ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMF008

DESIGN, CONSTRUCTION, AND MAGNETIC FIELD MEASUREMENTS OF A HELICAL SUPERCONDUCTING UNDULATOR FOR THE ADVANCED PHOTON SOURCE*

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Abstract

A helical superconducting undulator (HSCU) was developed, built and installed at the Advanced Photon Source (APS). Implementation of a unique design of the single conductor turn around scheme during winding allowed for a compact end's termination of the device. Inherent to the coil winding design was the gradual reduction of the magnitude of the magnetic field at the ends of the device. The details of the coil housing design along with the HSCU magnetic measurement results are described.

INTRODUCTION

An HSCU with the parameters shown in Table 1 has been developed and built at the Advanced Photon Source (APS) of Argonne National Laboratory. Installation into sector 7 of the APS storage ring took place in December 2017. This is the first HSCU installed at the 3rd generation synchrotron radiation facility intended to provide x-rays for user experimental programs. During the 1970's an HSCU was developed for FEL experiments at Stanford [1]. In 1984, an HSCU was installed in a straight section of the VEPP-2M storage ring in Novosibirsk to measure the polarization of the electron-positron colliding beams [2].

Table 1: HSCU Magnet Parameters

Parameter	Value
Magnetic Length [m]	1.2
Period [mm]	31.5
Magnetic diameter [mm]	29
Coil inner diameter [mm]	31
Coil outer diameter [mm]	39.09
Number of turns per helix	138
Conductor diameter [mm]	0.75
On-axis field [T]	0.41 ($B_x = B_y$)
K value	1.2 ($K_x = K_y$)
On-axis photon energy [keV]	6

A helical undulator provides circularly polarized radiation which is on axis dominated by the first harmonic [3]. The absence of higher harmonics has the benefit of reducing the heat load on the beam line optics and has the potential to eliminate the use of any beamline optical components, including monochromator. An early analysis revealed that the aperture flux of the HSCU without the monochromator could be two orders of magnitude greater than that of the standard undulator A used at the APS with a Si-monocromator. Results of the analysis are shown in Fig.1. This benefit could be realized even with the large diameter of the winding mandrel that was required due to the horizontal beam stay clear of 26 mm at the APS.

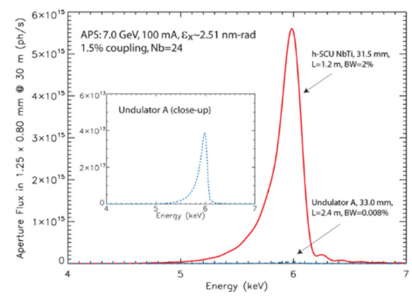

Figure 1: Aperture flux comparison of the HSCU and undulator A. Flux difference shown in the plot is dominated by the difference in bandwidth. The bandwidth for the HSCU is 2% and the bandwidth for the UA is 0.008% from the monochromator bandwidth and detector efficiency.

DESIGN AND CONSTRUCTION

In an HSCU the helical magnetic field is created from a bifilar helical coil winding geometry with one helix offset from the other by one half of an undulator period [4]. Current in one helix is opposite to the adjacent helix that results in the cancellation of the longitudinal field component. Derivations of the on-axis field and previous simulation results with an air core and the effects on the field strength when iron is used as the winding mandrel can be found in [5,6]. Several prototypes of HSCU for the ILC were built and tested to measure the effects of various geometries and materials to compare with a magnetic model [7]. Also, of consequence are the fields at the ends of the HSCU [6,8] which can affect the trajectory of the photon beam and the electron beam in the storage ring. The field integral requirements on the HSCU were the same as the planar undulators at the APS, Table 2.

Table 2: APS Field Integral Specifications

Field Integral	Specification
$\int B_y dz$ [G-cm]	80
$\int B_x dz$ [G-cm]	25
$\int dz \int B_y dz'$ [G-cm^2]	10000
$\int dz \int B_x dz'$ [G-cm^2]	3200

* Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.
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A model of the HSCU design were created in Radia to provide guidance on the choice of coil pack geometry and the tapering off of the field at the ends of the device to meet the specifications in Tables 1 and 2. Another goal was to reduce the cross section of the core and potting mold to fit within the second generation cryostat vacuum vessel developed at the APS [9]. After epoxy impregnation the magnet remained inside the mold which served as a strongback and provided cooling via channels for liquid helium (LHe).

Once the geometry and end turn-around design were complete, the winding mandrel was machined from low carbon steel by a partner vendor and wound at the APS. The winding structure in the main body of the model and wound HSCU is depicted in Fig. 2.

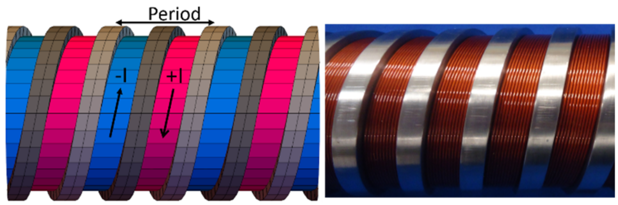

Figure 2: HSCU coil structure from the Radia model (left) and the completed structure (right).

Transitioning from one helix to the other was completed at each end of the structure. With the goal of keeping the structure as compact as possible, a series of turn-around pins were designed so the wire completed a 180° turn to transition to the adjacent helix. Spacing of the pins and their diameter allowed the coil pack to be reduced over two periods. This novel design allowed the structure to be a uniform diameter which simplified the epoxy impregnation mold, allowed for continuous winding with a single NbTi superconductor, and the turn-around design gradually reduced the coil pack geometry at the ends. The turn-around structure is shown in Fig. 3.

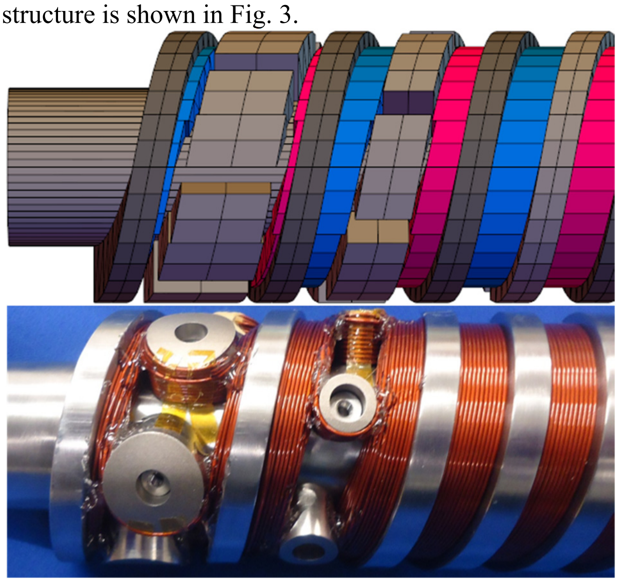

Figure 3: Approximation of the end turn-around pins in the Radia model (top) and the HSCU after winding (bottom).

Modelling of the magnetic field suggested that correction coils were needed at the ends of the magnetic structure to correct the trajectory angle of the electron beam through the device and correct any angle at the exit. A pair of dipole correctors, horizontal and vertical, were designed to be attached to the end of the mold. The corrector assembly is shown in Fig. 4 during the final assembly of the HSCU.

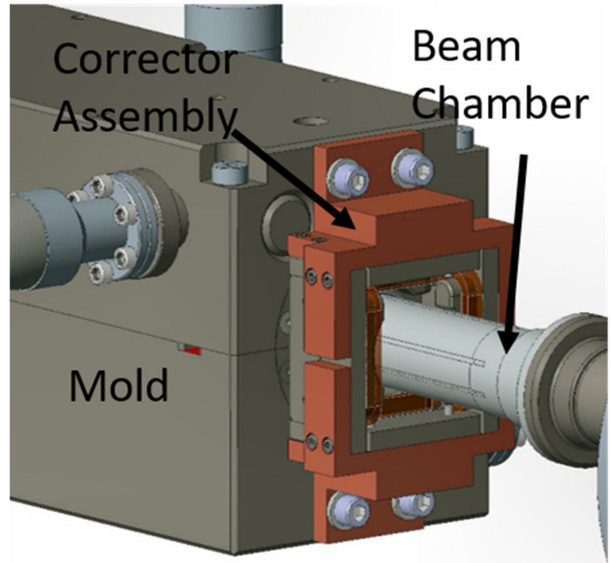

Figure 4: Final assembly of the HSCU showing the potting containing the magnet, horizontal and vertical corrector assembly, and the beam chamber.

MAGNETIC MEASUREMENTS

Characterization of the magnetic field of the HSCU was performed after the magnet was cooled down to LHe temperature inside the cryostat. The same magnet measurement system described in [10] was used to perform the HSCU measurements. It should be mentioned that prior to the final magnetic field measurements in the horizontal cryostat, the magnet was powered and tested in a vertical LHe bath cryostat to perform the initial coil training and preliminary magnetic field measurements. A field of 0.41 T was verified at 450 A at this initial training (Fig. 5), and the coil was trained above 500 A, which it reached after 21 quenches. After subsequent cooldowns in the horizontal cryostat, the magnet required five or less quenches after a thermal cycle to reach 500 A.

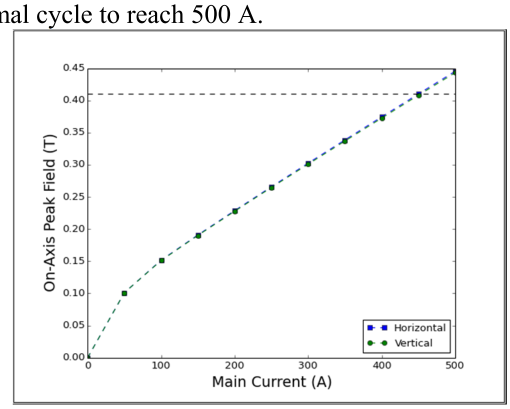

Figure 5: HSCU on-axis field as a function of current. Dashed line represents the design field of 0.41 T.

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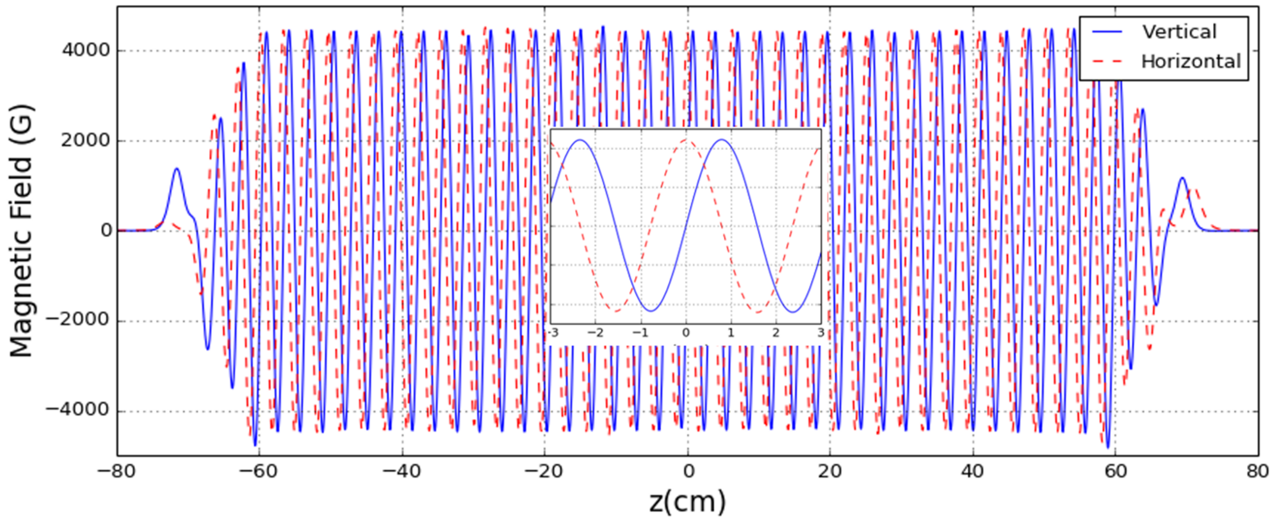

Figure 6: On-axis Hall probe field scan with the end correctors energized. The main current was set to 500 A.

Field scans and tuning of the field integrals using the corrector magnets were performed iteratively in the horizontal cryostat using three measurement techniques: Hall probe, rotating coil, and pulsed wire. Figure 6 shows a typical field scan with the Hall probe and the magnet energized to 500 A. Shown in Fig. 7 are two field scans at 500 A that demonstrate the effect of the end correctors. A lookup table was created for feed forward control of the corrector power supplies to ensure the integrals remained within the APS specifications during a current ramp. The lookup table values were recorded in 50 A increments of the main power supply.

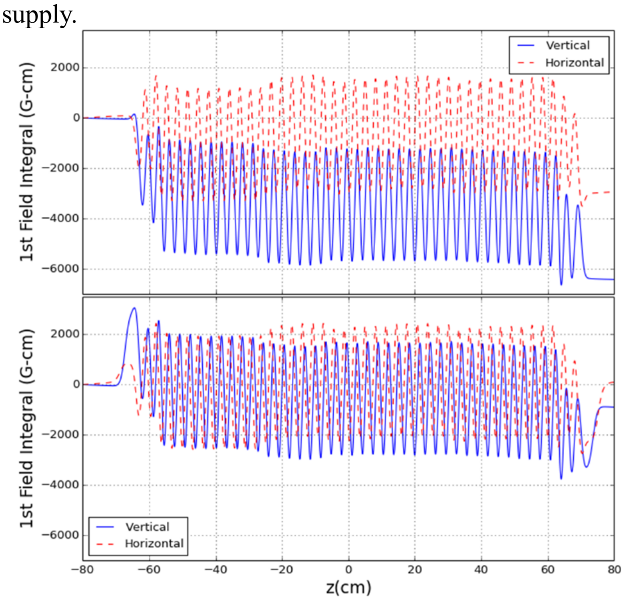

Figure 7: Horizontal and vertical 1st field integrals without (top) and with (bottom) the corrector coils energized.

CONCLUSION

A novel HSCU was developed and built at the APS. It was commissioned in the storage ring in January 2018. A unique winding scheme was developed and a winding mandrel was designed and manufactured. The magnetic field was characterized to ensure transparent operation to the stored electron beam.

ACKNOWLEDGMENTS

Thank you to Roger Dejus for performing the aperture flux calculations and supplying Figure 1.

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02 -06CH11357.

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