15 mm, is made of a 0.3 mm thick stainless steel foil. This is coated with a 30 µm copper layer to minimize resistive wall heating from the electron beam. The magnet is powered with closed gap.

A passive quench protection system based on cold diodes is applied to the undulator coils. Quench detection is implemented in the main power supply, and triggered by the voltage difference across the two coils.

Training of the magnet together with measurements of the magnetic field quality have been performed in CASPER II, the conduction-cooled test facility developed at KIT [3, 5].

TESTS WITHOUT BEAM

Before installation of SCU20 in the storage ring KARA several tests have been performed.

The time required to cooldown the magnet is approximately 5 days, as shown in Fig. 2. The minimum temperature reached by the coils is below 3.5 K. A warmup time of nearly 4 days is achieved.

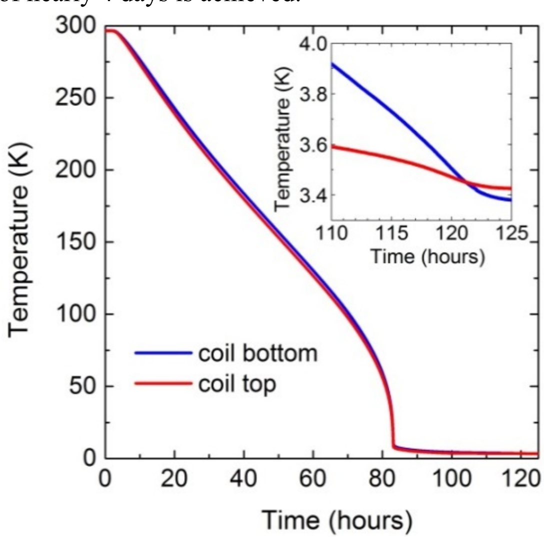

Figure 2: Temperature of two sensors placed in the top (red line) and bottom (blue line) coil, respectively.

During the testing period only one quench was observed, a few minutes after one of the ramps to maximum current of the main coils. The temperature increase of the coils up to 15-17 K after a quench is shown in Fig. 3a). The quench of the main coils is shown if Fig. 3b) with the abrupt decrease of the current from 400 A to 0 A. Approximately 15 minutes after a quench, the temperature of the coils decreases below 4 K and they can be powered again.

As shown in Fig. 4, the stability of the magnet was successfully tested for one week. Together with the main coils, AUX1 and HH DS have been powered to the values needed to compensate the field integrals inferred from the measurements of the coils performed in CASPER II.

The beam vacuum was tested several times before installation. In cold conditions a pressure of 2.5× 10^{-10} mbar was measured.

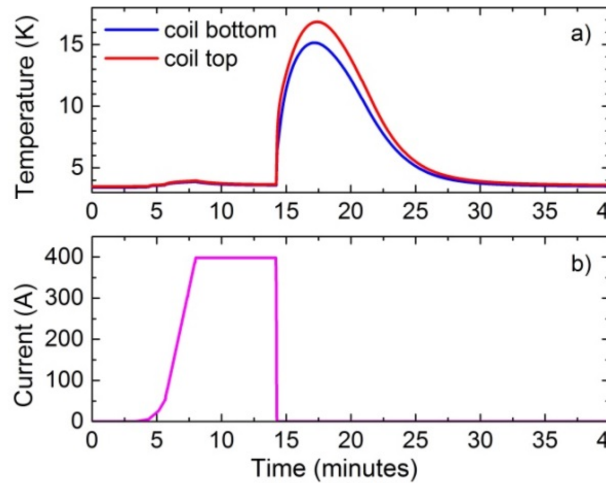

Figure 3: a) Temperature of the top and bottom coil during a quench. b) Current of the main coils as a function of time. The abrupt decrease of the current from 400 A to 0 A indicates the quench.

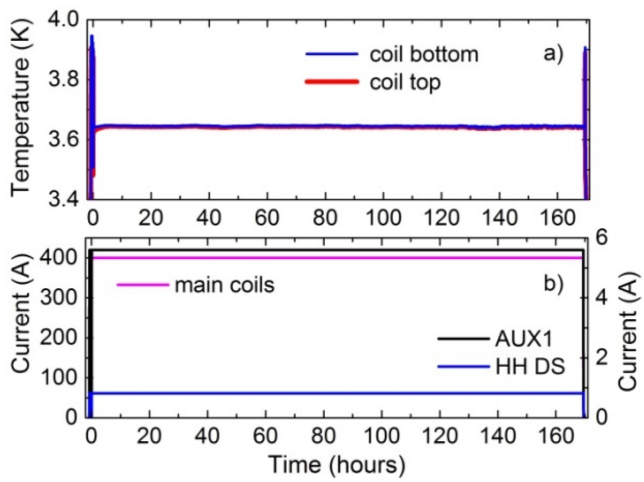

Figure 4: a) Temperature of the top and bottom coil during a stability test of the coils. b) Current of the main coils (left axis, magenta line) and of the correctors (right axis, blue and black lines) as a function of time.

INSTALLATION AND TESTS WITH BEAM

SCU20 was installed in the electron storage ring during the shutdown in December 2017. The liner was filled with nitrogen during warm up and it was exposed to air for less than 12 hours. This was possible since the ring vacuum was closed during the same day in which SCU20 was lifted in the storage ring.

The beam lifetime (23 h at 100 mA) was recovered in about 3 weeks of beam operation of the storage ring at 2.5 GeV, after installation of SCU20.

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The alignment procedure, performed at room temperature is similar to the one used for the previous undulator with 15 mm period length and it is described in [1].

SCU20 is producing high brilliant X-rays for the NANO beamline since January 2018. Since then SCU20 operation has been very reliable and no quench was observed. SCU20 is transparent to the electron beam by using the same correctors as the ones found in the measurements performed in CASPER II: AUX1 and HH DS. The values of the current needed in AUX1, determining the second vertical field integral, are very close to the values obtained in CASPER II. The values of HH DS had to be slightly changed. The adjustment of the currents in the vertical correctors (AUX1 and HH DS), as the ones in the horizontal correctors, was performed in few hours.

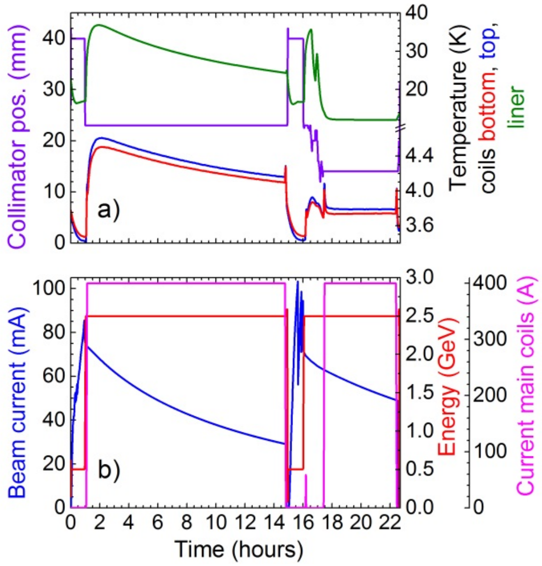

Figure 5: a) Position of the horizontal collimator (violet line) and the temperature of the top (blue line) and bottom (red line) coils as well as of the liner (green line) as a function of time. b) Beam current (blue line), beam energy (red line), and current in the main coils (magenta line) of the SCU20 as a function of time.

The liner is protected by the synchrotron radiation from the upstream bending magnet by a horizontal collimator. This was shifted, exposing the liner to an additional 8 W of synchrotron radiation, without affecting the operation of SCU20 (see Fig. 5). This demonstrates that SCU20 can accept at least 8 W beam heat load. Figure 5 shows also that the coils have an operation temperature margin of at least 0.8 K (normal operation at 3.8 K, but working also at 4.6 K), as well as the excellent thermal decoupling between liner (35 K) and coils (4.6 K).

An accurate spectral characterization is ongoing at the NANO beamline. First measurements of the photon spectrum, reported in Fig. 6, show from the position of the 7th harmonic that the peak field on axis is in very good agreement with the one measured in CASPER II of 1.18 T [2].

It is possible to change the photon energy of the different harmonics SCU20 by changing the current in the main coils (tuning), which does not appreciably affect the orbit (< 3 µm rms). This was measured during machine physics with the other beamlines at the KIT synchrotron: tuning of SCU20 is compatible with the operation of all the beamlines while performing their most sensitive experiments.

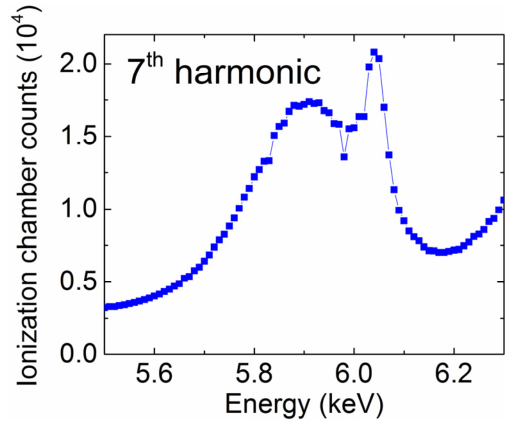

Figure 6: Seventh harmonic of SCU20 measured at the NANO beamline through 30 µrad x 30 µrad with an ionization chamber at 2.5 GeV electron beam energy [2].

CONCLUSION

SCU20 is the first commercially available undulator worldwide: a robust device, with reasonable delivery time, easy handling during installation and operation and providing superior performance compared to other available technologies.

ACKNOWLEDGEMENT

The authors would like to thank: M. Hagelstein, T. Baumbach, C. Heske, A.-S. Müller, and V. Saile (KIT) for supporting the project, to the IBPT technical group and in particular to Th. Fischböck, M. Süpfle, A. Völker (KIT) for support during installation, to M. Schuh (KIT) and the NANO beamline staff for their help during the SCU20 tests, and to all other beamlines at the KIT synchrotron for their feedback during tuning experiments.

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