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STATUS OF THE SUPERCONDUCTING UNDULATOR PROGRAM AT THE ADVANCED PHOTON SOURCE*

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Abstract

Since 2013 there has been at least one superconducting undulator (SCU) in operation at the Advanced Photon Source (APS), currently there are two planar SCUs and one helical SCU. The combined operational experience of SCUs at the APS is more than 11 years and counting. Through all these years, APS SCUs operated with the predicted or better than predicted radiation performance and with 99% availability. With this demonstrated reliability and experimentally confirmed spectral performance, the APS upgrade project is planning on leveraging the advantages of SCU technology. The present planar SCUs are comprised of 1.1-meter long magnets, each operated within a 2-meter long cryostat, while the planar SCUs for the upgrade will have two 1.8-meter long magnets operating within a 5-meter long cryostat. Progress is also being made in other areas of SCU development with work on an arbitrary polarizing SCU, referred to as SCAPE, and a planar SCU wound with Nb_3Sn superconductor. A Nb_3Sn SCU is being designed with two 1.3-meter long magnets within a 5-meter long cryostat, and installation is planned for 2021. Also under development are the alignment and magnetic measurement systems for use with the 4.8-meter long cryostat.

INTRODUCTION

Utilizing the proven advantage of SCUs for generating hard x-rays and building on the success of years of reliable operation of superconducting undulators (SCUs) at the APS [1], the APS upgrade (APSU) project has decided to incorporate SCU technology to leverage the capability of generating higher on-axis magnetic fields at a given magnetic period and gap than other undulator technologies. Combining SCU technology with the upgrade of the storage ring to a multi-bend achromat lattice along with a doubling of the stored beam current, the generated x-rays of the APSU are expected to be two to three orders of magnitude brighter than the APS.

Planar SCUs for APSU will scale the previous design of a single 1.1-meter long undulator housed in a 2-meter long cryostat to two undulators housed in a 4.8-meter long cryostat. Presently, the cryostat and magnets are being fabricated and testing of the first article is planned for 2020. Also under development are a novel magnetic measurement system that will allow the SCU magnetic field to be characterized under normal operating conditions after final assembly in the long cryostat and an alignment system that will provide position data during cooldown of the cryostat.

Development of a superconducting arbitrary polarizing emitter (SCAPE) is also continuing after the testing of a 0.5-meter long prototype. A feasibility study of modulating the undulator field of a SCAPE style magnet using alternating current is on-going.

In advance of the shutdown of the APS for APSU, development of a Nb_3Sn SCU is underway. Two 1.3-meter long SCUs wound with Nb_3Sn superconductor are being prepared to be assembled into a 4.8-meter long cryostat. Installation is planned for 2021 to allow for testing and operation on the APS storage ring.

HISTORY OF SCUs AT THE APS

Installation and subsequent commissioning of the first 0.33-meter long, 16-mm period SCU, SCU0, in sector 6 at the APS occurred in 2013. SCU0 was replaced by a 1-meter long, 18-mm period SCU [2], SCU18-2, in September of 2016. SCU18-1, also 1-meter long with a period length of 18 mm, was installed in sector 1 in May of 2015. And the most recent SCU to be incorporated into sector 7, see Fig. 1, in 2018 was the 1.2-meter long helical SCU with a 31.5-mm period.

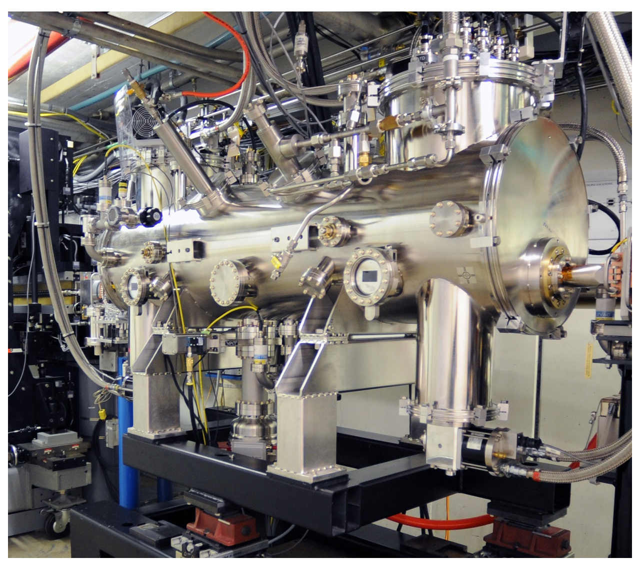

Figure 1: HSCU cryostat installed in sector 7 of the APS storage ring. Photo: R. Fenner.

In each case the undulator was installed on the storage ring during one of the three maintenance periods of the APS. At the end of the mantenance period and before the start of

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Table 1: SCU Operational Statistics

		SCU0 and SCU18-2			SCU18-1			HSCU		
Year	**APS**	**Oper.**	**Down**	**Quench beam/ self**	**Oper.**	**Down**	**Quench beam/ self**	**Oper.**	**Down**	**Quench beam/ self**
2013	4871 h	4189 h	20 h	34/3	-	-	-	-	-	-
2014	4926 h	4391 h	174 h	32/2	-	-	-	-	-	-
2015	4940 h	4834 h	0 h	26/1	3059 h	0.1 h	5/0	-	-	-
2016	4941 h	4647 h	0 h	9/0	4585 h	0.3 h	11/1	-	-	-
2017	4840 h	4756 h	0 h	8/1	4818 h	0.75 h	13/2	-	-	-
2018	4853 h	4755 h	5 h	14/1	4710 h	0.59 h	14/2	751 h	0 h	0/0
2019	3383 h	1564 h	4.3 h	7/1	3359 h	0 h	5/0	815 h	0 h	0/0
Total	**32,754 h**	**29,136 h**	**203.3 h**	**130/9**	**20,531 h**	**1.74 h**	**48/5**	**1566 h**	**0 h**	**0/0**

user operations, the SCUs were commissioned to verify the undulator field quality met the storage ring requirements. In all cases the devices were immediately turned over to the beamline for user operations. The combined operation of SCUs at three sectors of the APS has exceeded 11 years.

Displayed in Table 1 are the operational data of the three sectors. Shown are the operating hours, downtime, and quench data for each SCU in comparison to the delivered beamtime of the APS for a given year. The quench column data distinguishes between a quench of the SCU due to a loss of the electron beam in the storage ring and a self quench.

It is important to note that stored beam has never been lost because of a self quench of an SCU. A self quench occurs roughly once a year. Beam induced quenches were significantly reduced after the installation of an abort kicker in 2015 [3]. The increased downtime of SCU0 in 2014 was due to reduced capacity of one of the cryocoolers after routine maintenance. Overall, the availability of SCUs for user operation has been in excess of 99 %.

SCU AND SUB-SYSTEMS FOR APSU

Four planar SCUs consisting of two undulator magnets residing in a 4.8-meter long cryostat are planned to be installed in APSU. The two undulators can be assembled as either a single in-line configuration, or an independent canted configuration. The period length is either 16.5 mm or 18.5 mm and the longest undulator magnet will by 1.9 m for the in-line configuration. All of the magnets will be wound with NbTi superconductor. Reduction of the magnetic gap from the current 9.5 mm for APS to 8 mm for APSU can be achieved due to the vertical beam stay clear of 6.3 mm and a reduction of the aluminum beam chamber wall thickness to 0.4 mm at the thinnest location. This allows for a vacuum gap of 0.45 mm between the magnet and beam chamber to provide for thermal isolation.

Major components of the cryostat include the vacuum vessel, thermal shield, liquid helium (LHe) tank, magnets, and beam chamber (see Fig. 2). There are three cooling circuits provided by up to seven Gifford-McMahon cryocoolers: thermal shield, beam chamber, and magnet. More details of the cryostat can be found in [4, 5].

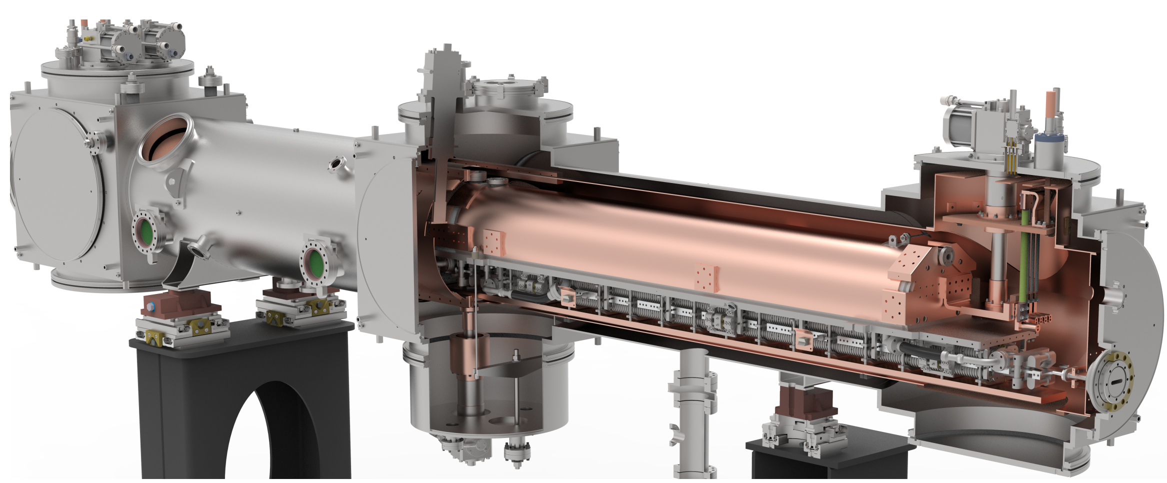

Figure 2: Rendering of the APSU cryostat showing the thermal shield, end turret current leads, LHe tank, beam chamber, and magnets supported from below the LHe tank .

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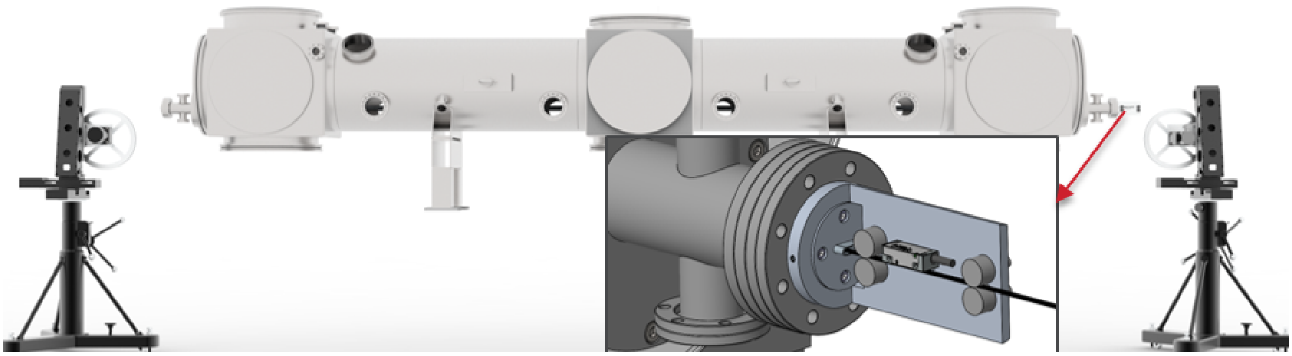

Figure 3: Hall probe drive system mounted on survey and alignment stands at either end of the production cryostat. The inset picture shows the flexible encoder scale and readhead that is used for position feedback during data acquisition [7].

To monitor the position of the beam chamber and magnet assemblies inside the cryostat, a laser scanning tool and method was developed [6]. The laser displacement sensor and drive assembly are mounted on an external, optically clear window flange of the cryostat. There are four targets mounted on each undulator assembly that are scanned to determine the position of the cold mass assembly when the cryostat is undergoing a cooldown. Relative shifts can be monitored during thermal cycles and long term stability of the alignment of the SCU can be tracked.

After the challenges of the cryostat details have been resolved and the SCU is operational, the undulator magnetic fields have to be characterized in the lab to verify the requirements are met to enable user operation in the storage ring. A new magnetic measurement system [7] has been developed to provide the capability to perform magnetic measurements while the magnet is powered after final assembly in the 4.8-meter long cryostat. The system consists of a guide tube placed in the beam chamber aperture and heated to room temperature. This allows for ambient pressure and temperature calibrated Hall effect sensors to be used. Both Hall sensor field scans and wire based measurements are accommodated by the system.

A novel drive system for the Hall sensor based measurements has been designed and constructed. Combining a tensioned, flexible, liinear encoder scale between two spools and using an accompanying readhead to acquire position data, the need for a long linear stage is eliminated (see Fig. 3). All components of the system have been acquired and the system is currently being commissioined in the lab by measuring a previously characterized permanent magnet undulator.

Nb_3Sn SCU AND SCAPE

Progress on the development of an SCU using Nb_3Sn based technology[1] is proceeding after testing several short prototypes [8] which were used to incrementally improve the manufacturing of the magnet design. The final short model reached 100 % of the short sample prototype and the design is being scaled up to test a 0.5-meter long undulator structure before manufacturing the full length undulator with 1.3-meter long magnets. Two undulators will be operated within a cryostat very similar to the APSU design and installation on the APS storage ring is planned for 2021.

An investigation into modulating the undulator field in a SCAPE style SCU [9] using alternating current is underway as part of a laboratory directed research project. Modulating the field in this manner incurs losses in the superconductor and may affect the performance of the undulator. Several short prototypes were wound with various conductor and coil configurations to quantify the losses based on the frequency and amplitude modulation of the current [10].

[1] Nb_3Sn project is developing in collaboration with FNAL and LBNL.

CONCLUSION

Development of high quality SCUs at the APS continue in preparation for the APSU. A 4.8-meter long cryostat is currently in production and expected to be completed in the fall of 2019. Manufacturing of the planar magnetic structures is expected to be complete at the beginning of 2020. Supporting subsystems have been developed to aid in the alignment and magnetic measurement of the undulator in the long cryostat. Progress on the implementation of a Nb_3Sn based SCU is progressing along with a feasability study on modulating the undulator field of a SCAPE style device.

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