BEAM-BASED ALIGNMENT OF THE FIRST SUPERCONDUCTING UNDULATOR AT THE APS*

Katherine C. Harkay[#], Laura Boon, Michael Borland, Louis Emery,
Robert L. Kustom, Vadim Sajaev, Yuko Shiroyanagi, Aimin Xiao
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. The magnet cores are mounted on but thermally isolated from the beam vacuum chamber. Protecting the SCU0 from high beam-induced heat loads was an important requirement before operating the SCU0 in the storage ring. Precise alignment of the beam vacuum chamber with respect to both the electron beam orbit as well as the synchrotron radiation generated in the upstream dipole magnet was therefore extremely important. The beam vacuum chamber was instrumented with nine thermal sensors. Using the sensors, the chamber alignment was determined with 100-micron accuracy. This accuracy is 10 times higher than in a standard aperture scan. Other advantages of the thermal sensor-based alignment method include isolating the SCU0 alignment from other components in the orbit bump and providing good longitudinal spatial resolution. The chamber temperatures agreed well with the predicted heat load and dependence on steering. This novel beam-based alignment method and results will be presented.

INTRODUCTION

One of the many challenges of operating a small-gap superconducting undulator in a high-energy synchrotron light source is protection from excessive beam-induced heat loads [1]. For the test superconducting undulator (SCU0) recently installed in the APS [2], this is accomplished through several key features, including an out-of-vacuum design, thermal isolation of the beam chamber from the magnet coils, 40-W cooling capacity on the beam chamber, and a photon absorber to shield the SCU0 from synchrotron radiation from the upstream bending magnet (BM). Precise alignment of the magnet structure and beam vacuum chamber is also essential for proper heat-load protection, as is a well-controlled beam orbit while the device is in operation. Prior to installation in the APS, the SCU0 beam vacuum chamber and magnetic structure were transversely aligned to within ±150 μm relative to fiducials mounted on the vacuum vessel. Correction values were determined for a “cold fiducialization,” based on measurements before and after cooldown on the test stand [3]. After installation and cooldown *in situ*, beam-based alignment was used to confirm that the SCU0 chamber position was reproduced and that it remained stable during operation. A standard aperture scan was performed first, followed by beam-based alignment using thermal sensors. The results are described below.

APERTURE SCAN

A standard aperture scan involves steering the electron beam vertically through the chamber until the edge of the beam scrapes the walls and the beam lifetime decays to a small value (typically < 10 min). The extreme values of the vertical beam position monitors (BPMs) are recorded to give a measure of the aperture. With a standard 5-m-long ID chamber, a combination of parallel- and angle-bumps can be used to determine the chamber alignment. However, the SCU0 was installed in sector 6 (ID6) downstream of a half-length ID chamber. Sector 6 thus has two small-aperture chambers and several transitions. Therefore, only parallel orbit bumps were implemented to confirm the overall chamber alignment.

The full vertical aperture of the SCU0 chamber is nominally 7.2 mm and the ID chamber is 7.5 mm. The aperture scan was performed using 2 mA in a single bunch, chosen low to protect the SCU0 but with sufficient BPM response. For comparison, the same measurement was repeated in ID21, a 5-m-long, 7.5-mm, full-height ID chamber known to be well aligned. A model four-corrector parallel bump was used to change the correctors, and a special global orbit configuration closes the bump, with the P1 BPM readings allowed to vary. P0 BPMs are located at the ends of the insertion device (ID) chamber, but they have inaccurate response at large orbit values (> 1 mm). P1 BPMs have a better response at large orbit values but there is a defocusing quadrupole between the P1s and the ID chamber ends. Because a model orbit bump produces a parallel orbit shift in the ID, it can be assumed that the orbit at P1 is nearly the same as P0. The aperture was determined from the P1 readings.

The results are given in Table 1. The ID6 results are very good in terms of symmetry, and the full range is comparable to ID21. The accuracy of this method in determining the chamber center is estimated to be about ±1 mm, given that the full range determined from the scan is ~3 mm smaller than the nominal chamber aperture.

Table 1: Aperture Scan Results for ID6/SCU0 and ID21

Sector	Steer up (mm)	Steer down (mm)	Full range (mm)
ID6	2.2	-2.2	4.4
ID21	2.2	-1.8	4.0

---

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

#harkay@aps.anl.gov

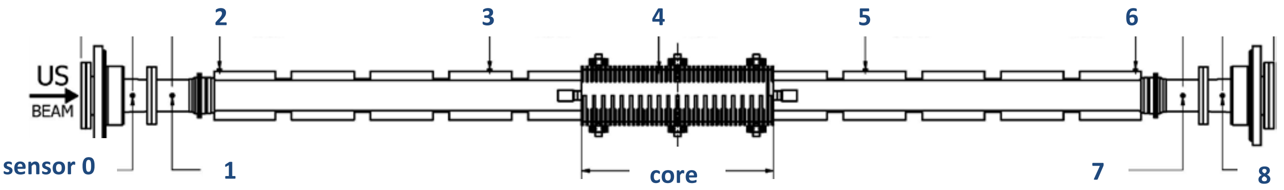

Figure 1: Thermal sensor locations, SCU0 beam chamber (top view). The chamber is stainless steel at sensors 0, 1, 7, and 8 and aluminium at sensors 2-6. The chamber is 2.06 m and the undulator core is 0.34 m in length.

ID STEERING

The SCU0 chamber is instrumented with nine thermal sensors mounted along its length; the locations are shown schematically in Fig. 1. The thermal sensors were used in a novel method of determining the chamber alignment, which is to steer the electron beam in the chamber and observe the temperature response of the thermal sensors. The beam steering was performed by changing the P1 set points and using a global orbit configuration to close the bump, keeping the P1 errors close to zero. The model orbit bump method (as used in the aperture scan) would be preferred since BPMs are not as accurate as correctors. However, the set point method was more straightforward given that it permitted a more complex orbit bump that did not also steer the beam in the BM (see next section). In this case, the image-current resistive-wall heat load dominates. The net resistive-wall heat load increases when the chamber is not centered in the chamber. Therefore, the sensor temperature variation can be used to determine the center of the chamber with respect to the user beam orbit. To maximize the effect, a relatively high image-current heat load is preferred (high bunch current). At the same time, to minimize the risk of accidentally steering high total bending-magnet radiation heat load into the chamber, low current, 25 mA, was used in 24 bunches. Figure 2 shows a typical measurement at sensor 3. The equilibrium temperatures for different vertical orbit offsets were fit to a parabolas to find the minima.

The effect of moving the beam vertically off the median plane was analyzed using the method of images in a planar geometry [4]. The surface current density variation was computed as a function of beam offset. The total power in both walls was then computed and normalized to the total power at zero beam offset. To compare with the data, the measured sensor temperature rise was converted to power using the chamber heater calibration [5]. The agreement is very good (see Fig. 3).

The SCU0 chamber vertical alignment as measured by the chamber thermal sensor minima is shown in Fig. 4. The accuracy is about ±100 µm. The original alignment (black) revealed an offset of 0.3-0.5 mm with respect to the user beam orbit. Partial in-tunnel realignment (red) reduced the offset to < 0.3 mm. Measurements after six months of operation (blue) show that the chamber position remains stable. In addition to the high accuracy, this method isolates the SCU0 alignment from other vacuum components and provides longitudinal spatial resolution limited only by the sensor spacing.

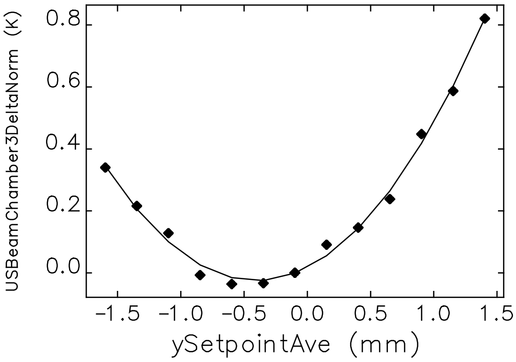

Figure 2: Temperature variation at sensor 3 with vertical beam steering in SCU0.

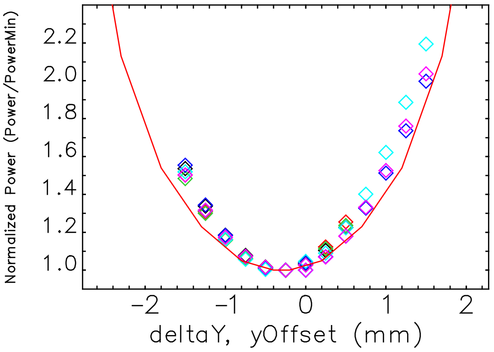

Figure 3: Normalized heat load using calibrated chamber temperatures (sensors 3-5) as a function of the vertical beam offset in the SCU0. The red line shows the theoretical normalized total power (offset by -0.3 mm).

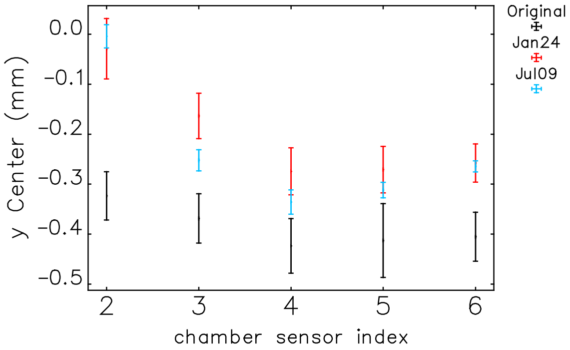

Figure 4: SCU0 chamber vertical alignment history.

BM STEERING

The availability of thermal sensors on the SCU0 chamber allows a measurement that is rather unique. With perfect alignment and vertical beam steering exactly at the midplane in the main bending magnet (BM), the out-of-plane BM radiation power on the SCU0 chamber is only ~0.2 W. However, vertical ray tracing [6] and photon beam power calculations [7, 8] show that significant synchrotron radiation power (10s of W) can intercept the chamber when the beam is steered in the bending magnet, which steers the photon beam. Studies of BM steering serve two purposes: to measure the relative alignment between the BM and the SCU0, and to establish allowable limits on the photon beam steering.

In order to minimize the image-current heating of the SCU0 chamber by the beam, low bunch current was used (324 bunches). The global orbit configuration was set up to steer the BM exit source point while keeping the ID/SCU0 source point fixed. To limit the maximum BM power to below ~30 W, the beam current was limited to 20 mA. Figure 5 shows a typical measurement at sensor 6. The data show a vertical chamber displacement consistent with ID beam steering (see Fig. 2). The data also show that vertical beam offsets of less than ±1 mm at the BM exit give relatively small temperature increases. Larger steering can potentially steer x-rays in the BM radiation centroid into the SCU0 undulator core, which should be avoided.

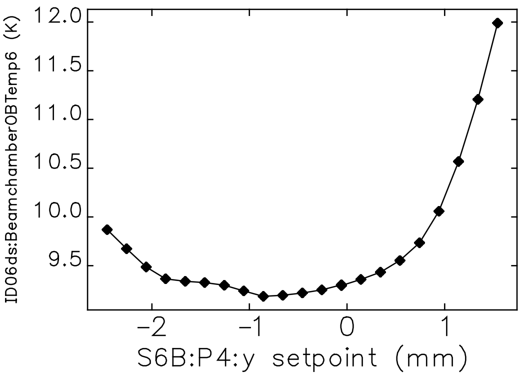

Figure 5: Temperature at sensor 6 with vertical beam steering in the BM.

SUMMARY

The beam was used to measure the alignment of the beam vacuum chamber of the test superconducting undulator (SCU0) at APS using two different methods. A conventional aperture scan confirmed that the overall alignment of ID6/SCU0 was consistent with a well-aligned ID chamber. Beam-based alignment was also carried out using thermal sensors mounted on the SCU0 chamber. The thermal sensor method allowed the vertical chamber alignment to be measured with 100-µm accuracy, which is 10 times higher than the aperture scan. After partial in-tunnel realignment, the SCU0 chamber was confirmed to be aligned to within 0.3 mm, and its position has remained stable over six months of operation. Steering the beam in the BM gives vertical chamber offsets that are consistent with steering in the SCU0, and confirms good relative alignment between the SCU0 chamber and the BM source. Standard beam orbit control and a beam position limiting detector interlock are implemented during SCU0 operation.

ACKNOWLEDGMENT

The authors wish to thank APS staff who contributed to the SCU0 project, especially in the following areas—alignment: J. Penicka, W. Jansma, S. Wesling; installation: J. Gagliano, J. Hoyt, R. Bechtold; wiring: S. Bettenhausen; and design: D. Skiadopoulos, E. Trakhtenberg.

REFERENCES

[1] Y. Ivanyushenkov et al., IEEE Trans. on Applied Superconductivity, 21 (2011) 1717; Y. Ivanyushenkov et al., Proc. IPAC2012, p. 744 (2012); journals.iucr.org/s/issues/2013/03/00/s130300aps.pdf
[2] K. Harkay et al., WEOAA3, NA-PAC'13.
[3] J.M. Penicka and W. Jansma, private communication (2012).
[4] R.L. Kustom, private communication (2012).
[5] K. Harkay et al., WEPSM06, NA-PAC'13.
[6] M. Jaski, private communication (2012).
[7] R. Dejus, private communication (2012).
[8] L. Boon et al., Proc. IPAC2011, THPC186, p. 3332 (2011); L. Boon et al., THPAC06, NA-PAC'13.