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A PHASE SHIFTER FOR INLINE UNDULATORS AT THE ADVANCED PHOTON SOURCE UPGRADE PROJECT*

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Abstract

Several undulator lines for the Advanced Photon Source Upgrade (APS-U) will consist of two inline undulators. In order to keep the undulators operating with optimal phasing over the full range of gaps, a phase shifter will be included between the undulators. A design has been developed for a phase shifter that will serve for a variety of undulator period lengths and gap ranges. The permanent-magnet phase shifter will use SmCo magnets to reduce the risk of radiation-induced demagnetization. The available space between the undulators is tight, so magnetic shields are placed between the undulators, the phase shifter, and the corrector magnet that is also located in the inter-undulator space. While these shields guard against magnetic cross-talk between the devices as the undulator and phase shifter gaps change, they do have an effect on the end fields of the devices. These end-field effects are examined and relevant tolerances are set and presented.

INTRODUCTION

Preparations for an upgrade to the APS are well underway. Changes to the insertion devices are included in the upgrade, both because of the change from an e-beam energy of 7 GeV to 6 GeV, and to allow users to take advantage of the improved electron beam characteristics. For eleven beamlines, the plan is to have two inline undulators that can be operated in tandem. Getting the full photon amplitude from the pair of undulators requires that they operate in phase with each other over the full range of usable undulator gaps so that destructive interference between photons from the two undulators is minimized.

INLINE UNDULATOR SECTOR

The inline undulators for APS-U will be the accustomed full length of 2.4 meters. They will come in a variety of period lengths, depending on the user's choice, and some will be revolver undulators that offer a choice between two period lengths for users seeking greater flexibility. Between the undulators will be a phase shifter and a corrector. The anticipated layout is shown in Fig. 1. The distance from the end of one undulator to the beginning of the next is 197 mm, which puts the magnetic components close enough together that magnetic shields are required to interrupt magnetic crosstalk. Shields are at both ends of the undulator so the undulators are more readily swappable without retuning. The distance between the end of the undulator strongback and the nearest face of the shield was set to 20 mm based on experience tuning many undulators at APS. Note that the distance from the face of the last undulator pole to the nearest face of the shield will be slightly larger than 20 mm and will vary with period length - while the strongback length can be set to 2400 mm, the magnetic structure length must be an integer number of half periods.

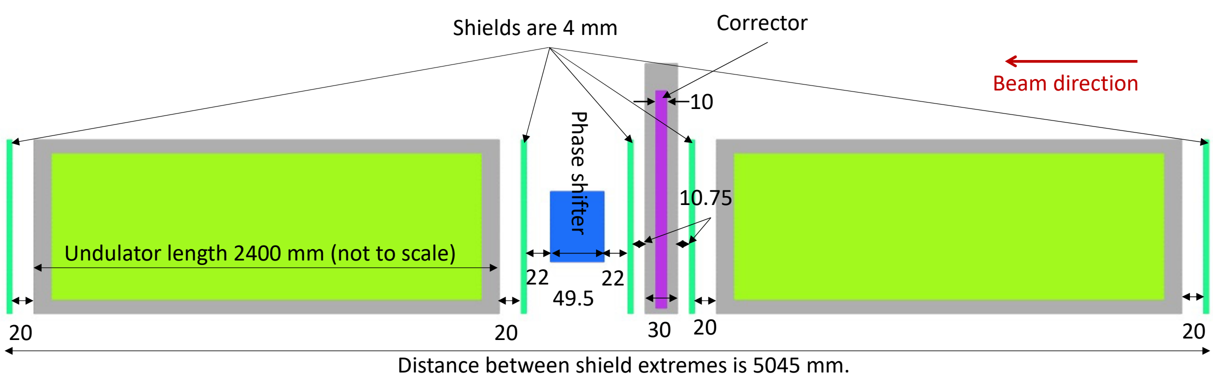

Figure 1: Sketch of the inline undulator sector. The undulators are not to scale. The overall machined length of the vacuum chamber flat section is 5050 mm; keeping the distance from the far ends of the shields to 5045 mm allows for the radius at the end of that flat section. The gray borders around the undulator and corrector are non-magnetic support structure.

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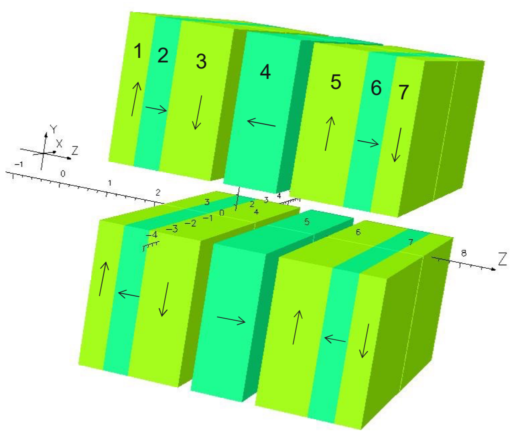
DESIGN FOR THE PHASE SHIFTER

The design of the phase shifter, shown in Fig. 2, was adapted from Wolf's design for LCLS-II [1, 2]. It has the advantage of including no iron so the effect of ambient magnetic fields is minimized. The symmetric 4-pole design makes the 1st field integral ∫By dz through the shifter zero by design. Also, Wolf took care to balance the lengths of the magnets and drift spaces so the 2nd field integral ∫∫By dz dz' (i.e., the trajectory offset) would also be zero, at least for the free-standing shifter.



Dimension	Magnet #	cm
X	All	6.5
Y	All	2.5
Z	1,2,6,7	0.45
Z	3,4,5	0.9
Z	spaces	0.225

Overall length in z = 4.95 cm

Figure 2: Top: Sketch of the phase shifter design. Arrows indicate the magnetization direction of the individual magnet blocks. Bottom: Magnet block dimensions are given.

PHASE SHIFT REQUIRED

The intent is to have a single phase-shifter design that will suit inline undulators of any of the period lengths expected to be used in an inline configuration. This means that the maximum phase slippage must be at least as long as the longest wavelength photons that will be produced by any of the undulators, which are the 2.5 keV photons from the 3.0-cm-period undulator with a wavelength of 4.959 Å. The phase slippage is given by [1]

$$S = \frac{L}{2\gamma^2} + \frac{1}{2\gamma^2}\left(\frac{q}{m_e v_z}\right)^2 PI,$$

where the phase integral *PI* is

$$PI = \int_{-L/2}^{L/2}\left(\int_{-L/2}^{z} B_y\,(z_1)dz_1\right)^2 dz.$$

The first term of the slippage is from the free-space distance and does not change, so we ignore it in favor of the second term, which is the slippage due to the magnetic field of the shifter. The phase integral is a convenient term to describe the shifter's contribution and variation with phase shifter gap.

The variables in the conversion between PI and slippage are: the relativistic γ for a 6 GeV electron, the charge and mass of the electron, and, effectively, the speed of light. The conversion factor, 1.248E-15 cm/(G^2 cm^3) gives a required phase integral for one wavelength of a 2.5 keV photon of 3.973E+07 G^2 cm^3. As shown in Fig. 3, a shifter made of either NdFeB (Shin-Etsu N42SH grade assumed) or SmCo (Shin-Etsu grade R42HS at 25 ºC is assumed) permanent magnets would provide sufficient range in the phase integral.

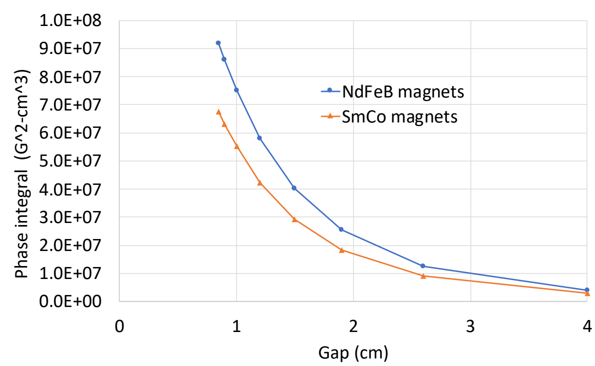


Figure 3: Calculated phase integral for two versions of the phase shifter – one using NdFeB permanent magnets, the other with SmCo. Either can cover a range >4E+07 G^2 cm^3.

Since both NdFeB and SmCo magnets meet the field strength requirement, either can be chosen. Considerations of radiation-induced demagnetization of permanent magnets drive the choice to SmCo. The pronounced and rapid radiation demagnetization seen years ago at APS was remedied in one of the worst sectors by replacing the NdFeB undulator with a SmCo-based one. Twenty years later, that SmCo device is still doing well. Small levels of demagnetization are still occasionally found in NdFeB undulators in other sectors after years of operation, though. With 11 phase shifters planned, the additional stability of SmCo seems advisable.

FIELD INTEGRALS AND TOLERANCES

Wolf's original design has 1st and 2nd field integrals through the shifter that are intrinsically zero. However, the realities of fitting everything into the straight section, with the resulting need for magnetic shielding between components to avoid crosstalk, will change that. Calculations done to examine the changes found that the (symmetric) presence of shields at the ends of the shifter doesn't alter the 1st field integral, but does affect the 2nd field integral, as shown in Fig. 4. The ~1.5 µm displacement is small compared to the horizontal beam size, which is 12.9 or 14.7 µm, depending on the operating mode [3].

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Given the phase shifter's sensitivity to the shields, it is reasonable to check the tolerance on the shield placement in z (the beam direction). Model calculations were run with the downstream (DS) shield at the nominal 2.2 cm distance and the upstream (US) shield displaced by ±0.5 mm from nominal. The 2nd field integral doesn't change by much, but there is an effect on the 1st field integral, as shown in Fig. 5. While the 0.75 µrad angle is less than the ~2.5 µrad horizontal divergence in the beam [3], we can easily do better. If the shields are mounted directly to the phase shifter with standoffs, the error, and angle, will be smaller.

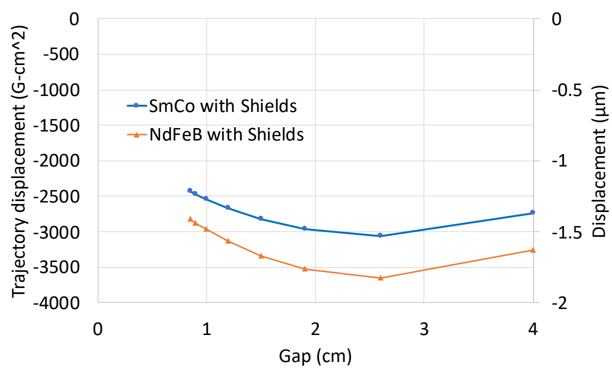

Figure 4: 2nd field integral (also trajectory displacement) through the phase shifter with shields present. For the SmCo case, a 6 GeV beam results in a displacement of ~1.5 µm.

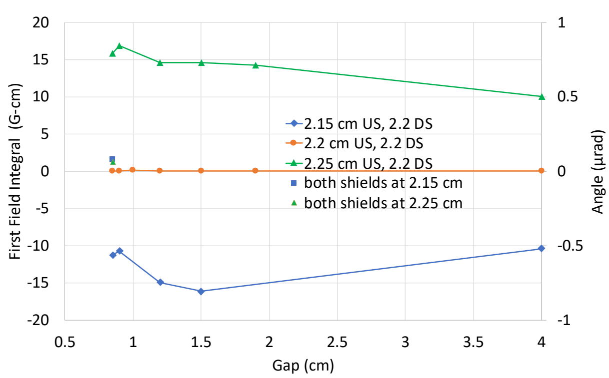

Figure 5: 1st field integral when shields are misplaced by 0.5 mm in z. For an asymmetrical misplacement, an angle of 0.75 µrad is introduced in the electron beam by the shifter. If both shields are misplaced symmetrically, there is no angle.

MULTIPLE IN-PHASE SETTINGS

The phase shifter can provide at least one wavelength of phase slippage. This means that no matter what the phasing is between the undulators initially, the phase shifter can bring the undulators into proper phasing for any photon energy they produce. For higher energy photons, there will be several settings of the phase shifter, spaced by one wavelength in slippage, that will put the undulators in phase. Users wishing to scan the photon energy will be able to choose where to start the scan to minimize resetting the shifter during the scan. Table 1 shows, for a few photon energies, the range in degrees (360° = 1 wavelength) of phase slippage between 0.85 cm minimum gap and a gap of 4 cm. The two rightmost columns break that into wavelengths and additional degrees.

Table 1: Available Phase Slippage Range

Photon Energy (keV)	Slippage Difference (deg.)	Wave-lengths	Additional degrees
2.5	587	1	227
4	939	2	219
6	1408	3	328
8	1878	5	78
10	2347	6	187
12	2817	7	297
16	3756	10	156
20	4694	13	14
25	5868	16	108
30	7042	19	202
35	8215	22	295
40	9389	26	29

REQUIRED GAP ACCURACY

The two undulators need to be sufficiently in phase for the best angular flux density. This was examined by Dejus [4] to determine a required accuracy in z spacing for some inline undulators that were installed without a phase shifter. He found that an 18.4° error in phase would reduce the angular flux density in the 1st harmonic by <1%. For the 3rd harmonic, that represents a 55° error in phase and the flux density dropped 4.2% or 6.8% for undulators too far or too close, respectively. We'd like to do better than this. Consider the feasibility of 10° as a maximum allowable phase error. The worst case for the allowed gap error is with a 40 keV photon beam and an in-phase condition near minimum shifter gap. The allowed gap error then is 7 µm. The decision was to aim for 5 µm as a conservative choice.

CONCLUSION

The anticipated behavior of the phase shifters has been modeled, and SmCo magnets were chosen. The effects of the magnetic shields on the field integrals through the shifter were investigated and, where necessary, tolerances were set. The number of wavelengths of phase slippage available was found for a few photon energies, and a requirement for the gap accuracy was determined. A vendor has done the mechanical design and is in the process of fabricating and magnetically tuning the phase shifters; the first delivery is expected shortly.

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