

PHASE SHIFTERS FOR THE FLASH2 FEL

M. Tischer, P. Neumann, A. Schöps, P. Vagin, DESY, Hamburg, Germany

Abstract

The FLASH2 SASE undulator section consists of 12 IDs. Each of them is followed by an intersection component comprising a phase shifter and various parts for diagnostics and beam steering. The phase shifter is a compact and simple electromagnetic chicane and has to assure constructive interference of the radiation of adjacent undulators for all wavelengths. The magnetic performance, field errors and the hysteresis behavior have been investigated and were found to be within the required accuracy. The results are discussed in relation to the undulator settings. From these data, tables for steering the phase shifter current as function of undulator gap were derived and implemented in the control system.

INTRODUCTION

Segmented undulators, which shall radiate coherently, usually require a phase shifting chicane magnet which extends the drift length of the electron beam between the undulators such that the emitted radiation fields of both devices will interfere constructively. Fig. 1 displays one of the intersections in the SASE undulator section of FLASH2. Besides the phase shifter, a beam-loss monitor, a wire scanner, a beam position monitor, an ion getter pump, and the quadrupole magnet can be seen, the latter sitting on a vertical and horizontal mover stage.

Phase shifters have been designed and built at many FEL facilities as either electromagnetic or permanent magnet chicanes [1-6]; in particular, pure permanent magnet shifters are widely used as they benefit from easier magnetic tuning. On the other hand, electromagnetic shifters allow for a simple integration of an additional horizontal steerer. A compact phase shifting unit has been implemented at SPARC [3] where the chicane is included in the end of the magnet girders of each undulator.

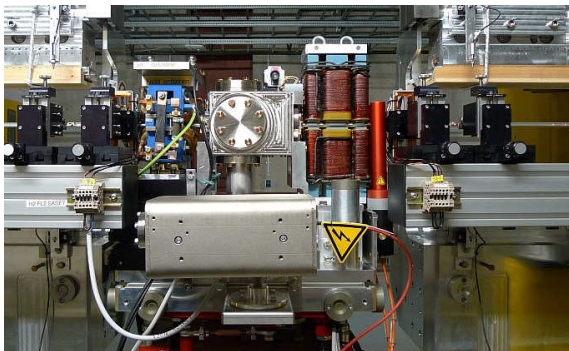


Figure 1: An intersection segment between FLASH2 undulators carries a BLM, the electromagnetic phase shifter, partly a wire scanner, an ion getter pump, a cavity BPM, and a quadrupole magnet mounted on a mover.

For the new FLASH2 undulator line, the same type of electromagnetic phase shifters is used as is in operation in the sFLASH seeding experiment at FLASH since several years. The phase shifters with a total length of 150 mm consist of three coils which are powered in series to create a simple -1/2, +1, -1/2 triangular bump. The two half poles comprise an additional corrector winding which is used for both, cancellation of residual kicks of the shifter and also as a dedicated horizontal steerer with a maximum strength of about $\pm 60 \mu\text{rad}$ (at 1 GeV). The phase shifter's yoke is made from laminated relay iron and only the pole pieces consist of bulk material in order to keep hysteresis effects small.

MAGNETIC MEASUREMENTS

With respect to a photon of wavelength λ_R , an electron in a magnetic field B will accumulate a phase delay of

$$\Phi = \frac{2\pi}{\lambda_R} \int_{-\infty}^s \frac{x'(s')^2}{2} ds'$$

where the angle x' of the electron trajectory along s is given by the 1st field integral $\mathcal{J}_1$:

$$x'(s) = -\frac{e c}{\gamma m_e c^2} \mathcal{J}_1(s) = -\frac{e c}{\gamma m_e c^2} \int_{-\infty}^s B(s') ds'$$

When λ_R is expressed in terms of the undulator K-parameter and period length λ_U , the phase advance in a chicane magnet can be written as

$$\Phi_{PS}(s) = \frac{2\pi}{\lambda_U \left(1 + \frac{K^2}{2}\right)} \left(\frac{e c}{m_e c^2}\right)^2 \cdot \int_{-\infty}^s \mathcal{J}_1^2 ds'$$

Φ_{PS} separates in a K-value dependent factor $\phi_{PS}(K)$ and the phase integral

$$PI = \int_{-\infty}^s \mathcal{J}_1^2 ds'$$

which describes the slippage length in magnetic units and in our case depends only on the excitation current I of the coils.

All 12 phase shifters have been characterized by Hall probe and stretched wire measurements to determine the phase integral and kick error, respectively. Fig. 2 displays the phase integral PI along the device for different currents. A maximum field of 0.12 T is induced in the central pole of the phase shifter at the maximum operation current of 8.8 A. For such a moderate field level, no significant saturation in the iron yoke is expected and hence, a parabolic dependence on the current is expected for the phase integral. A normalization by I^2 allows for a closer inspection and is shown in Fig. 3 for a current series up to $I_{\max}$ and back. The pure square dependence can be seen by the constant proportionality factor and is sufficiently well fulfilled for currents down to ~ 2 A. A

hysteresis behavior of the chicane is clearly visible but remains in a range of $\sim 0.3\%$ or less and is within the validity range of the I^2 description. As these assumptions become poor for currents below 2 A, the phase shifter operation will be limited to currents above this value.

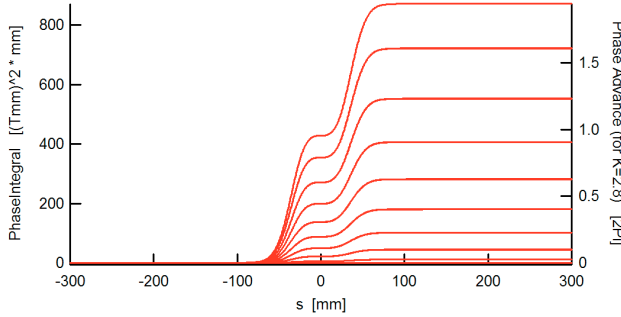


Figure 2: Hall probe measurements of the phase integral along the chicane for different currents up to $I_{\max} = 8.8$ A.

All phase shifters were measured systematically and the phase integrals fitted by a 2nd order polynomial. A small variation in the order of a few percent was found in the strength of all phase shifters. The devices cover a phase advance of about $1.9 \dots 8.5 \cdot 2\pi$ for undulator K-parameters of $2.8 \dots 0.5$ (for $K=2.8$, compare right axis of Fig. 2).

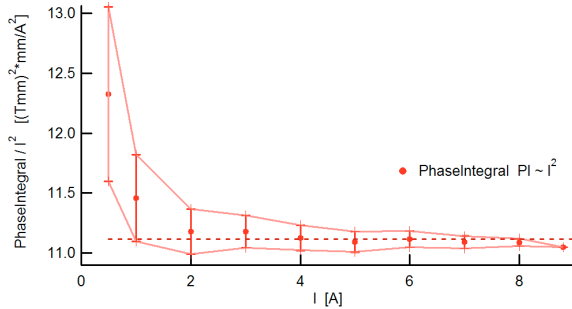


Figure 3: The phase integral normalized by I^2 reveals a small hysteresis in the order of only 0.3% .

The maximum beam displacement in the phase shifter is about 170 Tmm^2 which corresponds to $50 \mu\text{m}$ at an electron energy of 1 GeV. Due to tiny manufacturing imperfections, the series of three magnets in the chicane produces a small total kick which also depends on the excitation current. The total field integrals have been calculated from the Hall probe data and have been verified by independent measurements with a stretched wire probe. Both methods agree within 5 mTmm as is shown in Fig. 4. The residual field integrals amount to about 40 mTmm at maximum current; these kicks can be easily corrected by a feed-forward setting of the correction coil. However, the residual kick does also show a hysteresis behavior of up to $\pm 15 \text{ mTmm}$ (corresponding to $\pm 4 \mu\text{rad}$ angular kick at 1 GeV) at phase shifter settings where the remaining field integrals are biggest. As the hysteresis is in the same order as the residual kick errors, it needs to be considered in the feed-forward correction.

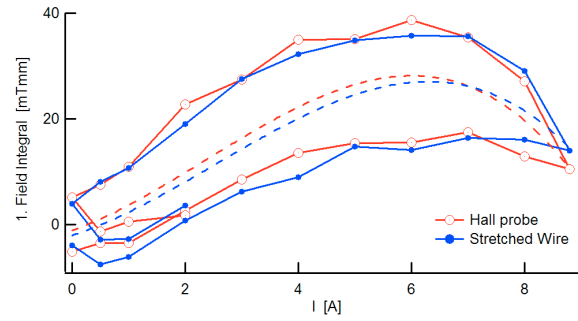


Figure 4: Remaining residual kicks of the phase shifter are in the order of 40 mTmm and are compensated by a small embedded corrector coil which is also used as a regular steerer. A hysteresis of $\sim 15 \text{ mTmm}$ is observed in some cases.

The corrector coil in the phase shifter distributes its kick equally towards the two half poles at the ends of the chicane and is powered by a bipolar power supply. A maximum current of 3.5 A is intended for operation which induces a field of $\sim 0.04 \text{ T}$. The strength of this coil must be known for an automated feed-forward correction of kick errors and has been determined by stretched wire measurements. A very similar response function was found for all devices, exemplarily depicted in Fig. 5. As expected for such a small excitation of the coil, hardly any hysteresis behavior can be observed; a strength of 63 mTmm/A is extracted from the measurements. While this value was obtained with the main coil assembly being unpowered, a small reduction of the slope can be seen for the case with the main coil powered to $I_{\max}$. Though this decrease by about 0.3% is completely irrelevant for closing the phase shifter bump in view of the hysteresis of the residual kicks, this systematic effect can easily be considered for the secondary use of the corrector coil as a dedicated vertical beam steerer in the undulator section. Extensive beam steering at this location should, however, not be necessary and will usually be a sign for a poor orbit; besides, any kick and its correction by the steerer will induce an additional phase shift to the electron beam.

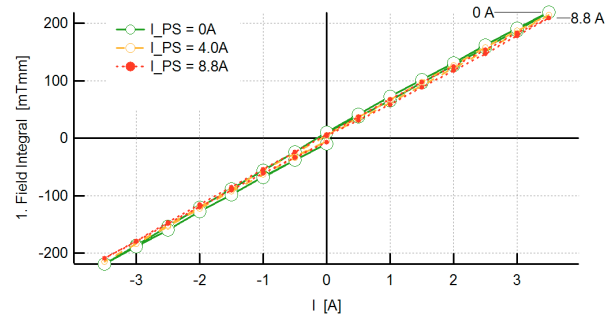


Figure 5: Response function of the corrector coil for different current settings of the main coil assembly; a reduction of the slope by $\sim 0.3\%$ is found at maximum current of 8.8 A of the main coil.

Fringe fields are usually a matter of concern if they interfere with other magnetic elements and create crosstalk between them. The FLASH2 phase shifter has a magnetic gap of 13 mm, the distance towards the intersection quadrupole is about 250 mm which corresponds to $\sim 20\times$ the gap. At the maximum operating current of 8.8 A, the central and outer coils are excited to a field of 0.12 T and 0.09 T, respectively. At such a distance of 250 mm behind the chicane, the fringe field has decayed to a value of only $25\mu\text{T}$ which is in the order of the ambient field level and therefore considered to be irrelevant in terms of cross-talk into the iron poles of the adjacent quadrupole. Despite a detailed magnetic characterization of all magnet elements, beam-based alignment procedures will be applied to refine the parameters for the different magnet servers in the control system.

PHASE TUNING

A segmented SASE undulator line requires appropriate phase matching in the intermediate drift sections which has a geometric length of 800 mm for FLASH2. The vacuum phase advance ϕ_D in the drift section L is defined by the difference in average drift speed of an electron of energy γ and the photon emitted in the undulator with a wavelength λ_R ; the relation can be rewritten by the usual resonance formula so that the phase advance solely depends on the undulator K-value and period length λ_U .

$$\Phi_D = \frac{2\pi}{\lambda_R} \frac{L}{2\gamma^2} = \frac{2\pi}{\lambda_U} \left(1 + \frac{K^2}{2}\right) L$$

At FLASH2 with a drift length of 800 mm, ϕ_D adds up to values of $5\dots 23\cdot 2\pi$ for undulator K-parameters of $2.8\dots 0.5$. Also, an error of 0.5 mm in the drift length induces an uncertainty in ϕ_D of 1° and 5° , respectively.

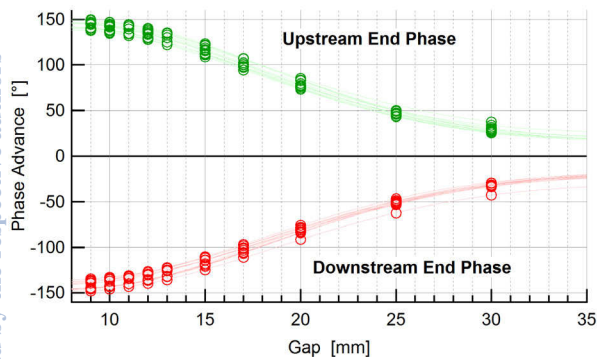


Figure 6: Phase advance from the end field terminations of the FLASH2 undulators, data and corresponding fits.

Additionally, the end field sections of the undulator induce a phase shift ϕ_{IDends} which is determined by the type of end field termination and is also dependent on the undulator gap as can be seen in Fig. 6. The phase advance from the end fields has been calculated from measured field maps of all undulators starting from the first/last full

pole towards the end of the magnet structure; it includes all fringe fields. ϕ_{IDends} varies over a large range within the working gap region; contributions from up- and downstream parts compensate each other to a large extent but there are non-systematic distinct differences remaining which result from the tuning of the end field modules depending on the individual magnetic errors of the undulators. As these variations can amount to about 10° , the phase advance of the undulator ends needs to be considered separately for both ends and all devices. The dependence on the gap can easily be expressed in terms of K and can be represented by a polynomial. By that means, a table of coefficients is used to calculate the total phase advance in the drift section and to determine the required phase shifter setting in an automated procedure during operation.

The current I of the phase shifter needs to be chosen such that its contribution ϕ_{PS} adjusts the total phase advance to a multiple of 2π :

$$\Phi_{Tot} = \Phi_{IDends}(K) + \Phi_D(K) + \Phi_{PS}(K, I) = n \cdot 2\pi$$

With $\phi_{PS}(K, I) = \phi_{PS}(K) \cdot PI(I)$ the required phase integral PI can be written as

$$PI(I) = 2\pi - \frac{Mod(\Phi_{IDends}(K) + \Phi_D(K) - \delta\phi)}{\phi_{PS}(K)}$$

where $\delta\phi$ was introduced as an additional manual offset or scanning parameter to be selected deliberately by machine operators. As described above, the current dependence of the phase integrals PI of all chicanes is expressed by 2nd order polynomials based on the magnetic measurement results. By that means, the actual current is calculated by an analytical function for each phase shifter depending only on the K-parameter of the adjacent undulators. This relation is implemented in an automated baseline procedure for operation of the phase shifters with additional refinement parameters for a phase offset or a kick angle.

REFERENCES

- [1] B. Diviacco et al, "Phase Shifters for the FERMI@ELETTRA Undulators", IPAC'11, San Sebastian, Sep.2011, p.3278 (2011).
- [2] Z. Wolf, "A PPM Phase Shifter Design", Technical Note, LCLS-TN-11-2, July 2011.
- [3] M. Quattromini et al., "Detailed K and phase error analysis of the SPARC undulator", SPARC-FEL-09/005 Report, October 2009.
- [4] H.H. Lu et al., "The permanent magnet phase shifter for the European X-ray free electron laser", Nucl. Instr. and Meth. A 605 (2009) p.399.
- [5] R. Ganter et al., "Techn. Overview of the SwissFEL Undulator Line", FEL'12, Nara, p.583 (2012).
- [6] H.G. Lee et al., "Design and Fabrication of Prototype Phase Shifter for PAL XFEL", IPAC'13, Shanghai, May'13, p.3564 (2013).