ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPM068

FIRST MAGNETIC EXPERIENCE WITH APPLE X KNOT UNDULATORS FOR SLS 2.0

S. C. Richter*, T. Schmidt, A. Arsenault, J. Raabe, M. Calvi
PSI Center for Photon Science, Villigen, Switzerland
P. Boehler, M. Giger, A. Keller
PSI Center for Accelerator Science and Engineering, Villigen, Switzerland

Abstract

The next generation of synchrotrons will have undulators with shorter periods, stronger magnetic fields, and thus higher radiation power. Consequently, concepts for reducing on-axis heat load will become more relevant. One possible idea is to introduce so-called APPLE "knot" undulators that shift the main energy peak off-axis. Thanks to almost on-axis injection, APPLE X undulators with a round vacuum chamber can be used for the upgraded SLS 2.0 at the Paul Scherrer Institute (PSI). This contribution presents an adapted concept of the APPLE knot customized to the needs of SLS 2.0 in the form of two-meter-long APPLE X undulators with a period length of 36 mm and a gap of 11.5 mm, named UE36kn. The presented design faces the challenge of dealing with up to 16 different magnetization angles introduced by combining and merging NdFeB magnets into four arrays with on-axis peak fields around 1 T. First measurement results showed qualitative agreement with calculations and prove the feasibility of these rather complex *B*-fields with high-quality permanent magnets.

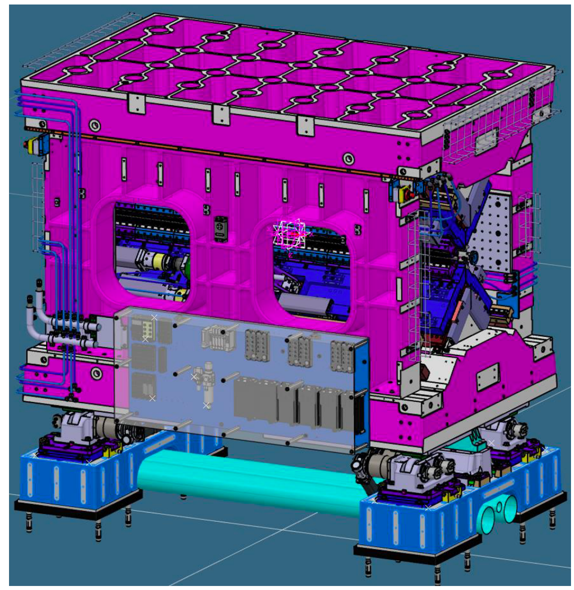


Figure 1: Schematic sketch of the PSI APPLE X frame.

INTRODUCTION

After more than 20 years of operation, the Swiss Light Source (SLS) at Paul Scherrer Institute (PSI) is undergoing a major update named SLS 2.0 [1]. The 288 m long accelerator tunnel was cleared and refilled in approximately a year, leaving only the booster synchrotron almost untouched. Not only is the electron energy increased from 2.4 GeV to 2.7 GeV, but more importantly, there is a horizontal emittance reduction, aiming at 157 pm. Undulators with shorter periods will replace most existing ones to make the best use of the advanced beam and deliver highly brilliant photon beams. Consequently, the beamlines will face higher radiation power, making concepts for reducing on-axis heat load more relevant, especially in the soft X-ray regime.

In the following, this challenge is tackled with a novel type of APPLE "knot" undulator, tailored to PSI's successful APPLE X design, which has already been in operation in SwissFEL for several years [2]: The result is the here presented UE36kn. The APPLE knot is a new undulator, designed to reduce the on-axis power of linear polarized light, similar to the figure-8, but with higher polarization purity. This characteristic is achieved by shifting the main energy peak off-axis due to their specific magnet design [3–6]. Originally designed with eight magnet arrays as an APPLE II device, PSI tailored the idea to the existing undulator frame by merging those into only four combined arrays, as explained in the upcoming section. Additionally, this novel design is a simplified version, reducing the number of magnet types to five. An overview of the mechanical design is given before the magnetic design is presented, followed by a brief comparative look at the first magnetic measurement results.

MECHANICAL DESIGN

An almost on-axis injection in SLS 2.0 makes the existing PSI APPLE X undulators with a round vacuum chamber an excellent and efficient choice: Originally designed for the round beam pipe of PSI's free-electron laser, SwissFEL, APPLE X undulators bring the permanent magnets as close to the beam as possible and have full photon polarization control. This design was already described in detail in earlier works for SwissFEL's ATHOS beamline [2]. Consequently, only the most important features and updates are briefly recapitulated here. Figure 1 shows a schematic overview of the installation in the SLS 2.0 tunnel. Cast iron is used for the 12.5 t heavy main support frame (colored pink). It has a length of 2.25 m, a height of 1.66 m, and a width of 1.42 m. The undulator frame sits on 5-axis cam-shaft movers for a flexible alignment in the micrometer to millimeter range, positioned on a bridge to make room for the water cooling

* sebastian.richter@psi.ch

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPM068

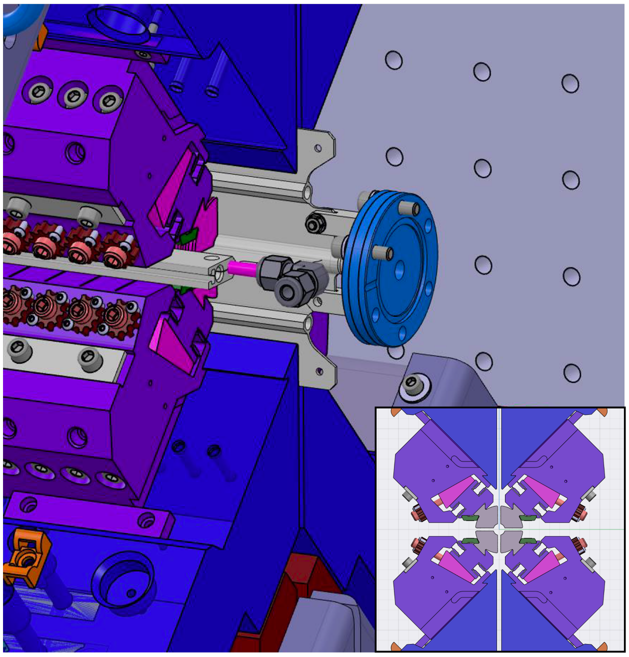


Figure 2: Schematic view of an undulator end, including the water-cooled vacuum chamber. The insert displays a cross-sectional view in beam direction at 11.5 mm gap.

pipes of the storage ring. Each of the four magnet arrays is mounted on a stainless steel shift plate, respectively (colored dark blue). The longitudinal shifts are mechanically limited to move ±47 mm, yet, the installation of the vacuum chamber will restrict this to approximately ±35 mm when installed in the ring. Here, the major working area will be defined by polarization shifts covering half λ_u, thus ±18 mm. As the knot magnet configuration may make larger shifts up to $\pm\lambda_u$ interesting for special modes, e.g., suppressing the knot configuration, this option will be investigated shortly during the magnetic measurement campaign. A close-up of this scenario can be seen schematically in Fig, 2, where a cross section of the four magnet arrays in beam direction is included at the bottom right. The shown minimum gap of 11.5 mm leaves slits of 3 mm in between the different magnet arrays for supporting the vacuum chamber or the magnetic measurement setup. Each array can be opened individually, creating a potential maximum gap of 31.5 mm. The radial gap shift is driven by wedges, operated by water-cooled motors, as the shift plates

MAGNETIC DESIGN

The design of the single $Nd_2Fe_{14}B$ magnets follows PSI's previous APPLE X design, the so-called fish-like shapes (cf. Fig. 2, insert). Here, the four fish-like shapes around the center depict the permanent magnets that are clamped at their dovetail. The "knot" magnet configuration results from combining the main undulator period λ_u with $1.5 \times \lambda_u$ by vector addition into one array as sketched in Fig. 3 for one super-period: in this case Halbach arrays with periods of $\lambda_u = 36$ mm and $\Lambda_u = 1.5\lambda_u = 54$ mm.

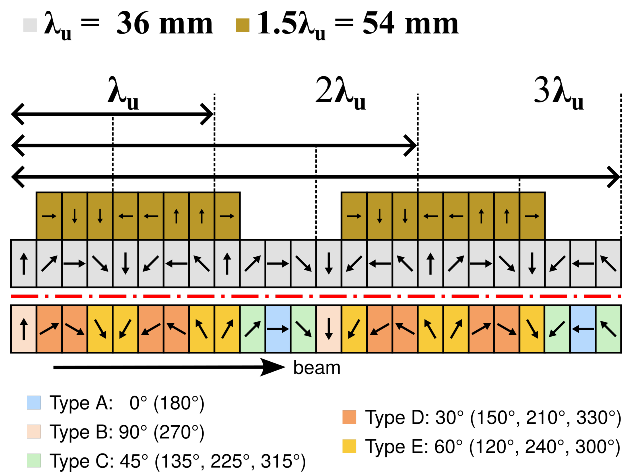


Figure 3: Schematic of creating the PSI APPLE X knot magnet design, by an adjusted weighted merging process.

Table 1: UE36kn Main Parameters

Parameter	Value	Unit
Magnet material	$Nd_2Fe_{14}B$	
Period length λ_u	36	mm
Super period $3\lambda_u$	108	mm
max. B	1	T
max. K	3.6	
Min. gap	11.5	mm
Hor./vert. slit	3	mm
Electron energy	2.7	GeV
Photon energy	260 to 1800	eV
Magnetic length	1.836	m
Module length	2.25	m
Number of periods	51	

The colorful vector array below the red dash-dotted line represents the result of PSI's adjusted merging process, which only exactly repeats itself after a so-called super-period of $3\lambda_u$ for UE36kn. Note that, compared to the original APPLE knot design, not only was the scaling factor of Λ_u varied ($\tan 30° \approx 0.57735$, instead of originally 0.5), but also some magnetization angles were manipulated manually. Both interventions were done to decrease the number of resulting magnetization angles to a reasonable number for industrial (series) production while having the least impact on the magnetic field design.

The magnets are manufactured by the company VACUUMSCHMELZE GmbH & Co. KG, Hanau, Germany, with tolerances of ±1.5° for the main magnetization angle and ±1.5% for the remanence field $B_r = 1.31$ T. With a magnet thickness of 4.5 mm, 24 magnets are needed to realize one super-period. There will be 48 magnets per periodic keeper by using similar magnet keepers, as for the ATHOS APPLE X design [2]. For the optimization process, four magnets are sitting on a tunable knob, being able to be shimmed ±100 µm via wedges and flexors driven by screws.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPM068

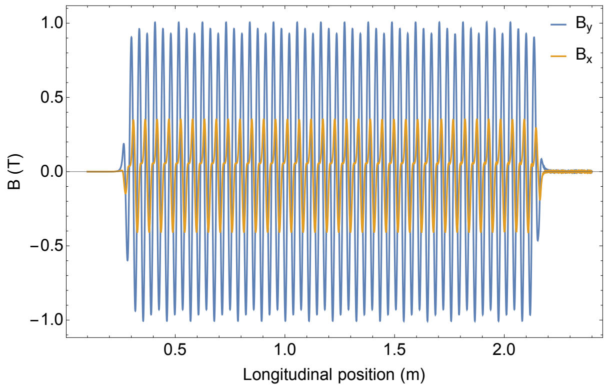
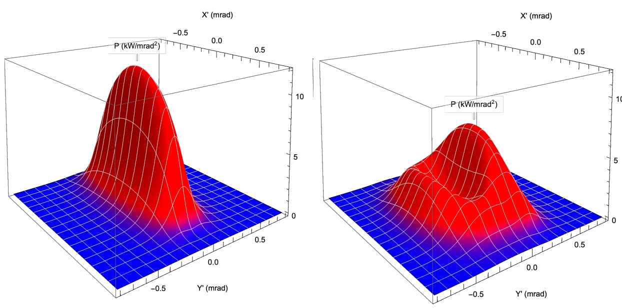


Figure 4: Calculated on-axis magnetic flux density (B-field) of UE36kn for the minimum gap in linear horizontal mode. The super-period $3\lambda_u$ is well visible in B_y. Beam in $\hat{z}$.



(a) UE36 (b) UE36kn

Figure 5: Angular power density (kW/mrad^2) calculated using SPECTRA, depicted for a 36 mm (a) periodic APPLE X and (b) an APPLE X knot magnet configuration. Both are in linear horizontal mode, sharing the same vertical axis.

An overview of the UE36kn main parameters is given in Table 1. For the beamline setup, two UE36kn are planned, optionally coupled with a phase shifter in between.

The above-described magnet configuration was implemented in a RADIA model [7]. Calculations of the on-axis B-field are shown in Fig. 4 for the linear horizontal case. Here, the super-period is well visible in the vertical field B_y. Additionally notable is the fact that the orthogonal field component is not equal to zero, but has a significant value.

The polarization purity for linear and circular polarizations was observed in calculations to be higher than 98.5% throughout the entire spectrum. As a result of the above-described peculiar B-field, the power density is heavily affected, as displayed in Fig. 5. Calculations show a significant decrease of the on-axis power density between a periodic UE36 and a UE36kn of about 60%, using SPECTRA [8].

FIRST EXPERIMENTAL RESULTS

As the magnetic optimization procedure is currently ongoing, a glimpse of the first measured data is given in the following.

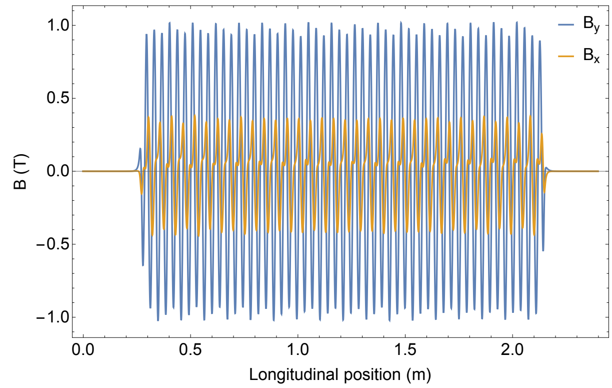


Figure 6: Measured UE36kn's on-axis magnetic flux density (B-field) for the minimum gap in linear horizontal mode. Peak fields and K agree qualitatively with calculations.

Figure 6 shows the measured B-field for the minimum gap of 11.5 mm. An overall qualitative agreement with the calculations above can be noted in the vertical field B_y, with minor deviations in the horizontal field B_x. Yet, the magnet arrays need to be fully aligned and shimmed, optimizing both fields according to calculations. The latter may be especially challenging for the following reasons: The four magnets on one shimming knob may vary extremely in magnetization angle, plus, the knobs may be highly coupled.

SUMMARY AND OUTLOOK

Within the SLS 2.0 upgrade at PSI, the insertion devices are being optimized to increase the flux brilliance as best as possible. Here, we present a possible solution to treat the resulting higher on-axis power by implementing an APPLE knot magnetic configuration into PSI's APPLE X undulator system. The benefits are clear: full polarization control with excellent polarization purity, and higher flux rates, but reducing the on-axis power by about 60% for the presented UE36kn. Yet, the relatively complex shape of the B-fields places high demands on magnet production and shimming.

The first experimental results already show a qualitative verification of the calculated B-fields, with all their complex features. This is a promising result for a successful operation in the ring, where installation is foreseen later in 2025.

The immediate next step is to optimize/shim the undulator UE36kn before a series of measurements will fully characterize the phase space. A more detailed analysis of the experimental data, as well as a working description of UE36kn to the full extent, is planned in a future publication, providing the complete picture.

ACKNOWLEDGMENTS

The authors thank M. Brügger for developing and supporting the measuring benches, including troubleshooting during the measurement campaign. Further thanks to S. Danner and R. Felder for excellent magnet keeper mounting, and the rest of PSI's ID-Team for general support.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC25-TUPM068

REFERENCES

[1] A. Streun, "SLS 2.0, the upgrade of the Swiss Light Source", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 925–928. doi:10.18429/JACoW-IPAC2022-TUPOST032

[2] T. Schmidt and M. Calvi, "APPLE X undulator for the SwissFEL soft x-ray beamline Athos", *Synchrotron Radiat. News*, vol. 31, no. 3, pp. 35–40, 2018. doi:10.1080/08940886.2018.1460174

[3] S. Sasaki, A. Miyamoto, and S. Qiao, "Design study of knot-APPLE undulator for PES-beamline at SSRF", in *Proc. PAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, pp. 1043–1045, https://accelconf.web.cern.ch/pac2013/papers/wepsm01.pdf

[4] S. Sasaki, A. Miyamoto, T. Mitsuyasu, N. Kawata, and S. Qiao, "Possibility for quasi-periodic knot-APPLE undulator", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2026–2028. doi:10.18429/JACoW-IPAC2014-WEPRO038

[5] F. Ji *et al.*, "Design and performance of the APPLE-Knot undulator", *J. Synchrotron Radiat.*, vol. 22, pp. 901–907, 2015. doi:10.1107/S1600577515006062

[6] F. Zhang, Z. Sun, Y. Qiao, and S. Qiao, "Practical design and performance of a new merged APPLE-Knot undulator", *J. Synchrotron Radiat.*, vol. 27, no. 6, pp. 1494–1498, 2020. doi:10.1107/S1600577520011753

[7] O. Chubar, P. Elleaume, and J. Chavanne, "A three-dimensional magnetostatics computer code for insertion devices", *J. Synchrotron Radiat.*, vol. 5, pp. 481–484, 1998. doi:10.1107/S0909049597013502

[8] T. Tanaka, "Major upgrade of the synchrotron radiation calculation code SPECTRA", *J. Synchrotron Radiat.*, vol. 28, pp. 1267–-1272, 2021. doi:10.1107/S1600577521004100