MAGNETIC DESIGN OF AN APPLE III UNDULATOR FOR SWISSFEL

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Abstract

For the SwissFEL at PSI beside the hard x-ray beamline to start with a soft x-ray line is planned to cover the wavelength between 0.7 and 7.0nm. For full control of the polarization of the FEL light, APPLE undulators are forseen. In this paper the design of these devices is introduced and the preliminary magnetic configuration together with the optimization strategy is presented in details.

INTRODUCTION

The SwissFEL free-electron laser currently under construction is designed with two beamlines: the hard x-ray beamline Aramis will be driven by the in-vacuum undulator U15 and will start operation with commissioning in summer 2016 being ready for user operation in 2017. The soft x-ray beamline Athos will be constructed in a second phase from 2017 to 2020. Both beamlines will have a self-seeding option [1].

While the U15 is trimmed to shortes period length, the focus on the soft x-ray undulator lies on a full polarization control by the users, that is circular, elliptical and linear polarizations to be rotatable from 0° to 180°.

The 5.8GeV SwissFEL shall accelerate two successive bunches in any of the rf – buckets coming with up to 100Hz. At an electron energy of 3 GeV the second bunch is extracted and sent into the Athos beamline where another linac can accelerate or decelerate the electrons by another 400MeV, so that the electron energy can be varied independently from the hard x-ray line within 2.6 – 3.4GeV. The wavelength range for the soft x-ray beamline shall be 0.7nm – 7nm (177eV – 1800eV). To reach with the 3.4GeV electron energy the minimum wavelength with a minimum K-value of 1 the period length is determined to 40mm. Accordingly to reach the 7nm with 2.6GeV a K-value of 4 is required.

The self-seeding chicane divides the undulator into two stages which allows to use planar devices before and for full flexibility APPLE type undulators in all modules of the second stage. The position of the self-seeding chicane has been optimized to be after 4 modules [2], which will result in 4 planar U40 and 8 APPLE type UE40 undulator modules.

The undulator design for SwissFEL is based on a modular support structure. One single frame is designed to support all kind of undulator types, planar in and out of vacuum [3] as well as APPLE undulator with their more complex forces. So for the UE40 only the shiftable magnet arrays, the magnets and their keeper have to be designed. The support structure with gap drive, the mover, the transport infrastructure and cabling etc. remains the same (see Fig. 1).

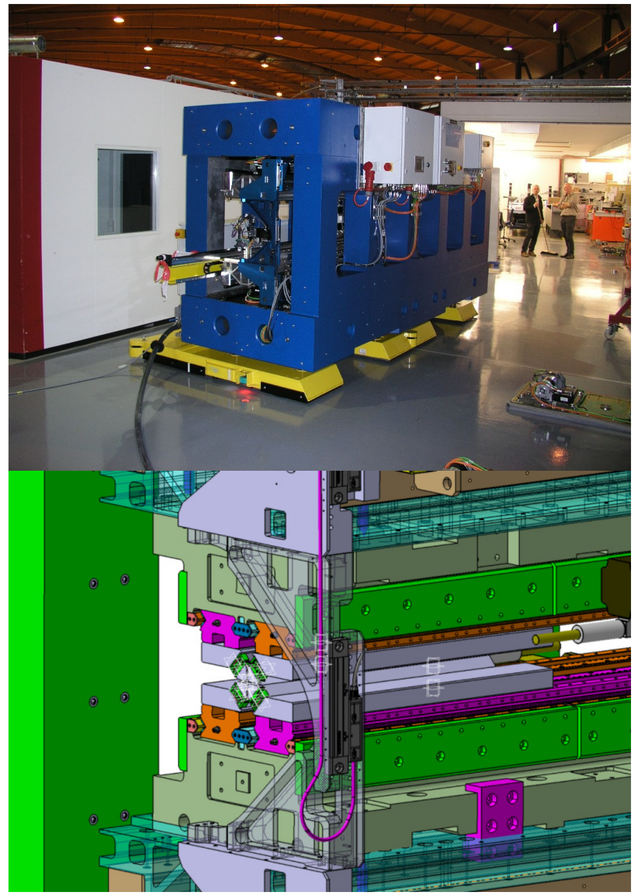

Figure 1: Modular support structure of the SwissFEL undulator series. This support structure out of cast mineral with a wedge based gap drive system can be equipped with planar in and out of vacuum magnet structures or APPLE magnet arrays.

As the APPLE undulators have to be properly aligned in vertical and horizontal direction, the mover system is a camshaft design with 5 degrees of freedom. Based on a SLAC design [4] these movers have already been used at PSI for the SLS girder and in-vacuum undulators. The movers have been reinforced and the drive system has been optimized so that they now allow the remote alignment of the undulator with µm precision. The alignment will be done by beam-based alignment with dedicated alignment quadrupoles. These are fixed quadrupoles made of permanent magnets, which are moved in and out by a simple pneumatic system. The system has been successfully tested with the prototype U15 undulator in the SwissFEL test injector [3].

Following the concept of the U15 the magnetic optimization of the UE40 shall also be based on adjustable keeper with a flexor design. Therefore the

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magnet design foresees the orientation of the magnets by 45° which allows the magnetic field optimization with a 1-dim flexor. However because of the 3-dim forces carefully FEM calculation are mandatory. Essential - especially with such flexible keeper - is to minimize the forces generated by the magnet structure. It helps that the UE40 has to be designed for a single pass FEL. As for the U15 the field (-integral) quality needs to be optimized only on axis without the need to take care on the halo particles especially during injection in storage rings.

In this paper the current magnet design for the UE40 will be presented. The existing designs will be discussed as well as the different magnet material options, and the optimization strategy including the vacuum chamber design. This paper will be the basis for a proper prototype design.

MAGNET DESIGN

Discussion of APPLE Designs

The development of undulators with variable polarization has seen beside the original APPLE II design by Shigemi Saski in 1993 [5] various add-ons in functionality or specializations, especially for single pass accelerators. The APPLE II design is the working horse in storage rings because it has no limitations for the horizontal dimension of the vacuum chamber. This and also a sufficient large good field integral region is an issue, especially for top-up injection. In addition it has maximum space for magnetic measurements with Hall-probes. APPLE II designs exist with variable gap but also in fixed gap implementations at Swiss Light Source (SLS) and Pohang Light Source (PLS). Fixed gap operation is more problematic because of problems which occur from transverse field gradients along the beam axis [6]. For linac driven undulators there are more options. In the APPLE III design by Johannes Bahrdt are the magnets magnetized under 45°. Only in the center the room for a round vacuum chamber is given, to the sides the magnets enclose the vacuum chamber giving room only for magnetic measurements [7]. This design increases the fields, which in return allows for shorter periods. A fixed gap design is the more recent DELTA design by Alexander B. Temnykh, where triangle magnets are soldered on a copper keeper allowing the most compact design [8]. Like in the classical Onuki undulator [**9**] the horizontal fields are generated with a horizontal magnetized magnet array pair (see Fig. 2). However for the price of limited access for magnetic optimization and the need for fixed gap operation.

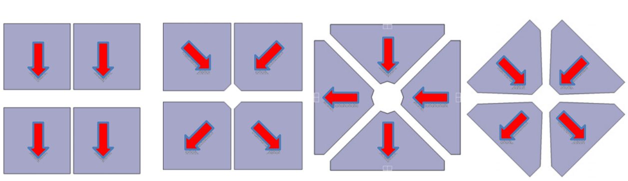

Figure 2: APPLE Designs: APPLE II, APPLE III [7], DELTA [8], proposed SwissFEL UE40.

The proposed design for the SwissFEL APPLE undulator is a APPLE III type with 45° magnetized magnets which like in the DELTA design have a triangle shape.

The triangle shape makes use of the fact that the contribution to the field from the magnet material which is cut away in anyhow negligible. Second, this shape allows an easier adaption to the keeper. New is that the shimming of the magnets is not 2-dimensional in horizontal and vertical direction but only 1-dimensional under 45° and so in parallel to the magnetization direction. This allows the adaptation of the flexor design used already in the U15, with some modifications, of course.

Gap Requirements

The minimum allowed gap is strongly related to the vacuum chamber design. Vacuum requirements as well as beam dynamic considerations in terms of wake-fields due to the geometry and surface roughness of the vacuum chamber. The design presented here assumes that a round vacuum pipe made of copper with an outer diameter of 6mm and inner diameter larger than 5.5mm could be sufficient. Assuming the APPLE III approach the minimum gap is beside the space for the vacuum pipe in the center only limited by the space requirements for the Hall-probe measurement system, which is currently in minimum 2.5mm.

Magnetic Materials

The standard permanent magnet materials used for undulators are various grades of NdFeB. With various stabilization techniques they can be used up to a remanence of B_r=1.25T, used i.e. in the SwissFEL U15. However, beside NdFeB there is also the older SmCo option. SmCo exits in two stoichiometries, $SmCo_5$ and Sm_2Co_{17}. The remanence of the SmCo magnets is weaker so that for the same field larger magnets or smaller gap is needed. But their temperature dependency is by a factor of 2 to 3 better, which is useful as the Athos undulators are positioned just beside linac 3 for the hard x-ray beamline in the same tunnel. In addtion for $SmCo_5$ the susceptibilities are smaller, which results in smaller shift dependent kicks on the electron trajectory. The coerciivty determines the radiation stability, which is reasonable for all these materials.

Table 1: Remanence, coercivity, temperature dependency and susceptibility parallel and transverse to the magnetization direction for Samarium Cobalt and Neodymium Iron Boron magnets. SmCo magnets are weaker but have lower temperature dependency and in case of SmCo5 lower nonlinearities

	B_r [T]	H_{cj} [kA/m]	dB/dT [%]	$X_{\parallel / \perp}$
$SmCo_5$	1.0	2400	0.05	0.01 / 0.04
Sm_2Co_{17}	1.1	2000	0.035	0.06 / 0.15
NdFeB	1.25	2300	0.1	0.06 / 0.15

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Energy Range for Various Polarizations

The energy range for APPLE undulator beamlines needs some special care. Often the maximum phtoton energy range specified can only be reached in linear horizontal mode. This is because in standard APPLE geometry the vertical field is stronger than the horizontal one by up to 30%. User might be interested to measure over the full range with horizontal and vertical polarization which means Kz = Kx. Circular light is required only for the K-α edges of the transition metals at around 700eV which is not critical. Only in inclined modes the field is weaker, because some flux is directed in the longitudinal field components. The design for the UE40 foresees to reach the K of 4 not only for the horizontal polarization but also for the vertical polarization. The stronger vertical field would then only increase the forces without benefit for user operation. Hence the design foresees a symmetric magnetic design with the minimum gap being equal to the fixed slit between the magnet rows on the left and the right side.

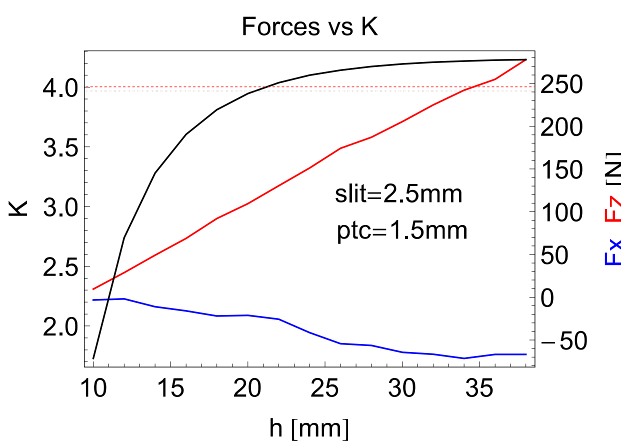

Figure 3: K-value and forces as function of magnet dimension. A diagonal h of 20mm allows already K = 4.

UE40 Design

Taking into account all the above remarks the following design for the UE40 is proposed: The magnets are fully symmetric at the minimum gap, magnetized under 45°. In addition the magnets could have a small angle of 2°, which further helps to reduce the forces and moments on the flexible keeper. The minimum photon energies are in this design equal for LH, LV and circular and reach the minimum value of 180eV. Only in inclined mode the minimum photon energies are larger, i.e. at an angle of 45° 330eV.

The forces scale linearly with the magnet dimensions while the field and hence the K-value saturates at a given magnet size. Therefore it is preferable to optimize the magnet dimensions to reach just the required K-value. To reach the required K = 4 at a gap and slit of 2.5mm with SmCo magnets a height of the diagonal of 20mm is sufficient which results in forces of up to 10kg on a single magnet holder. However, with the stronger magnet materials a K value of 4.3 and 4.8 could be reached in this configuration. For the vacuum chamber a diameter of 6.5mm is available. With a gap-slit combination of 3mm and a smaller chamfer at the center of 1mm only with SmCo a height of 25mm would be required (Fig. 3) and the free space for the vacuum chamber is with only 0.3mm less practically similar. With NdFeB 4mm gap-slit and 10mm diameter for a vacuum chamber are possible. This needs to be optimized including FEM calculations of the flexor keeper system described in the following.

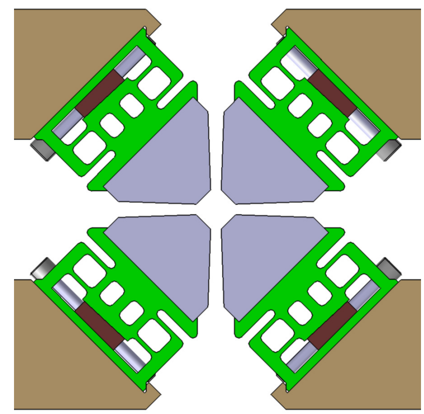

Figure 4: Radia model of UE40 magnet structure. The minimum gap is equal to slit width. Shimming like magnetization with 45° angle.

Flexor Keeper

The magnets are kept not in massive keeper but in an extruded aluminium profile which allows the shimming of the magnets parallel to the magnetization direction under 45°. The magnet position can be adjusted with µm precision by moving a 2° and hence self-locking wedge inside the keeper. A vertical kick is produced by shimming all four keepers identical with the same sign, a horizontal kick by shimming with alternating sign. Figure 4 shows a starting layout, used for FEM studies to optimize the geometries. Shimming with 30µm would result in a local field change of 0.07%, which produces a kick of 50Gcm. The maximum allowed shimming depends on the forces and the design of the keeper. In case of the U15 the preload of the keeper with the wedge is 60µm and the shim range is ± 30µm.

For APPLE undulators beside the vertical field variation also the horizontal field variation needs to be considered. Figure 5 shows the variation in circular and inclined mode. The good field region is with 50µm and 60µm to 80µm comparable to the vertical one. As a result the alignment specifications in both vertical and horizontal are very tight but can be handled with the cam-shaft movers in a remote controlled way.

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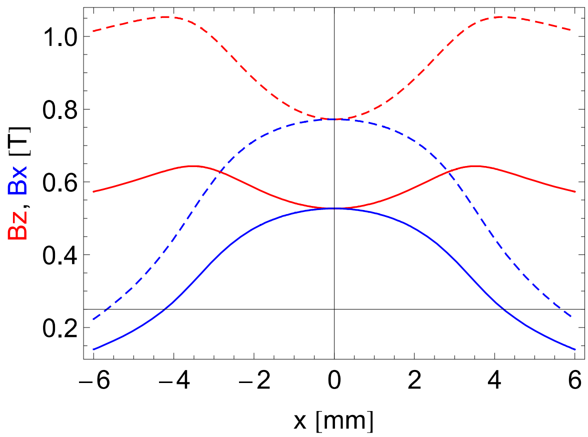

Figure 5: Transverse variation of the peak fields in inclined and circular (dashed) mode. The good field region of 10^{-4} is 50µm for the vertical field and 60-80µm for the horizontal.

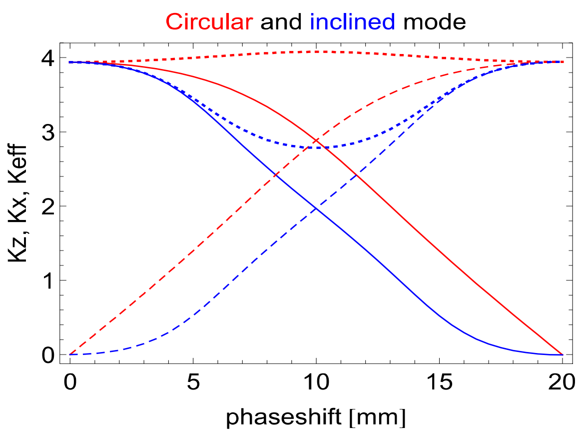

Figure 6: Shift dependent variation of Kz (solid), Kx (dashed) and Keff (dotted) for circular and inclined polarization. The 45° magnetization and slit = gap_{min} result in this symmetric plot.

The symmetric changes the shift variation, because both vertical and horizontal K-values are the same. As a result, the effective K-value in circular mode is even slightly larger and only the minimum effective K-value in inclined mode is smaller with the corresponding minim reachable photon energy of 330eV (see Fig. 6).

OPERATIONAL ASPECTS

APPLE undulators are normally operated with gap and shift variation. However it is also possible to run them in fixed gap mode like the UE40 undulator for the ADDRESS beamline at SLS. In fixed gap mode, there are field gradients at the nominal beam axis which may the affect the operation. At the ADDRESS beamline, the spectra in circular mode were found to be smeared out at their blue edge. The spectra could be recovered by changing the operating conditions: Instead of changing the energy by a relative shift of top versus bottom magnet arrays, the same energy can be set with a shift left versus right magnet arrays (Fig. 7). The reason is the relative large horizontal beam size in a storage ring while the vertical beam size is only 1% or less.

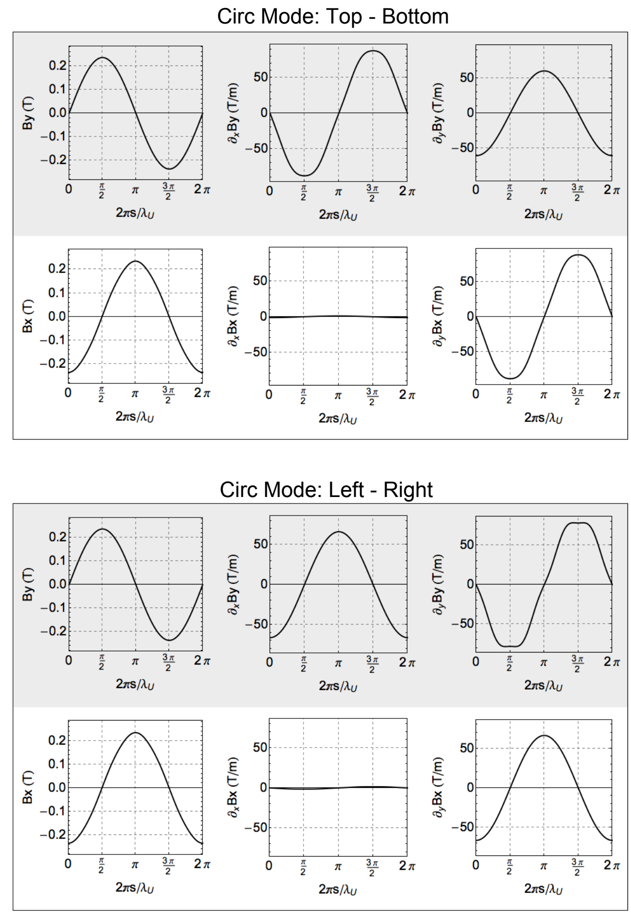

Figure 7: Field gradients in fixed gap APPLE operation with energy shift in Top - Bottom and Left – Right configuration.

For FELs with their small emittance the impact is appropriate small but should be noticed. For more flexibility and the common support structure, the APPLE undulator for SwissFEL will have shift and gap variation.

CONCLUSION

The soft x-ray line for SwissFEL shall provide full polarization control for the users. The presented UE40 design considerations propose the availability of all the major polarization states LH, LV and circular over the entire photon energy range. The design integrates the best of former designs and allows in addition the use of the flexor keeper design from the U15 undulator for an in-situ and automatized shimming under 45°. A horizontal field of 1.05T (K=4) for the horizontal field is pretty demanding. Small gaps are required and it is mandatory to optimize the forces wherever possible. Therefore magnet material is removed wherever possible which results in the delta shape of the magnets, the large slit width with its additional angle and the symmetric design.

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