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MAGNETIC CHARACTERIZATION AND PHASE ERROR TUNING OF A 1.5 m LONG NbTi SCU AT THE ADVANCED PHOTON SOURCE*

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Abstract

Prior to assembly into the operational cryostat each superconducting undulator (SCU) at the Advanced Photon Source undergoes testing in a LHe bath cryostat where coil training and magnetic measurements are performed. If necessary, the baseline magnetic measurements are used for phase error tuning which is achieved by adjusting the magnetic gap of the SCU at prescribed locations. An optimization routine using a genetic algorithm is used to determine the magnitude of the gap change. Once complete, the SCUs are incorporated into the production cryostat and magnetic measurements of the final assembly are performed. Details of the process during phase error tuning and LHe bath testing of a 1.5 m long SCU magnet are presented.

INTRODUCTION

As superconducting undulators (SCUs) are prepared for assembly and integration into the final operational cryostat, several test cycles are performed to verify operation and the undulator magnetic field characteristics. Initial testing is typically performed in a vertical dewar where the SCU is submerged in a LHe bath. Once cooled, the magnet coils can be energized and training quenches can be repeated until the magnet coil is able to exceed the designed operating current. Coil training can be paused to perform magnetic field scans using a Hall effect sensor at currents below the design current to characterize the undulator field at several operating points.

During the course of developing the 1.5 m long, 16.5 mm period SCU magnets, a test and measurement program was developed at the APS to ensure that each SCU is able to meet the requirements to be integrated into the storage ring. In particular, we were interested in exploring the capability to reduce the measured phase errors during the LHe bath testing phase. Due to the nature of the final assembly process it is much easier to make modifications to the magnetic gap and perform additional testing during the initial phase and carry the changes forward in the final assembly. The methods and techniques were adapted from the APS permanent magnet measurement program [1]. Similar programs have been developed at other labs working on SCUs [2].

MOTIVATION AND METHODS

The magnetic field quality is related to the uniformity of the magnetic gap and the quality of the machining of the magnet core which defines the positions of the superconducting coils [3]. Machining the SCU cores to high precision with tight tolerances is difficult and costly. Therefore it is beneficial to have a method by which the field quality can be improved or controlled after the manufacturing process. This leaves gap tuning or magnetic field tuning using shims to modify the on-axis field based on Hall sensor field scan data. Placing magnetic shims on the SCU is not trivial and was not attempted for this development process. The focus was placed on adjusting the magnetic gap at the gap spacer locations to reduce the phase errors.

Gap spacers are placed between two magnet cores to define the magnetic gap of the SCU. There are 11 locations along the length of the 1.5 m SCU. Gap clamps are used at each location to seat the pole faces of the magnets on the gap spacer, shown in Fig. 1.

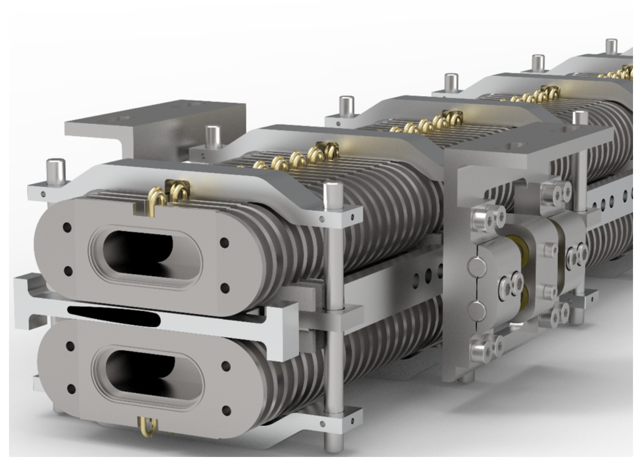

Figure 1: Two magnets clamped together in an SCU configuration.

After assembling the magnets into an SCU configuration the magnetic gap was measured on a granite table using a linear height gauge, The height gauge was programmed to touch the surface of the top magnet pole and then the bottom magnet pole. This measurement was performed at 64 locations on each side of the SCU. There are a total of 182 poles over the 1.5 m length. Figure 2 shows the measurement locations and Fig. 3 shows the probe tip in the magnetic gap prepared for a measurement.

The next step in the process was to integrate the magnets into the test assembly followed by performing magnetic measurements in a LHe batch cryostat. This served as a baseline measurement from which we could calculate the phase errors of the SCU. If the phase errors are below the

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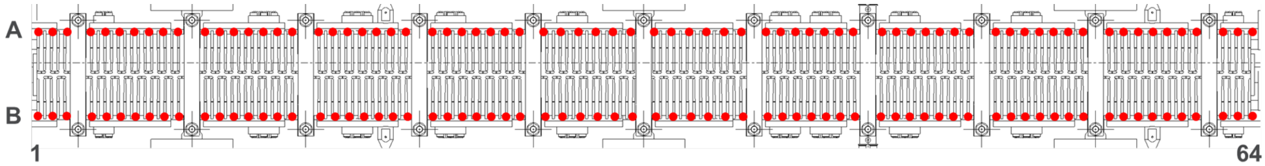

Figure 2: Linear height gauge magnetic gap measurement locations indicated by the red circles along both sides of the SCU.

Figure 3: Linear height gauge probe during the magnetic gap measurement.

requirement of 5° RMS then there is no need to make any gap corrections.

In the case where the phase errors exceed the specification, the magnetic field measurement data is fed into an optimization routine that analyzes the field data and provides gap modification values to reduce the phase errors. It was found in the permanent magnet measurement lab at the APS that a differential evolution algorithm, which is a variant of a genetic algorithm, works well for this optimization. Many software codes include an implementation of the differential evolution algorithm. For this study we compared the results from implementations using Python and LabVIEW. Both implementations produced similar results.

The routine attempts to minimize the phase errors by simulating the placement of shims to affect the magnetic gap. It is constrained to modify the gap only at the gap spacer locations. An initial set of shim values is randomly generated and a new field is calculated from the modified magnetic gap, which is linearly interpolated between gap spacers followed by calculating the new phase error which leads to the next iteration. Other constraints can also be input such as allowing only an increase in the gap or a maximum shim value. The global optimization routine is very efficient and typically converges to a solution within minutes.

Next, the SCU is disassembled to add the shims to the gap spacer locations suggested by the optimization routine. The magnetic gap is measured again on the granite table with the linear height gauge to verify the gap change. Then, LHe bath testing is performed again to measure the effect of the modified magnetic gap on the phase errors.

RESULTS

The procedure described in the previous section was performed on a 1.5 m long SCU with a period length of 16.5 mm and a nominal gap of 8.2 mm. A baseline measurement of the magnetic gap and the magnetic field were performed. Magnetic field data indicated that the phase errors exceeded the specification when the magnet was energized above 300 A.

Using the optimization algorithm we calculated shim values to be placed at the discrete locations of the gap spacers. Figure 4 shows the change in the gap from the baseline to after the installation of the shims as measured with the linear height gauge. The black triangles represent the shim locations and the thickness of the shim. The gap change agrees well with the intended change.

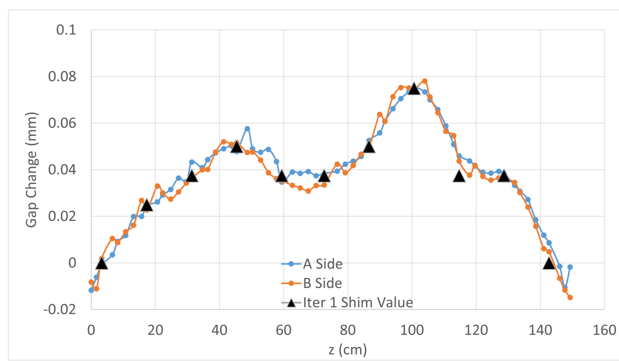

Figure 4: Change in gap from the baseline to iteration 1.

Shown in Fig. 5 are the field peaks at each pole location along the length of the SCU. The effect of the shims can be observed by the reduction in the magnitude of the field peaks, especially in the region where the shim values were the greatest. Taking the difference of the two plots of the field peaks it is possible to determine the effective change in the gap. Figure 6 shows the effective gap change along with the shim values and locations.

Magnetic measurement data is collected at various main coil currents during each iteration of LHe bath testing. Table 1 shows the RMS phase errors over a range of operating currents of the baseline measurement, the predicted phase error output from the optimization routine, and the actual result of the first iteration measurements. The phase errors were reduced at each level and brought within the specification of less than 5° RMS.

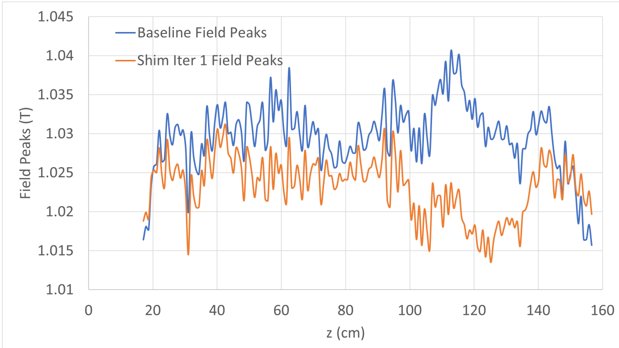

Figure 5: Field peaks of the baseline measurement and iteration 1.

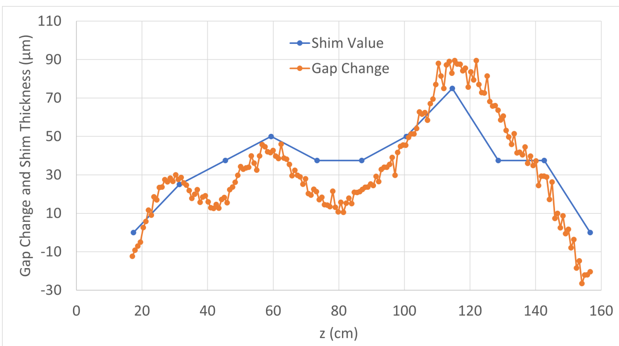

Figure 6: Effective gap change determined from the difference in field peaks of the baseline and iteration 1 magnetic measurement data. Also shown are the shim locations and values.

Table 1: RMS Phase Errors at Various Main Coil Currents

Current (A)	Baseline	Predicted	Actual
200	3.4°	2.5°	2.2°
300	5.0°	3.0°	3.3°
400	6.6°	3.2°	4.0°

CONCLUSION

A testing program was developed that allowed for the correction of out of specification phase errors of an SCU. By strategically adjusting the magnetic gap based on results produced by the differential evolution optimization algorithm, the phase errors were able to be reduced to a level that was within the specification. The process was successfully demonstrated on a 1.5 m long SCU. The phase error correction process may allow for the relaxation of tolerances of the magnet cores which could simplify the manufacturing process.

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REFERENCES

[1] M. F. Qian, R. J. Dejus, Y. Piao, I. Vasserman, and J. Z. Xu, "Experience with Algorithm-Guided Tuning of APS-U Undulators," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2915–2917. doi:10.18429/JACoW-IPAC2021-WEPAB130.

[2] Z. Chen, X. Yang, J. Wei, X. Zhang, X. Bian, Y. Li, and P. He, "Vertical measurement and on-line correction of the magnetic field for a 1.5-m-long superconducting undulator," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 1047, p. 167826, 2023, doi:10.1016/j.nima.2022.167826.

[3] J. Bahrdt and Y. Ivanyushenkov, "Effects of Geometrical Errors on the Field Quality in a Planar Superconducting Undulator," in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper MOPPP065, pp. 708–710.