ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEBD3

RECENT DEVELOPMENTS ON SUPERCONDUCTING UNDULATORS AT ANKA

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Abstract

A research and development program on superconducting undulators (SCUs) is ongoing at the ANKA (ANgstrom source KArlsruhe) synchrotron at KIT. This technology is of interest to improve the spectral characteristics of the emitted photons in third and fourth generation light sources. We present here the results obtained within the ongoing collaboration with the industrial partner Babcock Noell GmbH (BNG) on NbTi conduction cooled planar devices. Investigations on the application of alternative superconductors as well as a summary of the achievements reached to precisely characterize the magnetic field properties of SCUs and to measure the beam heat load to a cold bore are also described.

INTRODUCTION

ANKA (ANgstrom source KArlsruhe) and Babcock Noell GmbH (BNG) are pursuing a research and development program aiming to developing superconducting undulators (SCUs). The collaboration is focused on conduction cooled SCUs, with coils wound using NbTi wire, and with a movable vacuum gap.

The first milestone reached within the collaboration is the successful development and operation of a full scale (1.5 m long coils) superconducting undulator with 100.5 full periods of 15 mm (SCU15) in the ANKA storage ring. The spectral characterization is being performed at the IMAGE beamline. This full scale device demonstrates for the first time that superconducting undulators generate, while in operation in a storage ring, a higher magnetic field with respect to permanent magnet undulators including cryogenic cooled ones manufactured using the best material (PrFeB) available nowadays.

As a next step the collaboration is developing SCU20, a device with 20 mm period length for the NANO beamline at ANKA. Undulator mockup coils with 20 mm period length and 300 mm long have been designed, manufactured and tested.

In the first part of this contribution we focus on the performance of the SCU15 during the first months of operation in the ANKA storage ring. In the second section, we report on the 300 mm long mockup with 20 mm period length and its calculated spectral performance inferred from the measured magnetic field. The final section describes the tools and instruments not commercially available, under development at ANKA and necessary for the development of SCUs. These instruments are needed for precise magnetic field measurements and for measuring and possibly understanding the beam heat load to a cold bore.

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SCU15

ANKA and BNG designed, manufactured and tested a superconducting undulator with 15 mm period length and 100.5 full periods.

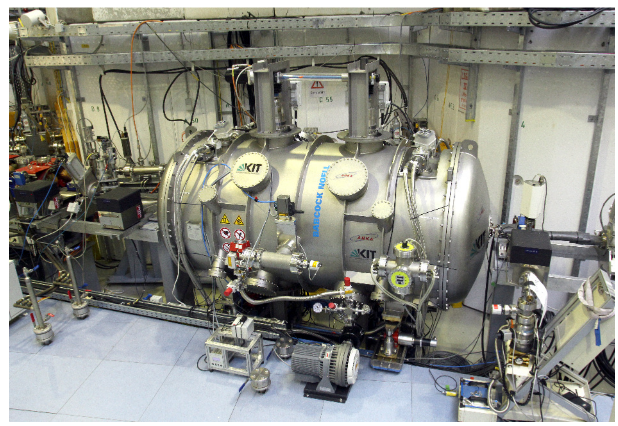

Figure 1: SCU15 installed in the ANKA storage ring.

The SCU15 has been assembled and successfully tested at BNG in summer 2014. The tests performed at BNG have been successfully repeated after transport at ANKA out of the ring. The test procedure included the cooldown, excitation, vacuum measurements and warm up of the system. Cooldown and warm up times of approximately 7 and 4 days, respectively, were achieved. The SCU15 was installed in the storage ring during the December 2014 shutdown and has been in operation with beam since the beginning of 2015 (see Fig.1).

One of the biggest challenges of the project was the development of the beam chamber (liner) which, together with the requirement for an UHV radiation-hard environment and low resistive losses [1], must open from 7 to 15 mm in operation at 10 K. Opening the vacuum gap to 15 mm is needed in the ANKA storage ring during electron beam injection and energy ramping. A movable gap might be appealing for other light sources during commissioning and/or operation, even if all other projects developing superconducting undulators in other facilities concentrate on fixed gap devices [2]. To be competitive with cryogenic permanent magnet undulators (CPMUs), high magnetic fields on axis are required; thus the coils of SCUs should be as close as possible to the beam axis, which can only be achieved by minimizing the distance between the liner and the coils. The SCU15 has

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a nominal magnetic gap of 8 mm and a beam stay clear of 7 mm, resulting in a distance between the inner surface of the liner and coils of 0.5 mm.

Taking into account of the measurements performed with the superconducting undulator demonstrator with 14 mm (SCU14DEMO) period length and 100 periods, developed within a collaboration between ANKA and the company Accel GmbH, and installed in the ANKA storage ring from 2005 to 2012, the SCU15 has been specified and designed to withstand a beam heat load of 4 W [3]. The electron beam heat load limited the operation of the SCU14DEMO to a peak field on axis lower with respect to the performance of permanent magnet undulators. With the SCU15 this problem has been overcome.

The coils and the liner of the SCU15 are thermally well separated, and the beam heat load does not significantly increase the coils temperature and does not affect the SCU15 operating current. The thermal separation is obtained by keeping a distance of 0.2 mm over 1.5 m between the liner surface (liner thickness = 0.3 mm) and the coils [4].

Figure 2 (top) shows the current in the main coils and the corresponding temperature of the top and bottom magnets, which remain below 3.6 K during normal user operation. The beam parameters are shown in the plot on the bottom. In conduction cooling the operating margin of the system is increased by 0.6 K with respect to the one in a LHe bath with a fixed operating temperature of 4.2 K. This allowed to safely operate the SCU15 with beam at 2.5 GeV without quenches.

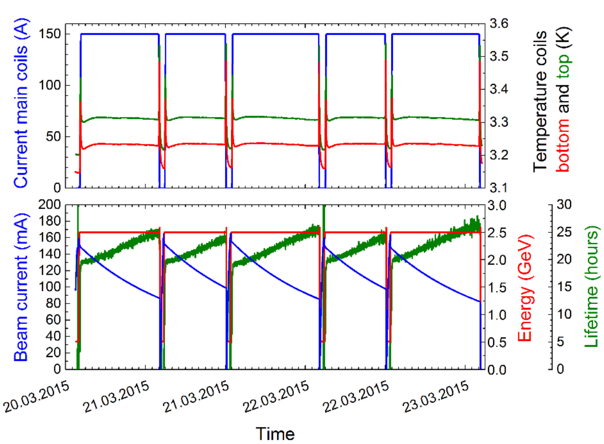

Figure 2: Top. Current of the main coils (blue line) of the SCU15 and the temperature of the top (green line) and bottom (red curve) coils as a function of time. Bottom. Beam parameters as a function of time: current (blue line), energy (red line), lifetime (green line).

As a result of a repair on the coils, which required the bypassing of the windings in the last groove of one coil, the first and second field integrals are not compensated. The asymmetry in the end fields produces a constant magnetic field along the coils and a bending of the trajectory, which results in an observed reduction in intensity and broadening of the odd harmonics. The field integrals are compensated by one horizontal corrector of the ANKA storage ring placed upstream with respect to the SCU15. Though superconducting Helmholtz coils are installed in SCU15, they are not strong enough to fully correct the field integrals.

The measured flux through a pinhole with 50 μm diameter at 14.9 m from the source, using a Si 111 channel cut monochromator and an ionization chamber (Oken Ltd, Japan), is shown in Fig. 3 as a function of the photon energy. A second ionization chamber and a filter wheel are used for calibrating the energy. The ionization chambers were filled with nitrogen at 900 mbar. The magnetic peak field inferred from the position of the third harmonic is 0.73 T, which is about 16% higher than the peak field of 0.62 T [5] achieved with a CPMU using PrFeB with the same period length of 15 mm and beam stay clear of 7 mm.

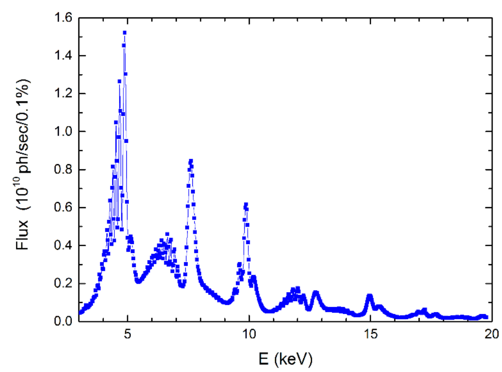

Figure 3: Flux generated by the SCU15 with 150 A operating current in the coils, at 2.5 GeV and normalized to 100 mA, through a pinhole of 50 μm diameter at 14.9 m, measured with a channel cut Si 111 monochromator and an ionization chamber.

SCU20

As part of the collaboration, ANKA and BNG designed, manufactured and tested a 300 mm undulator mockup with a period length of 20 mm. The main changes of the design with respect to the SCU15 are reported in Ref. [6]. In addition, the staggering of the wire on the back part of the coils has been eliminated by winding each next groove one after the other. Moreover, correction coils for the first and second field integral have been integrated in the coils. The test in liquid helium made in the test facility CASPER I showed that the coils reached 400 A without quenching, the nominal current being 380 A. In conduction cooling, with the coils operating at 4 K, a current of 688 A was achieved [11]. The critical temperature at nominal operating current is 6.2 K, resulting in a temperature margin of at least 2 K.

The flux through a slit of 1 mm x 1 mm at 10 m from the source has been calculated using the ANKA beam parameters and the measured magnetic field of the SCU20 mockup. The higher spectral performance with respect to CPMUs can be appreciated in Fig. 4, where it is compared (blue line) with the flux calculated using the ideal magnetic field of a CPMU with 20 mm period length made of the best material

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available PrFeB (red line). These calculations have been performed using the program B2E [7].

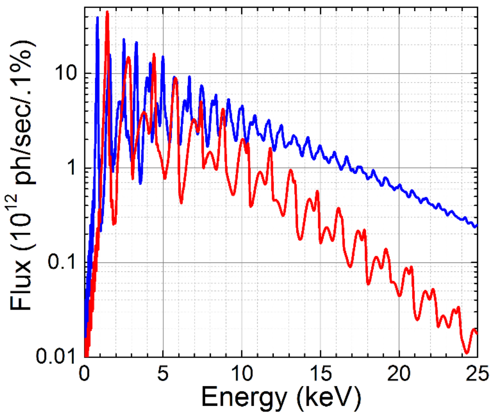

Figure 4: Flux through a slit of 1 mm x 1 mm at 10 m from the source calculated using the ANKA beam parameters, a beam stay clear of 7 mm and the measured magnetic field of the SCU20 mockup (blue line) at the nominal current 380 A. This is compared to the flux calculated using the ideal magnetic field of 0.74 T [8] of a CPMU with 20 mm period length made of the best material available PrFeB (red line).

HTS TAPE STACKED UNDULATOR FOR TABLE TOP FEL

Following the proposal from S. Prestemon at al. [9], within a KIT internal collaboration between ANKA and the Institute of Technical Physics (ITEP), a compact HTS tape stacked undulator is under development. This concept which offers advantages for short periods (< 10 mm) and narrow gap devices, could be used for table top free electron lasers. The first magnetic field measurements (shown in Fig. 5) above a 12 mm wide HTS structured tape have been successfully performed in CASPER I (liquid helium bath) with a Hall probe [10]. The period length is 8.05 mm. The tape is structured at the ITEP-KIT with a Trumpf picosec YAG-IR laser.

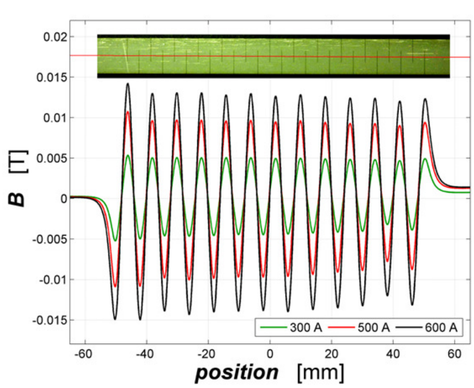

Figure 5: Magnetic field line profiles 2.05 mm above center of structured tape for 300, 500, and 600 A [10].

MAGNETIC FIELD CHARACTERIZATION

An important milestone has been reached with the commissioning of the horizontal in vacuum magnetic field characterization setup CASPER II. Using the SCU20 mockup it was possible to perform first local magnetic field and field integral measurements with this facility. CASPER II can be used for magnet training and for characterizing the magnetic field properties of conduction cooled undulator coils up to about 2 m long. Next the SCU20 1.5 m long coils will be characterized. More details are given in Ref. [11].

BEAM HEAT LOAD MEASUREMENTS

In order to measure and possibly understand the beam heat load to a cold bore, a cold vacuum chamber for diagnostics (COLDDIAG) has been built [12]. COLDDIAG was installed in November 2011 in the Diamond Light Source (DLS). Because of a mechanical failure at one thermal transition, it was removed after only one week of operation. After optimizing the design of the liner thermal transition, COLDDIAG was successfully installed a second time in the DLS in August 2012 and has been taking data till August 2013, when it has been removed to make space for a new insertion device. A significant discrepancy is observed between the beam heat load measured [12] and values predicted by heating due to geometrical and resistive wall impedance [13]. More details are given in Ref. [14].

CONCLUSION

Significant progress has been achieved in the development of superconducting undulators. Most relevant is the reliable operation of a full scale device (1.5 m coils) with 15 mm periond length installed in the ANKA storage ring, which reaches for the first time, while in operation with beam, higher fields than CPMUs with the same geometry.

ACKNOWLEDGMENT

We would like to thank: M. Hagelstein, T. Baumbach, C. Heske, A.-S. Müller, and V. Saile (KIT) for supporting the project, the ANKA machine group and the IMAGE beamline staff for their help during the SCU15 tests. A special thank goes to E. Huttel (ANKA-KIT, SESAME) for his help and fruitful discussions.

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