DEVELOPMENTS IN SUPERCONDUCTING INSERTION DEVICES*

E.R. Moog# and Y. Ivanyushenkov
Advanced Photon Source, Argonne National Laboratory
9700 S. Cass Ave., Argonne, IL 60439, U.S.A.

Abstract

A number of superconducting insertion devices are installed and in operation worldwide, including wavelength shifters, superbends, and wigglers. Superconducting undulators, with their shorter periods and more demanding field quality requirements, present additional challenges and are still under development. An overview is given of many of the devices that have been built and installed worldwide. Many light sources have had superconducting undulator projects. The status of these projects is discussed.

INTRODUCTION

Superconducting insertion devices represent both an old technology, in that the first superconducting devices were built in the late 1970s, and a new developing technology, in that the details of building a superconducting undulator for use on third-generation storage rings are still under development. We will review earlier work and then discuss where today's projects stand.

Early superconducting devices were built in several locations nearly simultaneously. A free-electron laser (FEL) demonstrated at Stanford University [1] was based on two helical superconducting magnets. [2] Shortly thereafter, the concept was brought from the single-pass setup at Stanford to the storage ring ACO in France. [3] Meanwhile, studies were being carried out in Siberia where a superconducting device was installed on the VEPP-3 storage ring. [4]

After this flurry of activity circa 1980, the interest in superconducting insertion devices waned. Rare-earth magnets were newly available and suitable for use in insertion devices. They were easy to use, could deliver impressively strong magnetic fields, and obviated the need for all the cryogenic baggage that came with superconducting technology. Insertion devices based on permanent magnets then became standard at light sources worldwide. A few normal-conducting devices were still developed, though typically for longer periods where there was space for coils and cooling, and where there was a need for rapid switching for some component of the magnetic field direction. Permanent-magnet technology was developed in a variety of geometries to meet a variety of needs for polarization.

With the inexorable progression of ever more challenging user requests for desired photon characteristics and more photon flux without excessive heat load, interest in superconducting technology has revived.

*Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

#emoog@aps.anl.gov

WAVELENGTH SHIFTERS

One way of reaching higher photon energy is with a stronger magnetic field that makes a tighter single bend in the stored beam. This can be done with a three-pole wiggler, or wavelength shifter, where there is a central strong-field pole sandwiched between two weaker poles. The integrated field is such as to provide a zero net deflection to the stored beam. Such a superconducting wiggler, with a 4-T center field, was built and installed at the European Synchrotron Radiation Facility (ESRF) in 1994. [5] It was used for about 5 years, until more restrictive radiation safety standards prompted a change to a 3-T permanent-magnet wiggler. A similar 6.4-T superconducting wavelength shifter was also built and installed at MAX-Lab in the late 1990's. [6]

Superconducting wavelength shifters also received significant attention at the Budker Institute, where quite a number were developed that were intended for various light sources. The list is shown in Table 1. [7] For the highest-field 10-T shifter, Nb_3Sn was used for the inner section of the coil on the center pole. [8]

Table 1: Wavelength Shifters Built at Budker INP

Intended Light Source	Magnetic field in T: max and (normal)	Year
Siberia-1 (Moscow)	5.8 (4.5)	1985
PLS (Korea)	7.68 (7.5)	1995
LSU-CAMD (USA)	7.55 (7.0)	1998
SPring-8 (Japan)	10.3 (10.0)	2000
BESSY-II (Germany)	7.5 (7.0)	2000
BESSY-II (Germany)	7.5 (7.0)	2001

The Taiwan Light Source also has found a wavelength shifter to be appealing to their users. A 6.5-T, warm-bore, cryogen-free device was installed in 2002. It provides 5-33-keV photons to three beamlines. [9,10]

SUPERBENDS

Rather than occupy space in a straight section in the storage ring, as wavelength shifters do, a superconducting single-bend magnet can be installed in place of a regular bending magnet, such as the "superbends" that were implemented at the Advanced Light Source (ALS) at Berkeley in 2001. Three of the 36 existing bending magnets were replaced. The original normal-conducting magnets have 1.3-T field and bend through an angle of 10°. The replacement superconducting magnets produce a 5-T field to accomplish the same 10° bend (in a smaller distance). The new superbends produce photons with a critical photon energy of 12 keV, as opposed to 3.1 keV for the original magnets, thereby providing the desired higher energy photons to users. [11] Four beamlines can be served by each superbend magnet.

In addition to all of its wavelength shifter experience, the Budker Institute built a superbend magnet that was installed on BESSY-2 in 2004. The 9-T superbend was designed and built in a collaboration between Budker and BESSY-2. [12] This magnet has four superconducting coil sections, with two based on Nb_3Sn conductor and the other two based on NbTi (one of which is for correction).

WIGGLERS

The desire for higher-energy photons is also what led to the development of the two superconducting MAX-Wigglers. The MAX-Wigglers are based on NbTi superconductor that is wound around an iron core and then epoxy impregnated. There are matching coils above and below the gap. A cold-bore vacuum pipe runs between the upper and lower arrays of coil-wrapped poles. The superconducting coils and cores are immersed in a liquid He bath. With a 320-l He reservoir and a consumption rate of 2.5 l/hr, the wiggler can operate for 5 days. The two wigglers have been operating successfully for nearly a decade. [13] Some parameters of these devices are given in Table 2.

Table 2: MAX-Wiggler Parameters

Wiggler period	61 mm
Vertical beam stay-clear aperture	10.2 mm
Horizontal beam stay-clear aperture	70 mm
Magnetic aperture	12 mm
Total length of magnetic assemblies	1512 mm
Cryostat length, flange to flange	2.5 m
Total number of poles	49
Peak field	3.54 T
Deflection parameter K	21.2

The Budker Institute also turned its expertise in superconducting devices to wigglers, building devices for many light sources. The list of recent devices is shown in Table 3. [7, 14]

The Taiwan Light Source also built and installed some superconducting wigglers. One, a 3.2-T, 6.0-cm-period wiggler with 32 poles, was installed in 2004. It provides 5-20-keV photons to three protein crystallography beamlines. In addition, three similar devices with only 16 poles but with a modification to allow for a wider beam chamber have been installed. [9, 15]

UNDULATORS

Superconducting wavelength shifters, superbends, and wigglers are currently enabling good science at many light sources. Nonetheless, many light sources would like a superconducting undulator (SCU). Projects at various labs and in industry have sought to develop a superconducting undulator, resulting in some partial successes and other positive developments along the way. However, a fully functioning superconducting undulator for a synchrotron radiation source is still in process.

There was, however, a helical superconducting undulator installed on VEPP-2M to make measurements of the polarization of the colliding electron and positron beams. It was installed in 1986 and used for about 8 years. [16]

An attempt to build a superconducting undulator took place at Brookhaven National Laboratory, as part of an FEL at the Accelerator Test Facility. Due to a length limitation at the machining company, the undulator was to consist of three segments butted end-to-end to make the full yoke. A good-quality field was achieved within an undulator segment, but the field at the transitions between the segments was problematic. [17]

Later, a vertical test facility that could be used to test and measure SCU magnetic structures was built for use in National Synchrotron Light Source (NSLS) projects or, possibly, as part of a collaboration. [18]

Table 3: Superconducting Wigglers Built at Budker INP

Light Source	Field (T)	Period (mm)	No. of poles	Pole gap (mm)	Year
BESSY-II	7	148	17	19	2002
ELETTRA	3.5	64	49	16.5	2002
CLS	2.1	34	63	13.5	2005
DLS	3.5	60	49	16.5	2006
Siberia-2	7.5	164	21	19	2007
CLS	4.2	48	27	14.5	2007
DLS	4.2	48	49	13.8	2009
LNLS	4.1	60	35	18.4	2009
ALBA	2.1	30	119	12.6	2010

Another test device was built jointly by ANKA and the Karlsruhe Institute for Technical Physics and tested on the Mainz Microtron (or MAMI). It had superconducting wires wrapped in grooves that were cut into an iron core. Liquid He flowed through the center of the top and bottom iron cores, whose separation could be adjusted. The device was tested with a low beam current and gave promising results. [19]

Since then, work has proceeded at ANKA and the Karlsruhe Institute for Technology (KIT), along with contributions from industrial partners. A proof-of-principle demonstration occurred at ANKA in 2005 when a 14-mm-period, 100-period device with NbTi coils was installed. The magnetic gap of the device can be adjusted to 16, 12, or 8 mm, or opened to 25 mm during injection and ramping up of the beam in energy. A thin foil separates the beam vacuum from the SCU insulating vacuum. The device worked when it was tested with beam at ANKA, but it heated up more than expected, even with a gap of 12 mm. [20] This beam-induced heating limits the performance of the undulator.

Research has been and is going on into the cause of the heating. The expectation is that it is due to electron multipacting in the device. Bombardment of the walls by electrons can result in direct heating of the cold wall, thereby raising the temperature of the superconducting cores. It can also cause an increase in pressure when gas on the surface of the chamber desorbs. Calculations show that this desorption and heating alone cannot explain measured results, however. Instead, they are consistent with multipacting, where one electron hits the wall, knocks out other electrons that get accelerated due to an unfortunate arrival time for the next beam bunch, and then in turn hit the wall, knocking out more electrons in a cascading process. [21] Other possibilities that have been considered include synchrotron radiation from upstream magnets, resistive heating by image currents, or ion bombardment. [22] A diagnostic vacuum chamber, COLDDIAG, is in preparation and planned for installation on the Diamond Light Source in June 2011. [23]

The ANKA/KIT team is now partnering with Babcock-Noell and a new SCU, 100.5-periods long, with a 15-mm period, using NbTi, is close to realization. The new design is also cryogen-free, but the beam liner and the superconducting coils are thermally isolated and separately cooled. Magnetic measurements on the magnetic structure have found that with some simple mechanical shimming, phase errors of 3.5° should be reachable. [24]

A very active program has been ongoing at the Taiwan Light Source to develop superconducting undulators. Various winding procedures were tested, and prototype magnet structures were evaluated. [25] A scheme using iron pieces to shim the field of an SCU was simulated and tested, as was a scheme using an additional trim coil, with good agreement between simulation and measurement. It was noted, however, that shimming without the need for additional coils was less expensive in both heat loss through current leads and need for power supplies. [26] A measurement system in a vertical dewar is being used to characterize the field, though there is a challenge in knowing the precise position of the sensitive area of the Hall probe due to thermal contraction. [27]

The International Linear Collider project seeks to use a helical SCU as part of its positron production system. Research has been carried out by the HeLiCal collaboration in the United Kingdom toward building such an undulator. A number of short prototypes were successfully built and tested at the STFC Rutherford Appleton Laboratory. [28] Eventually, a full scale, 4-m-long, superconducting helical undulator was built [29]. Work is beginning on a planar SCU for Diamond and possibly a Nb_3Sn design. [30]

The team at the Advanced Photon Source (APS) has been working toward a superconducting undulator for some time in order to satisfy requests by users for more photons at higher energy. Initial test windings were successfully done using NbTi conductor. [31] Later, some testing was done with Nb_3Sn conductor. Although the maximum achievable current was limited by flux jumping because of a poorly-chosen conductor (the superconducting filament strands were too big), the current that was reached was still encouragingly higher than achievable with NbTi. [32] Collaborations were established with both Lawrence Berkeley National Laboratory and the National High Magnetic Field Lab in Tallahassee, FL to pursue the development of a Nb_3Sn-based SCU. As part of the collaboration, each of the three labs fabricated a short test magnetic structure section, and all three of the test pieces succeeded in reaching the expected critical current, showing that an SCU based on Nb_3Sn conductor is feasible. [32, 33, 34] Nonetheless, the additional challenges involved with Nb_3Sn conductor, and the ease with which a minor oversight during the fabrication process can result in a magnetic structure that won't work, led to the decision to first pursue an SCU based on NbTi. There are still many details to resolve on the way toward making an SCU that would be compatible with installation on a storage ring, especially a storage ring where there is significant emphasis on the goal of a reliability over 97%.

An assembled design for the core on which the superconducting wire would be wound was chosen, instead of machining grooves into a solid block. Poles are made separately and the surfaces that will touch the conductor are polished smooth. The central core is also polished, and the poles fit into notches machined in the core. The result is that any surface the superconductor touches has been polished smooth. This helps prevent shorts between the conductor and the core. Winding techniques were developed and refined at the APS. For the epoxy impregnation, assistance at the initial stage was obtained from Sasha Makarov and his co-workers at Fermilab. More recently, vacuum impregnation capability has been developed at the APS.

A number of short, 10-pole, 1.6-cm-period-length magnets were built and tested at the APS to verify construction techniques. Subsequently, three 42-pole magnetic assemblies, two with iron central cores and iron poles and one with aluminum core and iron poles, were manufactured and tested in a vertical helium bath cryostat. It was shown that replacement of the iron central core with an aluminum one leads to a drop in peak field of about 7%. The magnetic structures were trained up to about 760-A quench current. The designed operating current ranges from 200 A (to generate 25-keV photons in the first harmonic) to 500 A (to produce the field of 0.64 T required for generation of 20-keV photons).

In order to achieve low phase errors and the associated high brightness at higher harmonics, special attention was paid to precise machining and assembly of the magnetic cores followed by precise winding with the round 0.75-

mm NbTi wire. The measured deviation in the core groove dimensions was only about 9-μm r.m.s. As a result, remarkably low phase errors were measured for the magnets. A phase error of about 2° r.m.s. at the nominal operating current was recently achieved without any shimming. For comparison, the standard APS Undulator A hybrid permanent magnet device is routinely tuned to have phase errors about 4°, but this usually requires careful magnetic shimming of the device. This successful result of the R&D phase now leads to the next stage of building the first test superconducting undulator for APS users.

In order to design the cryostat that would keep the magnetic structures cold, the APS sought the assistance of the team from the Budker Institute. Two key experienced individuals (N. Mezentsev and V. Syrovatin) spent a few months at the APS working with APS staff to design a cryostat that was suited for the APS SCU. One conceptual change was made from the cryostats that have been used for the Budker wigglers. Instead of having the magnetic structure immersed in liquid He, the design for the APS is based on a thermosiphon cooling scheme, with a reservoir of liquid He and piping that takes the cryogen through the cores of the magnetic structure and then back to the reservoir to be recondensed. It will be a closed system. The beam chamber is thermally isolated from the magnetic cores and is expected to be at about 20K. [35] After the departure of the Budker engineer, the detailed drawings are being finished by APS personnel. They are nearly complete, and procurements are beginning.

A magnetic measurement system also must be designed for the completed undulator. Again, the APS has benefited from the expertise of the Budker Institute by having V. Lev and V. Tsukanov visit the APS to develop a conceptual design for a measurement system. The measurement system will be an adaptation of Budker's warm bore system, but with the ability to measure the field using a translating Hall probe, a stretched rotating coil that can also translate, and a stretched twisted coil. [36]

SUMMARY AND DISCLAIMER

A lot of good work has been done through the years on a variety of types of superconducting devices for light sources, and laboratories around the world have been involved and made their contributions. It is inevitable with an overview like this that some excellent work that has made valuable contributions has been overlooked, but it was not by intent.

We look forward to an exciting future for superconducting undulators!

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