ADVANCES IN SUPERCONDUCTING UNDULATORS *

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Abstract

Superconducting technology could be employed for building undulators with enhanced parameters for synchrotron light sources and free-electron lasers. Expected and measured performance of superconducting undulators will be presented. Although superconducting technology is already working in superconducting wigglers, the development of superconducting undulators was slowed down by a variety of challenges that will be discussed. Possible solutions with examples will be presented. Finally, an overview of recent developments in superconducting undulators is presented in this paper.

INTRODUCTION

Insertion devices (IDs) are essential parts of modern and future light sources. The trends for IDs of future light sources are reviewed in [1]. Until now most IDs have been built using permanent magnets as a source of magnetic flux. At the same time, there is a growing interest in electromagnetic devices that use superconducting windings. As a matter of fact, superconducting wigglers are a well-established technology; such IDs are being used in many synchrotron light sources [1]. In comparison, the development of superconducting undulators is lagging behind the progress being made with superconducting wigglers.

This paper follows the review of developments in superconducting insertion devices given in [2] and concentrates on superconducting undulators (SCUs). The motivation of developing SCUs is first discussed, followed by a list of challenges. Examples of recent developments towards finding the solutions are then given. Finally, an overview of activities in superconducting undulators is presented.

SCU MOTIVATION

Interest in SCUs is stimulated by the fact that the SCUs can reach, for the same vacuum gap and period length, higher field events with respect to cryogenic permanent magnet undulators (CPMUs)—the state-of-the-art of permanent-magnet-based undulators. The undulator peak field for both technologies is compared in Table 1 [3]. In this table, NbTi-APC refers to a NbTi-superconductor with artificial pinning centers (APC).

A similar comparison is given in [4]. A careful analysis of CPMU and SCU technologies concludes that above the period length of 10 mm SCUs produce the highest fields. For the smaller period lengths, CPMUs can compete with NbTi SCUs, whereas Nb_3Sn or NbTi-APC devices are still superior.

Table 1: CPMU and SCU Comparison [3]

	CPMU PrFeB	SCU NbTi	SCU NbTi-APC
Undulator period, mm	15	15	15
Magnetic gap, mm	5.2	6	6
Undulator peak field B, T	1.0	1.18	1.46
Undulator parameter K	1.40	1.65	2.05

SCU CHALLANGES

Development of SCUs is progressing relatively slowly due to several challenges. The first one concerns the requirement of high quality field from an undulator magnet. The second one is operating the SCU magnet coils at high current densities and providing adequate cooling in the presence of beam heating.

The first and second field integrals should be kept at a minimum to avoid electron beam position deviation by the undulator magnetic field. To achieve the highest performance of an undulator at higher harmonics, the phase error should also be kept at a level of a few degrees RMS. Those requirements are not easily achievable for multipole magnetic structures.

Cooling complex multi-coil superconducting magnetic structures of SCUs in the presence of heating by an electron beam is another challenging task. The possible solutions are discussed below.

SCU MAGNET

Magnet Design

A planar SCU generates a periodic magnetic field in a plane. For this, a set of linear currents is required as a minimum [5]. For practical reasons, a set of small racetrack coils (with dimensions of few a cm in height by a few cm in length) is used forming a multi-coil structure supported by a magnet former. The coils are usually vertically oriented due to a relatively short (15-30 mm) period length in the undulators. One undulator period contains two coils with the currents going in opposite directions. A magnet former, or a core, can be made of magnetic or non-magnetic material. A complete SCU magnetic structure is then made of two such magnets separated by a magnetic gap where a beam vacuum chamber can be located [6].

Such a magnetic design is adopted in the SCUs for the National Synchrotron Radiation Research Center (NSRRC), Taiwan [7], Advanced Photon Source (APS), USA [8], Diamond Light Source (DLS), UK [9], and Shanghai Synchrotron Radiation Facility (SSRF), China [10]. In the SCU for ANKA there is no beam vacuum

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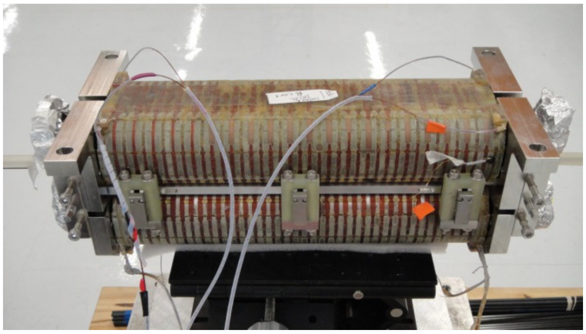

Figure 1: Magnetic structure of the test superconducting undulator SCU0 at the APS [8].

chamber, but a thin liner is used to shield SCU coils from the electron beam [11].

The above scheme is suited for winding SCU coils with the low-temperature superconductor (LTS) wires although the exact designs could vary. Both NbTi and Nb_3Sn superconductors were successfully used for making SCU magnet prototypes, but NbTi has been used so far in the completed devices.

There also have been attempts to use high-temperature superconductors (HTSs) for SCU magnets. The idea of making a zigzag-like pattern on the HTS YBCO ($YBa_2Cu_3O_7$) tape is suggested in [12]. An SCU magnet could then be built as a stack of such tapes. The expected field of this undulator could exceed 1 T for a period length of 7 mm and beam aperture of 2 mm. An undulator with such a small pole gap is targeted primarily at free electron lasers.

A prototype of an HTS magnet was built and tested by the ANKA group and Babcock Noell GmbH [13]. The achieved field was lower than the field of a NbTi-based magnet. This is due to a very low packing factor in a winding made of the HTS tapes, where a superconductor layer is very thin and occupies only about 1% of the tape overall thickness.

Magnetic Shimming

Magnetic and mechanical shimming is usually used to tune conventional undulators to achieve the required field integrals and phase errors. It is a common perception therefore that magnetic shimming should also be employed for SCUs. In the case of superconducting devices where a magnetic structure is enclosed in a cryostat, such an approach requires development of new shimming techniques.

One possibility for planar SCUs is to add extra iron pieces to a magnetic pole as described in [14]. The measured maximum field compensation is 2.43% for a shimming piece of height 25 mm in a 130-pole undulator magnet with period length of 15 mm and a 5.6-mm pole gap. An additional magnetic flux could be injected into a pole when a trim coil is mounted directly on the outer faces of the iron pole with a trim iron piece [15].

A concept of passive shimming, based on Faraday's law of induction, was suggested [16] and experimentally tested [17]. The induction-shimming system consists of a set of overlapping closed high-temperature superconductor (HTS) loops attached to the surface of the superconducting undulators. Each HTS loop covers two adjacent undulators' magnet poles. The undulators' field errors induce currents in the HTS loops and, as a result, the magnetic field generated by these induction currents minimizes the field errors. The compensation effect at a level of 6 mT was measured at a distance of 7.15 mm from the SCU test magnet having a period length of 14 mm. The estimated correction field would be about 17 mT for an undulator with a period length of 15 mm and a pole gap of 5 mm with a peak field of 1.5 T [17].

Superconducting switches are also suggested for use in SCU shimming as described in [18]. This concept utilizes a single current source and a set of superconducting switches to control the current direction in the trim coils.

At the same time, the experience of the APS group demonstrates that magnetic shimming is not required for a relatively short (300-mm-long) undulator magnet. The magnet former was machined with a precision of about 10 µm, and the winding was done accurately on a computer-controlled winding machine. As a result, a phase error below 2° RMS was measured. The required field integrals were also achieved without any magnetic shimming. Such tight mechanical tolerances are practically impossible for longer magnets; therefore, theoretical work was started in order to simulate possible geometrical errors in superconducting magnet windings and calculate their effect on the field quality [19]. It was found that for a given field error range, the phase error scales with the square root of the undulator length. This work needs to be continued to better understand the sources of the field errors in SCU magnets.

SCU COOLING

Heat Loads

Design of an SCU cooling circuit requires reliable prediction of expected heat load in a superconducting undulator. Since an SCU is a superconducting magnet, all the heat loads that are typical for a superconducting magnet system are also present in an SCU. These are conduction heat leaks through current leads and cold mass supports, and radiation heat load from the vacuum vessel at room temperature to a cold mass at liquid helium temperature. Those heat loads could be calculated with good precision.

Another source of heat in the SCU is the electron beam itself. There is a variety of ways for electron beam to generate heat in a beam chamber, but the largest contribution at a level of tens of Watts per a meter of chamber length is due to resistive wall wakefields.

In addition, the SCU could be heated by any uncollimated synchrotron radiation from the upstream bending magnet. This can be mitigated by placing an absorber upfront of the SCU and by making the SCU beam chamber bore wide enough for the bending magnet synchrotron radiation to pass through.

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Cooling Schemes

The task of an SCU cooling circuit is to keep the SCU magnet coil cool in the presence of static heat leaks in the cryostat and beam heating.

One possibility is to place the SCU magnet into a liquid helium bath as in superconducting wigglers [20]. The drawback of this approach is that the beam heat goes directly into the coolant and requires substantial cooling power at 4 K. This cooling power could be provided by cryocoolers or by a cryogenic plant. Taking into account that a modern cryocooler delivers only 1.5 W of cooling at 4 K, this approach is limited to a modest heat load at 4 K. The usage of a cryoplant is likely to be cost effective when a long string of superconducting undulators needs to be built, like in free electron lasers. This scheme could be modified by placing a thermal screen, a liner, into a beam chamber bore. This liner could then be cooled by a separate circuit and take most of the heat from the electron beam.

It should be noted that the electron beam heats the SCU magnet when the beam chamber is in thermal contact with the SCU coils. This situation could be avoided by thermally insulating the SCU magnet from the beam chamber. A vacuum gap can simply be used as a thermal insulator. Such an approach is adopted in the SCU for the APS [21]. In this undulator the SCU coils are indirectly cooled by LHe passing through the channels in the magnet cores. The LHe is kept in a tank inside the cryostat and, together with the magnet and piping, makes a closed system. The He vapor in this system is re-liquefied by a recondenser that is located inside the tank and cooled by a cryocooler. An electrical heater is used to trigger a thermosyphon effect for circulating LHe through the magnet cores.

A group in the UK is going to employ a similar cooling scheme for their SCU but will decrease the operating temperature to 1.8 K to gain a safety margin and to achieve the required critical current [9]. A Joule-Thomson expansion valve will be added to a cryogenic circuit, and a pressure of 16 mbar will be required on the effluent side of the helium expansion. A special scroll pump will be used for circulating He through the undulator magnet.

Cryogen-free systems are also possible. The SCU coils are conduction cooled by cryocoolers as in the SCU that is currently being built by the ANKA group and Babcock Noell GmbH [22].

MAGNETIC MEASUREMENTS

Measurement of magnetic performance of an SCU is another challenging task as it requires building a dedicated magnetic measurement facility. The measurement techniques employed for conventional undulators could not be directly applied for SCUs as in these devices the magnetic structure is located inside a cryostat and operated at cryogenic temperature.

It is a common practice that undulator coils are tested in a vertical liquid helium cryostat. Such a system usually contains a single or several Hall sensors mounted on a vertical stage. An example of such a system is CASPER-I (Characterization Setup for Phase Error Reduction) developed at ANKA [23]. Similar systems were built at Brookhaven National Laboratory [24] and the APS.

Recently a more advanced measurement facility called CASPER-II has been built by the ANKA group [25]. This system is targeted at characterization of conduction cooled SCU magnets. It is based on a horizontal, cryogen-free cryostat with easy access to a test coil. The system is equipped with a Hall probe for local field measurements and a stretched wire for measuring the field integrals.

The APS group in collaboration with a team from Budker Institute, Novosibirsk, Russia, has designed and built a horizontal measurement system [26]. This system utilizes a warm guiding tube approach. In this scheme, a Hall probe is guided through a thin-wall warm tube that is stretched inside the cold bore of the SCU beam chamber. The bore of the guiding tube is open at the ends thus giving easy access to the Hall probes and measurement coils. The system has been successfully operated for parameterization of the first superconducting undulator at the APS [27].

The superconducting undulators for free electron lasers are likely to have a smaller pole gap than the SCUs for synchrotron light sources. A technique for magnetic measurements of small-gap SCUs needs to be developed. One promising approach is a pulsed wire technique that can be used for direct measurements of the first and second field integrals. The possibility of using this method for accurate trajectory and phase error measurements is demonstrated in [28].

EXPERIENCE WITH SCU OPERATION

A number of SCU prototypes have been built in various institutions around the world, but a quantity of completed devices is substantially smaller. Therefore any experience of operating a superconducting undulator on a light source is extremely valuable.

Superconducting undulator SCU14 was in operation at ANKA light source for several years after installation in 2005 [29]. This was a 100-period device with a period length of 14 mm and variable gap of 8-25 mm built by ACCEL Instruments GmbH. The magnet was conduction cooled by three cryocoolers. The measured photon spectra of SCU14 agreed very well with the calculations. Initial studies of the SCU heating by the electron beam concluded that the dominant heat source was the synchrotron radiation produced in the upstream bending magnets: 1 W per 100 mA stored current at a beam energy of 2.5 GeV and an undulator gap of 8 mm [30]. The heat load produced by the image current was found to be negligible. In the following years a nonlinear beam chamber vacuum pressure rise with the electron beam current was observed. The large variation of the beam heat load was also measured for different gaps—between 1.6 and 3 Watts for an 8-mm gap with 120-mA average beam current [31]. This was attributed to electron multipacting as the main beam heat source at ANKA for normal user operation [32].

The first superconducting test undulator, SCU0, was built and installed on the APS storage ring in December 2012. After commissioning in January 2013, the undulator is in user operation [33]. The SCU0 contains a relatively short magnet (330-mm length) in a 2-m-long cryostat [8]. The SCU0 magnet has a period length of 16 mm and a pole gap of 9.5 mm. It was designed to operate at a current of 500 A, but it routinely operates at a current of 650 A, delivering a magnetic field of about 0.8 T. The measured heat load on the SCU0 beam chamber is 16 W, which agrees very well with a calculated value of 14 W. For the eight-month period since commissioning, the device has demonstrated a LHe loss-free behavior. It is also observed that an SCU0 quench does not trigger an electron beam dump since the electron trajectory is deviated by only about 50 µm. On the contrary, an unintentional beam dump causes undulator quench. It takes about 20 minutes for the temperatures in the SCU0 to stabilize after quench. The device was characterized in terms of photon flux. As measured, the SCU0 produces about 40% higher photon flux at the photon energy of 85 keV as compared to a 2.4-m-long Undulator A, the most common hybrid undulator at the APS.

RECENT DEVELOPMENTS IN SCUs

A list of SCUs that have recently been built or are in the development stages (to the best of the author's knowledge) is given in Table 2. In this table SC stands for superconductor.

Table 2: SCUs Recently Built or Under Development

Light Source/ Institution	Period (mm)	Pole gap (mm)	K	No. of periods	SC	Status
NSRRC	15	5.6	1.96	≈132	NbTi	Proto-type
SSRF	16	9.5	0.9	10	NbTi	Proto-type
ANKA	15	5-16	2.1 max	100.5	NbTi	Being built
DLS	15.5	7.4	1.83	≈129	NbTi	Proto-type
NGLS/ LBNL	~20	TBD	TBD	~3000	Nb_3Sn	Proto-type
APS	16	9.5	1.2	20.5	NbTi	Built
	18	9.5	1.64	59.5	NbTi	Being built

CONCLUSION AND DISCLAIMER

Superconducting undulators continue to attract the interest of the light source community due to its promise of delivering high magnetic fields and therefore higher photon fluxes, especially at high photon energies.

In recent years a number of SCU prototypes have been manufactured and tested, and more undulators are currently being built. Various solutions are being suggested and implemented to overcome SCU challenges.

Experience gained in operating superconducting undulators confirms that such devices could successfully be operated in synchrotron light sources.

It is inevitable with an overview like this that some excellent work that has made valuable contributions to the development of superconducting undulators has been overlooked, but it was not intentional.

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