STATUS OF THE DEVELOPMENT OF SUPERCONDUCTING UNDULATORS FOR STORAGE RINGS AND FREE ELECTRON LASERS AT THE ADVANCED PHOTON SOURCE *

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Abstract

Development of superconducting undulator (SCU) technology continues at the Advanced Photon Source (APS). The experience of building and successfully operating the first short-length, 16-mm period length superconducting undulator SCU0 paved the way for a 1-m long, 18-mm period device— SCU18-1— which has been in operation since May 2015. The APS SCU team has also built and tested a 1.5-m long, 21-mm period length undulator as a part of the LCLS SCU R&D program, aimed at demonstration of SCU technology availability for free electron lasers. This undulator successfully achieved all the requirements including a phase error of 5° rms. Our team has recently completed one more 1-m long, 18-mm period length undulator— SCU18-2— that is replacing the SCU0. We are also working on a helical SCU for the APS. The status of these projects will be presented.

INTRODUCTION

Magnetic 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).

PLANAR UNDULATORS

Undulators SCU18-1 and SCU18-2 for 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 is 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
Operating current, A	450

LCLS R&D undulator

This undulator was built as a part of LCLS SCU R&D project aimed at demonstrating that SCU technology can achieve challenging specifications for FEL undulators [3]. The parameters of this device is given 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
Operating current, A	588

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As with all other superconducting undulators built at the APS, this device was wound with a round NbTi wire into grooves that are precisely machined on a steel core. Two cores form a magnet assembly, as shown in Fig. 1 [4].

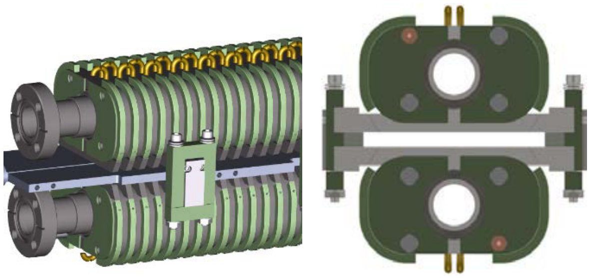

Figure 1: Assembly of two cores with precise spacers defining the magnetic gap.

The most challenging requirement for this device was to achieve a phase error below 5° rms over a 1.5-long magnet. In order to meet this requirement, a special R&D program was launched as described below.

Achieving low phase errors

The challenging requirement on the phase error triggered a dedicated study of field errors and their sources in a planar SCU. Preliminary simulation indicated that the magnet cores should be machined within the tolerance of 50 µm and must be precisely wound [5]. The core dimensions including core flatness, groove depth and width were measured. The core flatness after machining was within 33 µm peak-to-peak, the groove dimensions were within 30 µm for the groove depth and within 50 µm for the grove width. The cores were measured again after winding and showed no change in the flatness. The quality of conductor winding can be seen in Fig 2.

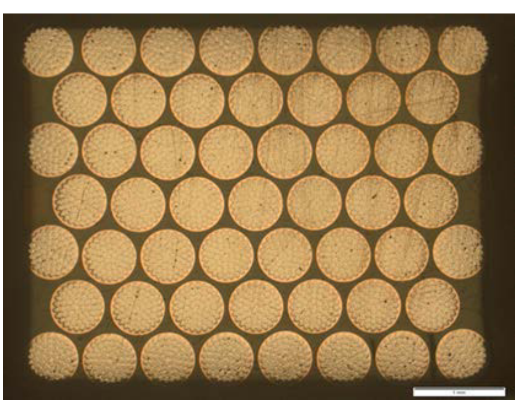

Figure 2: Photograph of SCU winding cross section.

After winding, the cores are impregnated with epoxy resin in a vacuum mold. This technological operation requires heating the mold with core in it up to 135 °C. The dimensional inspection of the impregnated core showed that core developed a bow at a level of 150 µm.

In order to compensate the magnetic gap enlargement due to the core bowing, design changes were implemented and a method of measuring the magnetic gap of the assembly was developed [6]. 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.

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 is greater than 5° rms, as seen in Fig. 3.

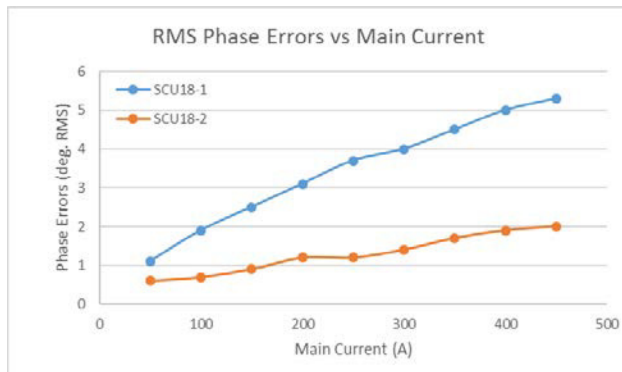

Figure 3: Phase errors versus the main current of SCU18-1 and SCU18-2.

CIRCULAR POLARIZING UNDULATORS

Helical SCU

Superconducting undulator technology offers a possibility of building circular polarizing undulators. We are currently working on a helical SCU (HSCU) for the APS. The parameters of the HSCU are listed 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

The expected spectrum of HSCU is shown in Fig. 4.

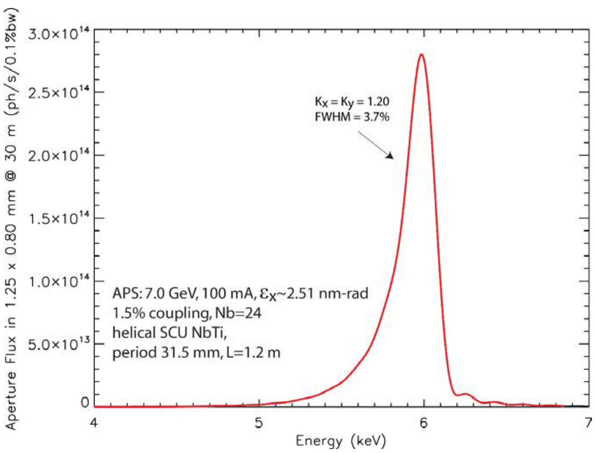

Figure 4: Calculated spectrum of HSCU.

This 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 [7]. The HSCU cryostat is more compact than the SCU0-type cryostat, and cheaper due to better utilization of standard vacuum components.

SCAPE

Some of the APS users would like to have a photon source, which can generate both circular and planar polarized photons. To answer this challenging request, we have developed a concept of a Super Conducting Arbitrary Polarising Emitter, or SCAPE. This electromagnetic undulator employs four planar magnetic cores assembled around a cylindrical beam chamber, Fig. 5.

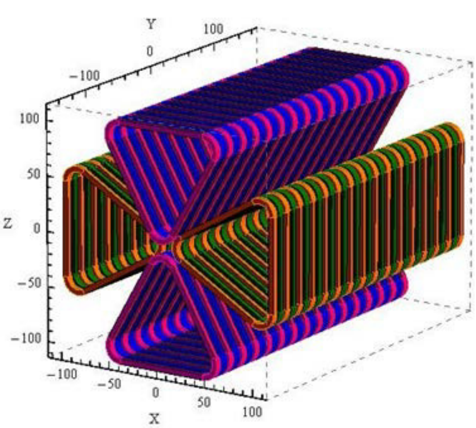

Figure 5: Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

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 vertical or horizontal pairs of cores are energized, a planar magnetic field is generated. The direction of polarization can be changed by reversing the currents in the coils.

Initial magnetic simulations suggest that the magnetic field at a level of 0.5 T can be generated in a SCAPE with the period length of 20 mm and the magnetic gap of 12 mm.

We are planning to build a prototype of this novel undulator in the near future. 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. In addition to the first short undulator SCU0 that has been in operation since January 2013, two 1-m long similar SCUs, SCU18-1 and SCU18-2, were built and installed on the APS storage ring over the course of two years. A 1.5-m long undulator was also fabricated and tested as a part of LCLS R&D project. Systematic study of the field errors in planar SCUs has led to a significant improvement in the undulators field quality. The phase errors of 2° rms were achieved without any magnetic shimming in SCU18-2 and of 3.8° rms in the 1.5-m long LCLS SCU undulator.

We are also working on a helical SCU for the APS as well as on a conceptual design of a novel universal SCU – SCAPE.

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