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UNDULATORS FOR BESSY III

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Abstract

HZB is in the process of developing a concept for a successor to the BESSY II synchrotron facility. The new facility will build on the strengths developed in Berlin over the last forty years in delivering flexibly polarised soft X-rays to dozens of beamlines. The successor facility BESSY III is planned to operate at 2.5 GeV, in comparison to the 1.7 GeV operation of BESSY II. This makes it easier to achieve the goal of delivering 1 keV photons to beamlines on the first harmonic of APPLE II Insertion Devices. It also makes it easier to achieve the aspiration of delivering tender X-rays up to 10 keV more routinely to users utilising in-vacuum APPLE II devices, Cryogenic Permanent Magnet Undulators (CPMUs) or Cryogenic APPLE devices. However, it also presents challenges in delivering the low energy photons below 10 eV, as period lengths of the relevant undulators must be increased, which in turn increases on-axis power. APPLE-KNOT designs are being pursued to overcome this issue.

The undulator group will also be planning Double Period Undulators (DoPUs) to offer beamlines broad spectrum coverage from 100 eV to 10 keV on the 1st and 3rd harmonics.

This paper outlines the first choices of undulators to be available to the successor facility BESSY III.

BACKGROUND

BESSY III intends to build on the successes of BESSY II as a facility offering low to medium energy (5 eV to 20 keV) undulator beamlines. The proposed increase in electron energy from 1.7 GeV to 2.5 GeV has a significant impact on the undulator choice required to deliver the desired photon spectrum. The current proposals for the storage ring can be found in the preliminary conceptual design report [1], which provides for 13 straight sections for insertion devices. The straight parameters are listed in Table 1.

Table 1: Straight Parameters

Parameter	Value
Straight Length	5.6 m
Electron Energy	2.5 GeV
Emittance	100 pm rad
$\beta_{x,y}$	3m, 3m
Momentum Compaction Factor	1.0 x 10^{-4}

UNDULATOR OPTIONS

The wide range of energy requirements and the desire for polarised photons at ever higher energies, requires a range of insertion devices to be examined. Two primary families of undulator will be considered: hybrid magnet arrays for beamlines where polarisation control is not required, and APPLE type devices where polarisation control is required (Fig. 1).

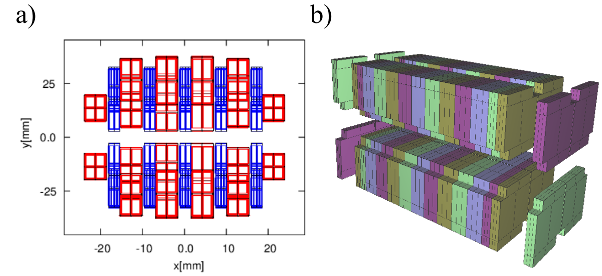

Figure 1: a) Hybrid undulator with permanent magnets (red) providing the flux, and iron poles (blue) focussing the field. Modelled with UNDUMAG [2]. b) APPLE II undulator; a pure permanent magnet undulator with upper and lower rows split. Adjacent magnet arrays can be phased with respect to each other to provide variably polarised photons. Modelled with RADIA [3].

Very Low Energy Beamlines

The lowest energy undulator beamline proposed for BESSY III expects to operate in the region of 5 – 200 eV, with full polarisation control. This requires a device with a K-Parameter of approximately 14. At a minimum gap of 13 mm, this requires a device with a long period length of approximately 125 mm. The total power output of such a high-K device amounts to 9 kW, with an on-axis power density of 6.5 kW.mrad^{-2}. In order to reduce the on-axis power output of this device, an APPLE-KNOT [4] design is being pursued.

Investigations into how to achieve a reduction of on-axis power load, whilst maintaining photon flux through a central aperture for BESSY III are in their infancy. A 120 mm period device is being studied to determine the best manner in which to apply the KNOT field to an APPLE-II device. The goal of the KNOT field is to push the electron trajectory ever so slightly off-axis, such that photon emission occurs when the electrons carry some vertical momentum [4].

The device was modelled using RADIA [2]. The KNOT field has been generated by an additional set of arrays placed outside of the usual APPLE II structure (Fig. 2).

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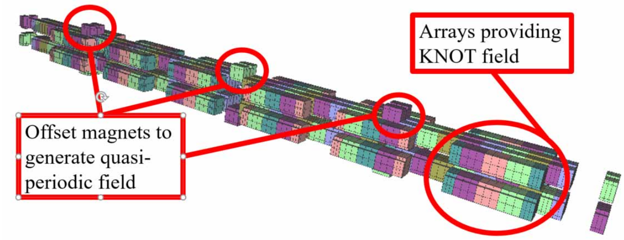

Figure 2: A RADIA [2] model of a quasi-periodic APPLE-KNOT undulator.

As in [4], the sense of these KNOT arrays have been rotated 90 degrees along the axis, to increase the horizontal field strength on axis. Similarly, the width of the main APPLE II magnets have been reduced so that the main APPLE II magnet cross section is only 20 mm across, and 30 mm deep. Early results indicate that an order of magnitude reduction of power is achievable on axis in the horizontal mode, and a factor of three in vertical mode, while maintaining the flux through the central aperture (Fig. 3).

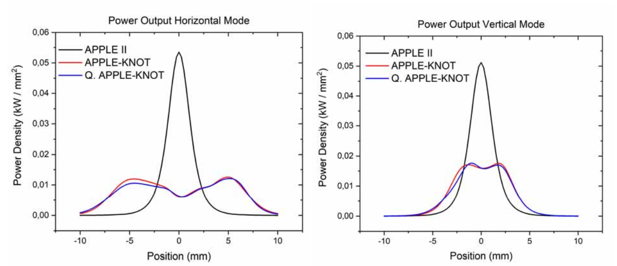

Figure 3: Comparison of power output between a conventional APPLE II device, and both normal and quasiperiodic APPLE-KNOT devices, in horizontal and vertical polarisation modes.

Photons at such low energies will be monochromated using a plane grating monochromator (PGM), which is unable to filter out contaminating higher harmonics. It has been briefly investigated if the implementation of a quasi-periodic structure is compatible with the KNOT field. The results indicate that the quasi-periodic structure does not interfere significantly with the on-axis power reduction, and does achieve the aim of pushing higher harmonics away from integer multiples of the fundamental. There is a reduction in flux of approximately 15% on the first harmonic, although this reduction may be a tolerable price to pay to eliminate higher harmonic contamination (Fig. 4). As can be seen in Fig. 5, the APPLE-KNOT has already eliminated the higher harmonics in the vertical mode, such that the quasi-periodic structure has no significant effect.

The reduction in the breadth of the APPLE II magnets in the APPLE II array of the APPLE-KNOT has led to a corresponding reduction in the peak field in the vertical mode. This will be addressed in the next steps in the design of the APPLE-KNOT undulator, where the magnets of the inner APPLE II array and the outer KNOT array are combined in the manner described in [4], whilst retaining the on-axis power reduction, and the efficacy of the quasi-periodic implementation of the APPLE II array.

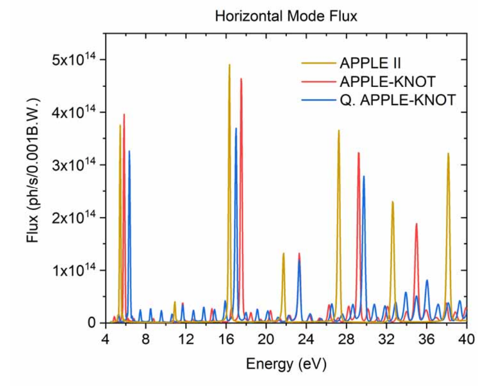

Figure 5: Flux through a 3 mm x 3 mm aperture at 10 m from the source, with a 300 mA electron beam. Devices in horizontal mode.

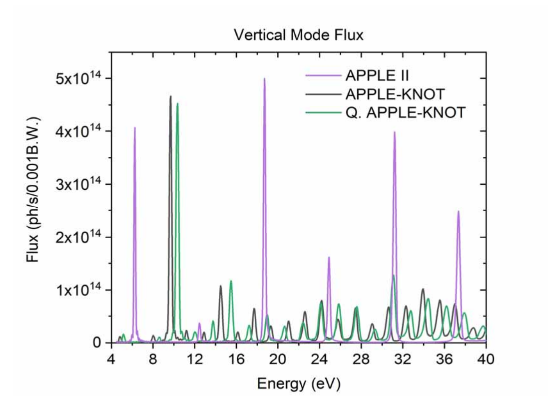

Figure 6: Flux through a 3 mm x 3 mm aperture at 10 m from the source, with a 300mA electron beam. Devices in vertical mode.

Low Energy Beamlines

APPLE II devices have been in operation at BESSY II for many years, and there is no intention of radically moving away from a technology that is well suited to supplying fully variable polarisation of photons in the energy ranges of 20 eV to 3 keV as the facility becomes succeeded by BESSY III. However, the improvement in injection schemes anticipated for BESSY III should allow for a reduction size of the required good field region of the undulators, resulting in a smaller magnet cross section being required in the undulators, and a lower volume of permanent magnet material needed. APPLE II devices continue to be developed and built by the undulator group at HZB, as exemplified by the UE51 device currently being assembled. The expertise in this area acts as the foundation for the development of the other devices described in this paper. APPLE II undulators will cover the energy range of 20 eV to 3 keV with period lengths from 56 mm to 80 mm.

Medium Energy Beamlines

The number of beamlines requesting polarisation control of photons at energies out of reach of conventional APPLE II devices is increasing. The standard offering for these beamlines at BESSY III will be the in-vacuum APPLE II, the first prototype of which is under development at HZB.

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The force compensation technique established in [5] will be exploited to enable operational gaps of 6 mm, enabling coverage from 100 eV to 8 keV on the first three odd harmonics, with undulator period lengths of 24-42 mm.

Individual component testing of keepers and columns has been completed. The latest version of the keeper has been subjected to a life-cycle test in a pressing jig, to demonstrate its ability to hold the magnets without perceptible magnet slip. The magnets are installed in the keeper, and subjected to a force of ±200 N. After an initial settling of 8 µm, the magnet remains in position to within 2 µm after 500,000 cycles (Fig. 7).

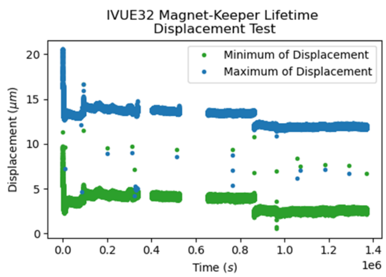

Figure 7: Results of Magnet-Keeper Displacement Test.

The columns have undergone deformation tests to verify the finite element analysis showing the bending of the components due the changing magnet forces during row shift operation is acceptably small. These results provide confidence going forward into the construction of an in-air prototype of the magnet arrays to be completed before the end of 2023.

Work is also ongoing to determine tolerances on the shielding foil that protects the magnets from damaging wakefield heating. It is mechanically challenging to bring a long foil over the shifting APPLE arrays, and it is currently proposed to shield each magnet array individually. This creates a longitudinal gap along the centre of the foil, and simulations have shown the importance of ensuring that the foils completely cover the magnets, and that the gap in the centre is as straight as possible [6].

Tender Energy Beamlines

Tender energy beamline requirements will be met with CPMU and Cryogenic APPLE devices. The CPMU technology is mature, as witnessed by the successful operation of the CPMU17 installed in BESSY II since 2018 [7]. The energy range to be covered by CPMUs at BESSY III will extend to 20 keV, with period lengths of 18 mm and 21 mm.

A cryogenic version of the in-vacuum APPLE II is also being developed at HZB that will be available to beamlines seeking polarisation control at tender X-Ray photon energies. An initial magnetic concept has been developed [8], and work has started on the mechanical design. The first components, the magnet keepers, have been designed (Fig. 8). Finite element analysis has shown the anticipated deflection during phasing motion to be in single micron figures. Design work for the Cryo-APPLE has now progressed to the cold magnet girder, which will be cooled using a liquid nitrogen delivered through a central bore.

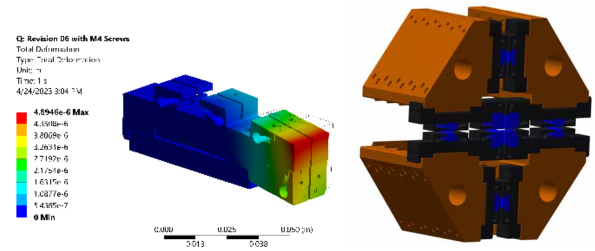

Figure 8: Left - Finite element analysis of primary keeper of the cryogenic APPLE under 100 N of vertical force. Right – Assembly of primary and secondary keepers on cold magnet girders, in a force compensation arrangement.

Broad Spectrum Beamlines

Some beamlines at BESSY III will be designed to offer a very broad spectrum, from a few eV, to 10s of keV. Such an offering is beyond a single magnetic structure to provide, so two options will be pursued, depending on if low and high energy photons are required simultaneously.

For the simultaneous case, two undulators will be installed in a single straight, much like the current installation of the EMIL straight at BESSY II [9], which contains a UE48 and a CPMU17. The proposed period lengths for this straight in BESSY III is a UE80, and a CPMU21.

The second approach that will be pursued is the construction of a double period undulator, in which two adjacent full length magnet arrays will be constructed such that each array can be shifted into the primary position [10].

This device is intended to be a double period in vacuum APPLE device of period lengths 42 mm and 24 mm.

CONCLUSION

A tentative ensemble of undulators has been suggested for the BESSY III facility. Using a range of technologies from room temperature out-of-vacuum devices to in-vacuum cryogenic helical devices, a spectral range of 5 eV to 20 keV is will be covered, as seen in Fig. 9.

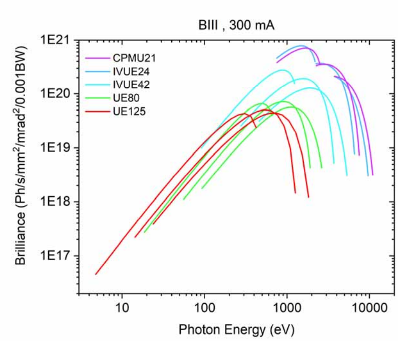

Figure 9: Brilliance Curves of representative undulators proposed for BESSY III.

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REFERENCES

[1] O. Schwarzkopf *et al.*, "Materials Discovery at BESSY", *Eur. Phys. J. Plus*, vol. 138, p. 348, Apr. 2023. doi:10.1140/epjp/s13360-023-03957-8

[2] M. Scheer, "UNDUMAG - A New Computer Code to Calculate the Magnetic Properties of Undulators", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3071-3073. doi:10.18429/JACoW-IPAC2017-WEPIK062

[3] O. Chubar *et al.*, "A three-dimensional magnetostatics computer code for insertion devices", *J Synchrotron Radiat.*, vol. 5, pt. 3, pp. 481-484, May 1998. doi:10.1107/S0909049597013502

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

[5] J. Bahrdt *et al.*, "In-Vacuum APPLE II Undulator", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4114-4116. doi:10.18429/JACoW-IPAC2018-THPMF031

[6] P. Volz *et al.,* "Loss Simulations on Shielding Foil Slit Errors", presented at IPAC'23, Venice, Italy, May 2023, paper WEPL160, this conference.

[7] J. Bahrdt *et al.*, "Characterization and Implementation of the Cryogenic Permanent Magnet Undulator CPMU17 at Bessy II", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1415-1418. doi:10.18429/JACoW-IPAC2019-TUPGW014

[8] E. C. M. Rial *et al.*, "Development of a cryogenic APPLE CPMUE15 at BESSY II", *J. Phys.: Conf. Ser.*, vol. 2380, p. 012018, 2022. doi: 10.1088/1742-6596/2380/1/012018

[9] S. Hendel *et al.*, "The EMIL project at BESSY II: Beamline design and performance", *AIP Conf. Proc.*, vol. 1741, no. 1, p. 030038, Jul. 2016. doi:10.1063/1.4952861

[10] A. Meseck *et al.*, "Triple Period Undulator", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1728-1731. doi:10.18429/JACoW-IPAC2019-TUPRB022