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Construction and commissioning of an APPLE-III afterburner undulator as a prototype for radiators in the new seeding line of FLASH2020+

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Abstract. An APPLE-III undulator with 17.5 mm period length operating at a minimum magnetic gap of 8 mm was installed downstream of the FLASH2 SASE undulators. This device serves as an afterburner and was designed to provide arbitrarily (also circularly) polarized light at the 3rd harmonic of the FLASH2 radiation with a wavelength of 1.33 nm to 1.77 nm (890-700eV), covering the absorption L-edges of the magnetic 3d elements. After characterization of the different polarization modes at different wavelengths in a first commissioning phase, first user experiments have been conducted.
Here, we report on our experiences with the mechanical and magnetic assembly of the APPLE-III UE17 as well as on magnetic measurements and tuning of trajectories and phase errors at the different polarization states.

1. Introduction

In the course of the FLASH2020+ project [1], a 3rd harmonic afterburner undulator has been installed and successfully commissioned downstream of the present FLASH2 SASE undulators. It is in user operation and provides arbitrarily polarized light in a wavelength range between 1.33 nm and 1.77 nm (890-700 eV) to widen the spectral range to the L-edges of Fe, Co, and Ni and allow for related research in the field of nanomagnetism.

To reach the spectral specification with an e-beam of only 1.35 GeV, an efficient magnet design had to be chosen and applied at smallest possible magnet gap. The APPLE-III concept [2] has therefore been selected, being more efficient in field generation for a round beam than the APPLE-II design and less bulky and more cost efficient than an APPLE-X device. In addition, as FLASH is a high repetition rate machine, higher beam losses are expected and it is necessary to be able to fully open the gap. In the APPLE-III magnetic layout, the B-magnets have a 45° tilted magnetization (Fig. 1) and represent, together with the longitudinally magnetized A-magnets, a Halbach structure of two crossed undulators. At closed state, the four quadrants are horizontally and vertically spaced by 1 mm with respect to each other and create an 8 mm magnetic gap across the diagonals for a round beam pipe with 6 mm inner aperture. The useful gap range in user operation (defined by the vertical slit size) is 1 mm to about 5 mm, longitudinal movement of the quadrants changes the phase shift between the two crossed structures and hence the polarization mode. The APPLE-III structure shown in Fig. 1 (left) has been combined with a magnetic force compensation scheme [3] to allow for a compact standard gap mechanics compatible with space and operation constraints at FLASH2. Table 1 lists the overall properties.

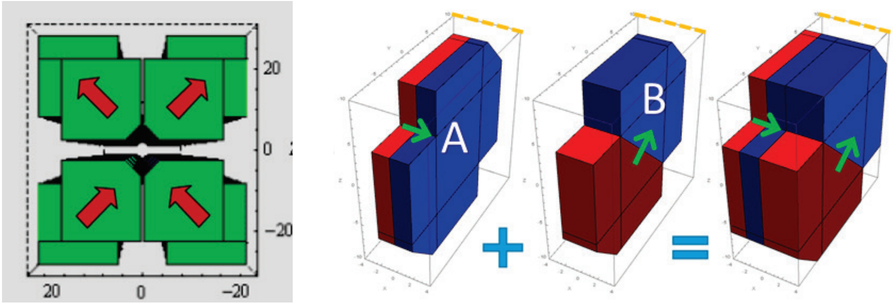

Figure 1. (left) Schematic configuration of an APPLE-III undulator magnet structure [2]. (right) Longitudinally (A) and transversally (B) magnetized blocks are glued to a pair as a smallest magnetic unit of this UE17.

Table 1. Specification for the APPLE-III UE17 afterburner (at 1.35 GeV beam energy).

Parameter	Specification
Wavelength range	1.39 nm – 1.77 nm (890 eV – 700 eV)
Period length	17.5 mm
Peak magnetic field	0.56 T
Max. K value	0.92
Phase error (rms)	<10°
Minimum gap	8.0 mm (spacing between diagonal quadrants), i.e. vertical Gap := 1mm between girders
Number of periods	137
Total length	2.5 m
Magnet material	NdFeB
B_r	1.32, 1.36, 1.26 T for A, B, comp. magnets

2. Magnetic configuration and mechanical design

At a period length of only 17.5 mm, the individual magnets in a Halbach configuration have a thickness of only ~4 mm with a cross-section of 20x20 mm^2. This imposes various mechanical difficulties which could be overcome by gluing single A- and B-magnets to AB- and BA-pairs with an easy axis direction approximately along the space diagonal (Fig. 1, right). In this meanwhile proven technology, the pairs can mechanically be treated as a single body. The NdFeB magnet pairs were covered by an epoxy-based coating for better corrosion resistivity. All force compensation magnets were treated in the same way as the function magnets, except for the grain boundary diffusion process which was applied only to the single function magnets before gluing to improve their coercive field $H_{c,j}$ by about 5 kOe. Due to the longitudinally split magnet arrays in an APPLE-configuration, force compensation magnets are required both in vertical and horizontal direction.

The magnetic forces are not cancelled completely in this configuration but reduced by about a factor of 8. While forces in all directions remain small for all shift modes, the torque of each keeper and also the shift girder doubles due to the compensation magnets. For mechanical stiffness reasons, the magnet keeper was therefore built with a thickness of a full period, i.e. 2 half-period magnet pairs.

Both, beam and compensation magnet pairs are clamped by Ti-clamps into the aluminum keeper body. Based on the experience with a short APPLE-III demonstrator [4], the initially intended tuning scheme by means of small correction magnets was changed to a virtual shimming concept to obtain a more local field correction mechanism for better phase tuning: A flexor mechanism integrated by wire-cutting in the aluminum keeper body allows for a small diagonal movement of the function magnets (Fig. 2 left and center). An adjustment by about ±150µm is induced by a brass wedge which is driven by a differential set screw from outside.

The keepers are assembled onto the movable shift girders via high-tolerated nose-pins to assure the correct periodicity along the 2.5 m length of the structure. The shift girders are connected to the main girders by customized high-precision linear bearings (Fig. 2 right). Despite these measures, a significant effort in mechanical shimming was needed to achieve a uniform positioning of the shift-girders towards each other within a transverse and vertical accuracy of ~50 µm. All four shift-girders are motorized by servo motors and furthermore carry Heidenhain absolute linear encoders. Hard stops at the girder ends also include so-called magic-finger containers for correction of residual magnetic multipole errors.

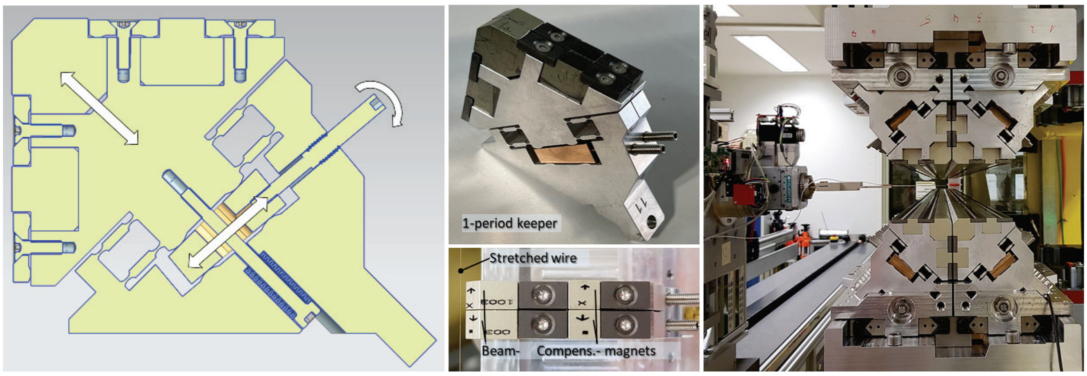

Figure 2: (left) Cross section of the magnet keeper; tuning of the function magnets is realized by a flexor mechanism allowing for a movement along the diagonal direction created by a wedge which is driven by a differential screw. (center) 2 half-period magnet pairs are mounted on a single-period keeper, but can be tuned independently due to a slit in the upper part. The force compensation magnets at both sides of the beam magnets provide the same periodicity. (right) Full 2.5 m long UE17 structure at the Hall probe bench.

3. Keeper measurements and Tuning

Based on the experience with the short demonstrator, the single magnets had not been sorted anymore by means of Helmholtz data before gluing. Instead, a full randomization of all magnets was enforced in order to avoid systematic errors. All glued magnet pairs were then characterized by Helmholtz measurements and sorted for minimization of the total magnetic moment when pairing an AB- with a BA-pair to a full period. Compared to random pairing, the sorting resulted in a reduction of the scattering of the total moment by a factor of 3 and helped to improve the initial magnetic configuration before tuning.

There are two possible configurations for the arrangement of the force compensation magnet rows around the beam magnets. The compensation magnets create either additional spurious dipole or quadrupole field components on-axis depending on the polarity of the compensation magnets; the latter is used for this UE17. Due to the small impact ($<10^{-3}$) on the on-axis field and despite their relaxed error specification, the compensation rows could be randomly assembled without prior characterization of single magnets or pairs.

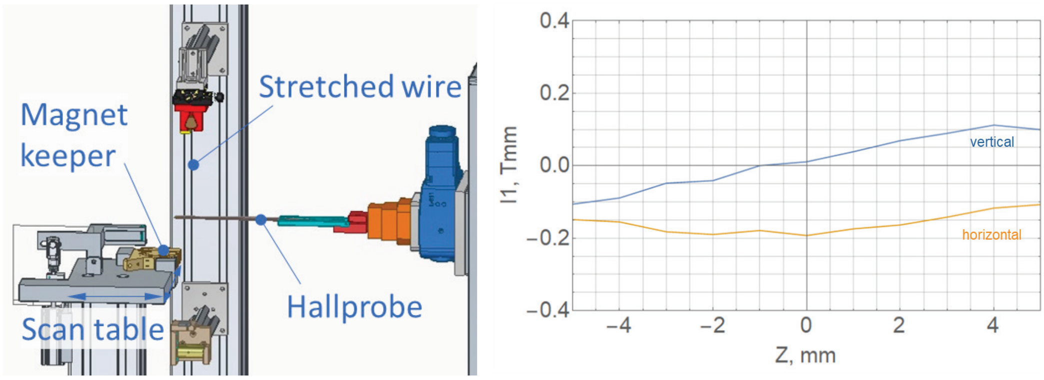

Figure 3. (left) Stretched Wire bench for keeper measurements. (right) Single keeper transverse dependence of field integral error used for sorting; z=0 corresponds to the later nominal beam position.

All completely assembled keepers were characterized by stretched wire measurements in order to obtain field integral error signatures for the sorting. For a full-period keeper, the total field integral is nearly zero and only shows the difference between two half-periods. In order to determine the strength of each half-period for the phase error sorting, additional on-axis Hall probe scans were performed to measure longitudinal field dependence.

A dedicated bench had been built for this purpose (Fig. 3 left). The keeper was fixed on a sintered metal vacuum chuck from BMS and moved by a PI precision xy-stage L-741 along the vertical, rigidly fixed 100 µm thick CuBe wire. A set of 3 ADC boards ADS1263EVM was used to digitize Senis F3A-03C 3D-Hall probe voltages for the field measurement along the beam axis. The same 3 ADCs were used for the stretched wire field integral measurements on-the-fly (Fig. 3 right), but connected in parallel to reduce the noise below 2Gs*cm [5] (measured reproducibility, including keeper mounting errors).

For the initial configuration of the full magnet structure assembly, the data of all keepers were then sorted for a global minimization of multipoles, on-axis trajectory and phase errors.

4. Undulator tuning results

The magnetic tuning was done at 2 mm gap in the horizontal linear mode while field maps were measured in all polarization modes at the Hall probe bench (Fig. 2 right). A 3-axis analog field transducer F3A from SENIS was used which had been calibrated in a spectrometer magnet against an NMR probe (METROLAB PT2025) to an accuracy of $\sim 3{\cdot}10^{-5}$.

The tuning of trajectory and phase error was done in several iterations, results are shown in Fig. 4 and Fig. 5, respectively. A small but distinct ~10 µrad kick in the vertical field trajectory builds up in all shift modes towards 10 mm gap (Fig. 4 top row) which is, however, already outside the operation gap range of up to 5 mm. This distortion could originate from an imperfect sorting of the keepers or from a localized magnetic deficiency of nearby parts of the support mechanics. For the horizontal field trajectory (Fig. 4 bottom row), only a minor gap dependence is obtained for all shift modes. The phase errors of the vertical and horizontal fields as displayed in Fig. 5 hardly vary for the different shift modes and gaps. Their rms values are summarized in Fig. 6 as a function of gap and for different shift modes. They remain below 5 (vertical) and 6 (horizontal) deg, respectively. Note for Fig. 4 and 5 that shift modes -1 (far left) and +1 (far right) both correspond to vertical polarization mode and that both trajectories and the phases show very good agreement.

The field integrals in transverse direction were measured by a stretched wire setup and were corrected together with some multipole errors by means of magic fingers magnets at both ends of the device. Figs. 7 a) and b) show the gap dependence of the on-axis vertical and horizontal kick as a function of gap for different shift modes. Remaining gap-dependent kick errors of about ±50 Gcm, together with an additional shift-dependent kick error of similar size (horizontal field only), are corrected in a feed-forward fashion by small air coils [6]. Field integrals at 2 mm gap for different shift modes are displayed in Figs. 7 c) and d). The kick error of the horizontal field was found to display a sinusoidal signature as function of shift as shown more clearly in Fig. 7 e). The DC-part of the residual field integrals at closed gap was adjusted such that it corresponds to the value at fully open gap.

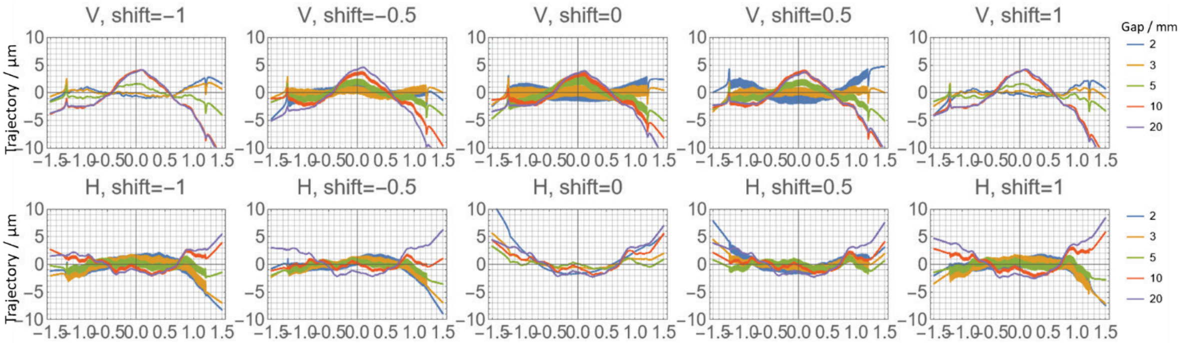

Figure 4. Beam trajectories (E=1.35 GeV) after tuning for vertical (top) and horizontal field component (bottom) in different polarization modes: vertical, left circular, horizontal, right circular, vertical (from left to right).

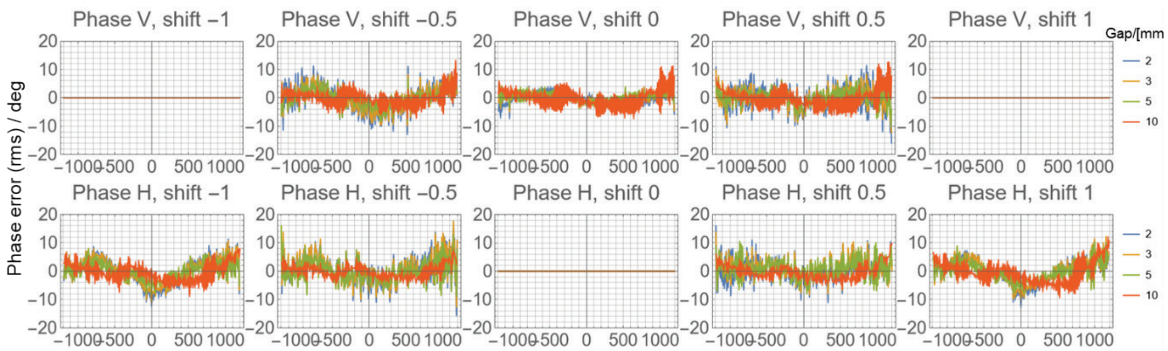

Figure 5. Phase error along the 2.5 m long UE17 for different polarization modes, separate for vertical (top) and horizontal (bottom) field component.

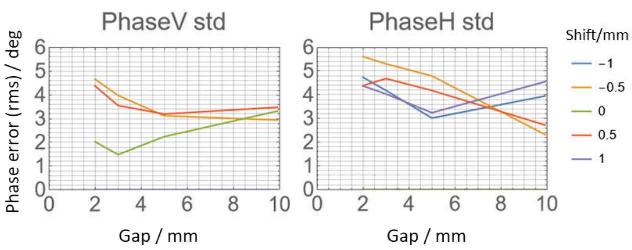

Figure 6. Resulting phase error as function of gap for all shift modes, plotted separately for vertical (left) and horizontal (right) field component.

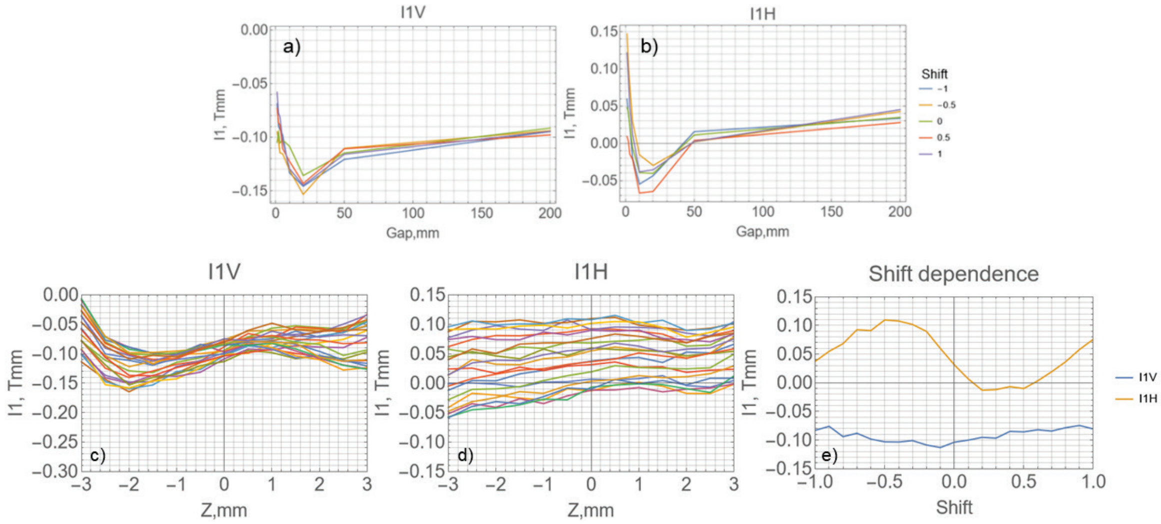

Figure 7. a, b) Residual kick errors of vertical (a) and horizontal (b) field as function of gap and shift will be corrected in a feed-forward fashion by means small air coils. c, d) Transverse dependence of kick errors at 2 mm gap for various longitudinal shifts; e) shift dependence of this error at 2 mm gap (c and d) evaluated at the on-axis position z=0.

5. Summary and outlook

Based on the insight gained from the set-up and commissioning of the FLASH2 afterburner undulator, we have adjusted the specifications and the design of the APPLE-III concept for the series of presently 6 undulators (out of finally 11 in the future) that will serve as radiators in the upgraded FLASH1 seeding beamline. The period length is 35 mm and the design of the magnet keepers that contain both the function and the force compensation magnets has been optimized.

The support structures, magnets and mechanical components of six radiators are currently in production and will be installed in 2025 together with 2 planar U84 modulators which are built in parallel.

References

[1] M. Beye, *et al.*, *"FLASH2020+, Conceptual Design Report"*, DESY, Hamburg, 2020. doi:10.3204/PUBDB-2020-00465

[2] J. Bahrdt, W. Frentrup, A. Gaupp, B. Kuske, A. Meseck, and M. Scheer, 2004 *Proc. SRI Conference 2003 AIP CP* **705** 215–18

[3] J. Bahrdt and S. Grimmer, 2019 *Proc. SRI Conference 2018*, AIP CP **2054** 030031-1–6

[4] M. Tischer, et al., *"Development of an APPLE-III undulator for FLASH2"*, SRI Conference 2021. AIP CP Journal of Physics: Conference Series, vol. 2380, 012017, 2022. doi:10.1088/1742-6596/2380/1/012017

[5] P. Vagin, A. Schöps, M. Tischer, "*Ongoing Developments of Magnetic Measurement Equipment for Undulators at DESY*", IMMW22, https://pages.cnpem.br/immw22/, https://indico.cnpem.br/event/2/contributions/46/attachments/43/216/IMMW22_MagnMeasuremDevelopments-IDs_DESY_Sep22.pdf

[6] K Götze *et al.*, *"Corrector coils with variable field direction for FLASH 2020"* , these proceedings.