STATUS OF THE DEVELOPMENT OF SUPERCONDUCTING UNDULATORS AT THE ADVANCED PHOTON SOURCE *

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Abstract

Superconducting planar undulator (SCU) technology has been developed and is currently in use at the Advanced Photon Source (APS). The successful experience of building and operating the first short-length, 16-mm period length superconducting undulator, SCU0, paved the way for two 1-m long, 18-mm period devices, SCU18-1 and SCU18-2. The first of those undulators has been in operation since May 2015, while the second one replaced SCU0 in September 2016, after completion of its continuous operation for over 3.5 years. The possibility of building planar SCUs with a high quality field has been demonstrated at the APS. The measured phase errors of SCU18-2 at the design operational current are only 2 degrees rms, for example. An FEL SCU prototype— a 1.5-m long, 21-mm period undulator— was also built and tested as part of an LCLS SCU R&D program aimed at demonstration of the availability of SCU technology for free electron lasers. This undulator successfully achieved all LCLS-II undulator requirements, including a phase error of 5 degrees rms. The superconducting undulator technology also allows the fabrication of circular polarizing devices. Currently, a new helical SCU is under construction at the APS. Installation of this device in the APS storage ring is planned for the end of 2017. In addition, the concept of a novel Superconducting Arbitrarily Polarizing Emitter, or SCAPE, has been suggested and is now under development.

INTRODUCTION

Superconducting undulators are electromagnetic undulators that employ superconducting coils for generating magnetic field. Simulations suggest that superconducting undulator technology outperforms other undulator technologies in terms of undulator peak field for a given magnetic gap and period length [1]. The higher undulator field leads to generation of higher photon fluxes, especially at higher photon energies. This predicted advantage of SCU technology was demonstrated at the APS by operational performance of the first superconducting undulator, SCU0. While only having a magnetic length of 0.3 m, this device generates a higher photon flux than a 2.4-m long hybrid undulator at the photon energies above 80 keV [2].

In addition, the SCU technology allows for the realization of various types of undulators, including planar and circular polarizing devices. This makes the SCU technology very attractive for both storage ring light sources and free electron lasers (FELs).

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PLANAR UNDULATORS

Undulators SCU18-1 and SCU18-2 for the APS

After the completion of SCU0, the APS team built two more planar undulators for the APS: SCU18-1 and SCU18-2. These devices are similar in design and use similar cryostats. Their parameters are given in Table 1. The SCU18-1 undulator has been in operation in Sector 1 of the APS since May 2015, and the SCU18-2 replaced SCU0 in Sector 6 in September 2016.

Table 1: SCU18-1 and SCU18-2 Parameters

Parameter	Value
Cryostat length, m	2.06
Magnetic length, m	1.1
Undulator period, mm	18
Magnetic gap, mm	9.5
Beam vacuum chamber vertical aperture, mm	7.2
Undulator peak field, T	0.97
Undulator parameter K	1.63

The measured flux of SCU1 in comparison with the 2.3-cm-period and 3.3-cm-period permanent magnet undulators U23 and U33 is plotted in Fig. 1. The measurements show SCU1's considerable gain over the two permanent magnet undulators. Starting from the 3rd, 5th and 7th harmonics of SCU1's are routinely used for multitude of x-ray experiments at Sectors 1 and 6 of the APS.

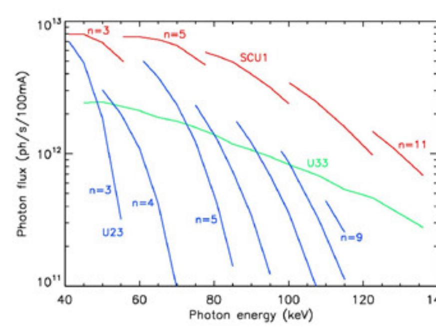

Figure 1: Measured odd-harmonic SCU1 tuning curves (red) of monochromatic flux through 0.5×0.5 mm^2 aperture at 27.5 m compared with those of permanent magnet undulators U33 (green) and U23 (blue).

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LCLS R&D Undulator

This 1.5-m long NbTi undulator was built in 2015-16 as a part of the LCLS SCU R&D project aimed at demonstrating that SCU technology can achieve challenging specifications for FEL undulators [3]. The parameters of the device are listed in Table 2.

Table 2: Parameters of LCLS R&D Undulator

Parameter	**Value**
Cryostat length, m	2.06
Magnetic length, m	1.5
Undulator period, mm	21
Magnetic gap, mm	8.0
Beam vacuum chamber vertical aperture, mm	5.7
Undulator peak field, T	1.67
Undulator parameter K	3.26

All LCLS-II undulator specifications have been met by the APS LCLS-II SCU prototype. The most challenging requirement— achieving a phase error below 5° rms over a 1.5-long magnet— triggered a dedicated study of the field error sources in a planar SCU. The precise measurements of the core geometry after each fabrication step revealed deformation of a core during a vacuum resin impregnation. In order to compensate the magnetic gap enlargement due to this core bowing, design changes were implemented and a method of measuring the magnetic gap of the magnet assembly was developed [4]. As a result, the external mechanical clamps are installed onto the magnet assembly at gap spacer locations distributed along the length of the device. In this arrangement, the magnetic gap is defined by the precision of the gap spacers that are machined to 10 µm rms. The technique was first tested in the LCLS SCU magnet where five clamps were installed over the length of 1.5 m. This magnet has achieved a phase error of 3.8° rms, thus meeting the specification requirement of 5° rms.

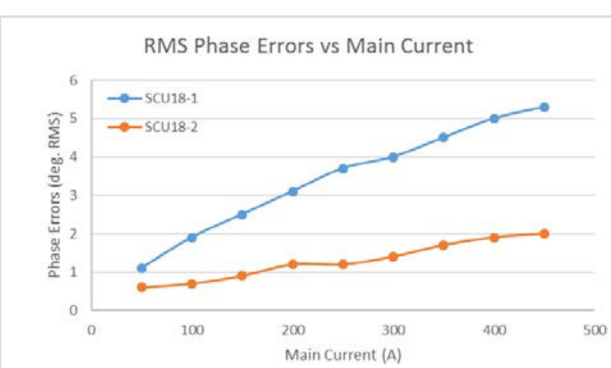

Figure 2: Phase errors versus the main current of SCU18-1 and SCU18-2.

The developed gap compensation scheme was fully implemented in the SCU18-2 magnet, which achieved a phase error as low as 2° rms. For comparison, the phase errors in the SCU18-1 magnet that does not have gap compensation clamps are greater than 5° rms, as seen in Fig. 2.

CIRCULAR POLARIZING UNDULATORS

Helical SCU

Superconducting undulator technology offers the possibility of building circular polarizing undulators based on helically wound coils. We are currently working on a helical SCU (HSCU) for the APS. The parameters of the HSCU are given in Table 3.

Table 3: Design Parameters of Helical SCU

Parameter	**Value**
Cryostat length, m	1.85
Magnetic length, m	1.2
Undulator period, mm	31.5
Magnetic bore diameter, mm	31.0
Beam vacuum chamber vertical aperture, mm	8
Beam vacuum chamber horizontal aperture, mm	26
Undulator field $B_x=B_y$, T	0.4
Undulator parameter $K_x=K_y$	1.2

This undulator will be used in Sector 7 of the APS for coherent scattering experiments by utilizing the 1st harmonic of the collimated direct x-ray beam. The HSCU quasi-monocromatic beam does not require additional monochromatization, and therefore the useful photon flux is expected to be two orders of magnitude higher compared to undulator A (U33), as shown in Fig. 3.

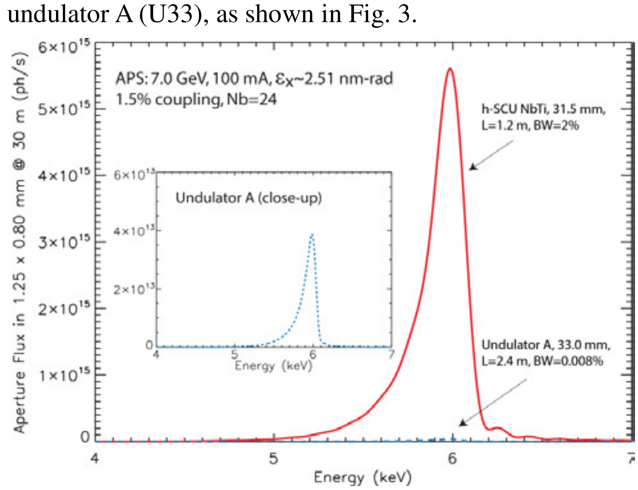

Figure 3: Calculated HSCU flux through 1.25 × 0.8 mm^2 aperture at 30 m compared with the aperture flux of undulator A (U33) after a monochromator.

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The HSCU magnet uses a pair of helical coils wound on a round former to generate helical magnetic field. A new winding scheme for such a magnet was developed at the APS. It allows for the building of compact helical magnets that have no components sticking outside the external diameter of the winding former (see Fig. 4).

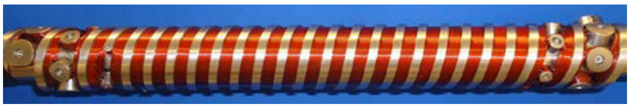

Figure 4: Helical SCU magnet prototype.

A 300-mm long magnet prototype was built and tested in a LHe bath cryostat. The field profile was measured with a moving Hall probe and showed a good agreement with the magnetic simulation, as seen in Fig. 5.

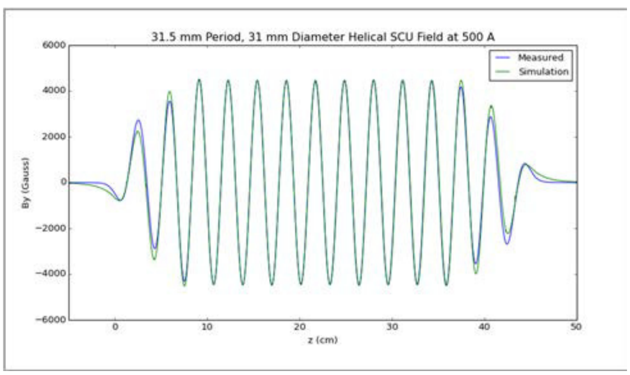

Figure 5 : Measured and simulated field of HSCU prototype magnet.

The helical undulator will use a new cryostat, which is designed based on the experience of operating three SCU0-type cryostats, as well as a rigorous thermal analysis [5]. The HSCU cryostat is more compact than the SCU0-type cryostat (see Fig. 6), and is cheaper due to better utilization of standard vacuum components.

Figure 6: Design models of SCU0-type cryostat (left) and HSCU cryostat (right).

SCAPE

Some of the APS users would like to have a photon source that can generate both circular and planar polarized photons. To answer this challenging request, we have developed the concept of a Super Conducting Arbitrary Polarising Emitter, or SCAPE. This electromagnetic undulator employs four planar magnetic cores assembled around a cylindrical beam chamber, as depicted in Fig. 7.

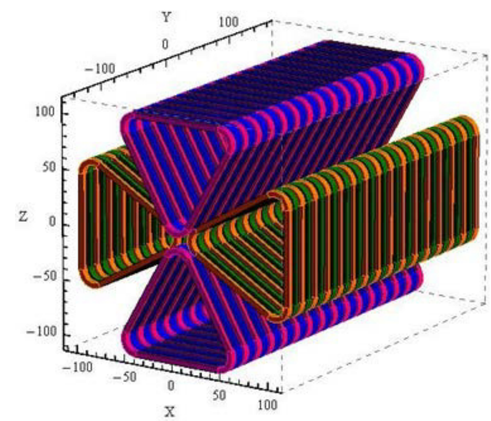

Figure 7: Concept of SCAPE— a universal SCU with four planar superconducting coil structures. A round beam chamber is not shown.

Each core contains a set of superconducting coils with the currents in opposite directions, similar to the planar undulator cores. When all four cores are energized, a circular magnetic field is generated. When either the vertical or horizontal pair of cores are energized, a planar magnetic field is generated. The direction of polarization can be changed by reversing the currents in the coils. More details on the SCAPE design are given in [6].

We are planning to build a prototype of this novel undulator in 2017. Such a device could be very attractive for a light source with a multi-bend achromat lattice that enables utilization of a round beam vacuum chamber, as well as for free electron lasers.

CONCLUSION

Work on development of superconducting undulator technology continues at the APS. The first short undulator, SCU0, successfully operated at the APS for 3.5 years. Two 1-m long similar SCUs, SCU18-1 and SCU18-2, were built and installed on the APS storage ring over the course of the last two years. A 1.5-m long undulator was also fabricated and tested as a part of the LCLS R&D project in 2015-16. In addition, circular polarizing superconducting undulators have been included into the scope of our work. The APS SCU team is currently working on a helical SCU for the APS, as well as on a prototype of a novel universal SCU – SCAPE.

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