Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

Corrector coils with variable field direction for FLASH 2020

To cite this article: Kathrin Götze *et al* 2025 *J. Phys.: Conf. Ser.* **3010** 012019

Journal of Physics: Conference Series **3010** (2025) 012019 doi:10.1088/1742-6596/3010/1/012019

Corrector coils with variable field direction for FLASH 2020

Kathrin Götze[1], Pavel Vagin[1], Paul Neumann[1], Sumera Yamin[1], Hasret Kekilli[1], Markus Tischer[1]

[1]Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany

E-mail: kathrin.goetze@desy.de

Abstract. Despite thorough tuning of insertion devices for storage rings or linear accelerators, a (usually gap dependent) kick to the electron beam remains and has to be corrected with the help of steerer coils. These small, resistive coils are placed upstream and downstream of an undulator and by varying the strength and direction of the generated magnetic field, they allow to deflect the beam by a small angle and to consequently correct its trajectory. For the upgrade of the free-electron laser FLASH at DESY Hamburg we have developed compact and cost-efficient air-cooled steerer coils based on a solid ferrite core around which four sub-coils are wound in a particular geometry. By energizing these coils separately, the deflecting field can be tuned and adapted to the gap dependent kick. The ferrite core enhances the coil strength by more than 50% compared to previous designs enabling them to generate 0.53(0.44)Tmm for horizontal (vertical) field at 1A while still making the steerer suitable for use in a slow feedback system. However, due to the proximity of some steerers to permanent magnet-based phase shifters, significant cross-talk between the two devices is introduced and needs to be mitigated.

1 Introduction

In the course of the upgrade of the free-electron laser FLASH at DESY to external laser seeding, two modulator undulators with planar magnet structure and six APPLE-III undulators will be installed in the FLASH1 branch to provide arbitrarily (also circularly) polarized light. This new beamline will allow for the generation of higher photon energies up to the nitrogen K-edge with full coherence and a high repetition rate. Each undulator will be equipped with two resistive correction coils installed on the upstream and downstream end, respectively. They will serve to correct gap-dependent residual kick errors and can be integrated into a slow feedback system.

In this contribution we present the set-up of the coils and show results of stretched-wire and temperature-dependent resistance measurements, before analyzing and compensating the cross-talk between the coils and neighboring permanent magnet-based devices.

2 Set-up and operation

Each corrector coil consists of two identical halves. Each half, again, is built up of a ferrite half core which is glued into a 3D-printed shell made from ABS [1] around which two sub-coils are wound. The shells extend beyond the ferrite core, so that the two halves of the coil can be screwed together and attached to the holder. We used 0.5mm thick copper wire with varnish coating. Each sub-coil has 94 windings on two layers. The general set-up of the coil is shown in Fig. 1 (a). The inner diameter of the finished coil is 35mm as the coil will be mounted around a CF16 flange of the vacuum chamber with an outer diameter of 34mm. Due to the geometry of the (store-bought) ferrite half cores, there is a 1.5mm gap on

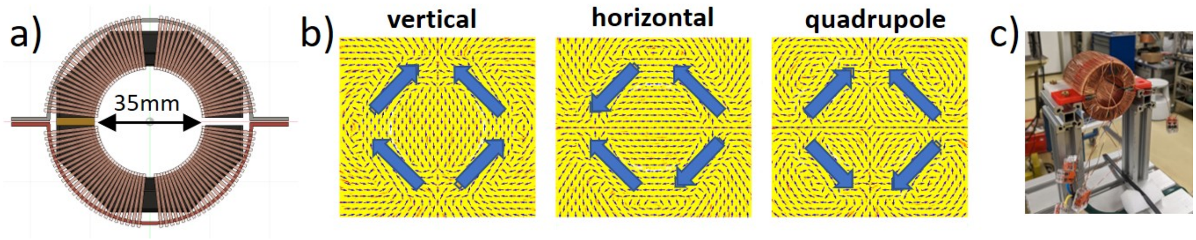

Figure 1: (a) Sketch of the corrector coil, on-axis view. Each corrector coil contains four sub-coils. Top and bottom half are different parts and can be taken apart easily for installation and maintenance. (b) Vertical, horizontal or quadrupole fields generated by different polarities in the sub-coils which can be powered independently. (c) Photographs of a corrector coil set up in the lab. the copperwire is wound around the ferrite core (not visible) and the 3D-printed shell (here: white and red).

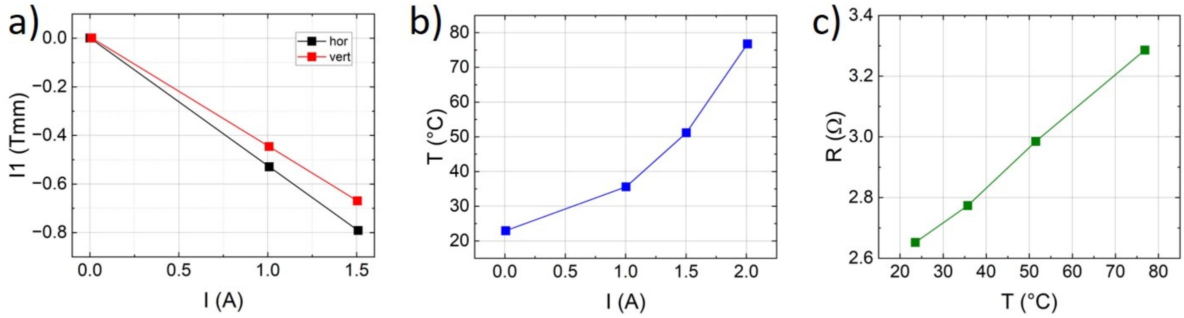

Figure 2: (a) Maximum field integral in the coil center as a function of current through all four sub-coils. Black: $I1_y(z)$ horizontal field H_z, red: $I1_z(y)$ of vertical field H_y. (b) Coil temperature as a function of applied current through all four sub-coils. (c) Resistance of two sub-coils in series as a function of temperature.

each side between the two halves. Iron spacers of matching thickness have been glued onto the ferrite in these positions to avoid a weakening of the field due to air gaps.

The corrector coil can be operated in different modes: depending on the polarity of each sub-coil, they can generate vertical, horizontal or quadrupole fields (Fig. 1 (b)), or any linear combination when powered independently. For example, an integrated quadrupole of 30mT (at 1A) could be used as an alignment quadrupole for undulators, if both were measured and aligned together in the lab before installation in the tunnel.

The assembled coil is shown in Fig. 1 (c). The length along the beam is 65mm and the height is 72mm. The design is compact and cost-efficient, made from components that are either easily available commercially or can be made in-house such as the 3D-printed shell or the iron spacers. The ferrite is generally suitable for high frequency use (>10MHz), however, for practical purpose the ramp rate will be limited and the coils are part of a slow feedback system.

3 Characterisation by stretched-wire and heating effects

The first field integral achieved by the corrector coils was measured with a stretched-wire set-up for both vertical field H_y and horizontal field H_z. Fig. 2 (a) displays the maximum value of $I1_y(z)$ for horizontal field (black symbols) and of $I1_z(y)$ for vertical field (red symbols) for different currents that were applied to all four sub-coils in series. Overall, the relation between $I1_{max}$ and current I is linear for both field directions. There are small differences between vertical and horizontal field as the spacers between the two ferrite halves lead to an asymmetry of the field enforcement.

In order to guarantee a safe operation of the coils, we also measured the heating effect of the applied current: Fig. 2 (b) shows the increase of coil temperature with increasing current. The temperature rises as a quadratic function of the current, reaching 77°C at 2A. As the coil will not be operated

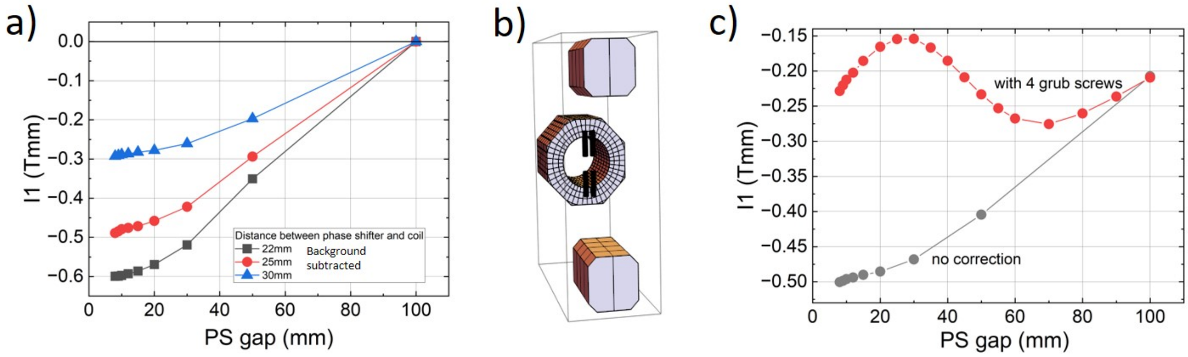

Figure 3: (a) Gap dependent vertical field integral I_y of coil and phase shifter for different distances between the two devices (background subtracted). No current was applied to the coil. (b) Set-up of the compensation scheme with the ferrite core of the coil, two magnetic screw pairs and the magnet block of the phase shifter (back to front). (c) Gap dependent vertical field integral I_y for 30mm distance between coil and phase shifter without correction screws (grey symbols) and with optimized screws configuration (red symbols).

with currents beyond 1.5A which corresponds to a temperature of about 50°C, there is no danger of overheating. However, for short times, the coils can also be operated safely with I between 1.5 and 2A. The increasing temperature of the coil also increases the resistance of the wire, as demonstrated in Fig. 2 (c): The resistance of two sub-coils in series increases linearly from 2.7Ω at room temperature to almost 3.3Ω at 77°C when operated with 2A, generating a power of 26W per half coil.

4 Cross-talk with permanent magnet-based phase shifters

On the FLASH intersections, some of the corrector coils will be mounted in close proximity to permanent magnet (PM)-based phase shifters [2, 3]. The phase shifters have been built and tuned to net zero first and second field integral along the beam axis. Unfortunately, the ferrite core causes a dampening of the fringe field of the phase shifter, leading to a significant kick error. Fig. 3 (a) illustrates how the first field integral on axis for both the (unpowered) coil and the phase shifter varies with increasing phase shifter gap. At minimum gap of 8mm, the presence of the ferrite leads to field integral errors between 0.6 and 0.3Tmm depedening on the distance between the two devices. A background signal measured at open phase shifter (100mm gap) has been subtracted from the data. In the original layout, the steerer coil was mounted just 22mm away from the phase shifter. Spatial constrains do not allow for a wide enough separation of the two devices to make the cross-talk negligible but the distance could be increased to 30mm withing the existing design, decreasing the effect by 50%. In order to mitigate the remaining cross-talk, we installed two sets of ferromagnetic dowels above and below the beam pipe, respectively, as displayed in Fig. 3 (b). The exact position and size of the dowels were calculated beforehand in Radia [4, 5]. These parameters were then refined based on stretched-wire measurement results. In the final configuration, the remaining kick could be reduced to 0.2Tmm with a ±0.06Tmm gap-dependent variation in vertical direction (red data points in Fig. 3 (c)). While the varying part is small enough to be easily forward-corrected by the steerer itself, the DC part can be corrected by a small displacement of the neighboring quadrupole sitting on a motorized mover.

5 Summary and Outlook

We have successfully designed, manufactured and tested 40 air-cooled, ferrite-enforced corrector coils for the seeding upgrade of the FLASH free-electron laser. The coils were designed to be compact and cost-efficient, taking the spatial constraints along the beam line into account. They can generate a field integral of 0.53(0.44)Tmm for horizontal (vertical) field at 1A but can also be safely operated at 1.5A and at higher current for shorter times considering heating effects.

The close proximity of some of the corrector coils to PM-based phase shifters introduced significant cross-talk, but this effect could be passively mitigated by simple measures such as the addition of ferromagnetic dowels between the two devices.

Installation in the FLASH tunnel is foreseen for mid-2025.

Journal of Physics: Conference Series **3010** (2025) 012019 doi:10.1088/1742-6596/3010/1/012019

References

[1] Acrylonitrile Butadiene Styrene

[2] P. N'gotta, P. Vagin, and M. Tischer. "Permanent Magnet phase shifters for FLASH2020+ FEL." Journal of Physics: Conference Series. Vol. 2380. No. 1. IOP Publishing (2022).

[3] K. Götze *et al.*, "Set-up and characterisation of a permanent magnet-based phase shifter series for FLASH2020" *these proceedings* (2024).

[4] P. Elleaume, O. Chubar, and J. Chavanne. "Computing 3D magnetic fields from insertion devices." Proceedings of the 1997 particle accelerator conference (Cat. No. 97CH36167). Vol. 3. IEEE (1997).

[5] O. Chubar, P. Elleaume, and J. Chavanne. "A three-dimensional magnetostatics computer code for insertion devices." Journal of synchrotron radiation 5.3: 481-484 (1998).