ALIGNMENT OF SUPERCONDUCTING UNDULATORS AT THE APS*

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Abstract

The Advanced Photon Source (APS) at Argonne National Laboratory is a 7 GeV third generation light source providing X-ray beams for research to the scientific community since 1995. In order to remain the leading synchrotron radiation source in the western hemisphere and to provide users with higher photon fluxes at higher photon energies, the APS decided to develop and build a series of superconducting undulators (SCU). After several years of R&D and prototype testing the APS Magnetic Device group, in collaboration with the Budker Institute of Nuclear Physics, designed and assembled the first full-scale superconducting undulator, SCU0. In December 2012 SCU0 was installed in sector 6 of the APS storage ring, and after successful commissioning was released for user operation on January 29, 2013. Since then it has proven to be a dependable radiation source for high-energy X-ray studies, delivering enhanced photon flux at energies above 50 keV. The second in the series, SCU1, is being assembled as of this writing. This paper investigates the alignment aspects of the SCU devices. The extreme temperature changes in combination with limited access to the magnetic structure and beam chamber due to extensive thermal isolation pose unique alignment challenges. The alignment procedures and technology used for assembly, testing, and installation in the APS storage ring as well as a novel beam-based alignment and stability monitoring method are presented.

INTRODUCTION

Vertical alignment requirements for SCUs are similar to conventional planar undulators from the magnetic field point of view. Protection from excessive beam-induced heat loads is an additional driving force for establishing alignment requirements for installation of a small-gap superconducting undulator in a high-energy synchrotron light source like APS. Precise alignment of the SCU beam vacuum chamber with respect to both the electron beam orbit as well as the synchrotron radiation generated in the upstream bending magnet (BM) is therefore very important. The 7.2 mm vertical aperture of the SCU0 beam chamber, location of the upstream ID chamber, location of the photon absorber shielding the SCU0 from synchrotron radiation from the upstream bending magnet (BM) were some of the key factors considered in establishing the alignment tolerances for SCU0. Table 1 lists tolerances relevant to alignment that are specified in the APS-U SCU0 Physics Requirements Document [1].

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SCU DESIGN OVERVIEW

The first two superconducting undulators, SCU0 and SCU1, were designed by Magnetic Devices Group of the APS to utilize the same cryostat design. The parameters of SCU0 and SCU1 are listed in Table 2 [2]. The cryostat design is based on a concept developed at the Budker Institute of Nuclear Physics in Novosibirsk, Russia for building superconducting wigglers [3]. A view of the undulator cryostat is shown in Fig. 1, and a cutaway view of the inside is depicted in Fig. 2. The main components include vacuum vessel, 60 K and 20 K thermal radiation shields, and a cold mass. The cold mass includes the two cores of the superconducting magnet assembly and the liquid helium (LHe) tank with piping. The magnet

Table 1: Alignment Tolerances

Alignment Tolerance	X [mm]	Y [mm]
Magnetic structure	±0.150	±0.150
SCU0 vacuum chamber relative to the magnetic structure	N/A	±0.150
SCU0 vacuum chamber relative to the U33 ID chamber	±0.150	±0.150

Table 2: SCU0 and SCU1 parameters

Parameter	SCU0	SCU1
Electron beam energy	7.0 GeV	7.0 GeV
Photon energy at 1st harmonic	20-25 keV	12-25 keV
Undulator period	16 mm	18 mm
Magnetic gap	9.5 mm	9.5 mm
Magnetic length	0.33 m	1.14 m
Cryostat length	2.06 m	2.06 m

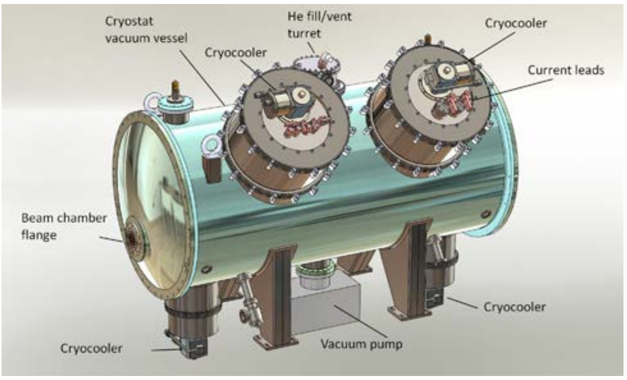

Figure 1: Cryostat

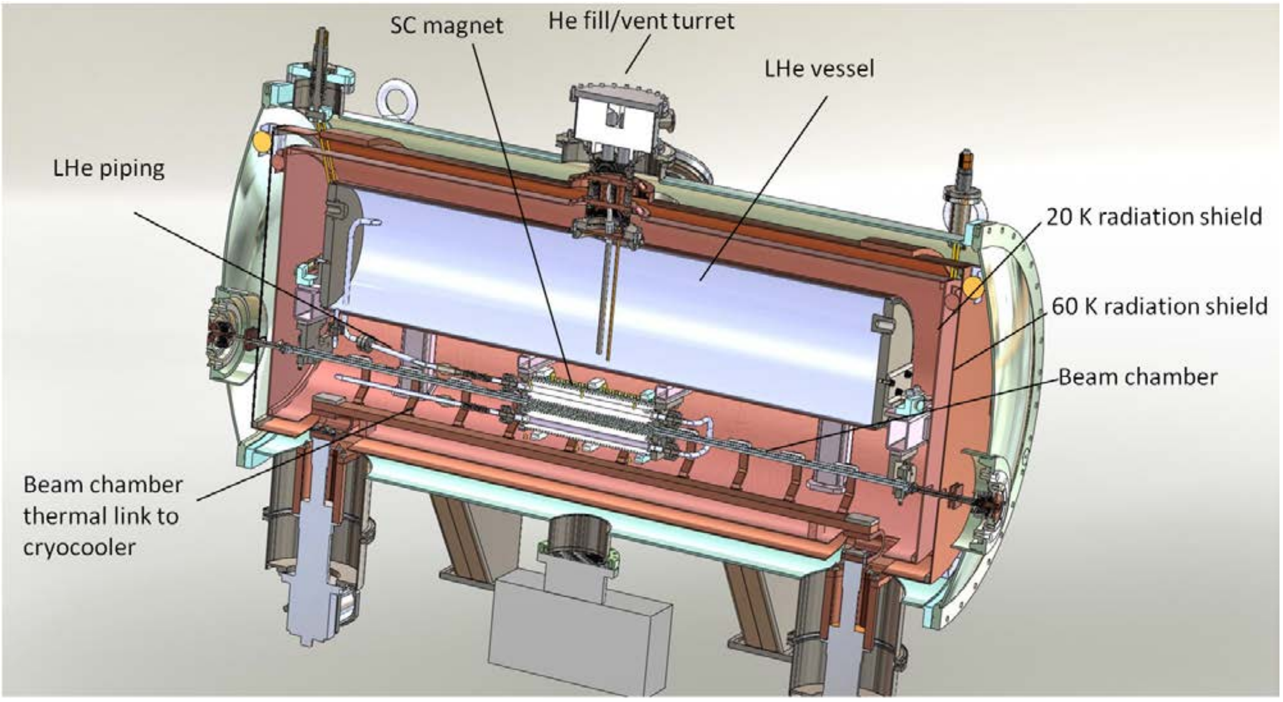

Figure 2: Cutaway view of the inside of the cryostat.

structure and the LHe tank are mounted to a stainless steel strong-back frame that is suspended inside the vacuum vessel by Kevlar strings.

The cold mass is maintained at 4 K by liquid helium circulating through the channels in the magnetic cores in a closed thermo-siphon loop. The beam vacuum chamber is thermally isolated from the magnet jaws and is kept at approximately 20 K by two lower cryocoolers that also cool the radiation shields to 20 K and 60 K. Two additional cryocoolers located in the turrets on top of the vacuum vessel are used to cool the current leads and the He re-condenser in the LHe tank.

ASSEMBLY AND FIDUCIALIZATION

Successful alignment of a complex device like SCU relies on the proven approach of employing precision alignment from the beginning of the assembly process. The first step requiring alignment support was the assembly of the cold mass components. Starting with the support frame resting on a flat surface in an inverted position the magnet structure and vacuum chamber were assembled and aligned to ±75 microns using conventional optical tooling methods (Fig. 3). The support frame

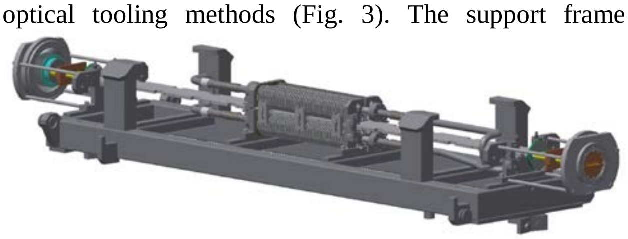

Figure 3: Magnet structure - vacuum chamber assembly.

was then turned over and oriented in the upright position so the four fiducials on top of the support frame could be measured. The fiducials are precisely machined so that a common center may be measured optically, with a laser tracker or with an articulating CMM (Fig. 4). The 3D coordinates of the fiducials were ascertained by combining optical and articulating CMM measurements. After fiducialization, the cold mass assembly (Fig. 5) was lifted onto the assembly fixture and the copper thermal links were fastened to the vacuum chamber.

Figure 4: Fiducial targets.

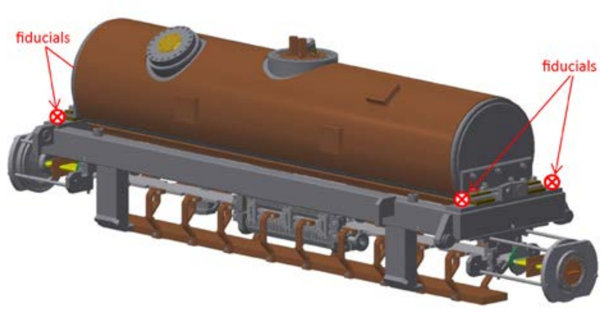

Figure 5: Cold Mass assembly.

The straightness of the vacuum chamber was checked for any deformations at this point. Then the vacuum vessel assembly with the 60 K and 20 K copper thermal shields already in place was moved onto the cold mass and aligned. The alignment of the cold mass within the

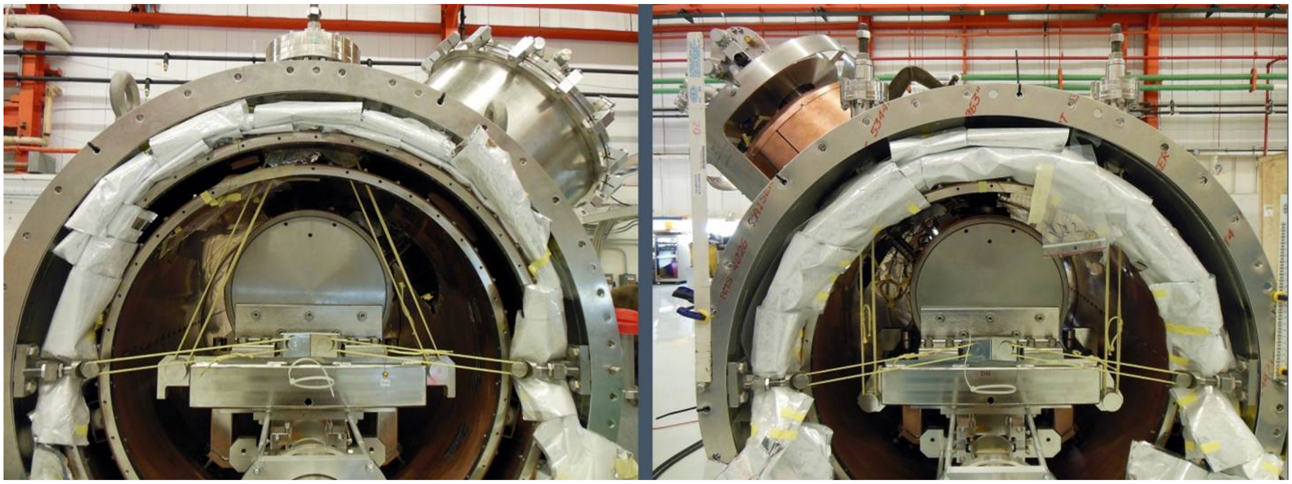

Figure 6: Kevlar band suspension system.

vacuum vessel assembly was accomplished by adjusting the Kevlar suspension bands (Fig. 6), while the coordinates of the vacuum vessel and cold mass fiducials were monitored with the laser tracker (Fig. 7). Throughout the process the optical level and four additional vertical fiducials on the top of the vacuum vessel were utilized to supplement the laser tracker data and improve the accuracy of the vertical alignment. Four jack screws are incorporated in the design of the Kevlar band suspension system to stress-relieve Kevlar for transportation from the assembly hall to the storage ring.

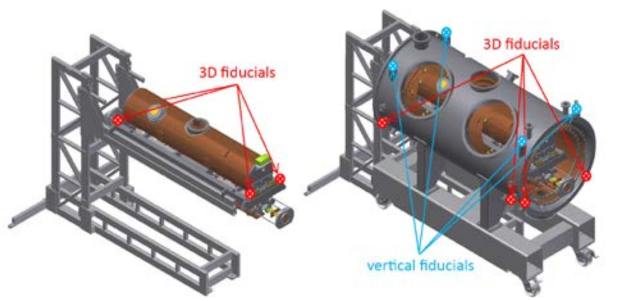

Figure 7: Vacuum vessel is moved into the cold mass and aligned.

The repeatability of the system was tested in the assembly hall before the cylindrical thermal shields were closed and vacuum vessel flanges were attached.

COOLING DISPLACEMENT TEST

The SCU0 was assembled and aligned in a room temperature environment. As the SCU0 would be positioned in the storage ring using fiducials of the vacuum vessel the effect of cooling on position and shape of the beam chamber/magnetic structure assembly within the vacuum vessel had to be measured and mitigated or compensated for. Since no more cold mass fiducials were visible at this point, the aperture of the beam chamber was monitored through the glass viewports. Seven pairs of spherical targets were placed in the beam chamber at

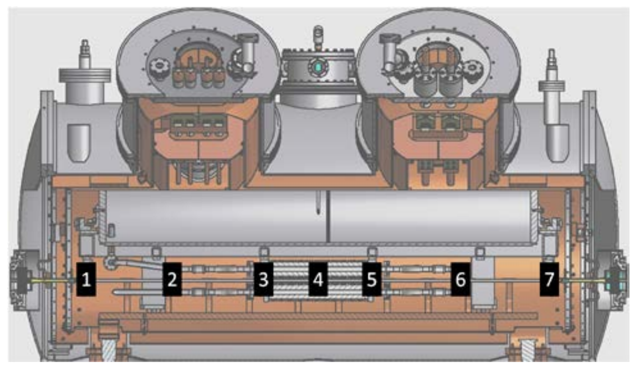

Figure 8: Position of bead targets inside the chamber.

predefined locations (Fig. 8). The pairs of sphere targets were "spring-loaded" with stiff wire to engage the cylindrical profile of the chamber in the horizontal plane (Fig. 9). By observing the top and bottom edges of the spheres by N3 optical level the position and shape of the beam chamber was measured during the cool-down and warm-up cycle (Fig. 10). The initial reference for the plots in the Fig. 10 is the state in which everything was at room temperature and normal atmospheric pressure.

Figure 9: Spherical target inside the prototype of the SCU0 vacuum chamber photographed through the alignment scope of the optical level.

The measurements made at room temperature and insulating vacuum inside the vessel indicated that the beam chamber dropped about 0.300 mm and a pitch of approximately 0.1 mrad was introduced. This was caused by atmospheric pressure in the bellows connecting the LHe tank to the top of vacuum vessel. When the system

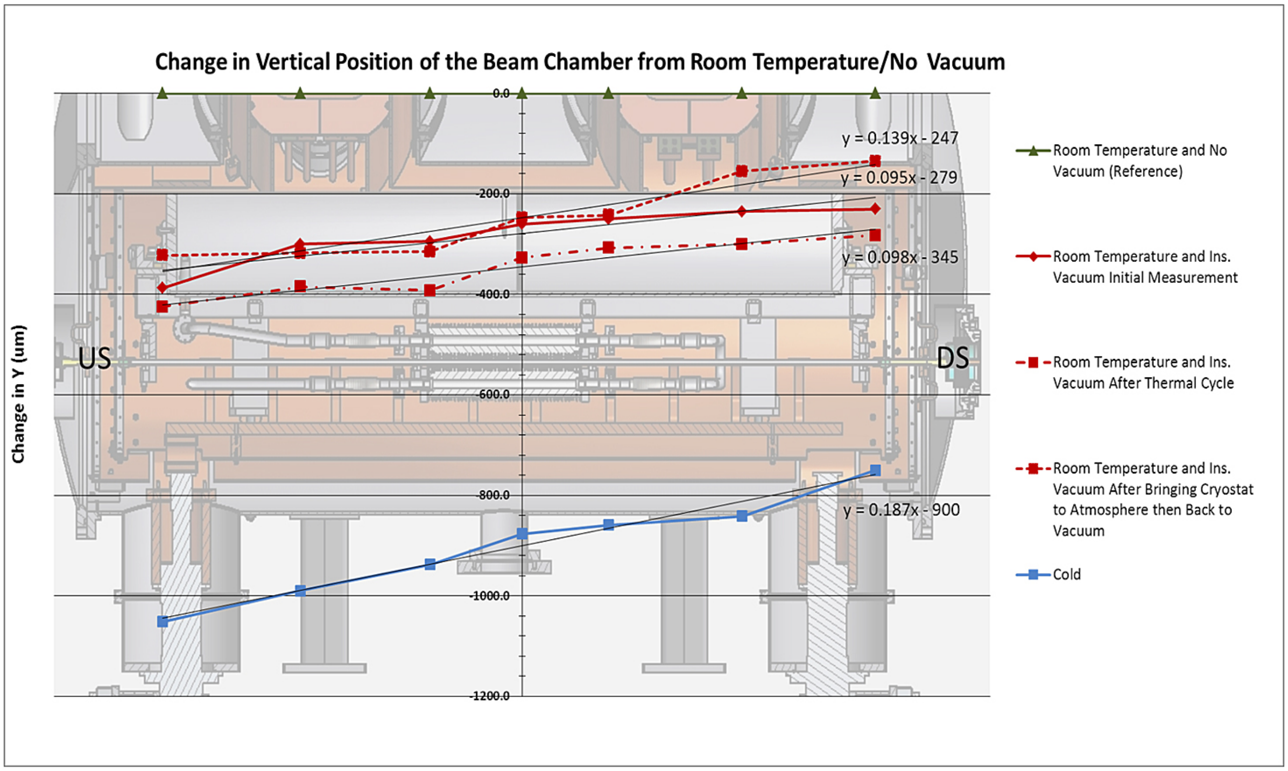

Figure 10: Vertical position of the cold mass during the cool down cycle.

was cooled down to operating conditions of 4 K the beam chamber was measured to be about 0.900 mm below the starting reference with a pitch of about 0.2 mrad, mostly the result of expansion of the Kevlar strings. With the system still under vacuum but warmed to room temperature, the vertical position stabilized 0.350 mm below the reference with a 0.1 mrad pitch. The vacuum vessel was then cycled up to atmosphere and back to insulating vacuum and then measured to be at approximately 0.250 mm below the starting reference with a pitch slightly greater than 0.1 mrad. To eliminate displacement of the beam chamber/magnets assembly during the cooling process portions of the Kevlar string in the suspension system were replaced with aluminum links (Fig. 11a-b). The length of the aluminum links was calculated to compensate for the thermal elongation of Kevlar and thermal contraction of stainless steel part of the suspension system during the cooling as well as mechanical elongation of the Kevlar caused by pressure difference. The theoretical values were verified during the next cool-down warm-up cycle. Because this cycle takes about 190 hours (8 days) to complete the measurements with spherical beads could not be repeated but beam chamber monitoring was incorporated into the magnetic measurement procedure. Magnetic mapping of SCU0 was done by inserting a Ti tube in the beam chamber and

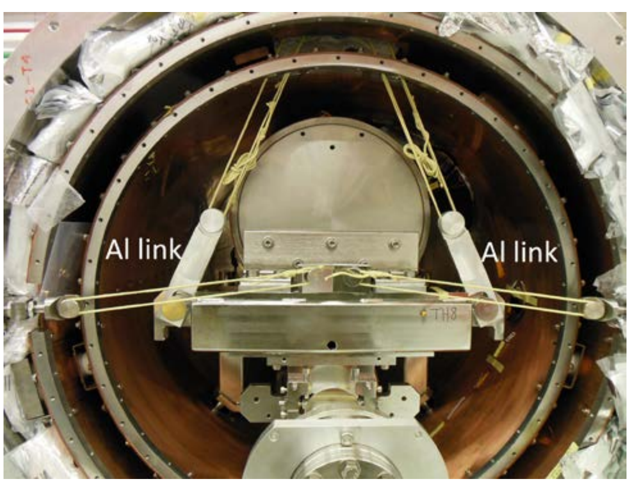

Figure 11a: Kevlar with added aluminum links suspension system (upstream end).

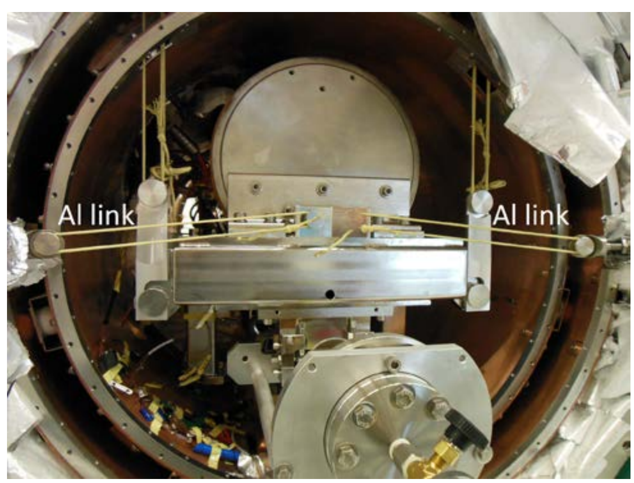

Figure 11b: Kevlar with added aluminum links suspension system (downstream end).

aligning it to the ideal beam centerline [4]. The Ti tube guided a carbon fiber tube holding a Hall probe (Fig. 12) on its long translation stage that was also aligned to the ideal centerline as established from the fiducials of the vacuum

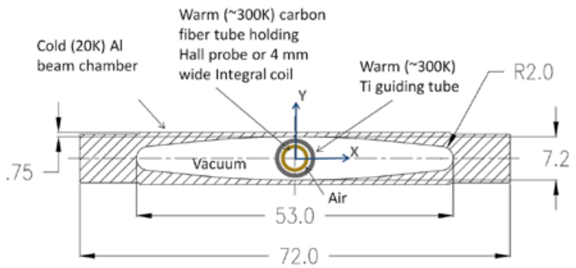

Figure 12: Magnetic mapping of SCU0.

vessel. To know the exact profile of the Ti tube, carbon fiber tubing with three strands of fiber optic cable placed in its center as an alignment target was alternatively used instead the Hall probe. A micro-alignment telescope with dual axis micrometer was utilized to monitor this target traveling through the Ti tube. This method, although less accurate than the technique using beads, proved that the suspension system modified with the aluminum links maintained the vertical position of the beam chamber during the cooling process, practically eliminating thermal shift.

ALIGNMENT IN THE APS STORAGE RING

The SCU0 device was installed in APS storage ring sector 6, downstream of a half-length insertion device chamber with 7.5 mm vertical aperture (Fig. 13). An optical level and precision transit-square were utilized to position the SCU0 at its ideal location within the ±0.150 mm x and y alignment tolerances. A laser tracker oriented

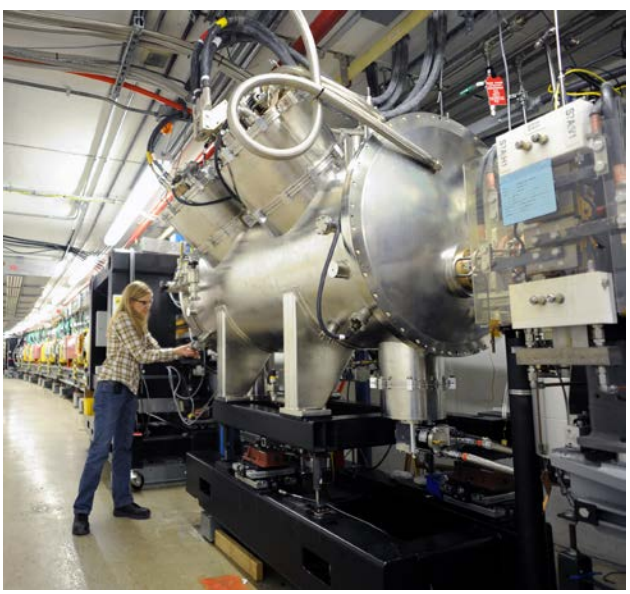

Figure 13: APS storage ring with the SCU0 installed.

to the storage ring control network was utilized to provide a redundant quality assurance check on the alignment and to map the final position of the SCU0 within the APS storage ring lattice.

Incorporating aluminum links into the Kevlar suspension system mitigated most of the thermal shift; however, minor discrepancies between warm and cold fiducialization were anticipated. Therefore, beam-based alignment was foreseen as a necessary final step to confirm and fine tune the position of the SCU0 after cool-down in the storage ring.

FINAL BEAM-BASED ALIGNMENT AND MONITORING

The electron beam was used to measure the alignment of the SCU0 beam chamber with respect to the APS storage ring beam orbit using two different methods. First, a conventional aperture scan confirmed that the overall alignment of ID6/SCU0 was consistent with a well-aligned ID chamber. The accuracy of this technique in determining location of the beam chamber vertical center is about ±1 mm. Second, a novel method that uses thermal sensors mounted on SCU0 beam chamber was developed at APS [5]. The SCU0 beam chamber was instrumented with nine thermal sensors mounted along its length; the locations are shown schematically in Fig. 14.

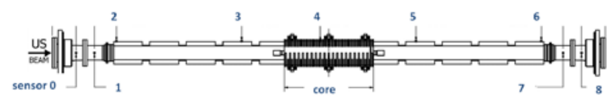

Figure 14: Thermal sensors layout.

The vertical position of the beam chamber is measured by steering the electron beam vertically within the chamber and observing the response of the thermal sensors. The chamber thermal sensor minima determine the vertical center of the SCU0 chamber with respect to the user beam orbit. The thermal sensor method allows the vertical chamber alignment to be measured with 100-µm accuracy, an order of magnitude better than the standard aperture scan. The first beam-based alignment measurements were performed during commissioning in

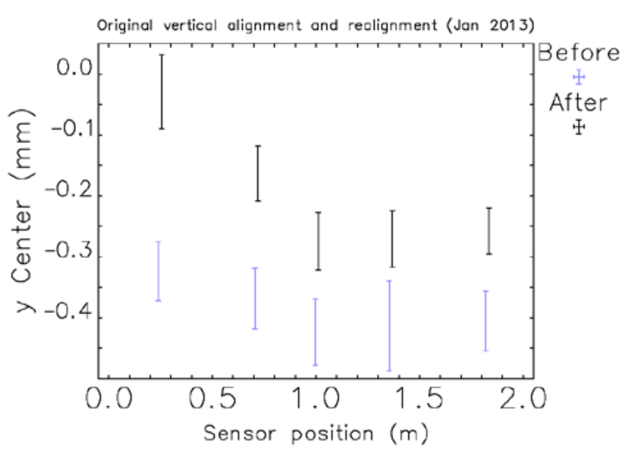

Figure 15: Vertical center of chamber with respect to the user beam orbit. Sensors 2-6, January 2013 data.

January 2013.The vertical alignment of the SCU0 chamber was confirmed to be very good (Fig. 15). The chamber was within ±0.075 mm along the length of the chamber centered about 0.4 mm below the user beam orbit (blue). SCU0 was partially realigned (black) to reduce the offset to less than 0.300 mm of user beam orbit (the limit of adjustment range was reached on the downstream side and no time was available to shim the adjustment system). The SCU0 chamber remained stable in this position for over 19 months (Fig. 16) while delivering 80 – 100 keV photons for user science.

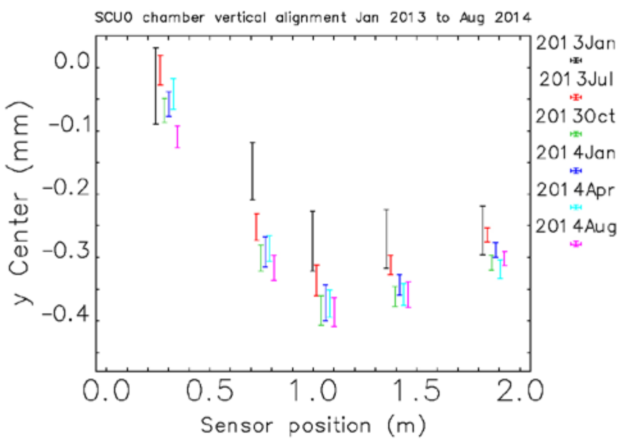

Figure16: Chamber stability over 19 months period.

During the August-September 2014 APS shutdown the SCU0 was realigned vertically to coincide with the user beam orbit (Fig. 17). The downstream adjustment system was shimmed to restore adjustment range, and the elevation of the SCU0 was adjusted to fit the beam orbit elevation. Realignment was confirmed again by the beam-based alignment method.

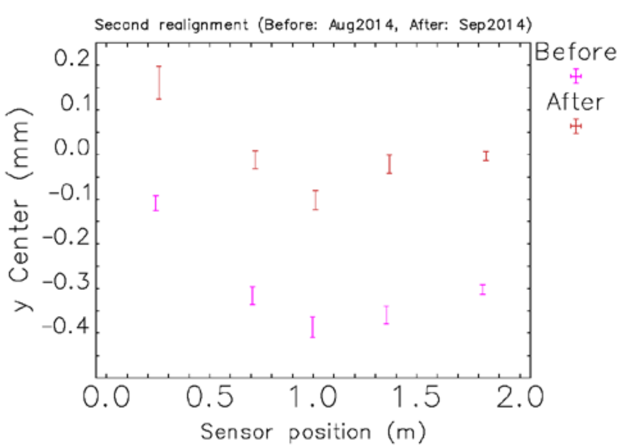

Figure 17: August 2014 realignment of SCU0.

In addition to SCU alignment this thermal sensor method was also used to confirm good relative alignment between the SCU0 chamber and the upstream 6BM source. Steering the beam in the 6BM gave vertical chamber offsets that were consistent with steering in the SCU0.

SUMMARY

The first prototype superconducting undulator was successfully installed and aligned in the APS storage ring and has delivered 80 – 100 keV photons to APS users for the last 19 months. A new spherical bead target technique was implemented for alignment of the SCU0 beam chamber and for quantifying thermal shift on the alignment of the chamber/magnets assembly. As a result, a unique suspension system combining Kevlar string with aluminum links was designed to eliminate any displacement of the chamber during the cooling of the SCU0. A novel beam-based measurement method that utilizes thermal sensors mounted on the SCU0 beam chamber was developed for fine alignment, and was successfully used to measure and verify the vertical chamber position during the initial phase of commissioning and later to monitor the stability of alignment during a year and half of operation. Significant knowledge was gained from the SCU0 installation, and many improvements are being implemented in the assembly and alignment of the next superconducting undulator, SCU1.

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