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Magnet System Optimization for Segmented Adaptive-Gap In-Vacuum Undulator

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Abstract. Segmented Adaptive Gap in-vacuum Undulator (SAGU), in which different segments have different gaps and periods, promises a considerable spectral performance gain over a conventional undulator with uniform gap and period. According to calculations, this gain can be comparable to the gain achievable with a superior undulator technology (e.g. a room-temperature in-vacuum hybrid SAGU would perform as a cryo-cooled hybrid in-vacuum undulator with uniform gap and period). However, for reaching the high spectral performance, SAGU magnetic design has to include compensation of kicks experienced by the electron beam at segment junctions because of different deflection parameter values in the segments. We show that such compensation to large extent can be accomplished by using a passive correction, however, simple correction coils are nevertheless required as well to reach perfect compensation over a whole SAGU tuning range. Magnetic optimizations performed with Radia code, and the resulting undulator radiation spectra calculated using SRW code, demonstrating a possibility of nearly perfect correction, are presented.

INTRODUCTION

The role of in-vacuum undulator technology in the success of 3rd generation synchrotron radiation sources can be hardly denied, especially for medium-energy sources where this type of Insertion Devices (ID) allow for reaching very high radiation brightness and flux in the hard X-ray spectral range [1] - [3]. The search for the most appropriate in-vacuum undulator parameters for spectral requirements of any particular X-ray beamline represents a constrained optimization problem [4], as, on one hand, undulator radiation flux is proportional to the undulator length, while, on the other hand, undulator magnetic performance is limited by accelerator physics constraints. Often, an optimal undulator length, resulting from solving this problem, appears to be smaller than the maximal length of ID which can be installed in a given straight section, and the minimal gap is considerably larger than the minimal gap allowed to be used in the straight section center. Several concepts for better exploiting space available in straight sections without sacrificing magnetic performance and violating the accelerator physics constraints have been proposed. First, the Common Resonant Energy (CRE) undulator for Free Electron Lasers, an out of vacuum undulator with continuous tapering of the gap to meet the "stay-clear" constraint and variation of a "period" in one long undulator, has been proposed [5]. The CRE undulator requires a vacuum chamber with complex profile that matches the electron beam envelope and it assumes a continuously varying magnetic “period” length over entire undulator length, which represents practical inconveniences for the construction and tuning. An alternative concept, of the Segmented Adaptive Gap in-vacuum Undulator (SAGU), was recently proposed [6]-[7]. In the SAGU concept, the primary goal of using in-vacuum undulator segments is to have as small as possible (but uniform) magnetic gap in each individual segment, and the entire undulator structure as long as possible. As far as we accept different magnetic gaps in segments, and yet wish the resonant fundamental photon energy in all segments be the same, we have to accept having different period lengths in these segments to compensate for the variation of magnetic performance due to the use of different gaps. This concept is in principle applicable to all popular undulator magnet technologies, however, we decided first to try to demonstrate its feasibility for the room-temperature hybrid undulator technology.

ELECTRON TRAJECTORY STEERING BETWEEN SEGMENTS

The general logic and practical approach to optimizing SAGU parameters were described in [6] and [7]. In this work, we concentrate on solving magnetic problems taking place at segment junctions.

An electron travelling in an undulator field with a deflection parameter K experiences a horizontal oscillatory motion whose angular amplitude is K/γ. In a SAGU, where all segments have different deflection parameters to compensate for different gaps, the amplitude of the electron oscillatory motion in each segment is different and the electron beam experiences an angular kick at each junction between segments. Assuming that the magnetic field at the junction between segments i and i+1 is null, the kick $\Delta x'_{i\to i+1}$ between these segments can be approximately expressed as:

$$\Delta x'_{i\to i+1} = \left|K_{i+1} - K_i\right| / \gamma \tag{1}$$

The angular offset in segment *i,* $\Delta x_i^{'}$, is equal to the sum of all the kicks $\Delta x'_{j\to j+1}$ with j ranging from 1 to i-1. When the length of each segment i is exactly a multiple of the period λ_i, the field in each segment is antisymmetric and the angular offset in segment i is:

$$\Delta x'_i = \gamma^{-1}\sum_{j=1}^{i-1}(K_{j+1} - K_j) = (K_i - K_1)/\gamma \tag{2}$$

If, on the other hand, the length of each segment i is equal to an odd number of half-periods, the field in each segment is symmetric and the angular offset of electron trajectory in segment i becomes:

$$\Delta x'_i = \gamma^{-1}\sum_{j=1}^{i-1}(-1)^{j+1}(K_{j+1} - K_j) \tag{3}$$

One can readily see from Eq. (2) that in the case of antisymmetric field in segments the angular offset accumulates from segment to segment and can reach very large values, e.g. in the middle of SAGU (in the case of its symmetric location with respect to a straight section center) or at its exit (in the case of a canted SAGU located asymmetrically with respect to a straight section center and occupying only a part of the section). In the case of the symmetric field in segments on the other hand the sign of the angular kick changes at each segment (see Eq. (3)), and a resulting electron trajectory in SAGU doesn't deviate strongly from the central direction (the trajectory produces "zigzags" around this direction). In most cases, such trajectory "behavior" is advantageous compared to an accumulating angular offset taking place at antisymmetric fields in segments. However, despite of the self-healing property of SAGU made of symmetric segments, the kicks at interfaces between segments may appear significant, up to a few Gm (depending on segment length), and need to be corrected to avoid any detrimental effect on the spectral performance of SAGU.

NUMERICAL SIMULATIONS

SAGU Parameters and Magnetic Calculations without Kick Correction

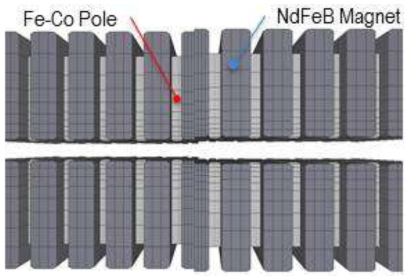
In order to accurately predict the kick angle of an electron in a realistic magnetic field generated by a room-temperature SAGU and to investigate different possible correction means, we built a magnetic model of a SAGU using Radia code [8]. The parameters of the room-temperature SAGU considered for these computations are summarized in Table 1. These parameters were optimized for the New-York Structural Biology Center protein crystallography beamline – NYX – to be located in a canted short straight section of NSLS-II. The proposed SAGU is composed out of three 0.69 m long segments, with the upstream edge of the first segment being located in the beginning and the downstream edge of the third segment in the middle of the straight section. The smallest gap among the three segments, ~3.55mm, is achieved in the third segment.

TABLE 1. SAGU parameters for NYX beamline to be located in a canted short straight section of NSLS-II.

Segment	Number of Periods	Min gap	Period	K_i max
3	36	3.55	18.24	2.205
2	33	4.705	20.18	2.048
1	29	6.3	22.42	1.887

The 3D rendering of a junction modelled with Radia is shown in Fig. 1(a). In our approach, each segment ends with a half-magnet (i.e. magnet with the longitudinal size equal to the half of longitudinal size of other magnets used in the segment). As one can see from Fig. 1(b) the kicks computed from Radia models are significantly smaller than the kicks predicted by Eq. (1), which is explained by magnetic interaction between segments edges, but still exceed 1 Gm. The kicks are almost constant over the main energy range covered by the SAGU and increase significantly at large fundamental energy values.

(a)



(b)

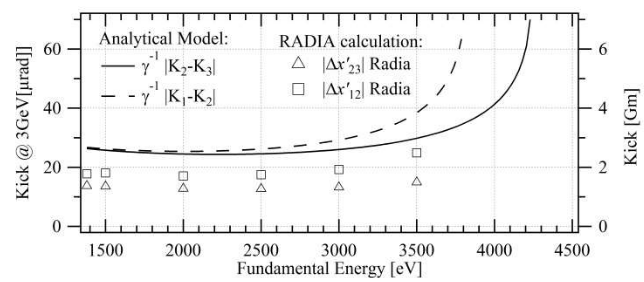
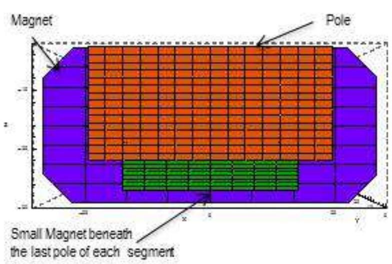


FIGURE 1. 3D rendering of a junction modelled with Radia (a) and kicks at the interfaces between different segments computed from Radia models (markers) and from Eq. (4) (lines) (b).

Magnetic Calculations and Optimization of Passive Kick Correction

Two simple means of correction were investigated. Out-of-vacuum coils located at junctions between segments is the most immediate and straightforward correction considered. However, the small variation of the kick with respect to the fundamental energy gave us the confidence that a passive correction can be also effective. The passive correction is achieved with small magnets placed beneath the last (and/or first) pole of each segment as shown in Fig. 2(a). The field integral achieved with such passive correction is compared (with opposite sign) to the kicks in Fig. 2(b). The height of the small magnets is optimized to provide the best correction over the full fundamental energy range covered by the SAGU.

(a)



(b)

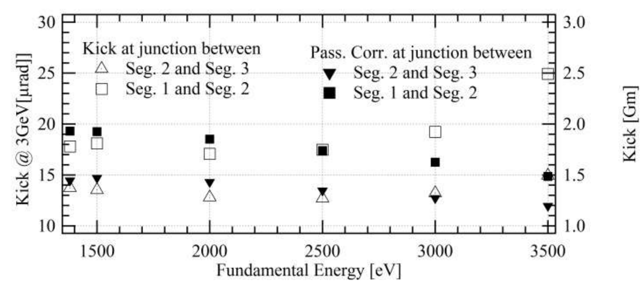
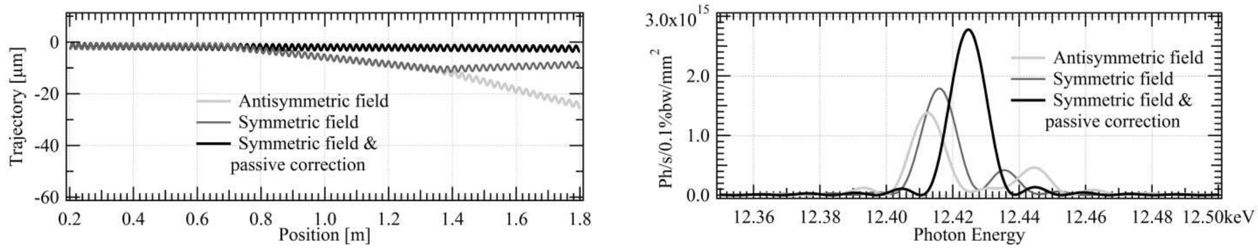


FIGURE 2. 3D rendering of the passive correction modelled with Radia (a) and kicks at the interfaces between different segments (hollow markers), together with the kicks created by the passive correction (filled markers) (b).

Spectral Calculations

To study the impact of the kicks and their corrections on spectral performance of the SAGU, we have performed a series of calculations of electron trajectories and on-axis single-electron synchrotron (undulator) radiation spectra using the magnetic fields computed with Radia. Figure 3 shows electron trajectories in the SAGU detailed in Table 1 and the results of the spectral calculations performed using SRW code [9]. Results of trajectory and spectral calculations confirm that the passive correction performed on the symmetric SAGU is very effective.



(a) (b)

FIGURE 3. Electron trajectories (a) and radiation spectra (b) at 5^{th} harmonic for a 0.5 A 3 GeV filament electron beam traveling in SAGU with antisymmetric and symmetric magnetic fields at minimum gaps in segments, without and with passive kick correction.

SUMMARY

Segmented adaptive-gap undulator with different period length in segments promises significant gain in spectral performance compared to a conventional in-vacuum undulator. Because of different deflection parameter value in segments, an electron experiences angular kicks at segment junctions as it travels throughout SAGU. We demonstrated that with proper selection of the field symmetry in segments, the impact of the kicks on the trajectory can be limited. Finally we demonstrated that a nearly-perfect passive correction can be implemented using small magnets beneath poles located near junctions between segments. A SAGU prototype is planned to be built at BNL.

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