Poster THPAB040

A Phase Shifter for Inline Undulators at the Advanced Photon Source Upgrade Project*

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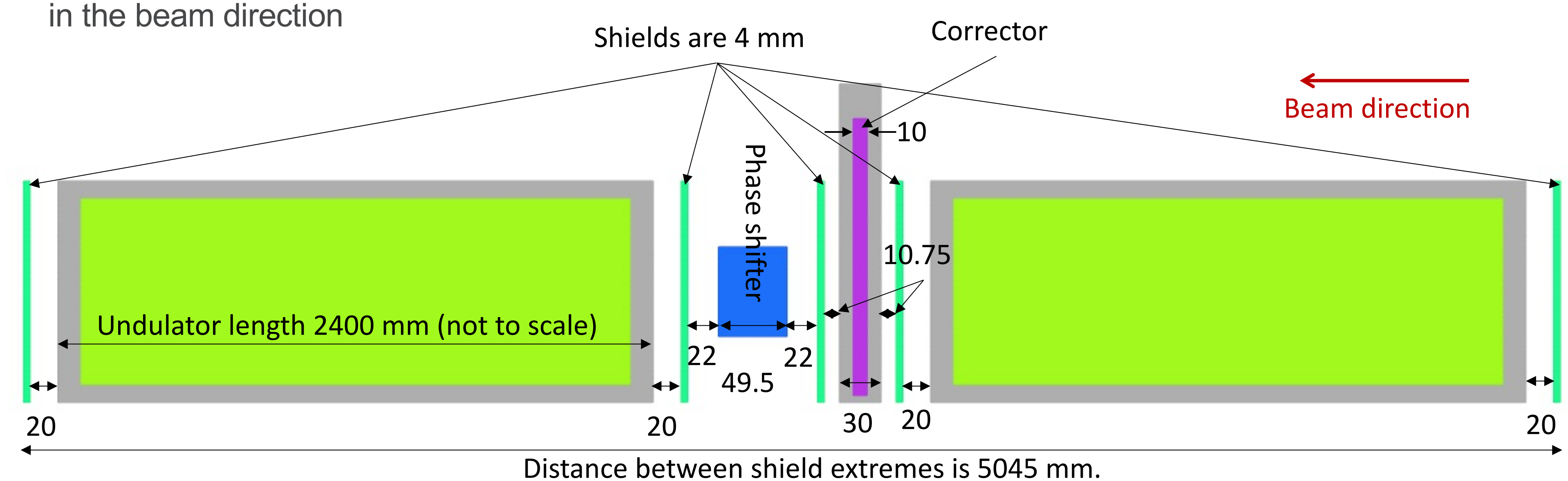
Sketch of overall straight section layout

Dimensions are mm, and
in the beam direction



Gray borders are non-magnetic support structures (e.g., the undulator strongback).
To maximize photon beam intensity for users, the undulators are 2.4 m long, the standard full length at APS. The phase shifter adjusts the phasing between undulators so they are in phase over the full range of operating gaps. It is a tight fit, so magnetic shielding is required to avoid magnetic crosstalk between devices.

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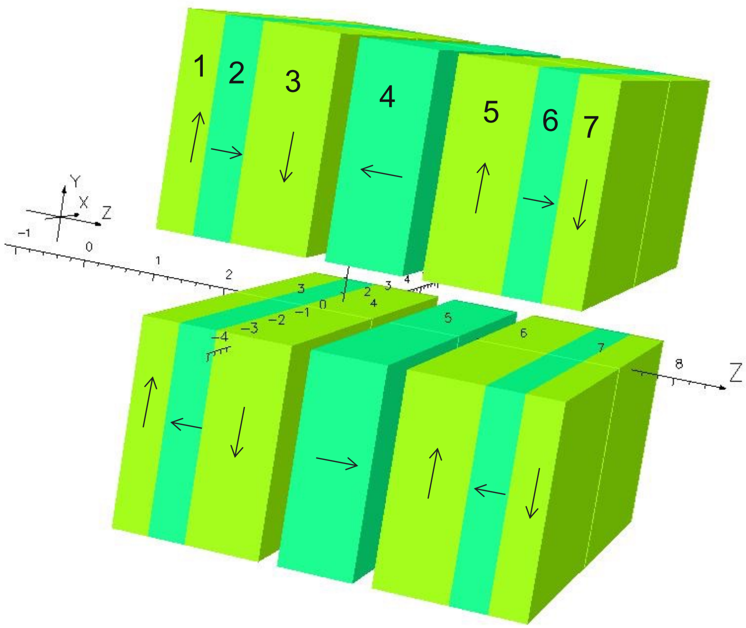
Model for the phase shifter



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

Phase shifter design is from Z. Wolf's design for LCLS-II.
Arrows indicate field direction of each magnet block.
No soft Fe means the shifter's field is unaffected by ambient fields.
The four-pole symmetric design gives zero field integral.
Design is balanced so 2nd field integral is also zero (without shields).

Z. Wolf, "A PPM Phase Shifter Design," LCLS-TN-11-2 (July 2011); also the Physics Requirement Document for the Undulator Phase Shifter, LCLSII-3.2-PR-0105-R1 (Nov. 2014)

Phase integral definition

Phase slippage *S* in drift space of length L:

$$S = \frac{1}{2\gamma^2}\ L$$

Inside an undulator or a phase shifter, this becomes (Z. Wolf, “A PPM Phase Shifter Design, LCLS-TN-11-2)

$$S = \frac{L}{2\,\gamma^2} + \frac{1}{2\,\gamma^2}\left(\frac{q}{m_e\,v_z}\right)^2 \int_{-L/2}^{L/2}\left(\int_{-L/2}^{z} B_y\,(z_1)dz_1\right)^2\ dz$$

Or

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

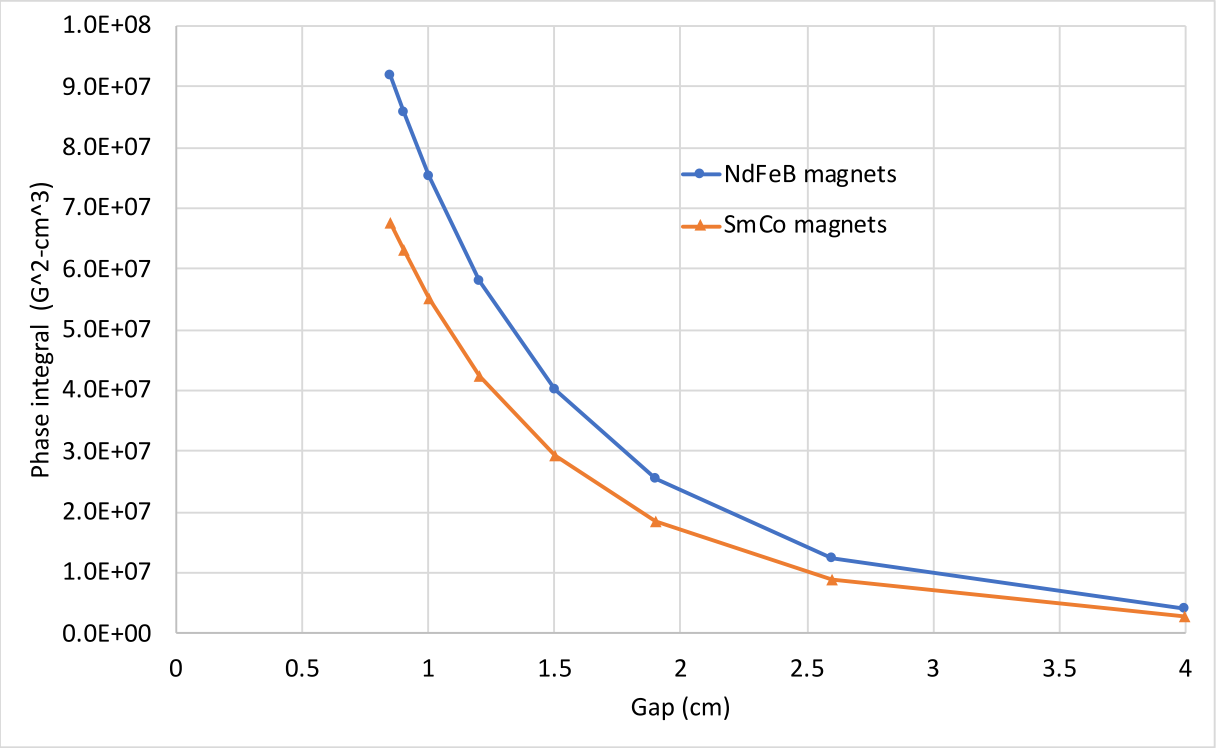
Where γ is the usual relativistic term, q and m_e are the electron charge and mass, v_z is the speed of light, and PI, the phase integral is

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

Note that *S* can be separated into drift space and magnetic field contributions.

Strength requirement for the shifter

- In setting strength requirements for the shifter, we consider only the phase integral (PI).
- The conversion factor from PI to slippage distance is 1.248E-15 cm/G^2-cm^3, assuming an e-beam energy of 6 GeV for γ.
- Shifter will be used with undulators with a variety of periods.
- Phase shift available must be at least one wavelength for longest wavelength produced by any of the relevant undulators, i.e., 2.5 keV or 4.959E-8 cm. In phase integral units, that's 3.98E+7 G^2 cm^3.



Either NdFeB or SmCo magnets work; choose SmCo

Slippage maxima found by magnetic model calculations are:

- NdFeB magnets: max PI is 9.19×10^7 G^2 cm^3.
- SmCo magnets: max PI 6.76×10^7 G^2 cm^3.

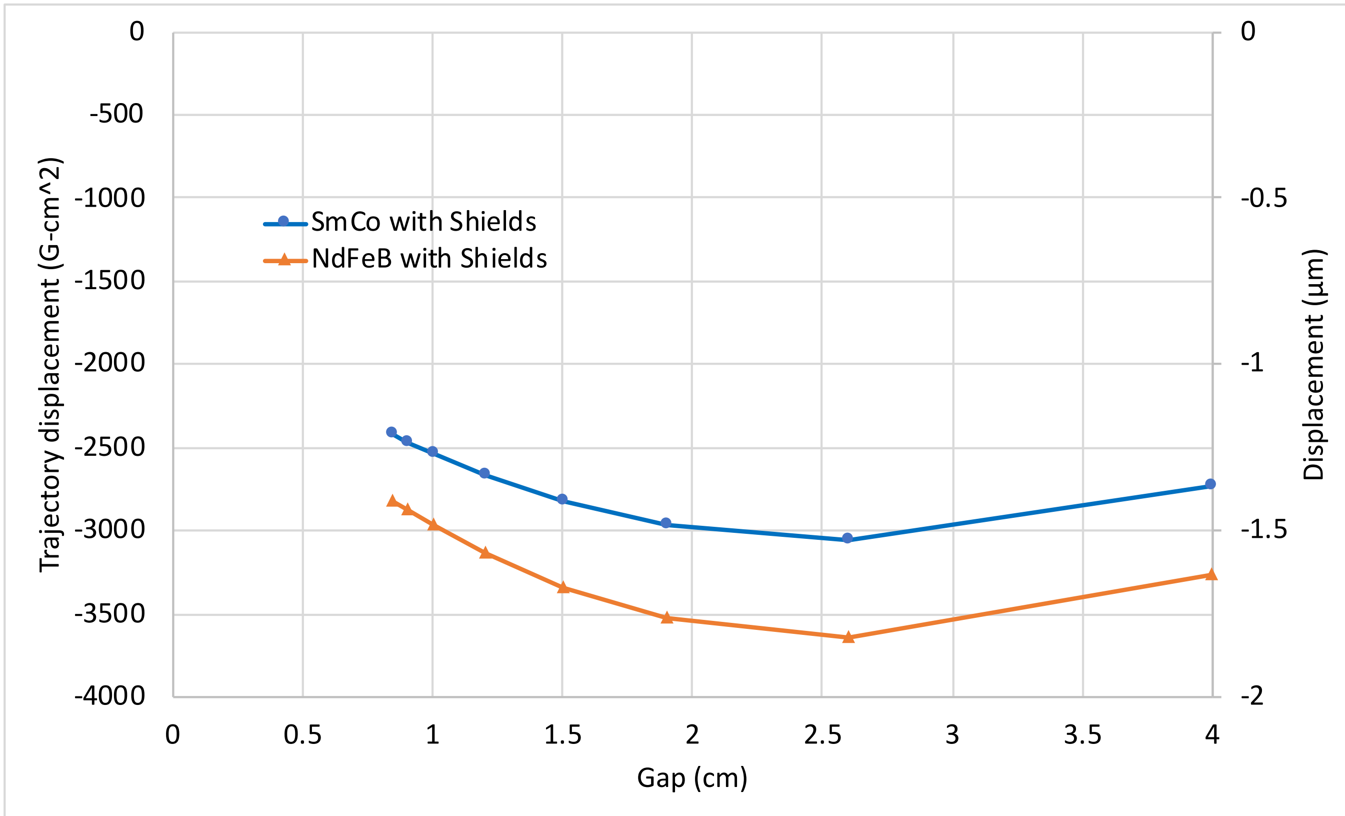
Both easily meet the phase integral requirement of 4×10^7 G^2 cm^3.

Radiation resistance determines the choice.
Years ago, APS saw rapid, radiation-induced demagnetization of undulators in Sector 4. (Undulator magnets needed remagnetizing after every 3-month-long run.)
This damage stopped when the NdFeB undulator was replaced with a SmCo-based one.

We want that reliability in the phase shifters.

Effect of adding shields

- Shields distort the balance in the phase shifter field.
- Symmetry is maintained so the 1st integral ∫By dz is still zero, but the 2nd integral ∫∫By dz dz' (the trajectory displacement) isn't.
- Displacement (shown at right) is nearly constant with gap, at ~1.2 to 1.5 μm displacement between the two undulators for SmCo.
- Compared to a horizontal beam size of ~13 μm, however, this is small.

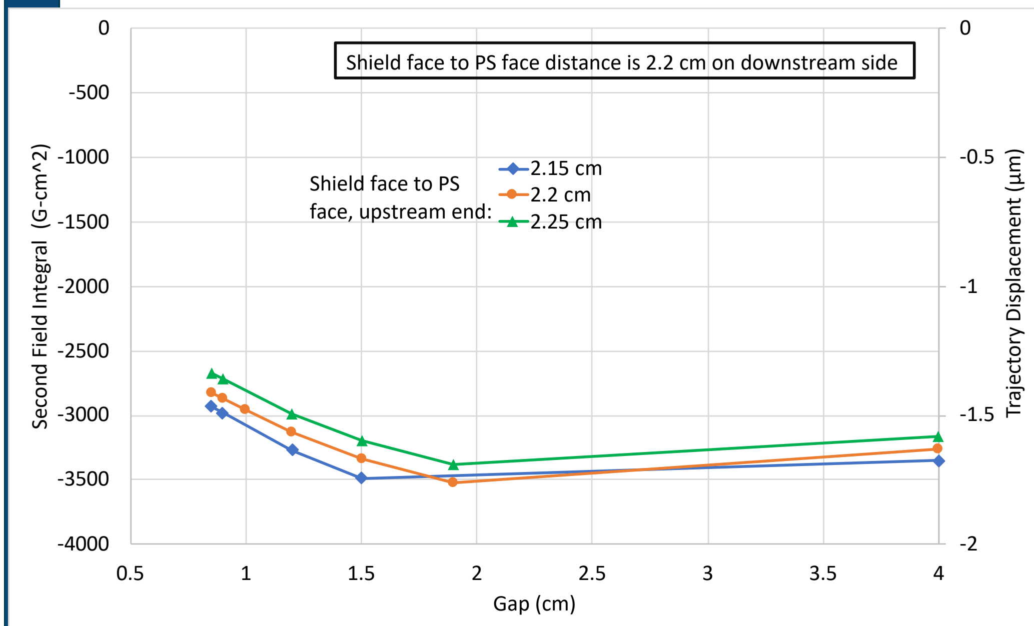


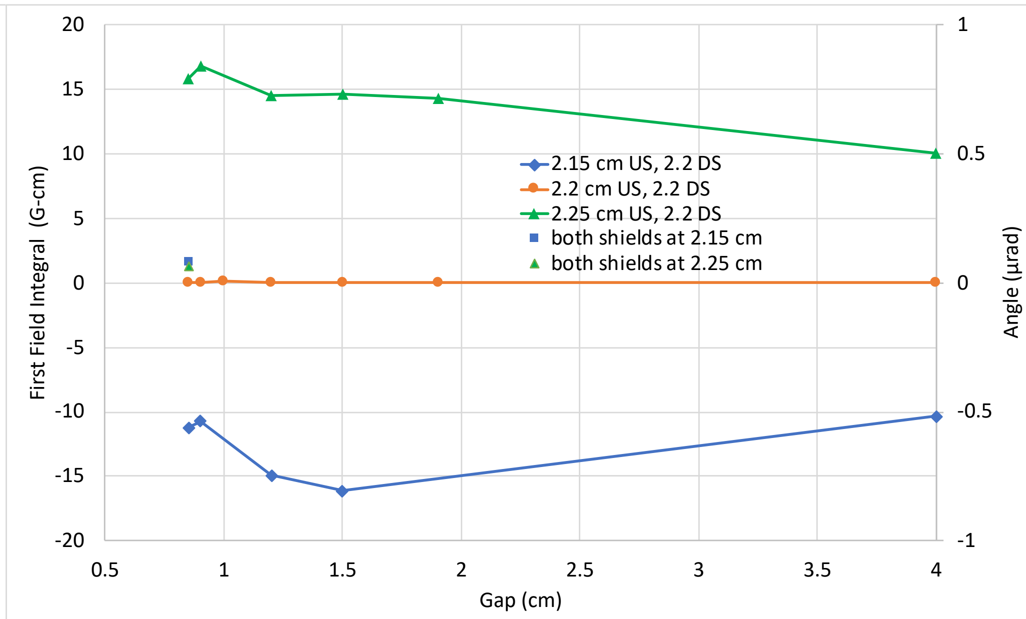
What if shifter-to-shield spacing is off by 0.5 mm?

Model the case where the upstream shield is moved by 0.5 mm from the nominal 2.2 cm (downstream shield stays at 2.2 cm). (Case of NdFeB magnets; SmCo would be similar.)

Second field integral: not much happens.

But the difference in the 1st integral is ~15 G-cm. Note points at min. gap that show a symmetric change in shield position. Maintaining symmetry is important!





Angle error doesn't exceed tolerance budget, but why spend a good part of that budget when shields can be mounted onto the shifter with standoffs so asymmetry errors are easily small?

How many wavelengths of slippage can the shifter give?

- For the longest photon wavelengths, the shifter adjustment range is required to exceed 1 wavelength, and it does.
- For the shortest, the shifter range spans many wavelengths.
- Table at right shows the range of phase slippage available, expressed in photon wavelengths, for the operating range of 0.85 to 4.0 cm shifter gap. Units are degrees (360° = 1 wavelength). For convenience, wavelengths + degrees are also shown.

photon energy (keV)	photon wavelength (Å)	photon wavelength (G^2 cm^3)	slippage difference (deg)	wave-lengths	additional degrees
2.5	4.95920	3.9728E+07	586.80	1	226.80
4	3.09950	2.4830E+07	938.89	2	218.89
6	2.06633	1.6554E+07	1408.33	3	328.33
8	1.54975	1.2415E+07	1877.77	5	77.77
10	1.23980	9.9321E+06	2347.22	6	187.22
12	1.03317	8.2768E+06	2816.66	7	296.66
14	0.88557	7.0944E+06	3286.10	9	46.10
16	0.77488	6.2076E+06	3755.55	10	155.55
18	0.68878	5.5178E+06	4224.99	11	264.99
20	0.61990	4.9661E+06	4694.43	13	14.43
25	0.49592	3.9728E+06	5868.04	16	108.04
30	0.41327	3.3107E+06	7041.65	19	201.65
35	0.35423	2.8377E+06	8215.26	22	295.26
40	0.30995	2.4830E+06	9388.87	26	28.87

Having a range of >1 wavelength affords the user some flexibility if the photon energy will be scanned and the desire is to avoid waiting for the shifter to readjust by 360° before resuming the scan.

Conclusion

- The magnetic design for a phase shifter has been completed and is now in the hands of a vendor for mechanical design, fabrication, and tuning.
- The shifter design is intended for use on the 11 beamlines for which dual inline permanent magnet undulators are planned. The undulators will have a variety of period lengths.
- We're looking forward to the deliveries!