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Development of an APPLE-III undulator for FLASH-2

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Abstract. The use of circularly polarized soft X-rays at the FLASH-FEL at DESY will be a very versatile tool for investigation of dynamic properties in nanomagnetism. For that purpose, the development of a variable polarization undulator was started to provide an afterburner downstream of the FLASH2 SASE undulators. It will serve to produce circularly polarized light with a wavelength of 1.33 nm to 1.77 nm (890 eV - 700 eV) to investigate the L-edges of Fe, Co, and Ni. This wavelength range together with the future maximum beam energy of 1.35 GeV at FLASH leaves only a small and ambitious parameter window for the undulator if a noteworthy tunability range shall be provided.

We report on design and development of an APPLE-III undulator with 17.5 mm period length operating at a minimum magnetic gap of 8 mm which will make use of a magnetic force compensation scheme. A short prototype has been built to verify and iterate both the mechanical and magnetic concept. Details on the keeper design, results of the magnetic measurements and the tuning concept will be presented.

1. Introduction

In the course of the FLASH2020+ project [1], an afterburner undulator shall be installed downstream of the present FLASH2 SASE undulators. It will provide circularly 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.

Even after the present energy upgrade of FLASH from currently 1.25 GeV to 1.35 GeV, radiation with variable polarization and a wavelength < 2 nm cannot be produced easily with present technology. Among the various permanent magnet-based concepts for elliptically polarized undulators, the so-called APPLE-III [2] and APPLE-X [3] designs provide the highest fields. Both types require a circular beam pipe and are therefore more suited for application at a linac-based FEL. Due to the FLASH requirement to fully open the undulator gap for the sake of better radiation protection during machine studies, but also for space and simplicity reasons, the decision was made for development of an APPLE-III undulator, a design that, so far, has not been realized. In addition, a force compensation scheme, like also proposed for APPLE-II structures [4], was implemented in the magnet design in order to keep the mechanical structure at moderate size.

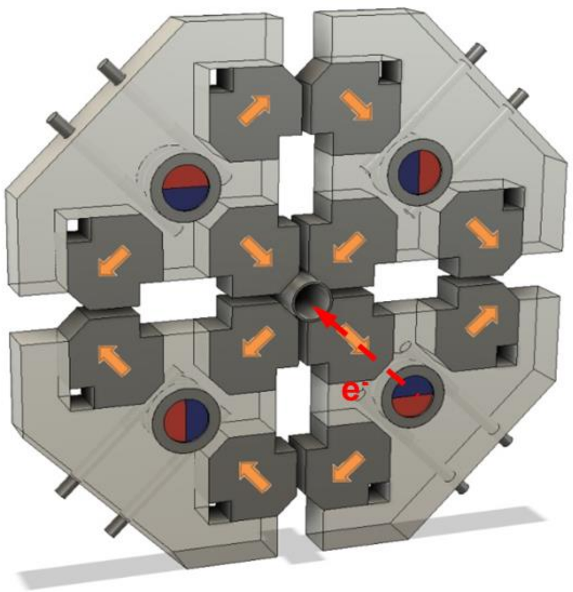

Figure 1. Arrangement of magnets in the APPLE prototype. Orange arrows indicate direction of magnetisation of the permanent magnets.

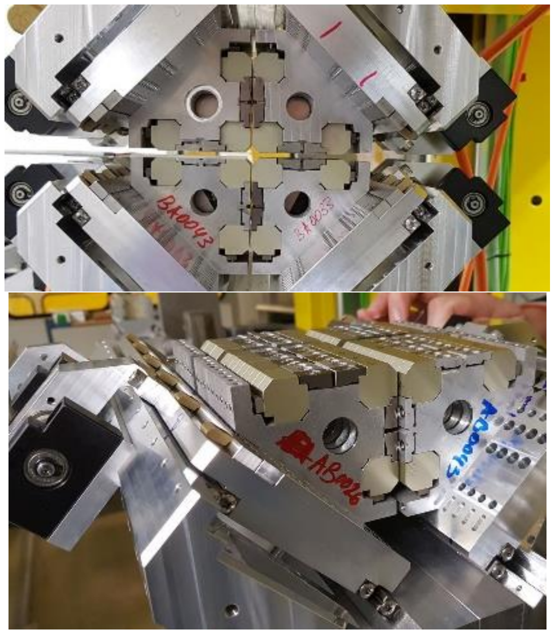

Figure 2. Pictures of the APPLE-III prototype. Top: View along the beam axis. Bottom: Bottom structure.

2. Prototype design and testing

In the APPLE-III configuration, the magnet structure consists of four permanent magnet arrays in Halbach configuration, where the B magnets of the inner arrays around the circular beam pipe are transversely magnetised with their easy axis along the 45° direction as sketched in figure 1. The outer arrays form the force compensation scheme and need to be implemented between both, top and bottom girder and also between rows on each girder. Our calculations show that a reduction of magnetic forces by roughly a factor of eight is obtained in this design. Further, a rotatable correction magnet located in each keeper behind the function magnet (red and blue in figure 1) and magnetised across the diameter was intended for tuning of the magnet structure. Following this scheme, a short prototype structure with a period length of 16 mm has been designed and constructed (figure 2).

The prototype support has a total length of ~250 mm and could be used to assemble different configurations like a full APPLE-III structure with about four periods or just a single quadrant with 16 periods. The setup was used to investigate mechanical, kinematic and magnetic properties of this new design. We tested, for example, the mounting reproducibility of the keepers onto the sub-girder, performing stretched wire measurements after repeated disassembling and assembling and found agreement within the noise level of < 5 mTmm.

The force compensation scheme was proven to work successfully as all the sub-girders were moving easily and smoothly in different configurations during manual test performances.

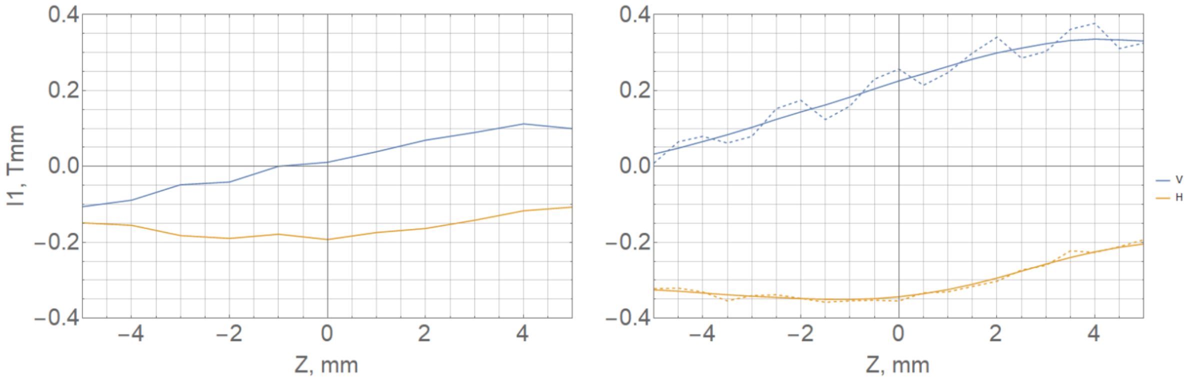

Figure 3. First field integral vs transverse position from measurements of the assembled prototype structure (left) and from simulations based on measurements of the individual keepers (right). Blue: vertical component, yellow: horizontal component. The dashed lines in the graph on the right show some systematic errors of the measurement system which is visible only when 32 individual measurements are summed up for prediction.

Before mounting the keepers onto the sub-girder, the field integral distribution for all single keepers was measured and used for sorting. Figure 3 shows a measurement of one quadrant with 16 assembled periods (left) which can be compared to a prediction from the individual keeper measurements (right). Reasonably good agreement was found in the transverse field integral distributions except for some global offset due to an imperfect consideration of the ambient field contribution in the measurement of the assembled structure and in the measurements of individual keepers as any systematic errors like ambient fields are multiplied by the number of magnets when summing up all the individual measurements for the prediction. These findings are a good basis for an efficient assembly and sorting of the later full-length device.

Magnetic measurements of the prototype revealed that a period length of 16 mm did not allow for the desired maximum field when also accounting for errors and tuning. In consequence, the required wavelength range would not be reached. We have, therefore, decided to increase the period length to 17.5 mm for the final version that will now be built. This includes a margin of 0.1 in K value for compensation of errors and consideration of shimming: 2x0.1 mm increase of the minimum gap due to virtual shimming, 0.2 mm gap failure, ~2% due to magnet chamfers introduced at a later stage of the design, and another 3% for various magnet errors. Table 1 summarizes all the important parameters for the APPLE3 undulator for FLASH-2.

Table 1. Parameters for the APPLE-III undulator as determined after final evaluation of the prototype.

	Specifications for 1.35 GeV electron beam energy
Wavelength range	1.39 nm − 1.77 nm (890 eV − 700 eV)
Period length	17.5 mm
Max. K value	0.92
Phase error (rms)	<10°
Minimum magnet gap	8.0 mm
Peak magnetic field	0.56 T
Total length	2.5 m

3. Magnet design

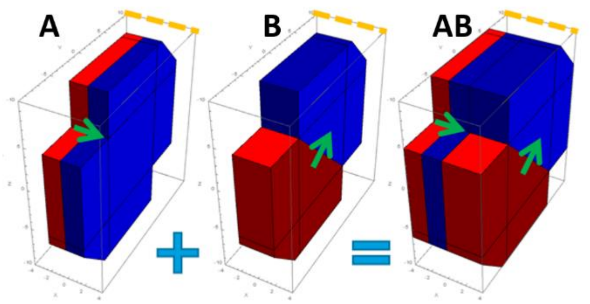

Figure 4. Magnets A and B. Green arrows indicate the direction of magnetisation; the dashed orange line represents the beam axis. Magnets will be glued together to form AB- or BA-pairs.

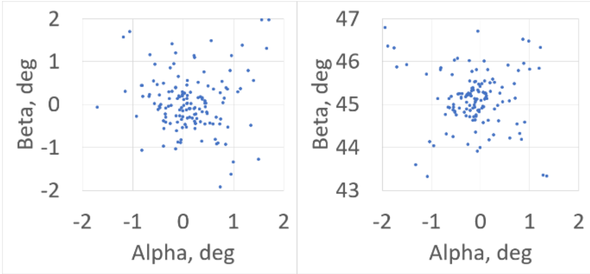

Figure 5. Error distribution of the magnetisation axis for magnets A (left) and B (right) as a result of Helmholtz coil characterization.

Two types of magnets, commonly named A and B, are used to build the APPLE-III magnetic structure: Type A is magnetised along the short edge, while type B is magnetised along the diagonal of the large plane. In order to improve stability and to simplify the mechanical design, magnets of type A and B are glued together in pairs as illustrated in figure 4. Both types are made from transversely dye-pressed (TP) material with $B_{r,min}$=1.32 T and $H_{cj,min}$=21 kOe. For magnet type B, first, larger magnets which are magnetised along the long edge are pressed and then wire-cut to the desired shape and dimensions. A grain boundary diffusion process (GBP) will add 5 kOe to the initial H_{cj}.

Figure 5 shows the error distribution for the magnetisation axis of A and B prototype magnets obtained by Helmholtz coil measurements. The magnetic errors of the individual magnets are small (<0.5 deg RMS) and randomly distributed, without any systematic order. This indicates good quality for such rather small magnets with a 45-degree magnetisation direction.

The gluing of the magnet pairs for the full-length device will be carried out after complete randomization of the magnets to reduce systematic errors. All magnet pairs will then be characterized by a Helmholtz coil set-up and by stretched-wire measurements.

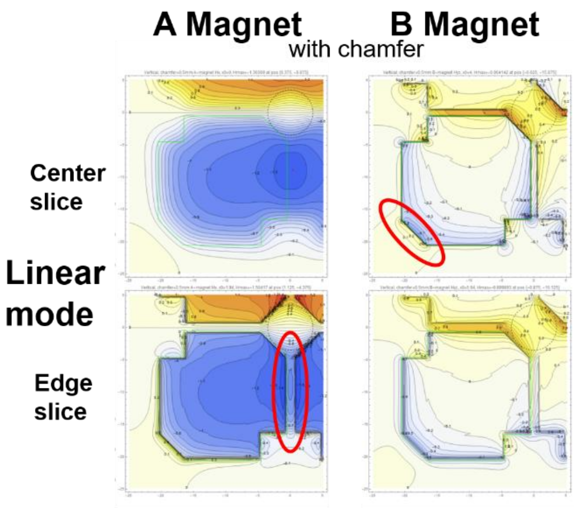

Figure 6. Demagnetising fields for A and B magnets in linear mode. Areas with strong demagnetisation effects are highlighted by red circles. On the colour scale dark blue and dark orange represent extremal positive and negative values, respectively, while white corresponds to zero.

Figure 6 shows the result of simulations of the demagnetisation effects for A (left) and B (right) magnets in linear mode. The demagnetisation of the centre slice is shown in the top row and the demagnetisation of the edge slice can be seen in the bottom row. For an A magnet without chamfer, the maximum demagnetisation occurs between rows (highlighted by a red circle). For the type B magnets, strong demagnetisation effects are observed on the edge opposite of the electron beam. Both effects can be remediated by introducing a 0.3 mm chamfer on the magnet edges.

Our studies on the magnet design resulted in the specifications that are summarized in table 2.

Table 2. Magnet specifications

	A	B	Compensation magnets
min B_r	1.32 T	1.36 T	1.26 T
min H_{cj}	21 kOe*	18 kOe*	26 kOe
Magnet cross-section	20 mm x 20 mm	20 mm x 20 mm	14 mm x 17.5 mm

*base specifications before GBD treatment (see text)

4. Mechanical design

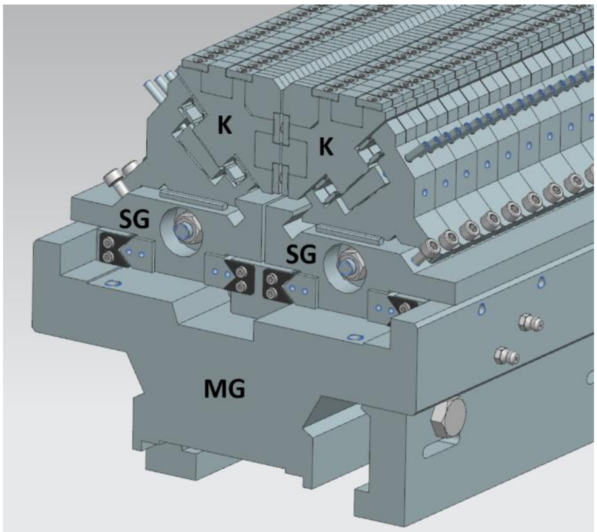

Figure 7. Design of the girder structure and keepers. MG: Main girder, SG: sub-girder, K: keeper.

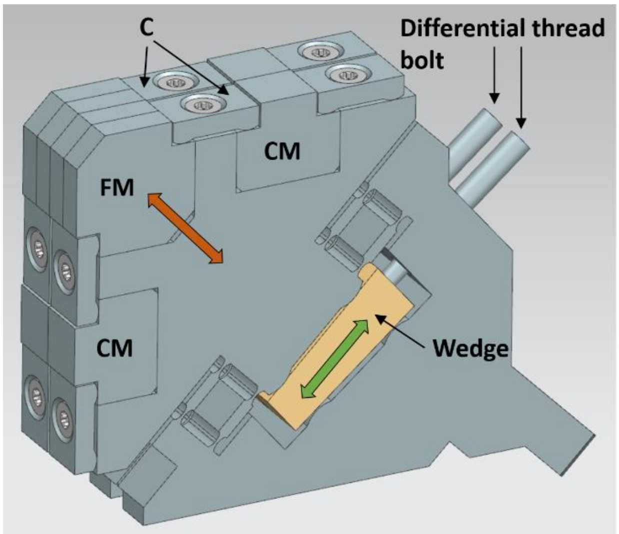

Figure 8. Keeper design. FM: function magnet, CM: compensation magnet, C: clamps. The wedge is moved by turning the differential thread bolt. Its movement along the direction indicated by the green arrow will move the function magnets in the direction of the brown arrow, towards or away from the beam.

Figure 7 shows a 3D model of the bottom girder and magnetic structure. Based on our experiences with the prototype, we have changed the design of the keepers (K in figure 7 and 3D model in figure 8) to make it more rigid: the new keeper will contain two pairs of glued AB- or BA-magnets. One such pair will correspond to half a period and two pairs will be mounted in each keeper which then contains one full period. Besides the function magnet pairs, the keeper also contains the force compensation magnets. They are similar in size and shape to the function magnets and will also be glued together in pairs. Titanium clamps with cylindrical clamping surfaces will keep the magnets in place, with one clamp per pair. Clamps are fastened by M3 countersunk screws. Instead of having correction magnets (see figure 1), which did not provide the desired local tuning, the new keeper has a movable wedge and the tuning mechanism with two differential thread bolts per keeper will allow for each function magnet pair to be adjusted individually perpendicular to the beam. The adjustment range is +/- 0.1 mm, corresponding to +/-3% field change to locally correct both trajectory and phase errors caused by magnetic errors of individual magnets.

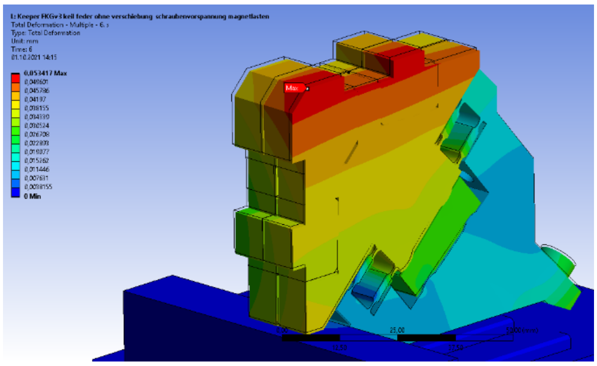

Figure 9. Deformation of the keeper. Colour scale ranges from 0 (dark blue) to 0.053 mm deformation (red) on a linear scale.

The force compensation reduces the overall net forces on rows and quadrants of keepers. However, the moments remain relatively high with 350 Nm per 1 m on each quadrant. All forces and moments were found to vary upon shifting the sub-girders: directions rotate with shift, but the magnitude stays nearly constant.

5. Summary and outlook

An APPLE-III undulator with an additionally implemented force compensation scheme has been developed as an afterburner at the present FLASH 2 FEL. It will extend the spectral range of the facility down to 1.4 nm and provide circularly polarized radiation. The device is presently in construction and shall be installed and commissioned next year, in 2023. It will also serve as a full-length prototype for a series of helical IDs to be built within the seeding upgrade of FLASH 1.

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