THE FIRST APPLE X KNOT UNDULATORS: MAGNETIC CHARACTERIZATION AND INITIAL PERFORMANCE

S. C. Richter*, A. Kleibert, C. A. F. Vaz, and M. Calvi,
PSI Center for Photon Science, Paul Scherrer Institute, Villigen, Switzerland

Abstract

Concepts for reducing on-axis heat load become essential as photon flux increases in next-generation synchrotrons, especially in the soft X-ray regime. Therefore, APPLE "knot" undulators are promising insertion devices, diverting most energy off-axis without compromising the polarization purity. The first two APPLE X knot undulators, each 2 m long and with a period length of 36 mm, were designed and built at Paul Scherrer Institute (PSI) and installed into the newly upgraded Swiss Light Source (SLS2.0) electron storage ring. This contribution presents the final magnetic characterization results of both novel undulators and derives photon characteristics, including how effectively the radiation power is expected to be reduced on-axis in contrast to a regular elliptical undulator, especially in linear modes. Further, their initial performance with the beam is demonstrated, providing a glimpse of the ongoing beamline commissioning and future operation.

INTRODUCTION

The latest upgrade of the Swiss Light Source SLS to SLS2.0 increased the electron beam energy from 2.4 GeV to 2.7 GeV and reduced the horizontal emittance to a target value of 157 pm. To exploit the improved beam parameters, most existing insertion devices are replaced by undulators with shorter magnetic periods, enabling significantly higher photon beam brightness. In particular for soft X-ray beamlines, this results in an increased radiation power incident on beamline components, making the reduction of on-axis heat load a critical issue. To address this challenge, a novel APPLE "knot" undulator concept was implemented, based on PSI's mature APPLE X design for SwissFEL's Athos line [1].

The resulting device, a 2 m-long UE36kn, with an undulator period λ_u = 36 mm, was designed to suppress on-axis radiation power for linearly polarized light, similar to figure-8 undulators, while providing enhanced polarization purity. This was achieved by a dedicated magnetic configuration that shifts the main radiation peak, thus higher harmonics, off-axis [2–5]. The original APPLE knot concept employs eight magnet arrays in an APPLE II–type configuration. For UE36kn, the design is adapted to the existing undulator infrastructure at PSI by merging the eight arrays into four combined arrays, with all magnets having the same remanence field B_r = 1.31 T, forming a main undulator period length λ_u = 36 mm. In addition, the magnetic design is simplified by limiting the number of different magnet types to five. A detailed design overview was given in a previous publication [6]. This paper presents the final results of the magnetic characterization, including derived photon characteristics, and the initial performance with the beam in SLS2.0 at PSI.

MAGNETIC CHARACTERIZATION

A compact measurement system was needed as the fish-like magnets on the four arrays in an APPLE X configuration spare only limited space for measuring at small gaps, as Fig. 1 demonstrates in a close-up. To deal with this constraint, a SAFALI-type system serves as the measurement setup consisting of a 3-axis Hall probe, introduced earlier [7].

After the magnet assembly was completed and before being able to assess the final magnetic field configurations experimentally, each undulator was aligned in two steps: First, the Hall probe's position was corrected for the horizontal and vertical positions, x and y, as well as pitch and yaw, respectively, while the beam is pointing along $\hat{z}$; all with respect to the magnetic field, utilizing a newly defined K parameter for the knot-magnet design. Second, minimizing the relative phase among the four rows by correcting the position of all four arrays to each other, leading to improved polarization settings, especially in linear modes. As a next step, the complete magnetic configuration was optimized by using the flexor/screw system introduced in earlier publications [1, 6]. As commonly done for undulators, the goal of shimming was to smooth the undulator field and reduce kicks as best as possible by minimizing the first and second field integrals and thus the phase error. Yet, the novel APPLE X knot magnet design comes with a challenge linked to the keeper design with respect to the shimming process: A single shimming knob consists of a pack of four magnets, each with a different magnetization direction. With a total of

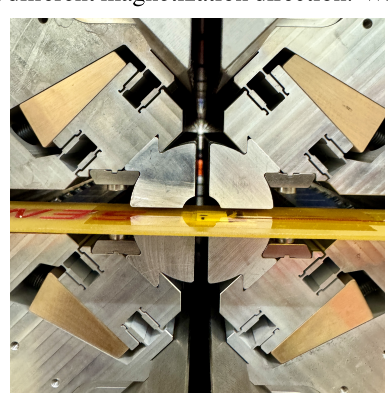


Figure 1: The APPLE X knot UE36kn and its four magnet arrays, including the flexor-based shimming system, during the magnetic characterization at a gap of 13 mm.

* sebastian.richter@psi.ch

six different knobs, some individual knobs may be strongly coupled. Consequently, a new shimming algorithm needed to be developed and tested. A more detailed description of this complex, novel shimming procedure and the new K definition for knot configurations will be published in the near future, as it would go beyond the scope here.

Experimental Results

Having set up both undulators as described above, the magnetic fields were assessed for various gaps and polarization modes. A selected subset from more than 1000 magnetic field profile measurements acquired per undulator UE36kn was then used for the characterization of the principal polarization modes; these cover linear horizontal (LH), circular (Circ), and linear vertical (LV) polarization. For the latter, we distinguish between a parallel and an antiparallel (LVas) shift. Figure 2 displays B-fields causing such polarized photons for UE36kn's minimum gap of 11.5 mm. Both field components, e.g., for LH, vertical B_y and horizontal B_x, quantitatively agree with calculations, thus giving a maximum $K \approx 3.6$. The undulators' magnetic field was calculated and designed using the software Radia [8] and was briefly presented earlier [6]. As is common for elliptical fields, the linear fields also have orthogonal components due to the knot design, helping to shift the main power load off-axis, as demonstrated later.

It is worth noticing that the smaller field component of the linear modes still showed some qualitative deviations from the calculated qualitative curve, e.g., in uniformity. This may be caused by the following: First, due to time constraints, the novel shimming procedure was only applied to the worst outstanding shimming knobs, end regions, and single groups of knobs to demonstrate the working principle. Second, a non-perfect perpendicular alignment between the respective Hall sensors within the used 3-axes Hall probe, which is given with a precision of $\pm 2\,^\circ$, was demonstrated to have a non-negligible impact, especially on these B-fields,

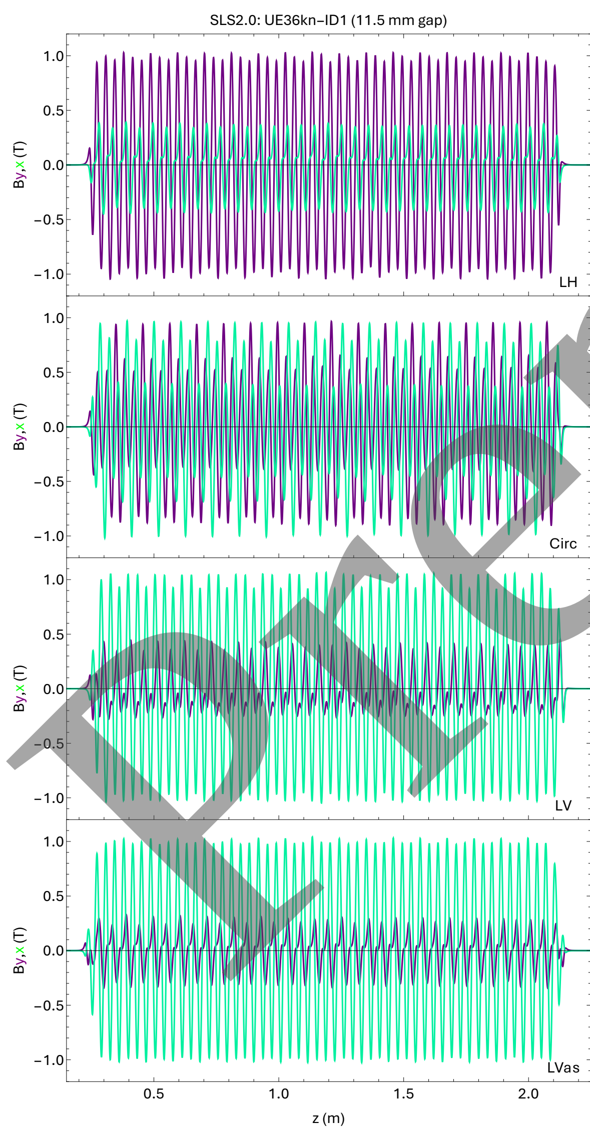
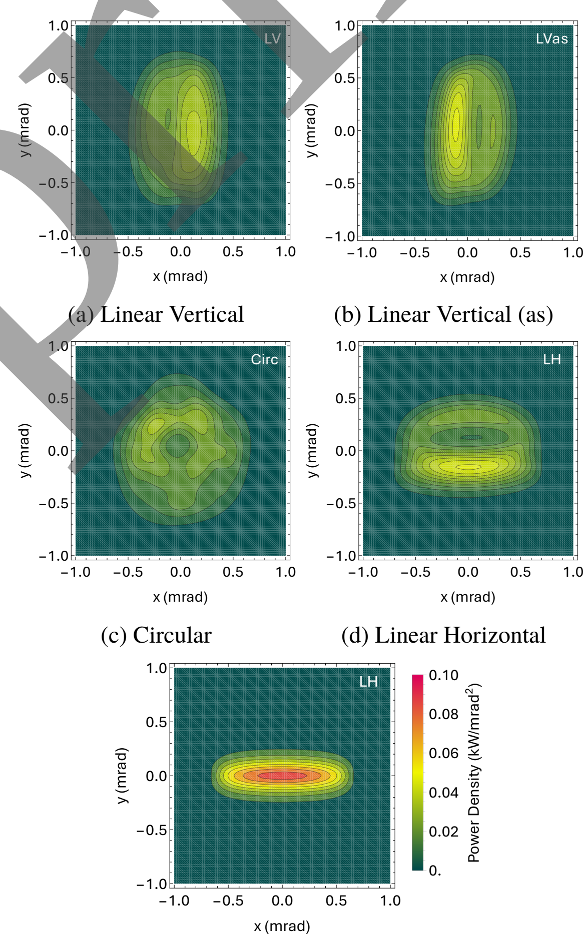


Figure 2: Measured UE36kn's on-axis magnetic flux density (B-field) for the minimum gap in the principal polarization modes. Peak field and K values agree with calculations.



(a) Linear Vertical (b) Linear Vertical (as)

(c) Circular (d) Linear Horizontal

(e) Linear Horizontal

Figure 3: Calculated angular power density (kW/mrad^2) based on experimental B-field scans, depicted for a 36 mm (a)-(d) APPLE X knot (UE36kn) and (e) an ordinary APPLE X magnet configuration (UE36). Same color bar for all plots.

caused by the knot-design. Nevertheless, this does not compromise the performance in any way, as demonstrated in the upcoming paragraph.

After having fully characterized both UE36kn undulators, the experimentally measured data were used as a base for calculating photon spectra, power, and polarization quality utilizing the software Spectra [9]. Agreeing once more with calculations, all principal polarization modes could be shown to be well above 98.5 % without any further optimization over the entire energy range. Equally important was the verification of the power distribution, directly derived from the measured fields. Figure 3 shows the power density in kW/mrad^2 for the UE36kn (a) to (d) in direct comparison with a calculated ordinary, elliptical magnetic configuration (e); the origin always being the central beam axis in plane. A clear decrease in on-axis power density can be noted due to the knot-field, thus changed electron orbits, especially for the linear polarization modes. These reductions can be quantified to more than 65 % impacting the central cone.

INITIAL COMMISSIONING RESULTS

In the summer of 2025, the first UE36kn was installed at the SIM beamline at SLS and was ready for commissioning and operation with an electron beam. The second UE36kn completed the beamline's undulator setup in early 2026. Three additional window frame coils, one upstream, one between, and one downstream, making local corrections feasible. Additionally, a phase shifter offers the possibility to use both devices as one 4 m device, located in between the two 2 m-long undulators.
Initial commissioning measurements in November 2025 demonstrated the perfect agreement between calculations and operation as shown in Fig. 4 for the linear horizontal mode. This was an important step as knot-type undulators come with the peculiar characteristic of a superperiod, equal to $3\lambda_u$ and non-zero perpendicular field components, also in linear modes [6]. Consequently, the resonance condition for an undulator with knot configuration may not be straightforward and thus, a new definition of K was introduced based on integrating both, B_x and B_y, taking the superperiod into account (c.f. Fig. 2). Next steps at the beamline will include

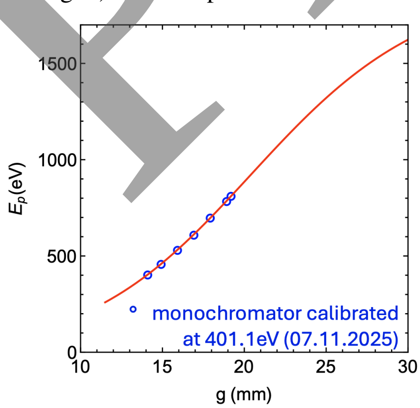


Figure 4: Initial photon assessment of UE36kn concerning photon energy over gap relation at the SLS-SIM beamline.

experimentally verifying the polarization purity and on-axis power measurements, and finally, the phase-matching. After the final beamline optics alignment, the first user operation is foreseen for late summer 2026.

CONCLUSION AND OUTLOOK

New insertion devices are being installed during the SLS2.0 upgrade to maximize photon beam brilliance while addressing the associated increase in on-axis radiation power. This challenge was tackled by the presented UE36kn, the implementation of an APPLE knot magnetic configuration within PSI's APPLE X undulator platform, being an effective solution.
The final magnetic assessment of both UE36kn undulators shows an agreement with both the calculated B-fields and the beamline requirements, i.e., providing full polarization control with high polarization purity while reducing the on-axis power by more than 65 %, without compromising photon flux. Consequently, both novel undulators were installed in SLS and are currently undergoing commissioning with the beam, in which they perform as expected, so far. A more detailed and complete analysis, as well as a working description of UE36kn to the full extent, is planned in a subsequent publication, providing the complete picture.
The immediate next step for now is to optimize the two undulators UE36kn for beamline operation, while two more knot-type devices are about to be manufactured at PSI with a single piece length of 4 m each, and main magnetic period lengths of 38 mm and 90 mm.

ACKNOWLEDGMENTS

The authors thank M. Brügger for developing and supporting the measuring and shimming benches, always with devotion. Further thanks to S. Danner and R. Felder for excellent magnet keeper mounting, and the rest of PSI's ID-Team for general support.

REFERENCES

[1] T. Schmidt and M. Calvi, "APPLE X Undulator for the SwissFEL Soft X-ray Beamline Athos", in *Synchrotron Radiation News*, vol. 31, 2018, doi:10.1080/08940886.2018.1460174.

[2] S. Sasaki, A. Miyamoto, and S. Qiao, "Design Study of knot-APPLE undulator for PES-beamline at SSRF", in *Proc. PAC2013*, Pasadena, CA USA, 2014, https://accelconf.web.cern.ch/pac2013/papers/wepsm01.pdf.

[3] S. Sasaki, A. Miyamoto, T. Mitsuyasu, N. Kawata, and S. Qiao, "Possibility for quasi-periodic knot-APPLE undulator", in *Proc. IPAC2014*, Dresden, Germany, 2014, doi:10.18429/JACoW-IPAC2014-WEPRO038.

[4] F. Ji *et al.*, "Design and performance of the APPLE-Knot undulator", in *Journal of Synchrotron Radiation*, vol. 22, 2015, doi:10.1107/S1600577515006062.

[5] F. Zhang, Z. Sun, Y. Qiao S. Qiao, "Practical design and performance of a new merged APPLE-Knot undulator", in *Journal of Synchrotron Radiation*, vol. 27, 2020, doi:10.1107/S1600577520011753.

[6] S. C. Richter *et al.*, "First magnetic experience with APPLE X knot undulators for SLS2.0", in *Proc. IPAC2025*, Taipei, Taiwan, Jun. 2025, pp. 1315-1318, doi:10.18429/JACoW-IPAC2025-TUPM068.

[7] X. Liang *et al.*, "Analysis of the first magnetic results of the PSI APPLE X undulators in elliptical polarisation", in *Nucl. Instrum. Methods Phys. Res. A*, vol. 987, 2021, doi:0.1016/j.nima.2020.164741.

[8] O. Chubar, P. Elleaume, J. Chavanne "A 3D Magnetostatics Computer Code for Insertion devices", in *Journal of Synchrotron Radiation*, vol. 5, 1998, doi:10.1107/S0909049597013502.

[9] T. Tanaka, "Major upgrade of the synchrotron radiation calculation code SPECTRA", in *Journal of Synchrotron Radiation*, vol. 28, 2021, doi:10.1107/S1600577521004100.