Variable period undulator with tunable polarization

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Introduction

The magnet structure of undulators is generally built as a periodic structure which creates a sinusoidal field with a fixed period length λ_u. Depending on the technology, the wavelength λ_R of the emitted synchrotron radiation can then be tuned by varying the field amplitude B_0 by either changing the current through the coils of an electromagnetic or superconducting undulator, or by changing the magnetic gap, i.e. the distance between upper and lower magnet girder of permanent magnet undulators. Likewise, the field amplitude can be changed by a longitudinal shift of top versus bottom magnet girder along the beam axis so that their fields partly compensate each other. Such a scheme had been introduced as an adjustable phase undulator (APU) [1] already in the early days of undulators and is used nowadays in DELTA [2] and APPLE [3,4] undulators. As the field amplitude is proportional to the undulator K-parameter via $K = B_0 \lambda_u e/(2\pi m_e c^2)$, this changes the emitted wavelength according to the well-known resonance equation $\lambda_R=\lambda_u/2\gamma^2(1+K^2/2)$, γ being the electron beam energy in units of rest masses. The strong decrease of the field amplitude towards shorter wavelengths is, however, also connected with a substantial decrease of the radiation intensity once K becomes smaller than 1. Therefore, an undulator can usually only be optimized for a particular wavelength. Tuning the radiation wavelength by changing the electron energy would allow to keep the K-parameter at a constantly high value, but is not feasible at a multi-user storage ring facility and is not regarded as useful even for free-electron lasers (FELs) due to various implications on the accelerator setup. Finally, a change of the undulator period length is a good mean to tune the emission spectrum because the K-parameter remains at higher values for a given tuning range compared to a tuning by changing the field amplitude. This will result in a better performance, both in terms of brightness and wavelength tuning range.

Permanent magnet undulators are usually made of brick-shaped magnet blocks organized as a Halbach structure. In a hybrid configuration, the vertically magnetized magnet blocks are replaced by high-permeability poles to concentrate and transfer magnetic flux from outlying parts of the permanent magnets towards the beam axis. There have been only a small number of proposed concepts for variable period undulators (VPU) in the past which might be related to the strong demands on mechanical and magnetic precision which is usually required in undulator design in order to reach the calculated performance with a real device. A development of a variable period undulator for a storage ring application was pursued at Argonne National Laboratory [5]. The design was based on an earlier undulator concept where a staggered arrangement of poles is excited by a strong solenoidal field which transforms to a periodically oscillating field on-axis. In the suggested design, the longitudinal positioning of the staggered poles was made adjustable by a mechanical drive mechanism. Previously, an alternative permanent magnet concept was proposed by Budker institute [6] that uses half-period units with variable spacing in between. Moreover, a full scale helical variable period undulator was designed and built for a THz-FEL application [7]. This scheme consists of half-period slices of two interleaved crossed-undulators. The mechanical design of the two latter concepts is based on the repulsive forces of the individual magnet structure slices. Another concept of a variable period helical undulator uses an adjustment of the magnetic field direction by rotating each undulator half period as a whole around the beam axis [8].

We present a new scheme which is based on an arrangement of cylindrical permanent magnets with diametral magnetization direction which are actively adjusted by motorized rotation to shape the magnetic field profile at will. This design goes beyond a variable period scheme as it provides full control not only on the period length λ_u but also on field amplitude B_0 and the phase φ of the sinusoidal field $B(x) = B_0 \sin(2\pi x/\lambda_u + \varphi)$. A magnet structure based on cylindrical magnets had also been built previously as a modulator or phase shifter between two undulators [9]. Our concept was initiated by a related development where we integrated cylindrical magnets, acting as a local phase shifter, into the center of a 2m long permanent magnet hybrid undulator installed at the 6GeV storage ring PETRA III at DESY [10]. The following sections discuss the concept and various operating modes, and also describe extended applications for generation of arbitrary fields or multipole lenses.

Concept

A simultaneous rotation of top and bottom magnets into the same direction by the same amount changes the magnetic field amplitude on-axis, exactly like for APU or DELTA undulators. The same rotation in opposite direction changes the phase, or longitudinally shifts the field. Changing the angle increment $\Delta\alpha$ between two neighbored magnets results in a change of the period length: Fig. 1 shows three different cases, left) $\Delta\alpha = \pi/8$, i.e. the period length is 8 times the magnet size, and $\varphi = \pi/4$ (symmetric); Fig. 1 center) corresponds to $\Delta\alpha = \pi/4$, a Halbach structure with a period length of 4 times the magnet size, and all the magnets rotated by $\pi/4$ to shift the phase φ by $\pi/8$; and Fig. 1 right) with $\Delta\alpha = 3\pi/4$ and $\varphi = 0$ (antisymmetric), providing an even shorter period length.

All three adjustments of amplitude, period and phase are more or less orthogonal to each other. So for example at some particular period length and amplitude setting, a rotation of all the magnets by the same angle would change only the phase. There is a slight amplitude modulation during the phase adjustment due to the discreteness of the magnet blocks. Also, a change of the period length affects the amplitude, especially at minimum period settings when the field amplitude is also somewhat decreased. When looking carefully, a very weak higher field harmonic is visible in Fig. 1. This is caused by the condition that the permanent magnets are not infinitesimal point dipole sources but have a finite size. The periodicity of this higher order field component roughly corresponds to the magnet diameter and does change only slightly with the main period length, and there is only negligible impact on the spectral characteristics.

The maximum period length can be set as large as the full length of the magnet structure to have a device with only a single period. It could even be turned into a dipole magnet by aligning all the magnets vertically. Except for special applications, the practical minimum period length is given by twice the magnet diameter, equivalent to a vertical alignment of all magnets with an opposite magnetization orientation of neighbored magnets. Then, the number of periods corresponds to half of the number of magnets in one array. Beyond that, the period length will decrease much slower with change of the angular orientation and the magnetic field will decay to zero once the period length reaches the limit of one magnet diameter.

Tuning the wavelength towards higher photon energy by shortening the undulator period length, is much more efficient in terms of brightness and flux of the undulator than decreasing the field amplitude in case of variable gap undulators (Fig. 2). The period length of a variable gap undulator can be optimized at some particular photon energy for a given minimum gap and electron energy. However, optimization for maximum brightness at high photon energy makes it impossible to reach the low photon energies and could even result in a limited tunability (i.e. energy gaps in between harmonics) for very short period undulators. On the other hand, a large period undulator with a high K-value, in order to reach lower photon energies, will have a poor performance when it is tuned to higher energy by opening the gap (e.g. the red curve U90 in Fig. 2). The dashed line shows the maximum possible flux performance of a virtual PPM undulator with an optimized period length for each fundamental energy, i.e. it is an envelope of all the fixed-period undulators at minimum gap. The tuning curve of the proposed variable period undulator (green) shows exactly the behavior of this envelope curve, but less bright due to the smaller magnet cross-section and hence lower overall magnetic field amplitude. The tuning towards higher photon energies is connected to a constantly increasing number of periods of the VPU. In comparison to a PPM undulator with a particular period length, it provides a higher average flux in a wider energy range.

Features

Compared to usual planar insertion devices (ID) with a fixed period length, the proposed magnetic structure does not limit the minimum wavelength because the period length can be set to any value as large as the ID length. In transverse direction, the only limitation is the vacuum chamber size defined by the required beam stay-clear. This allows one to have a single magnet structure with a tunable wavelength from THz to hard X-ray for a machine with a beam energy of a few GeV.

As each magnet is adjustable, this gives the opportunity to change the magnetic field at each "pole" independently and create a magnetic field profile with arbitrary shape. Equivalent to a gap tapering of a planar ID for broadening the spectral width, it is possible with this structure to change the period length and/or field amplitude along the structure and thus the K-value, and not necessarily linearly. Period length or field amplitude could also be changed locally at any arbitrary position in order to form a quasiperiodic undulator that suppresses or shifts higher harmonics. For the same purpose, a few of the magnets could be used to form an embedded phase shifter in the center of the undulator [10].

In the canted sections of storage rings, two IDs share the same straight section with a small dipole magnet in between for angular separation of the generated light. With a VPU a few poles can be used to form an embedded dipole magnet, while the longitudinal position along the insertion device remains variable. This provides a flexibility to change the ratio of undulator segment lengths and thus the intensity dedicated to each beamline.

Or in FELs, two halves of a VPU can be tuned to different wavelengths with a phase shifter as a delay line in between to enable pump probe experiments or different schemes for harmonic lasing [11], all with the same magnet structure. In the SASE process, both saturation length and pulse energy depend in a different way on the undulator period length and the K-parameter, e.g. according to M. Xie [12]. Increase of the photon energy without reduction of the field amplitude results in higher pulse energy and shallower slope of the saturation length curve and thus a wider photon energy range before the saturation length reaches the total length of the undulator. A variable period undulator covers a wavelength range that otherwise would require several magnet structures with different period lengths (e.g. revolver undulator) or an adjustment of the electron beam energy, which is an additional constraint when several beamlines share the same accelerator. This gain in performance is illustrated in Fig. 3 which shows saturation length (top) and pulse energy (bottom) for the FLASH II FEL at DESY. An ordinary undulator operated at different machine energies is compared to a planar and a helical version of VPU.

Furthermore, when the magnet structure is set to a large period length (few times higher than single magnet size), it is possible to change the shape of the magnetic field to strengthen lower harmonics. As an example, a square-shaped field profile will have a higher effective field amplitude than a sinusoidal, and could have a slightly higher intensity of the main harmonic at the same wavelength.

Finally, an adjustable phase φ of the magnetic field allows not only for a planar but also a helical undulator with tunable polarization to be implemented when the cylindrical magnets are split like in an APPLE undulator (Fig. 4b). VPUs show a brightness comparable to usual variable gap planar and helical IDs, and also have a higher wavelength tuning range, especially towards lower photon energies.

Horizontal fields

Storage rings usually have a non-circular beam aperture in the ID straight sections due to the flat beam. Variable period magnet structures can therefore only be planar with magnets above and below the vacuum chamber. In such a case, also the APPLE-II scheme can be implemented (Fig. 4b): The magnet structure is split along the beam axis in two parts that can be adjusted independently in order to generate horizontal fields. As is known, the horizontal field is created by sacrificing the vertical component.

However, for linear accelerators and diffraction-limited storage rings with a circular beam aperture it is possible to place four magnets around the vacuum chamber, creating a variable period equivalent of a DELTA undulator (Fig. 4a). In this case the horizontal and vertical fields are absolutely independent from each other and will add up. The field amplitude is $\sqrt{2}$ higher for both, linear diagonal and helical mode. This results in slight brightness increase in diagonal mode and up to a factor of 2 higher brightness in circular polarization mode (Fig. 2).

As for any other permanent magnet undulator, the field quality of a VPU sensitively depends on magnetic and mechanical errors in the magnet structure and effective means to correct for these errors. In case of VPU scheme as in Fig. 4a), are two magnet pairs create the vertical and horizontal fields independently. Then, vertical field errors of the “vertical” magnets could be corrected just by adding a small correction value to the rotation angle that defines the required magnetic field amplitude at this location. Horizontal field errors of the “vertical” magnets (e.g. due to errors in magnetization direction or mechanical alignment) could be corrected by setting an appropriate rotation angle of the flanking “horizontal” magnets, and vice versa. Having measured the field signatures of each magnet vs. angle, a 2x2 matrix could be constructed at each pole, that converts the desired horizontal and vertical field amplitudes to rotation angles of the related magnets and thereby corrects for the field errors.

Multipole fields

When each "pole" consists of four magnets as in Fig. 4a), aligning them opposite to each other allows creation of a quadrupole field. So, quadrupole lenses could be embedded anywhere in the insertion device as well. With 10mm aperture and 10mm magnet diameter, a maximum field gradient of up to 90T/m can be reached. As each of the four magnets can be rotated independently, the transverse position of the quadrupole magnetic center could also be adjusted.

The variable period analog of an APPLE-II structure (Fig. 4b) can also be shaped to create a strong quadrupole with high gradients of up to 90T/m. Due to the absence of horizontal/vertical symmetry it could, however, contain higher angular multipole harmonics for increasing radius which could be detrimental for the operation of storage rings.

If each of four magnets is divided into halves that could be rotated independently, a variable period equivalent of two crossed APPLE-II structures, e.g. “APPLE-IV” (Fig. 4c-e) is formed. This allows creation of higher multipoles up to an octupole inclusive adjustment of roll angle for sextupole and quadrupole components.

Conclusion

We have proposed a new type of a variable period undulator which is based on rotatable cylindrical magnets that can be individually controlled. A universal flexible magnet structure can thus be formed and adapted during operation which is well suited for application of various completely different FEL lasing schemes developed over time.

A mechanical design of such a magnet structure requires a detailed assessment of magnetic and mechanical tolerances. Since the size of the cylindrical magnets in the proposed undulator scheme is intrinsically small, the magnetic forces remain moderate. Despite a much larger effort for the control system, this may allow for a simple and cost-efficient mechanical support structure. Encouraged by positive experience with the integration of rotatable cylindrical magnets into a hybrid permanent magnet structure of a storage ring undulator, we have started work on mechanical studies of such a device. Fig. 5 illustrates a possible mechanical design which shall then lead to a short prototype as a next step.

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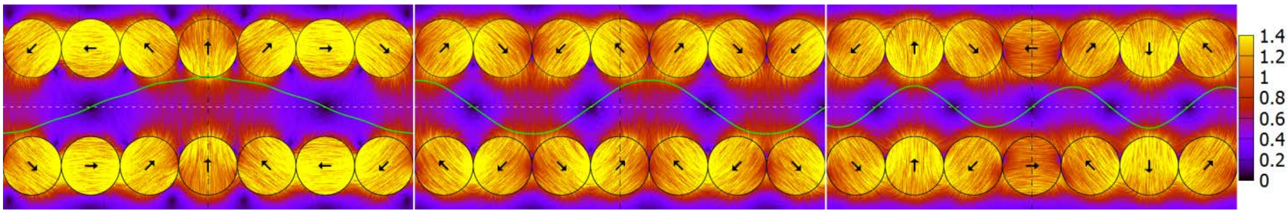

Figure 1: Magnet structures with variable period length, different field amplitude, or phase (π/4, π/8, 0) can be obtained by particular angular settings of all magnets. Arrows show the magnetization direction of each cylindrical magnet, the colors indicate the magnetic field magnitude |B| in [T], and the resulting sinusoidal vertical field on-axis is shown in green.

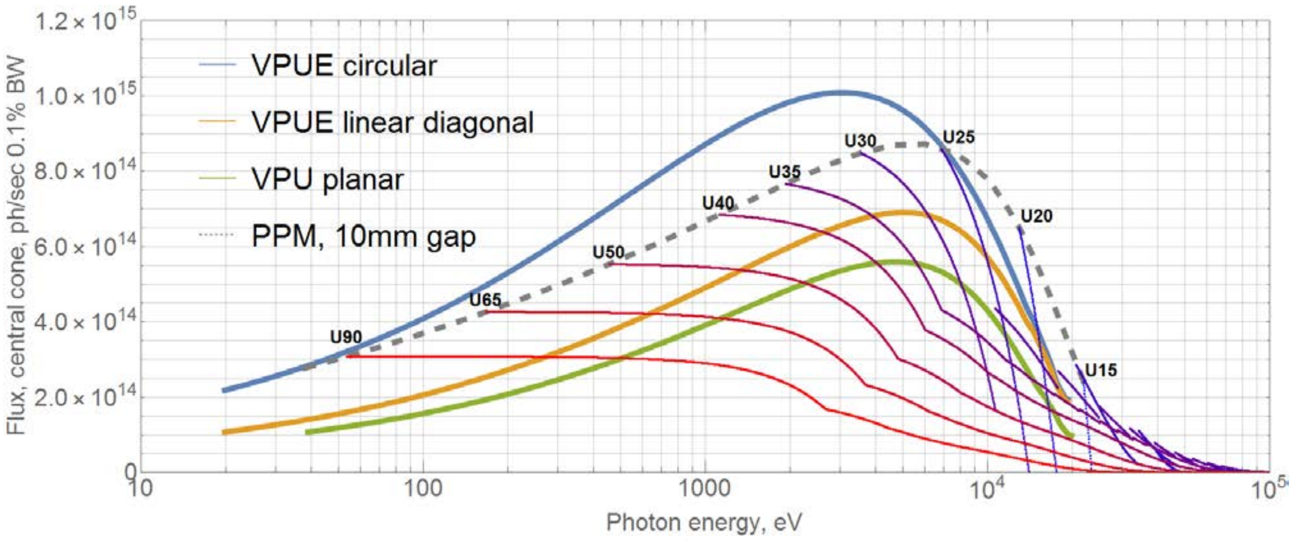

Figure 2: Central cone flux at 6 GeV electron energy for the 1st harmonic of different variable period undulators (magnet size 10mm x ∅10mm) in comparison to a series of planar PPM-Halbach undulators with different period length (magnet size 50mm x 50mm x $\lambda_u/4$), all with same length and minimum gap of 10 mm. The envelope (dashed-grey) corresponds to a virtual Halbach structure with continuously optimized period length; see text for details. Compared to a planar VPU (green), helical VPUE configurations (blue, orange) provide higher fields ($B_0\sqrt{2}$) and flux.

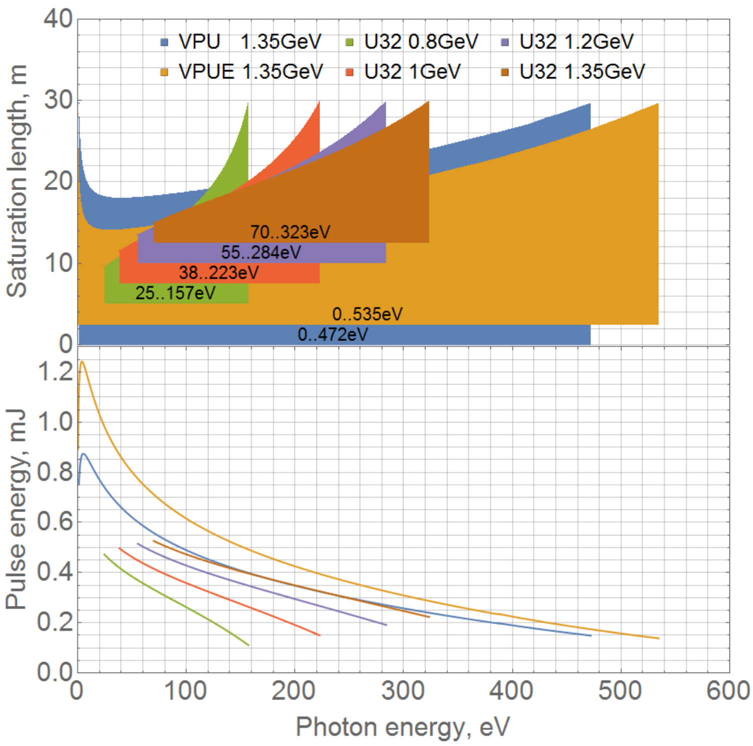

Figure 3: Saturation length and pulse energy of a planar hybrid undulator at FLASH II (31.4mm, 30m) for different electron energies in comparison to a planar and helical variable period undulator. For the variable gap undulator, the photon energy range is limited by minimum gap (maximum K) from bottom and by total the undulator length from top, when saturation length becomes larger. The variable period undulator is not limited by maximum K from bottom, and the less steep saturation curve reaches the total undulator length at higher photon energies.

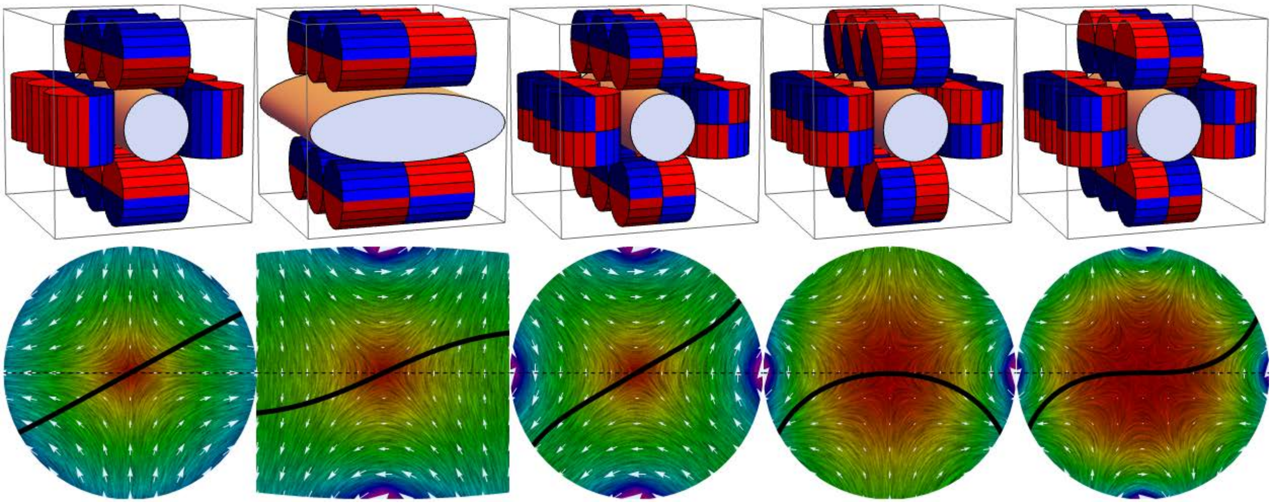

Figure 4: DELTA (a) and APPLE-II (b) configurations of variable period undulators with magnets aligned as skew and normal quadrupoles with up to 90T/m gradient. An "APPLE-IV" structure with magnets aligned to a 90T/m quadrupole (c), an $8kT/m^2$ sextupole (d), and a $3MT/m^3$ octupole (e) lens. Bottom plots show a field map in the transverse plane, black curves represent the transverse dependence of the magnetic field amplitude.

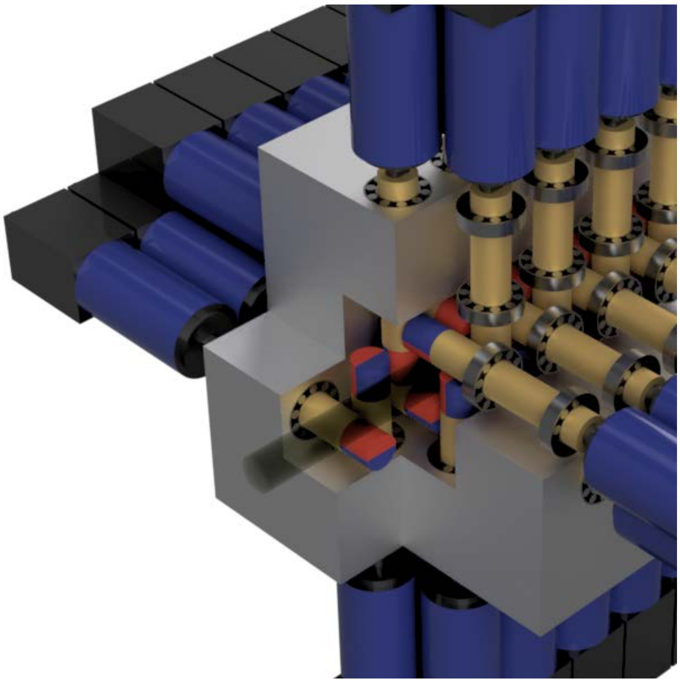

Figure 5: Model of a possible support structure for a variable period undulator (partly cut-out for better visibility) in an arrangement like Fig. 4a). Magnets around the vacuum chamber (semitransparent in the center) are fixed at the ends of a rotating axis which is guided by bearings and driven by a stepper motor with a planetary gearbox.