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Abstract. The proposed magnetic structure allows to control all the parameters of the sinusoidal magnetic field $B(s)=B_0 \cdot \sin(2\pi s/\lambda_U+\phi)$ of permanent magnet undulator: amplitude B_0, period length λ_U, and phase ϕ. The magnetic structure consists of diametrically magnetized cylindrical magnets at fixed positions. The field is adjusted by motorized rotation of each magnet. Tuning of radiated wavelength by changing the period length instead of field amplitude is more effective and results in a wider wavelength range and higher photon flux, especially for free electron lasers. Individual adjustment of the magnets allows for creating arbitrary shaped magnetic field and also for embedding other elements like phase shifters, dipoles, or multipole lenses into the undulator magnetic structure.

INTRODUCTION

Permanent magnet undulators are usually built from cubic magnetic blocks organized in a Halbach structure, or with additional high permeability poles to concentrate the magnetic flux and to increase the field amplitude by 10-20% at the same undulator period length and gap. In order to adjust radiation wavelength $\lambda_R = \lambda_U(1+K^2/2)/(2\gamma^2)$, where $K = B_0\lambda_U \cdot e/(2\pi m_e c^2)$, there are three options: changing the electron energy or γ, the magnetic field amplitude B_0, and undulator period length λ_U.

Changing electron energy is not an option for storage ring synchrotron light sources where lots of different beamlines share the same accelerator. The magnetic field amplitude could be reduced by moving the magnets away from the beam (variable gap undulator) which is used by most of the undulators, or by longitudinal shift of the magnetic structures, top versus bottom (adjustable phase undulator, APU) [1]. To change light polarization a horizontal magnetic field could be added either by making two crossed APU, called DELTA [2], or by two crossed planar variable gap undulators that could also be shifted longitudinally (APPLE-X) [3], or by dividing magnetic structures along the beam and shift them longitudinally to change vertical field to horizontal (APPLE-II) [4, 5].

However, changing the wavelength by reducing magnetic field amplitude results in a small wavelength tuning range. At a given electron energy, in order to reach longer wavelength, an undulator with large period length and K-parameter is required (Fig. 1, curve U90). But when it is tuned towards higher photon energy by reducing the magnetic field amplitude, the photon flux is very low, because the magnetic field should be reduced much more to reach the short wavelength with a large undulator period. Also number of periods is smaller than for a structure which has been optimized for the shorter wavelength. Alternatively, the undulator period could be optimized to have a maximum output at shorter wavelength (Fig. 1 curve U25), but then it is impossible to reach longer wavelengths, and there could be even gaps between harmonics towards shorter wavelength. When the K-parameter is too low, the intensity of the one harmonic could go to zero before the next harmonic starts. An ideal undulator would be a device that always has maximum field amplitude, but changes the period length to adjust the wavelength (i.e. the dashed envelope curve on Fig. 1). It would have maximum possible photon flux at any wavelength.

There have been a few concepts of the variable period undulator (VPU). At Argonne National Laboratory, the design was based on a solenoid with staggered arrangement of poles inside, which concentrate the longitudinal magnetic field and convert it to an oscillating vertical field [6]. At Budker Institute of Nuclear Physics, for a THz FEL there is a variable period undulator that consists of individual half-period magnetic blocks that could freely and independently slide along the beam [7]. This way the only position of last pole should be controlled, the repulsive magnetic forces would evenly distribute all the other magnets along the structure. There is a helical undulator at KAERI using the same principle with a two interleaved crossed undulators generating circularly polarized light [8].

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However, in these schemes, increasing the period length by inserting air gaps decreases the effective field for larger periods. As the number of periods is fixed, decreasing period length results in a shorter undulator generating less photons. Also, the light polarization of these devices is fixed. Another concept of a variable period helical undulator uses adjustment of magnetic field direction by rotating each slice around the beam [9]. That could smoothly adjust the period for circular polarization and change the polarization, but for a linear polarization would require an additional gap drive at each rotating slice, otherwise only switching of integer number of periods is possible.

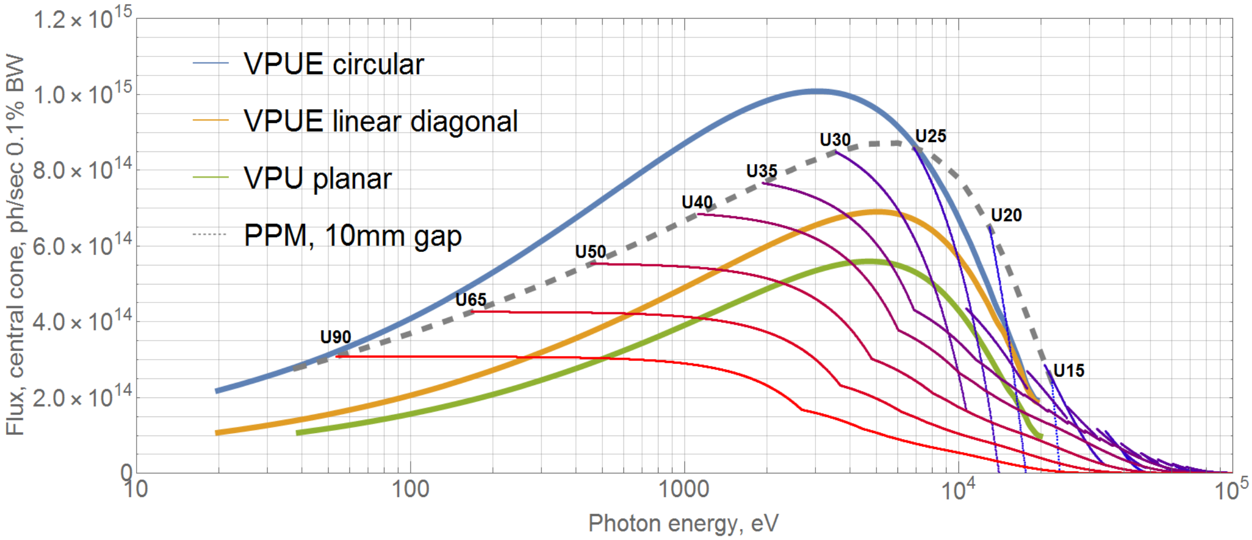


FIGURE 1. Central cone flux of PPM undulators with different period length (15 to 90 mm), compared to variable period undulators: planar (green) and helical (linear diagonal - orange, circular - blue). Same undulator length, same gap

CONCEPT

The proposed magnetic structure consists of cylindrical magnets with diametrical magnetization. Gap and position of the magnets are fixed but the field of each magnet is adjusted by rotating the magnets (Fig. 2). Individual adjustment of each magnet allows for creating an arbitrary shaped magnetic field, and in particular to create a Halbach structure with all parameters of the sinusoidal magnetic field $B(s) = B_0 \cdot \sin(2\pi s/\lambda_U + \phi)$ freely adjustable: amplitude B_0, period λ_U, and phase ϕ (longitudinal shift). Adjusting the angular difference between two neighbored magnets changes the period. In Fig. 2 the undulator period is steadily decreased along the structure. Rotation of all the magnets by the same angle changes the field amplitude, like in an APU. And rotating top and bottom magnets in the opposite direction adjusts the longitudinal shift of the field, to tune the light polarization in a helical device.

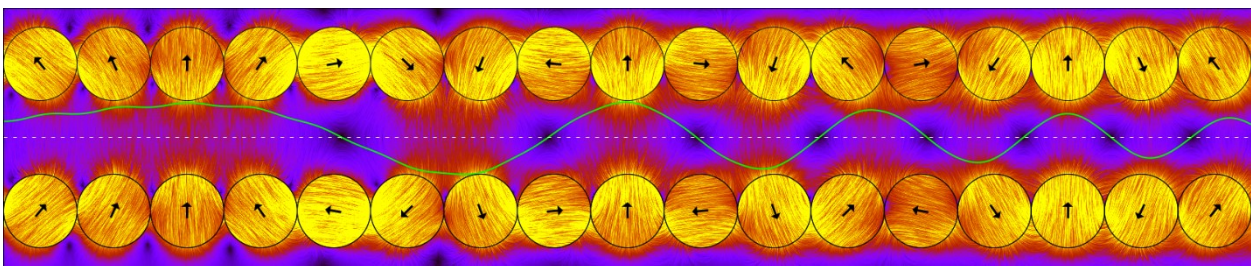


FIGURE 2. Variable period undulator magnetic structure. The green line indicates vertical magnetic field amplitude on-axis.

Spontaneous radiation

The resulting tuning curve of flux vs photon energy for the proposed variable period undulator (Fig. 1, green) shows the same behavior as an envelope curve of the PPM undulators with maximum magnetic field and different periods (Fig. 1, dashed), however the flux is slightly lower because of much smaller magnets Ø10mm x 10mm of the VPU compared to 50mm x 50mm x λ_U/4 PPM magnets. Nevertheless, the average flux of the first harmonic, integrated over whole bandwidth is larger than that of any individual curve of the variable gap PPM undulators.

The field of the variable period undulator could be increased by adding more magnets. For a circular aperture two identical crossed structures could be placed around the beam (Fig. 5a). In this case, when horizontal and vertical fields are summed in the same phase, the field amplitude is increased by factor of √2 in diagonal mode (Fig. 1, orange curve). For non-circular beam apertures, the magnet length could be enlarged (Fig. 5b) resulting in a similar field increase and larger transverse good field region. Also, magnets could then be separated into two independent rows along the beam, thus creating a variable period analog to the APPLE-II structure. In case of circular polarization, all the radiated power is condensed to the first harmonic providing even more flux (Fig. 1, blue curve).

Self-Amplified Spontaneous Emission in Free Electron Lasers

For the SASE process in an FEL, radiated photon energy of variable gap undulators is limited from bottom by the maximum K-parameter at minimum gap and by the saturation length from top. When the undulator magnetic field is reduced, to tune it towards higher photon energy, the SASE saturation length also increases [10]. And when it becomes larger than the total undulator length (30m for FLASH2 FEL [11], Fig. 3 top), the pulse energy would be below the saturation and decrease immediately with further increase of photon energy. The minimum photon energy could be additionally reduced by lowering the electron energy, but it also decreases the output pulse energy (Fig. 3 bottom), and, much worse, a variable electron energy severely complicates the optimization of accelerator operation parameters and creates additional constraints when several undulator beamlines share the accelerator.

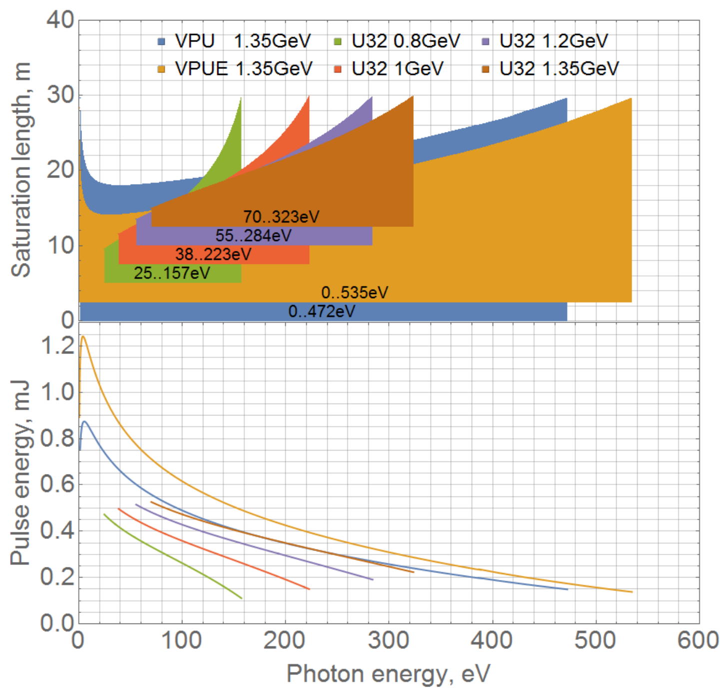


FIGURE 3. SASE Saturation length and photon energy range (top), and corresponding FEL pulse energy (bottom) for a variable gap undulator with 32mm period length at different electron energies, compared to a VPU, planar - blue, helical - orange.

The wavelength range of the proposed VPU is larger compared to conventional variable gap undulators. For a VPU structure, the photon energy is not limited from bottom, as the undulator period could be set to any large value. The only limitation is the electron beam excursion and vacuum chamber size. Even THz radiation for pump-probe experiments could be obtained with the same structure. At such low photon energy the electrons would lase without SASE, just because total electron bunch length is shorter than the emitted wavelength. When tuning the VPU to higher photon energies by reducing the period length, the number of periods is also increasing. This makes the saturation curve slope shallower and thus saturation can be reached at higher photon energy when using a VPU with the same undulator length. For long SASE FELs with a VPU structure even higher photon energies can be achieved, that would otherwise require a variable gap undulator with several different magnetic structures (e.g. revolver undulator) to cover such energy range.

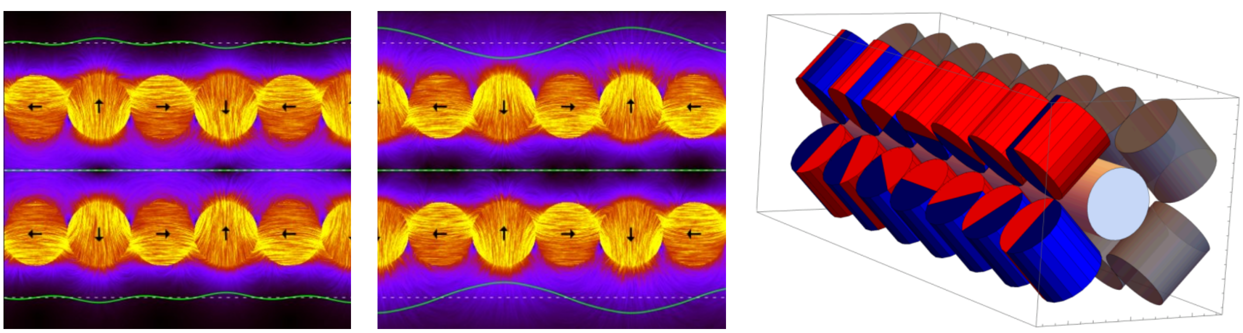
FEATURES

Phase Shifter

As each magnet of the VPU structure is rotated independently, the magnetic field can be adjusted at any position along the undulator. For example, the field could be changed locally to add a phase shift in the center of the undulator. Depending on the phase shift between two interfering halves of the undulator, the photon energy of different harmonics could be shifted with respect to their nominal position. For higher harmonics, the phase shift is multiplied by the harmonic number. So it is possible to find a phase shift where a particular harmonic shifted in one direction, while some others are shifted to the opposite direction (with a phase shift larger than π). Thus, particular higher harmonics can be additionally suppressed [12]. Such approach could also be used in a FEL for various harmonic lasing schemes [13].

Transverse Gradient Undulator

Adjustable Phase or DELTA undulators can set the field amplitude to zero by adjusting top and bottom structures opposite to each other (Fig. 4a), which works, however, only on-axis due to the antisymmetry. Longitudinal fields and also off-axis fields remain that could also create undesired transverse gradients of the K-parameter. With the adjustment of each cylindrical magnet independently in the VPU structure it is possible to turn the Halbach structure inside-out. This would zero not only on-axis fields, but also off-axis fields in the gap (Fig. 4b). By disabling individual rows of the VPU it could be turned it into transverse gradient undulator (Fig. 4c) with adjustable relative K-parameter gradient dK/K/dx up to 200m^{-1}. The “disabled” right half of the structure could even be tuned opposite to the left transverse gradient structure and increase the gradient, but by reducing the field amplitude on-axis. A transverse field gradient could be used for compensation of electron energy spread [14], to suppress the microbunching instability [15], or to increase the bandwidth of a FEL pulse [3, 16].



(a) (b) (c)

FIGURE 4. (a) Halbach structure undulator aligned to cancel the field on-axis, APU or DELTA. (b) VPU setting with a Halbach structure inside-out: creating fields outside and eliminating inside the gap. (c) VPU as a transverse gradient undulator.

Multipoles

For a helical VPU all four magnets could be set opposite to each other, thus forming a quadrupole lens with a gradient of up to 90T/m (Fig. 5a). A variable period APPLE-II structure with noncircular beam aperture can create a quadrupole field as well (Fig. 5b). But due to lack of horizontal/vertical symmetry, it could also have some other multipole harmonics, which could be crucial for operation of storage rings. Further, with two crossed APPLE-II structures (Fig. 5c-e) it is possible to create higher multipoles, a sextupole up to 8kT/m^2 and an octupole up to 2MT/m^3. Then the quadrupole and sextupole could also be rotated by an arbitrary angle (Fig. 4c - normal quadrupole, Fig. 4a - skew quadrupole). However, 8 motors to drive such a magnet arrangement would be difficult to accommodate mechanically. But it is possible to use a 4 magnet arrangement like in Fig. 4a, but separate magnet halves longitudinally (Fig. 4f) by mounting different halves of the magnets at different longitudinal positions. As the required amplitude of higher multipoles usually is not large, introducing just several divided magnets along the structure would only slightly affect the effective field amplitude, but allow also for correction of higher multipoles.

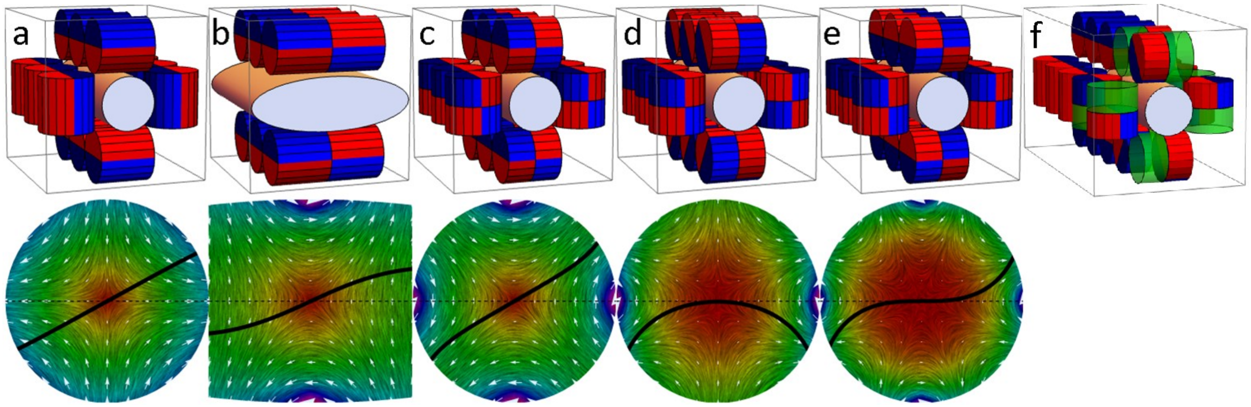


FIGURE 5. VPU magnet structure configured as multipole lenses (top) and corresponding field profile in the aperture (bottom): a - skew quadrupole, b - APPLE-II quadrupole, c - quadrupole, d - sextupole, e - octupole, f - longitudinal separation of the magnet halves.

TECHNICAL DETAILS

Mechanics

A magnet structure based on rotating diametrically magnetized cylindrical magnets was built previously as a phase shifter between two undulators [17]. The proposed concept of a VPU was initiated by a related development of a phase shifter embedded in the center of a 2m variable gap permanent magnet hybrid undulator installed at storage ring PETRA III at DESY [12]. This phase shifter is made like a very short 3-pole VPU with rotating cylindrical magnets, which overlayed with the hybrid structure just below the permanent magnet blocks. Being far from the beam axis it only slightly corrects the main undulator field but still introduces a sizable adjustable phase shift. Despite this undulator beamline is still in the commissioning phase all results so far can be regarded as a successful proof of the applied mechanical concept.

With the staggered alignment of the magnets and motors it is possible to accommodate both horizontal and vertical magnet rows (Fig. 6a) around the vacuum chamber with the motors twice larger than the magnets, to provide sufficient torque. Since the size of the cylindrical magnets in the proposed undulator scheme is small, the magnetic forces remain moderate and may allow for a simple and cost-effective mechanical support structure. A maximum magnetic force of 35N and torque of 0.6Nm has been calculated for Ø10mm x 10mm magnets with 11mm pitch (i.e. 1mm longitudinal spacing) at 10mm vertical gap.

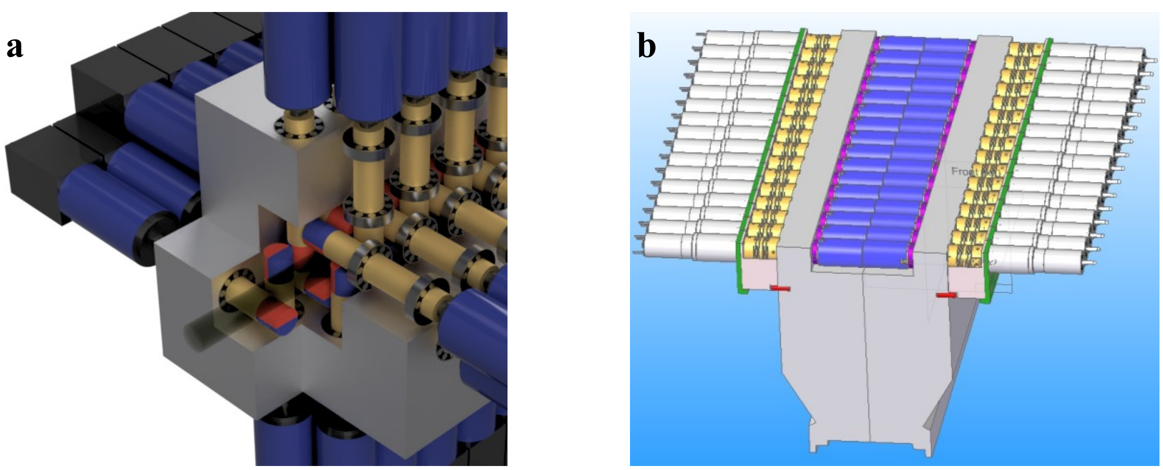


FIGURE 6. (a) Support structure model and magnet arrangement of a VPU. Magnets around the vacuum chamber (transparent in the center) are fixed at the ends of a rotating axes, which are guided by bearings and driven by a standard NEMA8 stepper motors with a planetary gearbox. (b) Model of bottom half of APPLE-II like VPU structure for noncircular beam aperture.

Magnetic errors

The main source of the dynamic magnetic field errors is the magnet positioning error caused by magnetic forces. In order to check influence of the magnet positioning error on the magnetic field, a 2m model of the variable period undulator was calculated with Radia [18]. Then every magnet was randomly rotated by ±0.5 degrees from its nominal position to simulate a backlash error of gearboxes. Such a dispositioning makes an additional phase error of less than 3 degrees rms. The trajectory distortion remains within the oscillation amplitude (Fig. 7).

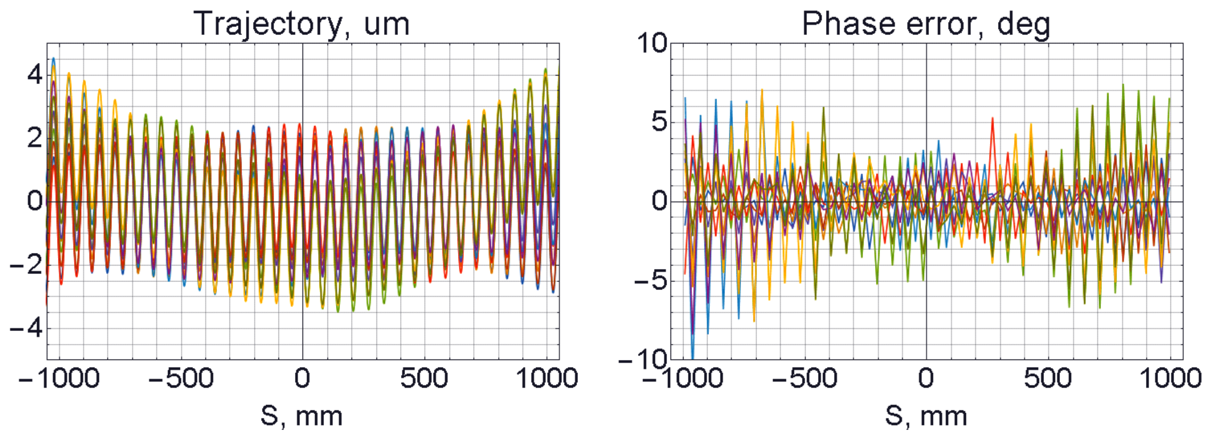


FIGURE 7. Trajectories (left) and phase errors (right) of the 2m VPU with magnets randomly rotated by ±0.5 degrees to simulate backlash error. The different curves show 10 different random error distributions.

However, the magnetic forces and torques are also periodic, as they originate from the periodic magnetic field of the undulator (Fig. 8). Thus, backlash error and magnet displacement due to bending of magnet support by magnetic forces are not random, but also periodic. Hence, exactly one half of the magnets would have a backlash error in one direction while the other half has it in opposite direction. This significantly reduces the influence of mechanical backlash on the field integrals and phase error.

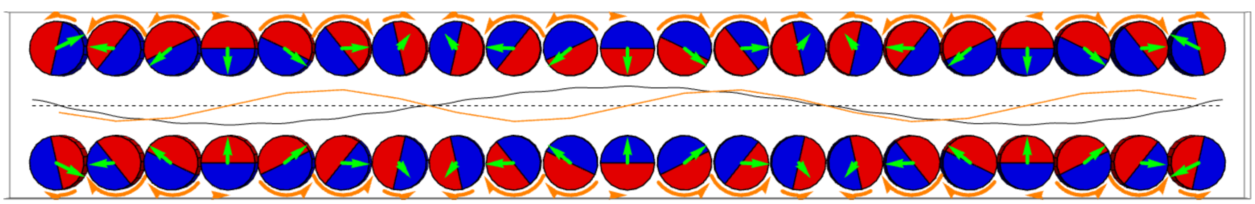


FIGURE 8. Magnetic field on-axis (black), magnetic forces (green) and torques (orange) acting on the individual top magnets.

Although a short VPU could rely only on the accuracy of the mechanics and still would have reasonable phase and trajectory errors, rotary encoders will be required for precise positioning of the magnets for longer undulators. As the encoder will be close to the electron beam it will accumulate significant amount of radiation dose, and therefore should not contain any semiconductor electronic parts for reliable operation. Such encoders could be implemented within the given space constraints using inductive rotary sensors [19]. Preliminary tests of such an encoder showed errors less than 0.1 degree.

There are also other magnetic errors of individual magnets like magnetization (amplitude and direction) or positioning errors. They are static and add a constant error or depend only on the rotation angle of the particular magnet, but not on the magnetic fields and positions of the neighbored magnets. These errors can be measured and then compensated by making a software correction to the angular position setting of each particular magnet. Some of these magnetic errors can also be compensated by virtual shimming, i.e. adjustment of magnet positions.

Reliable operation of such a huge amount of motion axes is also an issue. But in the same way like magnetic errors, the magnetic fields of a particular malfunctioning drive could be completely compensated by the neighboring magnets, which could be set to correct the undesired kick and provide a proper phase advance. That will increase the reliability of the VPU operation, though it complicates the control software.

CONCLUSION

The proposed magnetic structure based on rotating cylindrical magnets allows for creating software defined, arbitrary shaped magnetic fields. For the undulator sinusoidal field, the adjustment of the radiation wavelength by changing the undulator period length results in a wider wavelength range from THz to hard X-ray. Embedded multipole lenses and phase shifters integrated in the undulator field can reduce the length of intersections in FELs.

The same VPU structure can also be turned into: quasiperiodic undulator for a suppression of particular higher harmonics; figure-8 undulator to reduce heat load; transverse gradient undulator for compensation of electron energy spread or broadening of the spectrum.

Individual rotation of each cylindrical magnet can also be used to distinguish field changes from different magnets when using integral magnetic measurement methods, like stretched wire or coils. Thus, a longitudinal dependence of field integrals and phase error could be obtained using such a simple measurement methods. Only a software adjustment of the magnet's rotation angle is required in order to correct the measured field errors.

Encouraged by the positive experience with the integration of rotatable cylindrical magnet phase shifter into a hybrid undulator permanent magnet structure, we have started work on the short prototype of such a device.

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