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EXPERIENCE OF OPERATING A SUPERCONDUCTING UNDULATOR AT THE ADVANCED PHOTON SOURCE*

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Abstract

A superconducting test undulator SCU0 was installed into the storage ring of the Advanced Photon Source (APS) in December 2012 and has been in user operation since January 2013. The first year's experience of operating such a novel insertion device at the APS is summarized in this paper. The performance of the SCU0 as a photon source is presented. The measured heat load from the electron beam is described together with the observed cryogenic behaviour of the device. The effect of the SCU0 on the APS electron beam is also presented.

INTRODUCTION

Interest in superconducting undulators at the APS was stimulated by the fact that, for the same vacuum gap and period length, the SCUs can reach a higher magnetic field than any other undulator technology, including cryogenic permanent magnet undulators [1]. A decade-long activity at the APS on the development of SCUs culminated in December 2012 with the installation of the first test undulator SCU0 into Sector 6 of the APS storage ring, Fig. 1, which was commissioned in January 2013 [2] and has been in user operation since. This paper presents the year-long experience of operating a superconducting undulator at the APS.

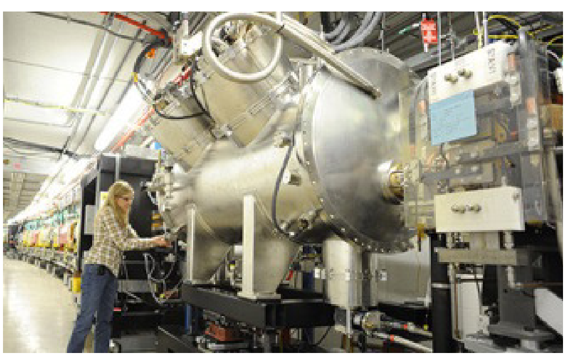

Figure 1: SCU0 installed in straight section 6 of the APS storage ring.

SCU0 PARAMETERS

The SCU0 incorporates a relatively short superconducting undulator magnet into a 2-m long cryostat. Description of the SCU0 can be found elsewhere [3-5], while the main parameters of the SCU0 are summarized in Table 1.

Table 1: Main Parameters of SCU0

Parameter	Value
Cryostat length, m	2.06
Magnetic length, mm	0.33
Undulator period, mm	16
Magnetic gap, mm	9.5
Undulator peak field, T	0.64* / 0.8 **
Undulator parameter K	0.96* / 1.20**
Photon energy at fundamental, keV	20-25* / 17-25**

* (design value) / ** (reached value)

EXPECTED AND OBSERVED HEAT LOADS

The SCU0 beam-induced heat loads are calculated and presented in [6]. Using the load maps of the cryocoolers given by a vendor, we estimated the observed heat loads on the thermal stages in the SCU0 as listed in Table 2. In this table, the 4-K stage refers to the SCU magnet and the helium circuit, the 20-K stage is the beam chamber and the internal thermal shield, while the 60-K stage corresponds to the outer thermal shield and the current leads.

Table 2: SCU0 Observed and Calculated Heat Loads

Beam current, mA	0	100	100	100	100
Bunch mode	0	24	324	24	24
SCU current, A	0	0	0	500	690
Observed (design) heat load, W					
4-K stage	1.20 (0.5)	1.20	1.16	1.30	1.45
20-K stage	0.1	14.6 (7.5)	4.1 (3.4)	14.5	15.3
60-K stage	80 (75)	97	85	112	128

The higher than expected heat load on the 4-K stage is likely due to excessive heat leak from the 20-K stage. As a result, the SCU0 is operating at a slightly higher pressure in the helium system. This issue is currently being addressed and will be improved in the next device.

The heat load on the beam chamber is also higher than calculated in [6]. This is likely due to the fact that the measured heat load includes 6 W resistive-wall beam

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chamber heat leaking from the warmer beam chamber transitions cooled by the 60-K stage, while in the 20-K stage calculations this heat leak was not considered.

OBSERVED SCU0 BEHAVIOUR

Magnet

The SCU0 magnet was designed to operate at the current of 500 A, but was operated mainly at 600—700 A, as clearly seen in Fig. 2. As a result, the undulator magnetic field of 0.8 T was reached. The SCU0 was operated during 84% of available user beam time.

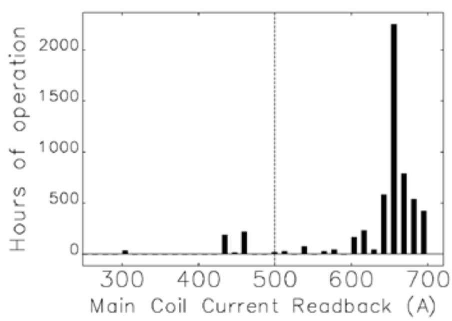

Figure 2: Histogram showing the SCU0 magnet operational current.

Cooling System

In the SCU0 the cooling power is provided by four cryocoolers [7]. We observed that actual temperatures in the system are below or at the design levels as given in Table 3. One can therefore conclude that a cooling system based on cryocoolers can provide an adequate cooling for a superconducting undulator.

Table 3: SCU0 Design and Observed Temperatures

Parameter	**Design temperature, K**	**Observed temperature, K**
Superconducting magnet	4.2	4.2-4.3
Beam chamber	20	9-13
Internal thermal shield	20	11-13
Outer thermal shield	60	34-36

The SCU0 superconducting magnet is cooled by liquid helium that passes through the channels in the magnet cores. Liquid helium (LHe) is contained in an internal tank that was initially filled with about 50 litres of LHe. Together with the magnet and associated piping, the LHe tank comprises a closed system. No helium loss in the system was observed in a 12-month period during normal operation, as shown in Fig. 3.

There was one occasion in Dec. 2013 when the cryocooler compressors stopped for a period of several hours when the chilled water supplied by an external water plant was shut down for maintenance. As a result,

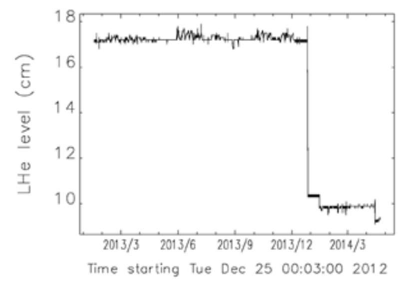

Figure 3: Level of liquid helium in an internal tank over a 15-month period.

the system started to warm up, and some helium was vented. The second drop in the LHe level visible on the plot is due to a small loss of helium during the replacement of a pressure safety relief valve. A third small drop occurred during a chilled water plant power outage. We did not add any helium into the system after those three losses. This did not cause any deterioration in the cooling system behaviour.

SCU0 Magnet Position Stability

The position of the SCU0 beam vacuum chamber, which is a part of the cold mass, was measured with the electron beam in Jan. 2013 after the initial cool down and chamber realignment, as described in [2]. Similar measurements were repeated in Jan. 2014, indicating that the beam chamber moved down by about 100 µm. This

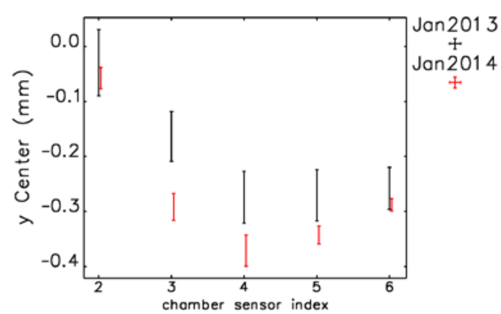

Figure 4: Measured vertical position of the beam chamber over a year period.

insignificant movement can be attributed to a creep of Kevlar strings that are holding the cold mass and the beam chamber inside the SCU0 cryostat.

Quenches

The SCU0 superconducting magnet quenches mostly when the electron beam is unintentionally dumped. The SCU0 is powered off during intentional beam dumps. A quench causes a magnet temperature rise from 4.3 K up to 10-15 K. It takes only 1-3 min for the core temperature to return back to 4.3 K, Fig. 5 (inset).

The pressure in the LHe tank after a quench is shown in Fig. 5. It is observed that the pressure rise in the tank due to a quench is about 70 Torr. It is also noticeable that the pressure drops in about 10 min to a half level of the pressure spike, but it then takes up to several hours for the

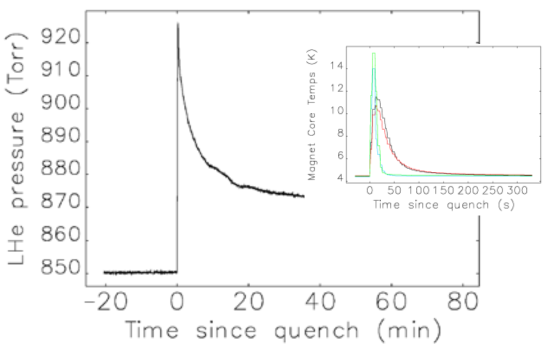

Figure 5: Pressure in the liquid helium system after a quench. Inset: Magnet core temperatures after the same quench measured by four temperature sensors on two magnet cores.

pressure to return back to the initial level. In any case, the pressure after quench does not reach the threshold of 1000 Torr for opening the pressure safety valve of the LHe circuit. Once the pressure decreases below 900 Torr, the SCU0 magnet could be powered up again.

SCU0 EFFECT ON THE STORAGE RING

During beam operation, the SCU0 beam chamber vacuum pressure is typically ~0.5 nTorr, measured on a cold cathode gauge located in the downstream transition. There have been no beam chamber vacuum pressure issues and no negative effects on the beam.

Cryocooler vibration has not been observed to adversely affect beam motion. Cryocooler vibration was measured on the beam chamber upstream of the SCU0. The integrated vibrational spectra power density (in the frequency range of 2-100 Hz) increased from 0.38 µm rms with the cryocoolers off to 0.68 µm rms with the cryocoolers on— less than a factor of two increase.

Magnet measurements show that the SCU0 meets the specifications for all design parameters except the skew quadrupole component [8]. The skew component is due to the geometry of the coil winding opposite the pole face (a new coil winding scheme will be used for the next device.) The skew quadrupole error produces a 10% change in beam coupling over a 700-A range. This effect is easily corrected by implementing feed-forward using adjacent skew quadupoles, which is checked at the beginning of every run and adjusted as necessary.

Beam tests were performed with fast and slow orbit feedbacks in open loop to better observe the effect of a quench. An induced quench caused very little beam motion, ~60 µm, and did not cause loss of the beam [2]. Over a 15-month operating period, only two unintentional quenches occurred with user stored beam. These quenches did not cause any beam loss, and quench recovery was transparent to storage ring operation.

The x-ray source properties of the SCU0 were characterized by measuring the photon flux passing through a bent-Laue monochromator and comparing the SCU0 photon flux with that from an in-line 3.3-cm-period length permanent magnet hybrid undulator (U33). At 85 keV,

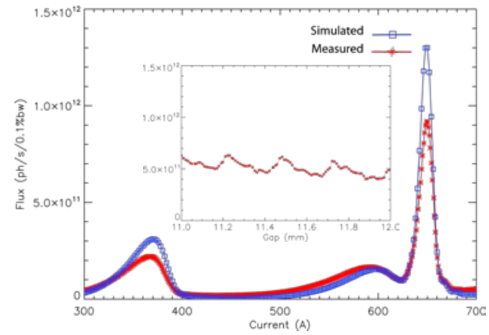

Figure 6: Photon flux comparisons at 85 keV. Main: Simulated and measured SCU0 photon flux. Inset: Measured photon flux of in-line U33.

the 0.34-m-long SCU0 produced ~45% higher photon flux than the 2.3-m-long U33. Figure 6 shows the simulated and measured photon flux at 85 keV for SCU0, and the measured photon flux for U33 (inset).

CONCLUSION

Since January 2013, the first test superconducting undulator SCU0 has been in user operation at the APS. The year-long experience of operating this device allows us to conclude that:

- Beam heat load can be correctly estimated.
- A cryocooler-based cooling system can be efficient.
- Helium loss-free operation is possible.
- SCU beam chamber does not require baking.
- Cryocooler vibrations do not disturb the beam.
- SCU quench does not cause beam dump.
- SCU can be successfully operated in user mode.

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