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# MAGNETIC FIELD CALCULATION OF SUPERCONDUCTING UNDULATORS FOR A FEL USING MAXWELL 3D*

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*Abstract*

An ANL-SLAC collaboration is working on design of a planar superconducting undulator (SCU) demonstrator for an FEL. As a part of this project, an SCU magnet prototype is planned to be built and tested. A planar SCU magnet consisting of a 1.0-m-long segment is being designed. Although OPERA is a standard tool for magnetic field calculation, ANSYS Maxwell 3D can also be used for a large and complex geometry. An ANSYS calculated magnetic field was benchmarked with the measured field profile of existing SCUs. This paper presents calculations of magnetic field and field integrals of 0.5-m-long and 1.0-m-long planar SCUs with a new end correction scheme. Then, an external phase shifter is also incorporated into the model. A crosstalk between a phase shifter and SCU magnetic structures is also presented.

## INTRODUCTION

To meet FEL-SCU [1, 2] magnetic specifications, a straight trajectory is required. That means the angle (1st integral), total shift (2nd integral), and non-straightness (shape of the 2nd integral) of the trajectory must be minimized. Traditionally, correction was achieved by reducing the main turns and adjusting the current in the last two grooves at either end (two groove scheme) [3]. However, it tends to minimize either a shift or an angle, not both, and often takes higher correction current [4]. As the core becomes longer, its non-straightness increases and the optimal correction current for 2d and 3d models do not necessarily agree. Thus, a new end correction scheme is introduced [5]. By reducing the number of main turns in the last three grooves and using one or two correctors at the end grooves, optimal correction current is reduced, and the calculated trajectory becomes straight (three groove scheme).

## MAGNETIC MODEL OF SCU WITH THREE GROOVE SCHEME

The three-groove scheme is applied to 21-mm-period SCU demonstrator model. The core material used is 1008 steel. Examples are shown for 2d and 3d models. Calculated 2nd integrals are compared for different lengths of SCUs.

Table 1 shows the undulator parameters for the demonstrator SCU. Figure 1 shows the end three grooves and three main grooves for the asymmetric case. The reduced main current is chosen to make the net ampere-turns close to zero.

Table 1: Undulator Parameters for the SCU

| | Unit | Value |
|---|---|---|
| Period | mm | 21 |
| Periods | N | 23.5 or 47.5 |
| Groove dimension | mm | 6.135*4.88 |
| Magnetic gap | mm | 8 |
| Cond. diameter | mm | 0.7 |
| Full coil turns | N | 53 |
| main | A | 588 |
| 1st groove current | A | -6*main-15*corr1 |
| 2nd groove current | A | +27*main-15*corr2 |
| 3rd groove current | A | -47*main |

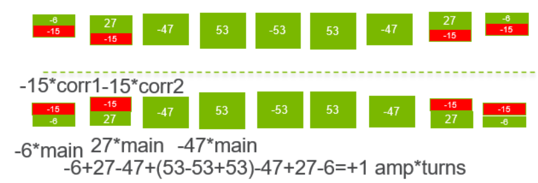


Figure 1: End correction scheme for all 2d and 3d models.

### *2d Model of a 21-mm-Period SCU*

A static magnetic field is calculated using ANSYS Maxwell 2d. For all cases, symmetry boundary conditions are not used. Figure 2 (left) shows details of the end correctors of the SCU. Figure 2 (right) shows the 2d model geometry of 0.5-m-, 1.0-m-, and 1.9-m-long SCUs. Two end corrections are identical except in length.

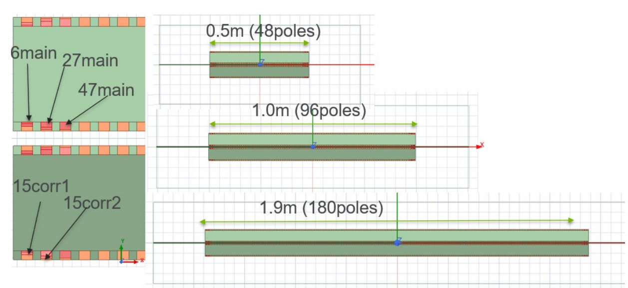


Figure 2: 2d models of 0.5-m-, 1.0-m-, and 1.9-m-long SCUs and details of the three end grooves.

Figure 3 (top) shows the calculated magnetic field of a 1-m-long SCU with optimal correction current (corr1=12.93A and corr2=12.58A). The peak field is 1.61 T (16100G). The 1st and 2nd integrals of this field are shown at the bottom.

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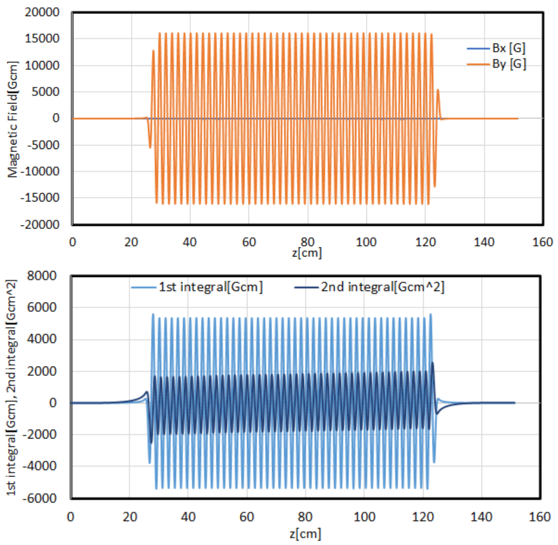


Figure 3: (top) Calculated magnetic field of 1-m-long SCU with the optimal correction current corr1=12.93A and corr2=12.58A in the 2d model. (bottom) The 1$^{st}$ and the 2$^{nd}$ integrals of the magnetic field: 1$^{st}$ integral=–1.04 G-cm and 2$^{nd}$ integral=16.9 G-cm$^2$.

Figure 4 shows the comparison of calculated magnetic field 2$^{nd}$ integrals for 0.5-m-, 1.0-m-, and 1.9-m-long SCUs as well as a combination of correction currents. Optimal correction currents agree within a few amps for the 0.5-m, 1.0-m, and 1.9-m cases. The 2$^{nd}$ field integral is within 40µTm$^2$ so that both shift and angle are small enough to ensure the straightness of the trajectory.

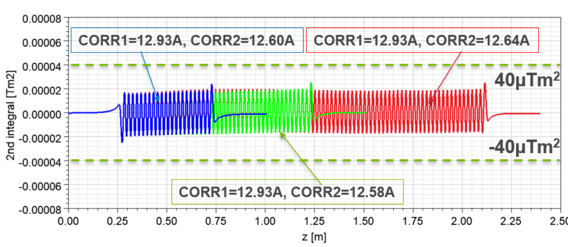


Figure 4: Calculated 2$^{nd}$ integrals of magnetic field with optimal correction current for 0.5-m-, 1-m-, and 1.9-m-long SCUs in the 2d model.

### *3d Model of a 21-mm-Period SCU*

A static magnetic field is calculated using ANSYS Maxwell 3d. Figure 5 (top) shows the geometry for a 0.5-m-long SCU (top), and a 1-m-long SCU (bottom) for a 3d model. The detailed view of the three end grooves is shown at the top left. The end correction schemes are the same as in Fig. 1 and Table 1.

Figure 6 shows a comparison between 0.5-m- and 1-m-long SCUs for a 3d model as well as a combination of optimal corrector currents for each case. The optimal correction currents for the 2d and 3d models also agree within a few amperes. These corrector currents are less than 50 A so that special high current lead pairs are not required, which makes the mechanical design of the cryostat simpler. The results of the 2d and 3d model calculations verify the validity of the three-groove scheme.

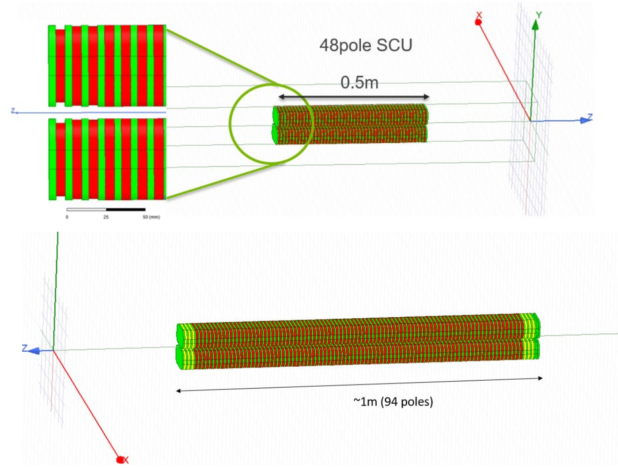


Figure 5: 3d models of (top) 0.5-m- and (bottom) 1-m-long SCUs and the detail of the end grooves.

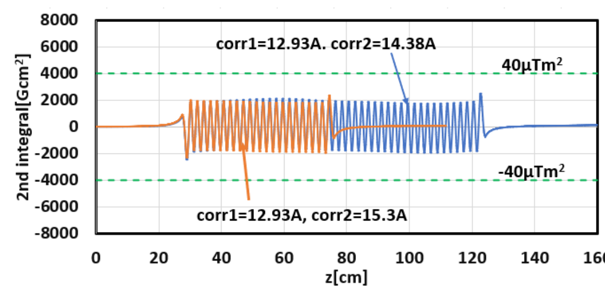


Figure 6: Calculated 2$^{nd}$ integrals of magnetic field with optimal correction current for 0.5-m- and 1-m-long SCUs in a 3d model. A 1-m-long SCU with corr1=12.93A and corr2=14.38A gives the 1st integral = 2.10 G-cm, and the 2nd integral = 109 G-cm$^2$ at z=160 cm.

## MAGNETIC MODEL OF AN SCU AND AN EXTERNAL PHASE SHIFTER

Once a straight trajectory is made by the three-groove scheme, a phase shifter needs to be designed. If the phase shifter is not integrated into the main SCU [6], then an external phase shifter is needed. The phase shifter should reach the required phase integral and not disturb the trajectory. Two types of external phase shifters are considered. One is a traditional 4-pole phase shifter that consists of a 4-pole 3-groove SCU with 8-mm gap and 21-mm period length [1, 7 – 9]. The other is a C-type phase shifter. The magnetic field of the C-type phase shifter is calculated for variable current C10 at constant current C20=10A*53 turns in Fig. 7(a). The 1$^{st}$ integral of this phase shifter is zero in (b). For the optimal C10 and C20, the 2$^{nd}$ integral is zero in (c). The phase integral of this optimal combination of C10 and C20 is shown in (d). Although the 1$^{st}$ integral of the standalone phase shifter is zero, when it is close to the SCU, it becomes non-zero due to the crosstalk between the phase shifter and the SCU.

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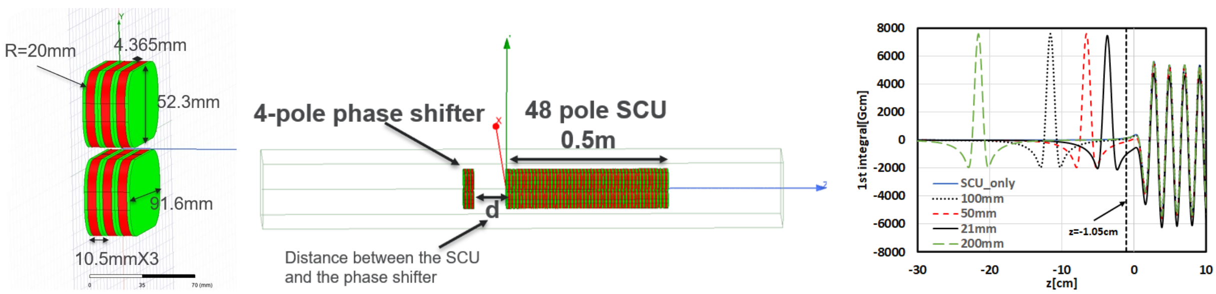


Figure 8: A design of a 4-pole phase shifter (left), the 0.5-m-long SCU and the four-pole phase shifter (middle), and the calculated 1st integral of the combined magnetic fields (right); z = 0 at the end of the SCU. The black dotted line is at z = –1.05 cm (a half period length) away from the end of the SCU.

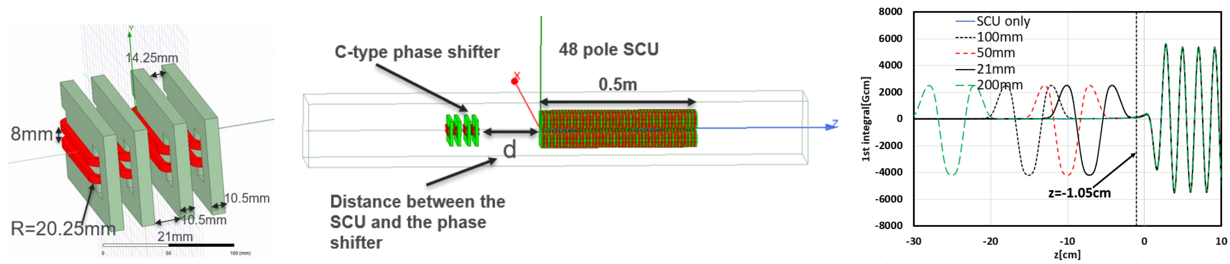


Figure 9: A design of a C-type phase shifter (left), a 0.5-m-long SCU and the C-type phase shifter (middle), and the calculated 1st integral of the combined magnetic fields (right).

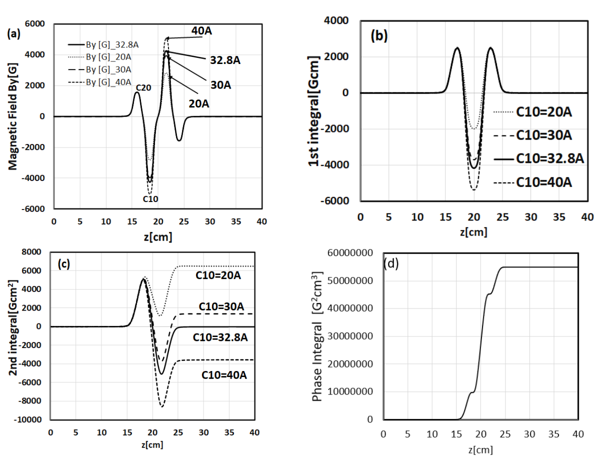


Figure 7: (a) Calculated magnetic field, (b) the 1st integral, and (c) the 2nd integral of the C-type phase shifter with different combinations of current; (d) phase integral for the optimal combination of currents C10 and C20.

To achieve the highest packing factor for FEL application, the distance between a phase shifter and the SCU needs to be minimized. So, a static magnetic field of a 0.5-m-long SCU with a phase shifter at various distances are calculated. The real SCU would be 1.0 m or longer; however, a 0.5-m-long SCU is used for faster convergence purposes. Figure 8 shows the design of the 4-pole phase shifter (left), the phase shifter and 0.5-m-long SCU (middle), and a calculated 1st integral of magnetic field (right). Figure 9 shows the design of the C-type phase shifter (left), the C-type phase shifter and 0.5-m-long SCU (middle), and a calculated 1st integral of the magnetic field (right). In these models, z = 0 at the end of the SCU. The crosstalk is calculated as the 1st integral change between SCU only and a phase shifter plus SCU at z = –1.05 cm (a half period). These changes are plotted as a function of the distance between the phase shifter and a 0.5-m-long SCU, as shown in Fig. 10. With the C-type phase shifter, the 1st integral change becomes less than –3G-cm when the distance is further than 10 cm. On the other hand, the 4-pole phase shifter needs to be further than 30 cm.

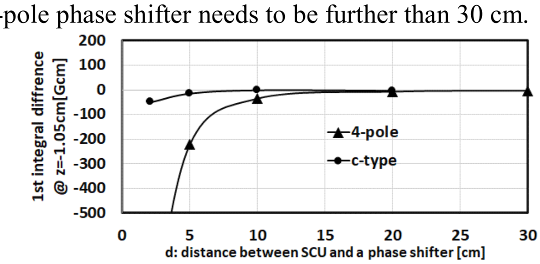


Figure 10: Comparison of 1st integral difference [G-cm] as a function of the distance between the SCU and the phase shifter.

## CONCLUSION

Three reduced main and corrector currents successfully minimized the 2nd integral within 40μTm² (4000 Gcm²) for a 1.0-m-long SCU using 2d and 3d models. The crosstalk between a C-type phase shifter and the main SCU is negligible if the distance is longer than 10 cm.

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