Recent undulator developments at DESY

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Abstract. The magnetic and mechanical design of the 2.5 m long planar variable gap undulators for the upcoming FLASH II project is based on the design of the current devices used for PETRA III. Amongst other things, several improvements concerning the rigidity of the girders and their roll angle adjustment have been implemented. Also the shape of the magnets has been adapted to achieve a sufficiently wide good field region despite the considerably smaller size of the magnets. The corresponding end pole configuration has been optimized in order to achieve minimum gap dependence of the field integrals. In addition to that, a short overview about the insertion devices for the upcoming extension of PETRA III and some issues related to that are given.

1. Introduction
FLASH, the free-electron laser for VUV and soft X-ray radiation at DESY in Hamburg, is currently being extended [1]. This effort includes a second undulator tunnel and a new experimental hall and will double the number of user end-stations which can be operated simultaneously. The present fixed-gap undulator system for FLASH I and the new FLASH II-undulators will share the same electron beam accelerator. Thus, variable gap undulators are mandatory in order to provide radiation of different wavelengths to both experimental halls independently. Their mechanical design is based on the devices currently operated at PETRA III, but there are several changes and improvements.

2. Magnetic design
Each of the 12 undulator segments for FLASH II has a length of 2.5 m. The magnet structure is a hybrid design with a period length of 31.4 mm. It provides a maximum field of 0.98 T and thus a maximum K-value of 2.87 at a minimum magnetic gap of 9 mm. The vacuum-chamber will be machined from an extruded aluminum-profile (see figure 1). Besides the central ellipse for the electron beam, there will be additional channels to be used for cooling and to accommodate optical fibers as beam-loss monitors.

![Figure 1](image-url)

Figure 1. Sketch of the FLASH II vacuum chamber. The central ellipse for the electron beam is 10 mm wide and 7.7 mm in height. The total outer thickness of the chamber is 8.6 mm at the center.
2.1. Bulk magnet structure
In comparison to the PETRA III magnet design, the width of the Vanadium Permendur poles and the NdFeB-magnets for FLASH II have been downsized significantly by 25 mm to 30 mm and 50 mm, respectively. This reduces the volume of magnet material needed and thereby the costs, and it also decreases the maximum magnetic forces acting on the support structure to 15 kN. Nevertheless this design still provides a good field region (with less than 1‰ horizontal field roll-off) which is more than ± 2 mm wide. Because of space constraints close to the vacuum-chamber the PETRA III magnets had beveled top edges. These bevels could be omitted for the FLASH II magnet design, which resulted in the improved horizontal field distribution (see figures 2 and 3).

![Figure 2. Front view of the FLASH II magnet structure.](image)

![Figure 3. Horizontal field roll-off calculated for 9 mm and 20 mm gap.](image)

2.2. End pole design
The end poles are designed in a 1:¼:¼ configuration. Their sizes and positions have been optimized for minimum gap dependence of the remaining field integrals using a recursive process in \textit{Radia} [2]. In a first step, the impact on the gap dependent trajectory offset and slope was calculated for each of the eight parameters (size and axial positions of the last two magnets and axial positions of the last two poles). These results were used for weighting the parameters during numerically minimizing the gap dependent trajectory changes in the second step of each iteration. In the working gap range of 9 mm to 30 mm the maximum expected change in the 1st field integral is \(6 \times 10^{-3} \text{Tmm} \). At an electron energy of 1 GeV this would correspond to a maximum deflection of 2 μrad. Although the finally measured gap dependence in the 1st field integral for a real tuned magnet structure may be slightly higher, it can be easily compensated for by dedicated corrector coils driven by the undulator control system. The simulation of the electron trajectory in the undulator for different gaps shows a peak to peak deviation in the 2nd field integral of 4 Tmm\(^2\) at the end of the insertion device (see figures 4 and 5). For 1 GeV electrons this relates to a negligible displacement of less than 1.5 μm. To allow for the correction of magnetic multipoles, there is a compact retainer for “magic finger” correctors attached to each end of the magnet structure.

![Figure 4. Simulation model for the endpole design.](image)

![Figure 5. Simulation of the beam trajectory for different gaps.](image)
3. Girders and drive system

The main focus of the magnet girder and support structure design was on minimizing the vertical deformations due to the dynamic magnetic load during gap changes (see figure 6). The changes to the drive system were done in order to simplify it and to make it more compact with respect to the height constraints at the upcoming PETRA III extension.

3.1. Magnet girder design

The experience from commissioning the PETRA III undulators led to another design goal, namely to increase the lateral stiffness of the girders despite their increased length. Therefore their cross section was changed from $550 \times 100 \text{ mm}^2$ to $400 \times 130 \text{ mm}^2$. Finite element calculations show that the maximum vertical deformation expected due to the changes of the magnetic load is $3.4 \mu\text{m}$ for the upper and $2.4 \mu\text{m}$ for the lower girder. Magnetic simulations yielded that the typical phase errors of $2^\circ$ to $3^\circ$ rms are only marginally compromised by this dynamic long scale girder deformation.

![Figure 6. (a) Comparison of PETRA III and FLASH II girder design. (b) Deformation of girders and support for maximum magnetic load.](image)

3.2. Drive system

The elaborate drive system for the PETRA III undulator was designed for maximum flexibility and used four completely independent axes. For FLASH II (and the PETRA III extension) this system had to be simplified due to space constraints and in order to make it more cost efficiently. Therefore two servomotors will drive a set of right- and left-handed spindles each, which are mechanically coupled. This setup still allows for flexible tapering of the device since the upstream and the downstream motors can be driven independently. A linear encoder system at each end of the magnet girders provides feedback signals for reliably adjusting the gap values on a micrometer scale.

4. PETRA III extension

Since DORIS III at DESY will cease operation for photon science by the end of this year, the facilities at PETRA III will be extended [3]. Ten insertion devices will be built for the new beamlines in two experimental halls close to the present one. These new instruments will cover the techniques so far only available at DORIS III in order to serve the needs of the existing user community also in the future. The new halls will be directly attached to the existing ring-tunnel whose building structure will remain unchanged. In the related arcs, the current FODO-structure will be replaced by double bent achromat (DBA) lattice cells. This will provide two 5 m long straight sections in each arc, which can accommodate a total of four pairs of canted 2 m long insertion devices equivalent to those currently in use at the already rebuilt octant of PETRA III. In contrast to these devices a canting angle of 20 mrad will be realized, which requires a more complicated absorber and vacuum chamber design.
4.1. Sources for high energy X-rays

Additionally, the long straight sections upstream the arcs to be modified will also be used for synchrotron radiation sources. In the north, an array of ten 4 m long damping wigglers is installed since 2009 [4]. A modification of the long final absorber will allow to use their radiation with a critical energy of $E_c=36$ keV. The magnet lattice in the east will be changed to provide two dispersion-free straights for a 4 m long in vacuum undulator and a wiggler. In both cases the radiation will be used for high energy X-ray materials science applications.

4.2. Standard and mini-undulators

All undulators for the PETRA III-extension will be planar devices and will provide full energy tunability to meet the requirements of the experiments. During the start-up phase only some of the beamlines will be equipped with cryogenically (LN$_2$) cooled double crystal monochromators like those operated at the current PETRA III beamlines. The others will be using a compact water-cooled double crystal monochromator [5]. This successful design is currently in use at several DORIS III beamlines. However there are some heatload limitations which do not allow these monochromators to be operated with a full scale undulator at PETRA III. Therefore these experimental stations will use so called mini-undulators with only about 11 magnet periods. At a later upgrade, when these beamlines will also receive LN$_2$-cooled monochromators, the preliminary mini-undulators will be replaced by full length 2 m magnet structures.

![Figure 7. Sketch of the transport concept for the insertion devices for the PETRA III extension. Manual movement in the accelerator tunnel is required due to lack of crane access. A degradation of the field quality due to these means of transport is not expected, since there is positive experience with this type of magnet structure concerning its mechanical stability during transport.](image_url)

4.3. Installation issues

There will be no crane or direct tunnel access at the installation positions of the undulators. Therefore the insertion devices have to be transported manually along the tunnel for up to several hundred meters to their locations. For this purpose a special compact transport vehicle was designed, which can be attached to the undulator support structure (see figure 7).

References

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