PROGRESS ON THE MAGNETIC PERFORMANCE OF PLANAR SUPERCONDUCTING UNDULATORS *

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Abstract

One of the primary goals of the superconducting undulator (SCU) program at the Advanced Photon Source (APS) is to achieve a high quality undulator magnetic field without the need for magnetic shimming to tune the device. Over the course of two years, two SCUs were designed, manufactured, assembled, and tested at the APS. Both SCUs were one meter in length with a period of 1.8 cm. After magnetic measurements of the first undulator were completed, several design changes were made in order to improve the quality of the undulator magnetic field. The design modifications were implemented during construction and assembly of the second SCU. The details of the design modifications along with a comparison of the magnetic measurement results will be described.

INTRODUCTION

Several superconducting undulators (SCUs) have been constructed and tested at the Advanced Photon Source (APS). Two of these undulators were built to the same specifications and constructed two years apart. Lessons learned from the magnetic performance of the first undulator, referred to as SCU18-1, were used to modify the assembly of the second SCU, referred to as SCU18-2. The primary goal of the modifications to the second assembly was to improve the uniformity of the magnetic field quality in order to obtain phase errors below 5 degrees RMS over the entire operating range without the need for magnetic shimming. Both SCUs were designed and built to the specifications listed in Table 1.

Table 1: SCU18-1 and SCU18-2 Specifications

Parameter	Value
Cryostat length, m	2.06
Magnetic length, m	1.1
Undulator period, mm	18
Magnetic gap, mm	9.5
Beam vacuum chamber vertical aperture, mm	7.2
Undulator peak field, T	0.97
Undulator parameter, K	1.63
Operating Current, A	450

MECHANICAL DESIGN

General Layout

The undulator field of an SCU is generated by energizing NbTi superconductor coils in grooves that are precisely machined on a magnetic core made of low carbon steel [1].

The quality of the magnetic field, i.e. repeatability of the peak magnetic field from one undulator period to another along the full device, strongly depends on the precision of grooves, quality of winding, and the uniformity of the magnetic gap. The high quality of APS SCU winding has already been reported [2]. In this paper we concentrate on the method of precise control of the SCU gap and results of the SCU performance when all three critical factors are well controlled. The specification of the machining tolerances of each core was determined through the use of simulation software where various geometrical errors were introduced and the effect on the phase errors could be determined [3]. Following winding and epoxy impregnation, two cores are assembled together and the magnetic gap is defined by precision-machined spacers, as shown in Fig. 1. The gap spacers are placed at locations where the poles extend outside of the body of the cores.

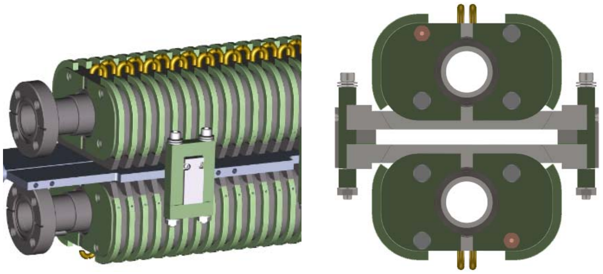

Figure 1: Assembly of two cores separated by the precision gap spacers.

Details of the Assembly of SCU18-1 and SCU18-2

After each core is manufactured, the flatness of the pole surface is measured to verify that it meets specifications. The flatness that is typically achieved after the final grinding process is 10 µm RMS with a peak-to-peak variation of 33 µm. The coil winding groove dimensions are also verified, typically within 50 µm and an RMS value of 15 µm. The periodicity is measured to verify there are no accumulated errors, typically 10 µm RMS and a maximum of 30 µm.

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

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After the SCU18-1 magnets were wound and epoxy impregnated, the flatness of the magnetic pole surface was measured before the assembly of the two cores. The measurement of the pole face revealed that the cores had developed a bow that would cause the magnetic gap to be up to 200 µm larger once the cores were assembled. The bowing of the cores has been attributed to asymmetries between the pole side and the opposing side of the wound core. The assembly of SCU18-1 proceeded and an effort to correct the deformation of the cores with the clamps on the extended poles was attempted. At the time there was no reliable method to check the magnetic gap of the assembly until magnetic measurements were made.

The cores of SCU18-2 exhibited a similar deformation after the winding and epoxy impregnation were complete. In anticipation of the deformation and a desire to have more confidence in the quality of the magnetic gap, two design changes were implemented and a method of measuring the magnetic gap of the assembly was developed.

External clamps were added and the gap spacers were extended, as shown in Fig. 2. The external clamps are made of titanium and stainless steel threaded rods and they are installed onto the assembly at each of the eight gap spacer locations distributed along the length of the device. The gap spacers were extended to prevent any distortion of the longer poles once the external clamps were torqued. In this arrangement, the magnetic gap is defined by the precision of the gap spacers.

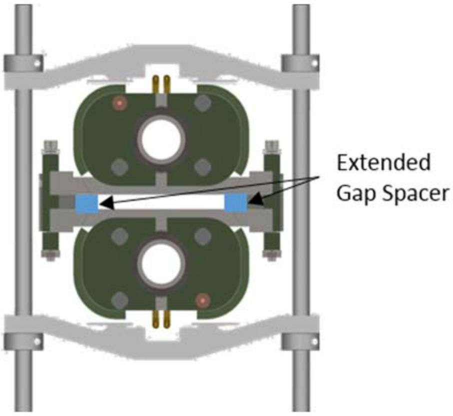

Figure 2: Assembled cores with external clamp and extended gap spacer.

After assembly of the cores and installation of the external clamps, the magnetic gap of SCU18-2 was measured at the eight locations of the gap spacers and clamps with a portable electronic feeler gage from Capacitec [4] which is shown in Fig. 3.

The surfaces of the poles at the measurement locations were cleaned of epoxy prior to assembling the cores. The gap measurement results are shown in Fig. 4 and it can be seen that the maximum variation in the gap over the length is around 25 µm. These measurements are made at room temperature and before the assembly is installed into the cryostat where there is limited to no access to the magnetic gap.

Figure 3: Capacitec Gen 3 Gapman portable electronic feeler gage [4].

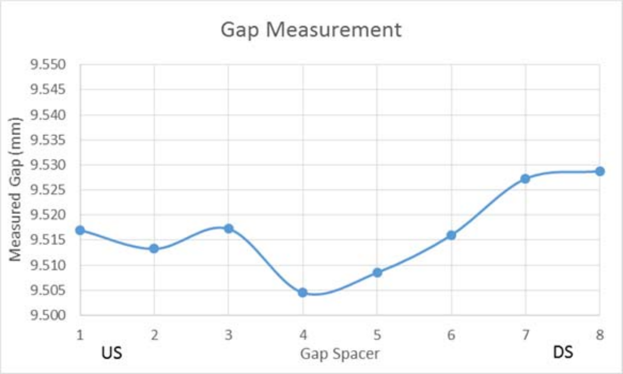

Figure 4: SCU18-2 measured gap at the eight gap spacer locations.

MAGNETIC MEASUREMENT RESULTS

Both assemblies, SCU18-1 and SCU18-2, were installed in horizontal cryostats and installed on the horizontal measurement system at the APS where magnetic field data is collected using a Senis 3-axis Hall probe and a rotating coil with a diameter of 4 mm. Measurement results of SCU18-1 were previously presented [5] and will be compared with the magnetic measurement data of SCU18-2.

The magnitude of the field peaks of both SCUs is shown in Fig. 5. The increase in the magnetic gap towards the end of the assembly of SCU18-1 is noticeable by the decrease in the magnitude of the peaks. The mean of the peaks of SCU18-1 and SCU18-2 were 0.9650 T and 0.9630 T, respectively. The standard deviation of the peaks for SCU18-1 is 0.0050 T and for SCU18-2 it is 0.0022 T. Four peaks on either end of each device are removed from the data.

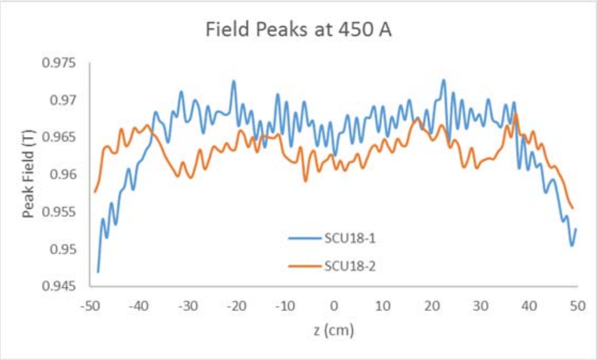

Figure 5: Field peaks of SCU18-1 and SCU18-2.

The field peaks indicate a significant improvement in the consistency of the magnetic gap. Using the Hall probe data, the phase errors versus the main current of both SCUs were determined and are shown in Fig. 6. The phase errors are calculated with 5 peaks removed from each end of the measured data. The improved consistency in the gap had a significant effect on the phase errors. At the designed operating current of 450 A, the phase errors of SCU18-1 were greater than 5° RMS and SCU18-2 had phase errors of 2° RMS.

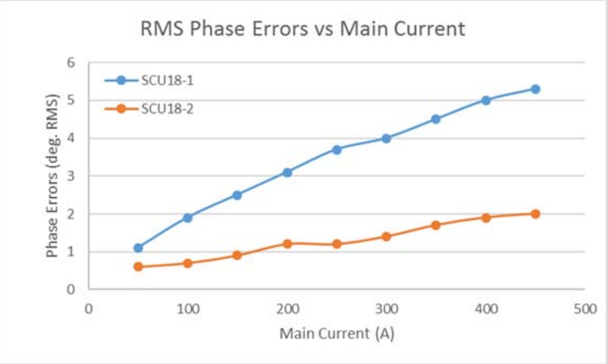

Figure 6: Phase errors versus the main current of SCU18-1 and SCU18-2.

Measurements of the integrated field were performed using a rotating coil. The on-axis, x = 0, y = 0, first and second field integrals, I1 and I2, were measured in the vertical and horizontal planes, y and x, respectively. The normal and skew components of the higher order multipoles were also recorded by measuring the integrated field at discrete points in x over the range x= +/- 6 mm followed by a polynomial fit of the data. The integrated field data are shown in Table 2. The values in Table 2 are at a main current of 450 A and are relative to the zero current measurement.

Table 2: SCU18-1 and SCU18-2 Integrated Field Data

Parameter	**Unit**	**SCU18-1**	**SCU18-2**
I1y	G-cm	20*	25*
I1x	G-cm	35	200
I2y	G-cm^2	25,000*	12,000*
I2x	G-cm^2	5,000	35,000
Normal Quadrupole	G	60	65
Skew Quadrupole	G	20	135
Normal Sextupole	G/cm	100	100
Skew Sextupole	G/cm	150	120
Normal Octupole	G/cm^2	60	40
Skew Octupole	G/cm^2	20	20

* After correction

It should be noted that there are correction coils that are available to adjust the values of the first and second field integrals in the vertical direction. These coils are external to the magnet assembly and are shown in Fig. 7. Currently, there are no correction coils available for the horizontal field integrals, though there are plans to add them to future SCUs. The source of the various integrated components of the field are being examined.

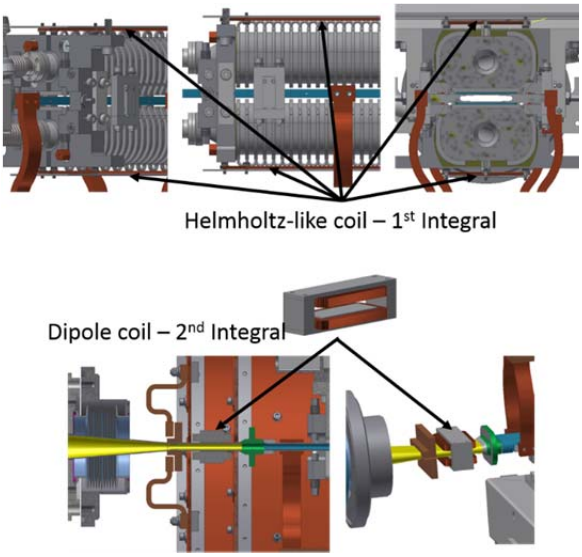

Figure 7: Vertical field integral correction coils.

CONCLUSION

Two similar SCUs, SCU18-1 and SCU18-2, were assembled and tested at the APS over the course of two years. Lessons learned during the testing of SCU18-1 prompted design changes and modified assembly techniques for the construction of SCU18-2. The results were a significant improvement in the undulator field quality, particularly related to the phase errors.

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