MAGNETIC MEASUREMENTS OF THE FIRST SUPERCONDUCTING UNDULATOR AT THE ADVANCED PHOTON SOURCE*

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Abstract

A superconducting (SC) undulator prototype designated SCU0 was installed in the APS storage ring in December, 2012, and is providing users with photons in the energy range of 80-100 keV. This device was assembled and tested during the majority of 2012. Detailed tests were performed related to cryogenics, vacuum, mechanical motion due to thermal contraction, and magnetic performance. Magnetic measurements have been performed using a horizontal measurement system, which utilizes Hall probes and an integral coil. The measurement system was configured without interfering with the cryogenic or vacuum systems of the SCU0 cryomodule. Some of the magnetic measurement results will be presented for local and integrated field measurements, integrated field uniformity, and integrated fields during a quench. The measured rms phase errors were typically less than two degrees. The measured change in the integrated field during an intentional quench was less than 35 G-cm. The magnetic performance of SCU0 has proven to be within design tolerance for field quality and quench characteristics. Beam-based integral measurements agree well with the magnetic measurements.

SCU0 BACKGROUND

SCU0 is a prototype superconducting undulator (SCU) that was installed in the APS storage ring during December 2012, and is presently operating successfully at the APS sector 6 beamline [1,2].

Table 1: SCU0 Magnetic Specifications

Period	16 mm
Magnetic gap	9.5 mm
Magnet length	331 mm
Design peak field	0.4 - 0.65 T
Design Current	200 - 500 A
Maximum achieved peak field	0.82 T
Maximum achieved current	740 A

Table 2: APS Undulator Error Tolerance

1st Vertical Field Integral	100 G*cm
1st Horizontal Field Integral	50 G*cm
1st Vert. Field Integral during quench	2100 G*cm
2nd Horz. And Vert. Integrals	1×10^{-5} G*cm^2
Normal and Skew Integrated Quadrupole	50 G

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The assembly of the SCU0 cryomodule began in January, 2012; the first magnetic measurements of the assembled device began in June 2012 and were completed in August. A second set of magnetic measurements was done in November and December of 2012. The first set of measurements was performed with the original pair of SC magnetic structures. From September to October, the SCU0 was disassembled to replace the Al beam chamber with a new design. In the process of disassembly one of the SC wires was possibly damaged. A spare magnet structure was available so it was installed rather than risk a failure of the suspect SC wire.

HALL PROBE MEASUREMENT RESULTS

The following section describes some of the typical measurement results while using a room temperature Hall probe to measure the local fields along the longitudinal axis (z). The measurement system utilizes a room-temperature Ti tubing, "warm-bore," as a guide tube for the carbon fiber Hall probe assembly. The Ti tubing is tensioned inside but isolated from the cold (~10 K) Al beam chamber. A similar concept is used by the Budker Instituite for SC wiggler magnetic measurements.

An overview of the measurement system is shown in Fig. 1. The 3.5-m-long stage is used to drive a carbon fiber Hall probe assembly through the Ti guide tube. Stages mounted to the ends of the SCU0 cryomodule provide support and tension for the Ti guide tube and horizontal transverse motion (x) for measuring up to ±10 mm from the central axis.

Figure 1: SCU horizontal magnetic measurement system with 3.5-m linear stage for Hall probe scans. SCU0 cryomodule is on the left.

1st and 2nd Field Integrals and Phase Errors

The measured 1st and 2nd vertical field (B_y) integrals from the measurements performed in August and December of 2012 are shown in Fig. 2 and Fig. 3. The final 1st integral values were +31 and -87 G*cm in August and December, respectively. The August measurements of

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the 1st integrals, with the original magnet structures, typically showed values below 35 G*cm when using the Hall probe system. With the replacement magnet structure, a current-dependent 1st integral was introduced. The current-dependent 1st field integrals from the December measurements are most likely due to stray fields from the configuration of the SC leads from the magnet structure to the terminals on the cryocoolers. The stray field appears to have been adversely affected after the replacement of the suspect magnet structure.

There is no provision for adjustment of the final 1st field integral value, but the 2nd integral is adjusted via end correction coils that are located on the ends of the magnet structures [3]. These end correction coils can be energized symmetrically or differentially with respect to each other. When adjusted differentially, a varying (along the length of the device) vertical dipole component is created, which affects the straightness of the 2nd field integral. Figure 3 depicts the 2nd field integrals with symmetrical and differential end-field correction currents measured in December and the original measurement in August. By adjusting the average and differential end correction currents, both the slope and straightness of the 2nd field integral (trajectory) can be optimized.

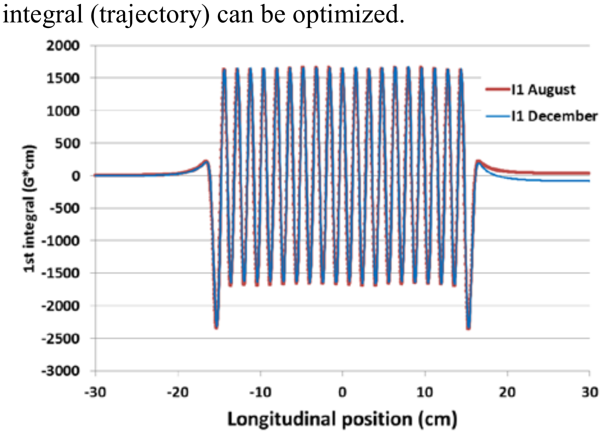

Figure 2: Plots of the SCU0 1st B_y field integrals at the design current of 500 A from August and December data. The final 1st integral values were +31 and -87 G*cm in August and December, respectively.

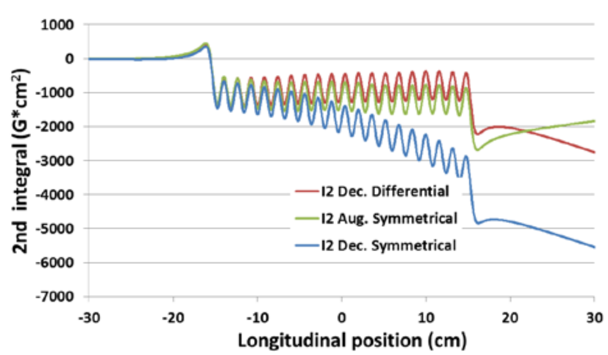

Figure 3: Plots of the SCU0 2nd B_y field integrals at the design current of 500 A from August and December data. The end correction coil currents were optimized using a 0.4% differential for the "Dec. Differential" case.

The measurements performed in August did not require any differential correction due to the fact that the 1st field integrals were naturally small and the 2nd field integrals were quite straight. Careful attention to SC lead dress was done during the initial assembly, but some compromises were made during the installation of the spare magnetic structure, which may have caused the increased stray field.

The data shown in this paper typically represents operation with optimized end correction coil currents set to minimize the 2nd field integrals using only symmetrical end correction currents. The measured K values from December and the phase errors from both the August and December measurements are depicted in Fig. 4.

The increased phase errors for the December measurements are due to a dipole component (from the SC stray field) that also affected the 1st field integrals, as shown in Fig. 2. If differential correction current was implemented, the phase errors during the December measurements could have been reduced to below 2 degrees and much closer to the August value of about 1 degree at 500 A.

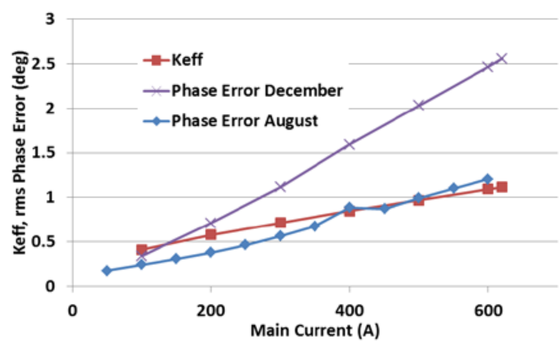

Figure 4: Plots of the SCU0 effective K value (K_{eff}) and phase errors as a function of current from the August and December Hall probe measurements.

INTEGRAL COIL RESULTS

A 4-mm-wide, 3.5-meter-long, single-turn stretched integral coil was used for measuring the static and dynamic 1st and 2nd field integrals as well as the multipole coefficients. The coil was rotated at 1 rps for the static field measurements and was fixed for measurements of the dynamic field integrals during a quench. The wire used for the coil was 100-µm-diameter CuBe stretched between two 4-mm-wide ceramic fixtures.

Static Integrated Field Measurements

The data in Fig. 5, labeled "I1 August" and "I1 December," were taken at fixed main coil currents. The data were recorded in the laboratory using the rotating coil system and using the storage ring with a beam-based integral measurement technique. The sign of the rotating coil field integral data was negated to agree with the beam-based data polarity. The data show that the change in the integrated field from 200 A to 500 A (the design operating range) was about 60 G*cm, which is within the APS tolerance of 100 G*cm.

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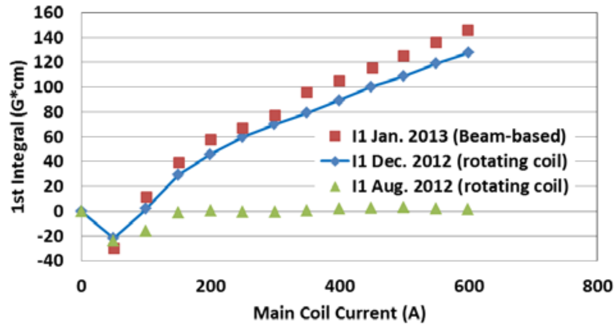

Figure 5: Plots of the SCU0 1[st] B_y field integrals as a function of current. These data were measured with a rotating coil in August and December, 2012, and using a beam-based technique with the APS storage ring in January, 2013.

Multipole Measurements

The rotating coil was also used to measure the integrated field uniformity over a horizontal range of ±4 mm. The curves in Fig. 6 show the integrated B_y (I1y) and B_x (I1x) along the x axis. It was discovered for the first time in August that a skew quadrupole component, which is larger than the APS undulator error tolerance, was present. It was decided to install the SCU0 as-is and use a feed-forward technique to adjust the beam coupling, if needed. This has proven successful in operation.

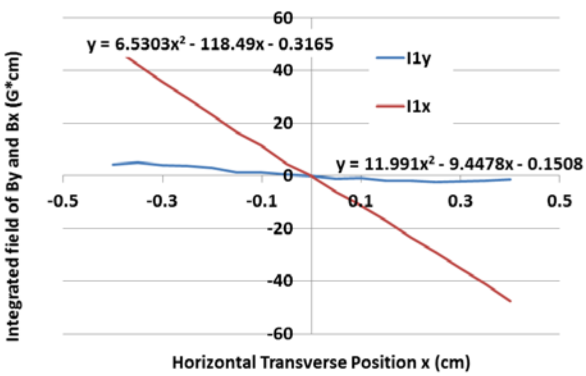

Figure 6: Plots of the SCU0 B_y (I1y) and B_x (I1x) 1[st] field integrals as a function of x position at a main coil current of 500 A. The normal and skew quadrupole components were -9.4 G and -118.5 G, respectively. The APS error tolerance is 50 G.

Dynamic Field Integral During a Quench

Measurements of the integrated field during quenches were done using a fixed coil. The data shown in Fig. 7 were taken during a forced heater-quench at 500 A. The 1[st] B_y integral curve was 35 G*cm p-p, which is 60 times less than the requirement of 2100 G*cm This low integral value is achieved by having the end correction coil currents slaved to the main current with an optimized look-up table. The look-up table was generated experimentally by optimizing the 2[nd] field integral (by adjusting the end correction current) at many fixed main coil currents.

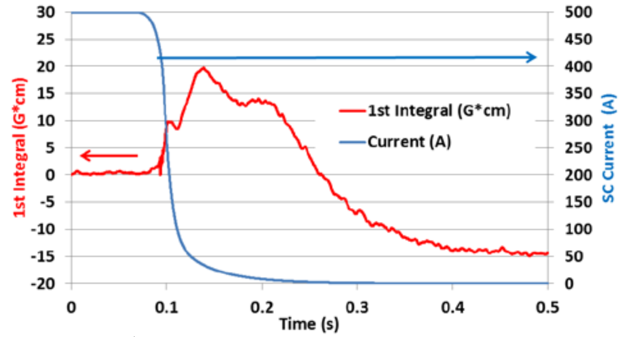

Figure 7: 1[st] B_y field integral and the main coil current as a function of time during a forced quench at 500 A.

CONCLUSIONS

The SCU0 magnetic measurements confirmed that all design parameters were within the APS error tolerances except for the integrated skew quadrupole component being slightly more than twice the 50-G tolerance. Measured phase errors were typically less than 2 degrees rms. The integrated field during a quench does not cause a beam dump; in fact it only causes a 60-µm beam motion. Comparing the August and December measurement results, it was found that initially the 1[st] field integral was very low and not current dependent, but after replacing one of the magnet structures, the 1[st] field integral was proportional to current but still within the error tolerance.

A new coil winding technique has been developed and will be implemented in the next SCU device. This new design was developed in order to minimize the skew quadrupole component, reduce machining cost, and improve the epoxy potting of the SC magnet structures.

The users in sector 6 have been routinely using the SCU0 at 685 A, 185 A above the design of 500 A.

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