ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF031

IN-VACUUM APPLE II UNDULATOR

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Abstract

APPLE II undulators are widely used in many synchrotron radiation facilities for the generation of arbitrarily polarized light, because they provide the highest magnet fields among all planar variably polarizing permanent magnet undulators (PMUs). So far, in-vacuum permanent magnet undulators (IVUs) have a fixed polarization, either planar or elliptical / helical. A variably polarizing in-vacuum undulator was never built due to the engineering challenges. We present the design of a new in-vacuum APPLE II, which will extend the photon energy range to tender X-rays in the 1.7 GeV storage ring BESSY II.

INTRODUCTION

BESSY II has a long tradition in the production and optimization of variably polarized light. Due to the low electron energy of 1.7 GeV the transition metals can be covered only with the 3rd undulator harmonic and the rare earth M-edges only with the 5th harmonic, sacrificing flux and degree of circularly polarized light. Pushing to shorter period lengths an R & D project for the development of all key components of an in-vacuum APPLE II has been launched in 2017. Based on the results of this project a full-scale in-vacuum APPLE II (IVUE) will be built. The device is dedicated to three ambitious experiments, two RIXS beamlines and one microscopy beamline. The RIXS beamlines will profit from the vertically linear polarized light from 250-1000 eV, whereas the microscopy beamline utilizes all polarization modes within 250-2000 eV.

With a magnetic length of 2.5 m, the minimum gap in a low beta section at BESSY II is 7 mm. The period length is 32 mm.

DESIGN CONSIDERATIONS

The challenges of an in-vacuum APPLE II are:

- Motors, encoders, gearboxes, screws
- Longitudinal bearing
- RF-Shielding foil and flexible taper
- UHV-compatible magnet assembling

In this paper will we address three of these key issues. The UHV-compatible magnet assembly will be subject of a forthcoming paper. The first HZB in-vacuum APPLE II will be operated at room temperature. Similar to the planar cryogenic undulators (CPMUs) a cryogenically cooled IVUE (CPMUE) will follow in a second step, once the IVUE is operational. Already now, the demands and constraints of a future cryogenic option are included wherever possible.

Several options of a longitudinal bearing were evaluated: 1) in analogy to the stiff needle bearings of conventional APPLE II devices, one may decide for ceramic needle bearings, which are commercially available. However, the lifetime is shorter, and a safe operation of the pre-stressed bearings at cryogenic temperature or at bake-out temperature for a room temperature device is doubtful. 2) Flexible joints made of thin metal sheets (e.g. wire cut from a solid bloc) permit a smooth longitudinal movement of the magnet rows in combination with a high transverse stiffness, counteracting the transverse magnetic forces (Fig. 1). The flexible joints of two neighbouring magnet rows are mounted onto a stiff in-vacuum girder, which is supported by only two columns (similar to the BESSY W/U [1]). The complete aligned unit of two magnet rows and one stiff girder is measured and tuned magnetically prior to installation into the vacuum chamber. In both cases, compact in-air phase drives are located at the upstream and downstream ends of the vacuum chamber. The coupling must be compatible with the gap motion; iii) in this design the longitudinal bearings are located outside of the vacuum tank (Fig. 2). Eventually, we decided for the 3rd option because it does not require the development of the ambitious flexible joints.

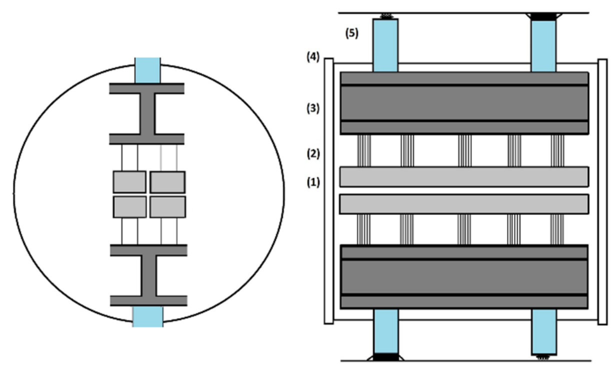

Figure 1: In-vacuum APPLE II design with flexible joints for longitudinal guiding during magnet row phasing.

MECHANICAL DESIGN

Two stiff in-air girders are coupled to a vertical support structure carrying the gap motors, gearboxes and bearings. The girders and the support are made from cast iron. A bionic optimization minimizes the overall weight. The phase drives are placed inside the in-air girders (Fig. 3). Thick columns support the in-vacuum magnet rows. The bellows will be designed to be compatible with the required longitudinal movement of ±8mm (or ±16mm). The projected device will not be operated in the universal mode [2], which does not provide big advantages at short wavelength [3]. The inclined mode requires a phase range of ±16mm, whereas the elliptical mode needs a range of ±8mm only, if all four rows are moved. Besides the inclined operation, the larger phase range bears the option

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of two fixed and two movable rows, which provides an advantage for the liner design (see section RF-shielding).

All longitudinal slides of one magnet row are rigidly coupled. Similar to planar devices a cryogenic design employs relative movements during cool-down (different thermal expansion coefficients). Pneumatic brakes may be utilized for opening and closing the connections between the individual slides.

The column number is minimized with a horizontally and vertically staggered arrangement, similar to the SwissFEL U15 IVU [4]. This includes a sinusoidal vertical variation of the gap centre, which is much less critical than a gap variation. The staggered design has two advantages: i) the risk of vacuum leaks shrinks with the number of bellows; ii) in a cryogenic in-vacuum APPLE II the number of heat leaks is reduced.

In contrast to IVUs considerable three-dimensional forces must be regarded. A thick column diameter in combination with a stiff support and drive structure can cope with these forces, whereas cryogenic considerations demand hollow columns with a high area momentum of inertia. The design employs a smart three-dimensional force compensation [5], which permits a further reduction of the effective column cross section.

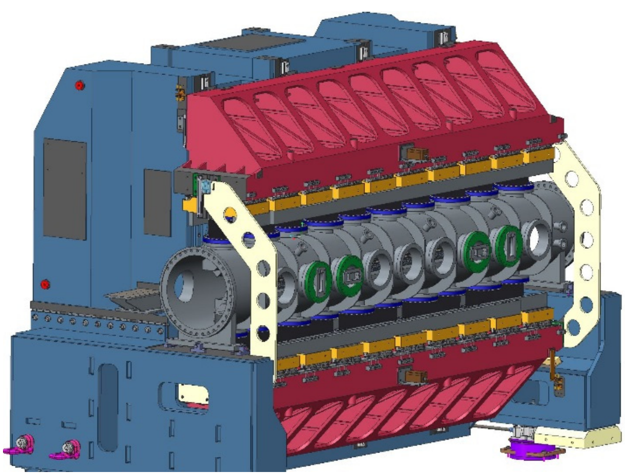

Figure 2: In-vacuum APPLE II design with motors, gearboxes, bearings in air.

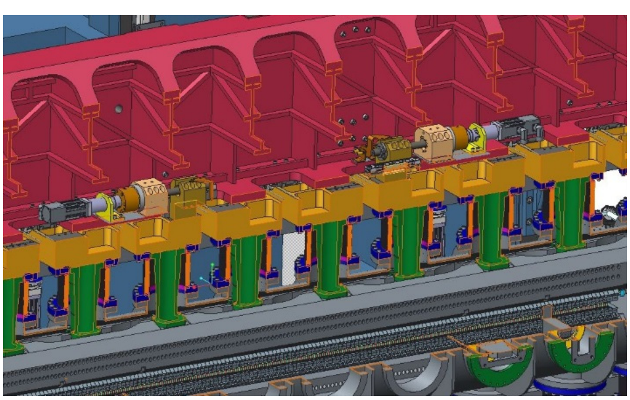

Figure 3: The phase motion units are located inside the in-air girders.

The direct gap and phase measurement relies on optical micrometers similar to the design of the HZB CPMU17 [6]. The units operate in air (mounted into the green flanges in Fig. 2), which simplifies the replacement in case of failure. The reading error is dominated by the optical quality of the windows. A typical non-linear error of $\leqslant 20\mu m$ can compensated with feed forward tables because the reproducibility is accurate to $\pm 1\mu m$. For redundancy, conventional absolute gap encoders (C-structures in Fig. 2) and absolute phase encoders (inside the in-air girders) are foreseen.

ASSEMBLY, ALIGNMENT AND MAGNETIC MEASUREMENT

The magnetic field quality relies on the mechanical precision of the critical components. The HZB CPMU17 demonstrated a high fabrication accuracy, where the gap variation between the assembled column pairs (without the magnet girders) was smaller than 20 µm. Nevertheless, phase tuning is necessary. For IVUs and CPMUs it is accomplished with an adaption of the individual column lengths which support the magnet girders. The vertical adjustment of the IVUE structures follows the same strategy. The horizontal alignment of the magnet rows is more delicate. New strategies are under investigation, particularly, because the transverse position of the columns may change during vertical adjustment.

Only recently, two new magnetic field measurement systems for in-vacuum applications were commissioned at the HZB. An in-vacuum Hall probe bench [7] and a moving wire system [8] were successfully operated for the magnetic characterization and tuning of the first HZB CPMU. The upgrade of these tools to a measurement length of 3 m is straightforward.

RF-SHIELDING

In planar IVUs and CPMUs the magnet structure is shielded with a 100 µm CuNi foil, which is not applicable here, because the magnet rows move longitudinally. Two separate foils on two adjacent rows may be possible, but the impact of the longitudinal slit including the geometric tolerances on the beam dynamics can hardly be simulated. Furthermore, the coupling of the flexible tapers is challenging. Alternatively, a fixed liner which is coupled via metal bellows to the support and drive system is attractive. An alignment from outside of the chamber, and the adaption of the liner to the taper section at the undulator ends is simple. The disadvantage is the loss in flexibility. At HZB the low alpha mode [9] implies the modification of the magnet lattice from alternating low and high beta to high beta sections only. A fixed liner would shrink the physical aperture and thus the injection efficiency and lifetime in this mode.

A split liner, which follows the vertical movement of the magnets, is adopted instead. Two half pipes are placed on the upper and lower magnet rows respectively. Half of the half Cu-liner is covered with Ni, which fixes the part over

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the fixed magnet row. The other half consisting only of copper is supported form the side. The fixture (Fig. 4 and Fig. 5) is attached to the fixed row. If needed, the liner can be aligned by means of piezo crawlers, which can easily be implemented. The distance between this half of the liner and the magnets is 100 µm. Maybe, this side of the liner must be cooled explicitly, because it does not have contact to the magnets. This can be accomplished with an additional cooling from the side (e.g. water).

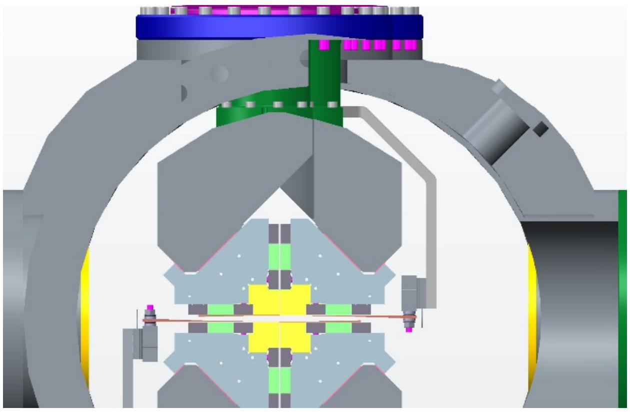

Figure 4: RF-shielding via a split liner. Over the fixed magnet row the liner is attracted magnetically. Over the movable row the liner is supported from the side (for details see text).

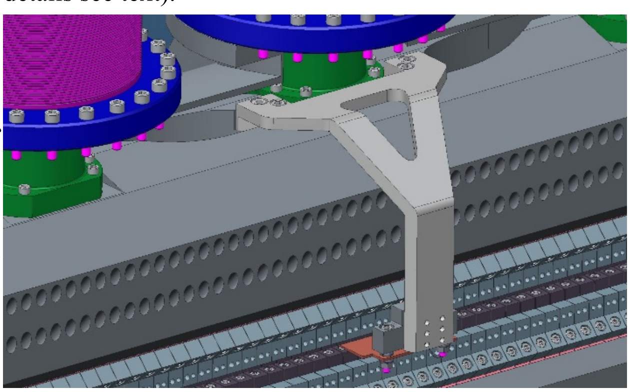

Figure 5: Support of the liner. If necessary, a fine positioning via piezo crawlers can easily be implemented.

The cross section of the liner halves is optimized for stability and sufficient thermal conductivity of the free-standing part. The inner / outer surfaces are elliptically / flat, respectively, having a thickness of 0.1 mm at the centre.

The flexible tapers have to cope only with the gap movement. Thus, a conventional IVU-taper design can be used. A specific three-dimensional link between the elliptical liner and the flat flexible tapers is foreseen.

OUTLOOK

Based on the experience with the first IVUE, an optimization of the complete system will follow. Particularly, the force compensation will help to reduce the total weight of the device.

In a next step a cryogenic design will follow. Most components can be transferred to the CPMUE. Open tasks are: i) cryogenic design with respect to minimum heat leaks ; ii) optimization of the magnet assembling strategy, which is compatible with low temperatures.

The HZB device will keep a planar APPLE II magnet structure, which is dedicated to a storage ring operation. On the other hand, the same concept can be used as well for next generation light sources like DLSR, FELs and ERLs. In these cases advanced magnet designs with higher magnetic fields can be implemented, such as APPLE III [10], DELTA [11], DELTA II [H.-D. Nuhn, private communication, 2017], APPLE X [12].

It is worth mentioning, that the presented design is an option also for in-air variably polarizing undulators. The support of the magnet rows at several points offers the chance to add slides for a transverse movement of the individual rows, enabling a transverse gradient undulator (TGU) operation [12]. Here, the column length is reduced to a minimum. In contrast to the APPLE X the magnet rows would move horizontally or vertically, where the vertical motion of neighbouring rows is coupled. An appropriate name resembling the motion geometry would be APPLE+. Particularly the force compensation may be very attractive for a simplification of the whole support structure.

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