END-FIELD ANALYSIS AND IMPLEMENTATION OF CORRECTION COILS FOR A SHORT-PERIOD NBTI SUPERCONDUCTING UNDULATOR*

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Abstract

A short period superconducting undulator (SCU) is being developed at the Advanced Photon Source (APS). The on-axis field of the prototype 1.6-cm period 42-pole SCU0 was measured with a cryogenic Hall probe system. Typical permanent magnet undulators provide end-field correction by decreasing the strength of the magnets on both ends of each jaw. In the case of the SCU0, a set of correction coils was wound on the two end grooves of each of the steel cores along with the main coils to provide the required end fields. These correction coils were connected in series and energized with one power supply to provide simple and symmetrical operation. The measured phase errors of the SCU0 were below 2 degrees rms without any local magnetic tuning of the device.

INTRODUCTION

The tolerance of the 1st and 2nd field integrals at the APS are 50 G·cm and 100,000 G·cm^2, respectively. In order to minimize the final 2nd field integral, permanent magnet (PM) undulators, typically, have the field strength of the last two magnets on each end reduced to approximately 75% and 25% of the average field strength. The 1st and 2nd field integrals for a PM undulator are typically tuned by shimming and adjusting the magnet strengths. The APS tolerance for undulator phase errors is 8 degrees rms, and typical APS PM undulators achieve 4 degrees rms [1].

The final 1st field integral along the beam axis for the SCU0 design should be zero due to the fact that any flux passing through the mid-plane must also return through the mid-plane. The 2nd field integral is dependent on the relative strength of the first few poles on each end of the SCU. The angle of the e-beam (while in the SCU on-axis field), and thus the photon beam, can be adjusted by changing the strength of the first two poles on each end. This is done with separate correction coils wound on the last two coil packs on each end of the SCU cores.

CORRECTION COIL DESIGN

The SCU0 consists of two all-steel cores with 42 individual steel poles secured to the core [2]. The main coils were continuously wound in grooves between the poles with 0.75-mm-diameter round NbTi superconductor manufactured by Supercon. The main coils consist of 41 coil packs with 39 turns per pack (7 layers per coil pack) on all but the last two grooves on each end. The winding technique is similar to previous Nb_3Sn and NbTi SCUs built at the APS [2]. Fig. 1 shows a single SCU0 core after winding both the main and correction coils.

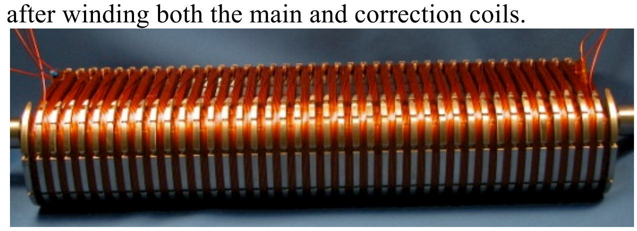

Figure 1: A single SCU0 core after completion of all winding and before potting with epoxy.

Fig. 2 shows the configuration of the main and corrector coils on one end of a core. The main coils were wound in opposite directions, but the correction coils were wound in the same direction.

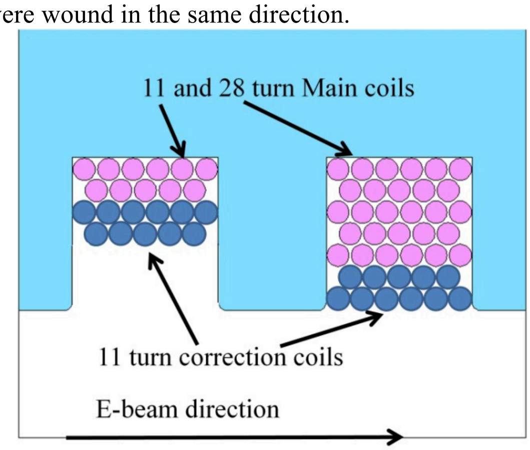

Figure 2: Winding configuration of the last two coil packs of one core. The magenta circles denote the main coils, and the dark blue circles the correction coils. The lighter blue depicts the steel core and poles.

Since the SCU0 main coil packs have 39 turns each, the last two coils on each end would need to be 29.25 and 9.75 turns in order to have similar end-field ratios as typical PM undulators. Since non-integer coil packs are not possible, a correction coil design was developed to obtain the desired end-coil Ampere-turn ratios. This correction scheme not only allows adjustable field reduction on the end poles, but also minimizes the longitudinal field in the central cores, which minimizes stray fields.

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Correction Coil Winding Details

Two fundamental design goals were considered for the correction coil configuration.

1. Minimize net Ampere-turns along the device.
2. Ability to adjust the 2nd field integral.

Since the SCU0 has 41 coil packs wound with alternating directions, to achieve zero net Ampere-turns, the center coil Ampere-turns must be canceled, and the following expression must be satisfied:

$$(11 - C \cdot n) - (28 + C \cdot n) + 19.5 = 0 \quad , \tag{1}$$

where C is a correction coil factor, and n is the number of the correction coil turns. The three terms from left to right represent the effective turns of the end two coil packs and half the center coil turns. Solving for $C{\cdot}n$ results in

$$C \cdot n = 1.25 \quad . \tag{2}$$

If n is chosen to be 11 (which comprises two conductor layers) then C becomes

$$C = \frac{1.25}{11} . \tag{3}$$

So as shown in Fig. 2, the last two main coil packs on each end of the cores were wound with 11 turns (closest to 9.75), and the penultimate main coil packs were wound with 28 turns (closest to 29.25). The 11-turn correction coils were wound on top of the 11- and 28-turn main coils. The correction coils were wound in the same direction with a continuous conductor for each of the two end coil packs. When energized, the effective Ampere-turns on the end coils was decreased and the penultimate poles increased, thereby allowing adjustment of the end-pole strengths and thus the 2nd integral.

For a non-magnetic core with this winding design, zero net flux in the cores would occur when the correction current I_c satisfies the following expression:

$$I_c = \frac{1.25}{11} I \ , \tag{4}$$

where I is the main current. The end two coil packs would also have 75% and 25% of the center coil Ampere-turns when the correction current agrees with Eq. (4).

Computer Simulations

Prior to winding the SCU0 coils with the above configuration, computer simulations using Opera 2D were carried out to confirm the operation with a steel core and poles. Due to the steel permeability, the correction current required to minimize the net flux in the core and the final 2nd field integral was less than the value calculated with Eq. (4). The simulation showed the correction current required to minimize the 2nd integral was approximately 51 A, whereas Eq. (4) predicted 56.8 A. Adjustment of the correction current in the simulation proved that the trajectory angle (in the SCU0) could be changed without affecting the phase errors or e-beam exit angle. The final value of the 1st integrals calculated from the simulation data were less than 50 mG·cm for correction currents of 0 A, 51 A, and 100 A. The 2nd integral could be adjusted from -167 kG·cm^2 (0 A correction) to 169 kG·cm^2 (100 A correction). (See Fig. 6 and Fig. 7.)

MAGNETIC FIELD MEASUREMENTS

Measurement Setup

All measurements were made with a calibrated cryogenic Hall probe from Arepoc. The SCU was in a vertical cryostat in a LHe bath. A carbon fiber (CF) tubing, which housed the Hall sensor, was coupled to a linear stage on the outside of the cryostat. The CF tubing traveled in a guide tube located at the central axis.

On-Axis Field and Field Integrals

Measured field integrals in Fig. 3 show very good agreement to the simulated data in Fig. 4. Measured fields in Fig. 5 show the effects of large changes in correction currents.

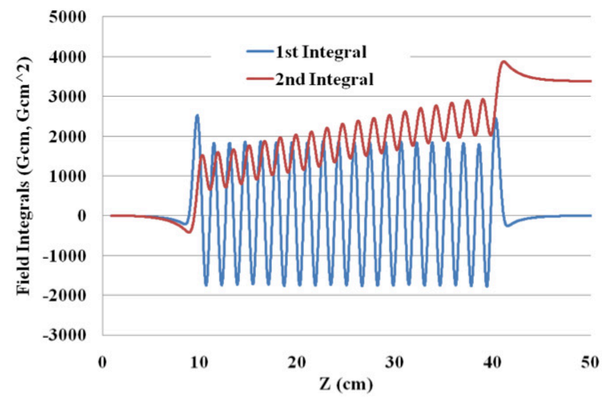

Figure 3: 1st and 2nd field integrals from measured Hall probe data from Fig. 5 with 51.5-A correction current.

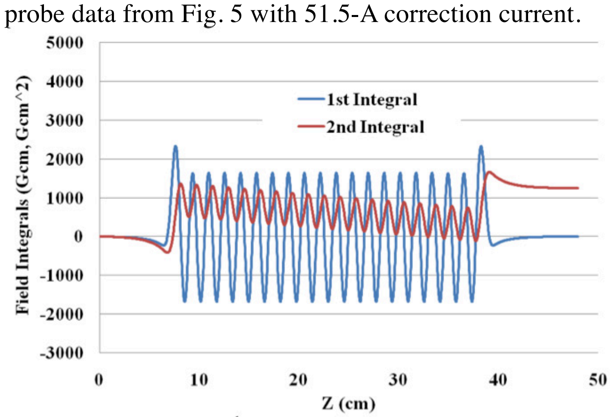

Figure 4: 1st and 2nd field integrals simulated with the Opera 2D computer code. Correction current was 51 A.

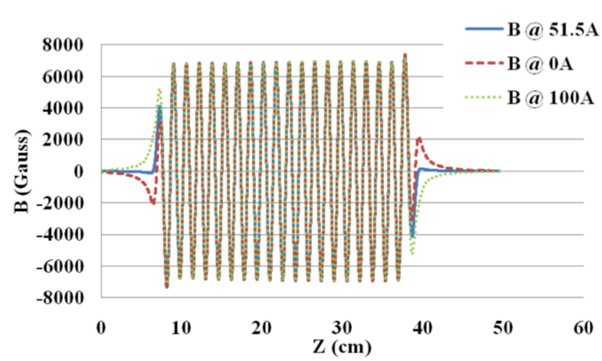

Figure 5: Field plots showing the effect of end-field correction currents at 0 A, 51.5 A, and 100 A.

The 1st and 2nd field integrals, with the above correction currents, are shown in Fig. 6 and Fig. 7 along with the simulated data. The APS beam energy is 7 GeV, so an average 1st integral of 5000 G·cm results in a trajectory angle of 200 μrad. Note that although the measured average 1st integrals were ±5000 G·cm, the final values were less than 25 G·cm. The final 1st field integrals were affected more by errors of Hall probe offset and the Earth's field than from the SCU0 field. The sensitivity of the photon beam angle to correction current was approximately 4 μrad/A. Using 100-A power supply, this end-field correction design would allow adjustment of the photon beam angle by ±200 μrad. The e-beam exit angle would be unaffected by this steering, but the offset would be a maximum of ±70 μm. See Fig. 7.

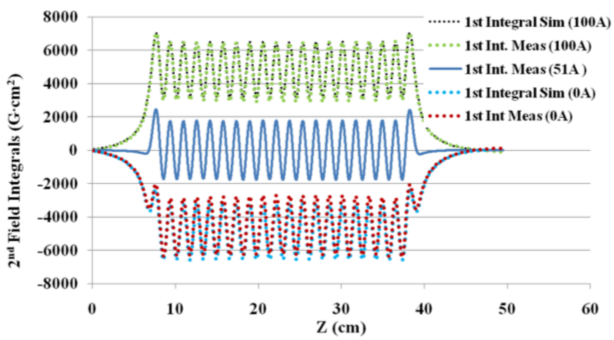

Figure 6: Measured and simulated 1st field integrals at 0-A, 51-A, and 100-A correction currents.

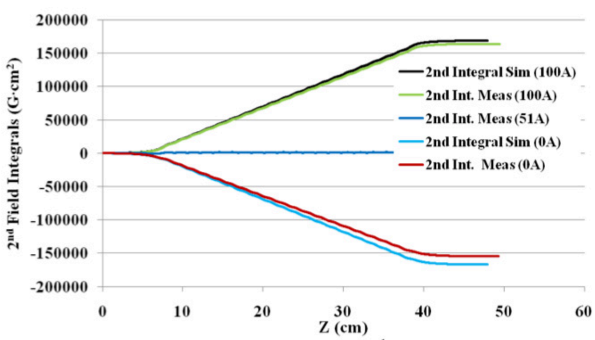

Figure 7: Measured and simulated 2nd field integrals at 0-A, 51-A, and 100-A correction currents.

Phase Errors

The phase errors of the SCU0 initially were approximately 4 degrees rms, which suggested a slight tapering of the end-to-end gap, see Fig. 8.

The SCU cores were slightly separated to install an Al vacuum chamber. During this process the gap alignment was inadvertently improved. Phase errors after this re-alignment were less than 2 degrees rms.

CONCLUSION

The end-field correction coil method presented above has proven to function very well for adjusting the 2nd field integral (beam trajectory) for the SCU0 device. The machining accuracy of the core and poles, along with the precision of coil winding, has produced a device with

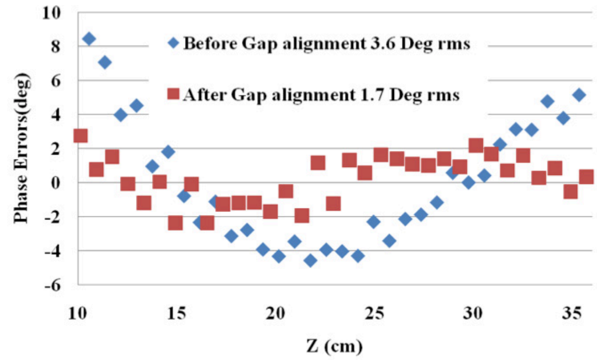

Figure 8: Phase errors before and after alignment of the gap, which corrected a small taper from end to end. Measured at 500 A with 51.5-A correction current.

exceptionally good field quality and low phase errors without resorting to local field tuning.

The results for the February 2011 SCU0 Hall probe measurements show rms phase errors of about 1.5 deg. The calculated degradation of the third harmonic is essentially zero. The fifth harmonic at 94.6 keV is expected to perform better than 97% of ideal. This is all for zero-emittance calculations. With the emittance included, the ratio to the ideal performance becomes even higher [5].

The ability to adjust the photon beam ±200 μrad without affecting the e-beam angle could be advantageous to the APS users. The operational issues associated with this new capability are yet to be determined.

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