APS SUPERCONDUCTING UNDULATOR BEAM COMMISSIONING RESULTS*

Katherine C. Harkay#, Laura Boon, Michael Borland, Louis Emery, Glenn Decker, Roger Dejus, Jeffrey Dooling, Charles Doose, Joseph Gagliano, Quentin Hasse, Yury Ivanyushenkov, Matthew Kasa, Jonathan Lang, Douglas Robinson, Vadim Sajaev, Nicholas Sereno, Karen Schroeder, Yuko Shiroyanagi, Denise Skiadopoulos, Martin Smith, Emil Trakhtenberg, Aimin Xiao, Alexander Zholents, Efim Gluskin, ANL, Argonne, IL 60439, USA

Abstract

The first test superconducting undulator (SCU0) was successfully installed and commissioned at the Advanced Photon Source (APS) and is delivering 80- to 100-keV photons for user science. All the requirements before operating the SCU0 in the storage ring were satisfied during a short but detailed beam commissioning. The cryogenic system performed very well in the presence of the beam. The total beam-induced heat load on the SCU0 agreed well with the predictions, and the SCU0 is protected from excessive heat loads through a combination of orbit control and SCU0 alignment. When powered, the field integral measured with the beam agreed well with the magnet measurements. An induced quench caused very little beam motion and did not cause loss of the beam. The device was found to quench during unintentional beam dumps, but quench recovery is transparent to storage ring operation. There were no beam chamber vacuum pressure issues and no negative effect observed on the beam. Finally, the SCU0 was operated well beyond its design requirements, and no significant issues were identified. The beam commissioning results are described in this paper.

INTRODUCTION

Superconducting technology was used to build a fully functioning short-period test undulator (SCU0) at APS [1, 2]. Superconducting undulators allow a higher peak magnetic field compared to conventional devices, which can greatly benefit the light source community [3]. The SCU0 was designed and developed at APS in collaboration with Budker Institute of Nuclear Physics (BINP), Fermi National Accelerator Laboratory (FNAL), and U. Wisconsin, Madison. The SCU0 has a period length of 16 mm, magnetic gap of 9.5 mm, magnetic length of 0.34 m, and operates with photon energy in the first harmonic of 20-25 keV. The design operating current is 500 A, giving a design field of 0.64 T. The SCU0 incorporates several unique features, including an out-of-vacuum design, a beam chamber that is thermally isolated from the magnet cores, and a cryocooler cooling system. The SCU0, with a 2-m-long cryostat, was installed in the APS storage ring in Dec. 2012 (see Fig. 1).

SCU0 commissioning was completed over approx. 110 hr during an extended machine start-up period, and the device was released for user operation on Jan. 29, 2013.


Figure 1: SCU0 installed in the APS storage ring.

COMMISSIONING PLAN

Prior to installing the SCU0, a test chamber with virtually the same length, aperture, and transitions as the SCU0 was installed in the storage ring. Beam-induced heat loads on the test chamber and transitions were tested, and key design improvements were implemented for the SCU0; in particular, a standard-aperture bellows, rf liner, and gate valve replaced a 7.2-mm-aperture assembly on the chamber transition upstream of the SCU0.

A detailed beam commissioning plan was carried out, and all the requirements were satisfied: (a) unpowered SCU0 is transparent to normal user operation; i.e., does not measurably increase storage ring impedance, nor decrease injection efficiency or lifetime; (b) powered SCU0 only perturbs the beam within the specifications; and (c) SCU0 is sufficiently protected from beam-induced heat loads. There were several commissioning goals, including assessment of thermal and vacuum monitoring, alignment procedures, cryogenic performance, beam orbit stability, quench response, field correction, x-ray performance, and operation procedures.

SCU0 EFFECT ON THE BEAM

An unpowered SCU0 is transparent to the beam if its contribution to the storage ring impedance and/or local vacuum pressure neither decreases the beam lifetime or injection efficiency nor lowers the beam instability threshold. As expected from the successful test chamber results, the SCU0 chamber was also transparent: the single bunch limit of 16 mA was preserved, and 100 mA could be stored in all three user bunch patterns. The measured betatron tune shift with current, which is a measure of the transverse impedance, did not change within the expected experimental error. The beam lifetime and injection efficiency were both in the normal range after the standard startup procedures were carried out.

---

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

#harkay@aps.anl.gov

Vacuum System

There were no beam chamber vacuum pressure issues and no negative effect observed on the beam. The beam chamber was cleaned using standard UHV techniques, but was necessarily exposed to air during the magnetic measurements. After the components were installed in the storage ring, the system was roughed down to the 2×10^{-7} Torr range on a cold cathode gauge (CCG) located in the downstream transition. A 24-hr, 130ºC bakeout was performed on the transitions upstream and downstream of the SCU0. The CCG pressure after the bakeout and before the SCU0 was activated was 3 nTorr. After cooldown and prior to injecting beam, the vacuum pressure was measured as 0.4 nTorr. The first 100-mA beam caused pressure transients in the 10-nTorr range, but after about four days of cold beam operation (10 Amp-hr), the pressure stabilized at ~3 nTorr. After 200 Amp-hr, the pressure was ~0.8 nTorr.

Mechanical Vibration

The cryocooler vibration was measured at three different locations: on the SCU0 support girder, on the SCU0 vacuum vessel near the beam level, and on the beam chamber about 0.4 m upstream of the SCU0. The cryocooler vibration power spectrum has a resonant frequency of 8.4 Hz. On the chamber, 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. The cryocooler vibration was not observed to adversely affect the beam motion.

Powered SCU0

The requirements on the SCU0 field-error tolerance are the same as that for the other planar IDs installed in APS [4]. The field-integral error tolerance was specified using simulations that include full-time orbit correction and real-time orbit feedback. Both an absolute limit as well as a rate-of-change requirement [5] were specified. Magnet measurements show that the SCU0 meets the specifications for all design parameters except the skew quadrupole component; the specification was 50 G and the measured value was 120 G at 500 A [6]. 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 produced a 10% change in beam coupling over a 700-A range, but this effect was easily corrected by implementing feed-forward using the adjacent skew quadupoles. The first field integral was determined using the beam by measuring the corrector effort while scanning the SCU0 current. The agreement between the beam and magnet measurements is within 10%, as shown in Fig. 2.

Quenches may produce a field disturbance on a time scale that is too fast for the real-time orbit feedback to correct. If the perturbation is very large, the resulting beam trajectory displacement could exceed the beam position limit detector (BPLD) limits and cause a beam dump. The specification was given as a tolerance on the quantity $\sqrt{I_1^2 + (I_2^2/\beta_U^2)}$, where I_1 and I_2 are the first- and second-field integrals, respectively, and β_U is the average beta function at the undulator ends. The magnet measurements show that the SCU0 meets this specification during a heater-induced quench. 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. In Fig. 3, slow orbit recovery occurs over about 0.5 sec after the quench.

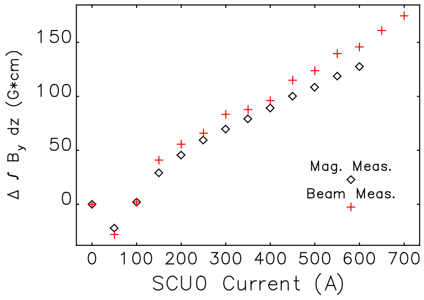

Figure 2: Field integral variation measured with beam.

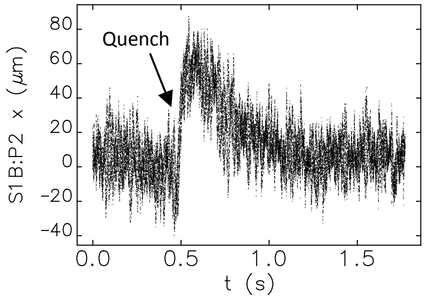

Figure 3: Effect of induced quench on the beam.

BEAM EFFECT ON THE SCU0

The total beam-induced heat load on the SCU0 agrees well with predictions (see Table 1), and the SCU0 is protected from excessive fault-induced heat loads through beam orbit control and SCU0 alignment. The cryogenic system performed very well in the presence of the beam, where magnet temperatures were maintained near 4 K while the beam chamber center temperatures were ≤13 K.

Beam-based Alignment

Precise alignment of the beam vacuum chamber with respect to both the electron beam orbit as well as synchrotron radiation generated in the upstream dipole magnet is extremely important. The beam vacuum chamber is instrumented with nine thermal sensors along its length [7]. Using the sensors and steering the beam, the chamber alignment was determined with 100-micron precision (see Fig. 4) [7]. This precision is more than 10 times better than what is achieved in a standard aperture scan. Other advantages of the thermal sensor beam-based alignment method include isolating the SCU0 alignment from other vacuum components in the orbit bump and providing good longitudinal spatial resolution.

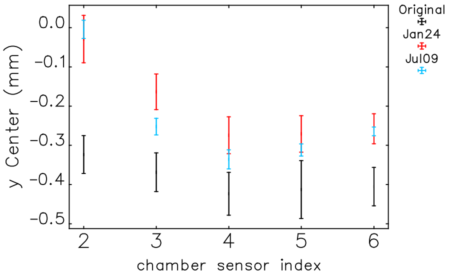

Figure 4: SCU0 chamber vertical alignment history (partial in-tunnel realignment shown in red).

Beam-induced Heat Load

Heat load predictions for standard 100-mA user operation were benchmarked using thermal sensors that measure temperatures at various locations in the SCU0 cryostat and along the electron beam chamber. Thermal analysis using the predicted electron beam heat loads, using three independent methods, agrees well with the observed measurements. Results are summarized in Table 1 for all three standard user bunch modes. For simplicity, the calculated values include only the dominant, image-current heating. In the chamber heater calibration, the predicted heat loads from Table 1 were converted to chamber temperatures by interpolating the heater data [8]. Using ANSYS, the heat load was modeled as a Gaussian image-current distribution. Agreement is excellent for both the central, Al part of the chamber as well as the SS warm-to-cold transitions [9]. Finally, the total 20-K heat load was measured using the bottom cryocooler 2nd-stage temperatures, fit to a model using vendor-supplied load map data [8]. There was no anomalous heat source; the agreement is remarkably within 1 K or 2 W.

Table 1: Predicted vs. Measured Center Chamber Temperatures and 20-K Heat Loads at 100 mA

No. of bunch-es	Chamb heater calib. (K)	ANSYS model (K)	Msrd. temp. (K)	Calc. heat load (W)	Msrd. heat load (W)
24	13.6	13.4	12.8	16.0	14.3
324	7.9	8.2	8.3	2.0	3.4
1+56	11.8	11.5	11.9	11.1	11.5

The device was found to quench due to beam losses during unintentional beam dumps. The SCU0 is powered off prior to intentional beam dumps. Over an 8-month operating period, only two quenches occurred with user-stored beam. These quenches did not cause any beam loss, and the cause is under investigation. Quench recovery is transparent to storage ring operation, and the impact of all quenches on SCU0 operation has been minimal due to rapid recovery.

PERFORMANCE

The SCU0 was operated at 650-700 A over 50% of the time, well beyond its 500-A design requirement. The SCU0 is routinely operated with 100-mA stored beam continuously near 650 A without a trip. The SCU0 was also operated at 150 mA, higher beam current than it was designed for, with no significant issues. Finally, no loss of He was observed over an 8-month operating period.

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, the 0.34-m-long SCU0 produced ~45% higher photon flux than the 2.3-m-long U33. Figure 5 shows the simulated and measured photon flux at 85 keV for SCU0, and the measured photon flux for U33 (inset).

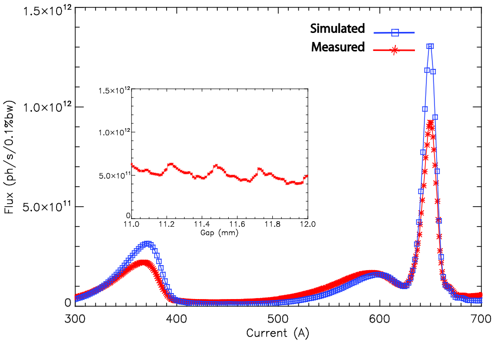

Figure 5: Photon flux comparisons at 85 keV. Main: Simulated and measured SCU0 photon flux. Inset: Measured photon flux of in-line U33.

SUMMARY

An almost decade-long R&D program on the development of superconducting undulators at the APS was successfully completed in 2012 with the installation into the APS storage ring of the first test undulator, SCU0. Beam commissioning was highly successful. The device has been in user operation since January 2013, delivering enhanced photon flux at energies above 50 keV.

ACKNOWLEDGMENT

We wish to thank the support of the APS management in long-term R&D and development of superconducting undulators. We also thank the APS team for their valuable contributions to the success of this project.

REFERENCES

[1] Y. Ivanyushenkov et al., IEEE Trans. on Appl. Superconductivity 21 (2011) 1717; Y. Ivanyushenkov et al., Proc. 2012 IPAC, MOPPP078, p. 744 (2012); journals.iucr.org/s/issues/2013/03/00/s130300aps.pdf
[2] Y. Ivanyushenkov, FRYBB1, NA-PAC'13.
[3] J. Bahrdt, Y. Ivanyushenkov, J. Phys. 425 (2013) 032001.
[4] Y.-C. Chae, G. Decker, Proc. of PAC1995, RAR24, p. 3409 (1996); http://www.JACoW.org
[5] APS Upgrade Preliminary Design Report (2012).
[6] C. Doose, M. Kasa, THPBA06, NA-PAC'13.
[7] K. Harkay et al., WEPSM07, NA-PAC'13.
[8] K. Harkay et al., WEPSM06, NA-PAC'13.
[9] Y. Shiroyanagi et al., THPAC07, NA-PAC'13.