SPECTRAL PERFORMANCE OF SEGMENTED ADAPTIVE-GAP IN-VACUUM UNDULATORS FOR STORAGE RINGS*

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Abstract

We propose an approach to the optimization of segmented in-vacuum undulators, in which different segments along an undulator may have different gaps and periods. This enables close matching between the gaps and the vertical "envelope" of electron beam motion in a storage ring straight section (carefully satisfying the associated vertical "stay clear" constraint) and, at the same time, precise tuning of all the segments to the same fundamental photon energy. Thanks to this, the vertical gaps in segments located closer to straight section center can be smaller than at extremities, and so the entire undulator structure can offer better magnetic performance than that of a conventional undulator with constant gap (and period) over its length. We present spectral flux and brightness calculation results for such segmented adaptive-gap undulators and demonstrate their gain in spectral performance over conventional undulators.

INTRODUCTION

The success of 3rd generation synchrotron radiation sources and their importance for modern science can be hardly overestimated. Thanks to small electron beam emittance and extensive use of undulators in numerous straight sections, these sources offer high brightness and flux of radiation in broad spectral range from infrared to very hard X-rays, and can accommodate large number of beamlines and experiments which can run simultaneously.

While formally, longer undulators can provide higher radiation spectral flux, in practice, magnetic performance of very long undulators may be limited by restriction for using small enough magnetic gap in these IDs, because this may violate electron beam "stay-clear" constraint and may result in reduction of the electron beam dynamical aperture and lifetime. The "stay-clear" constraint follows the electron beam motion envelope, therefore, the smallest magnetic gap value can be used in a short-length ID located at electron beam waist at a straight section center. This stimulated the development and use of short-length and period mini-gap in-vacuum undulators at a 2nd generation storage ring source [1]. Thanks to these pioneering works and subsequent large-scale efforts made in 3rd generation sources [2], [3] over the last ~15 years, the technology of in-vacuum undulators became very reliable and mature. For medium-energy 3rd generation synchrotron sources, the use of in-vacuum undulators is particularly important, because it allows for reaching very high radiation brightness and flux in the hard X-ray spectral range [4] - [6].

Since, on one hand, undulator radiation flux is proportional to the undulator length, and, on the other hand, undulator magnetic performance is limited by accelerator physics constraints, the search for the most appropriate in-vacuum undulator parameters for spectral requirements of any particular X-ray beamline represents a constrained optimization problem [7]. 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. These observations motivated us to explore possibilities for better exploiting space available in straight sections without sacrificing magnetic performance and violating the accelerator physics constraints. One such possibility, namely, a concept of segmented Adaptive Gap Undulator (AGU) with different period lengths in segments, is described in this paper. In this concept, the primary goal of using segments is to make magnetic gap in each part of undulator as small as possible, and the entire 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 variation of magnetic performance due to the use of different gaps). A similar idea of an 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 in [8]. As different from this work, in our paper, we emphasize the use of the segmented approach, with individual segments being conventional short undulators. From our point of view, this makes practical realization of this concept much more feasible.

DETERMINING PARAMETERS OF SEGMENTED AGU

Let us assume that the constraint on minimal magnetic gap in an insertion device as function of longitudinal position in a straight section of a storage ring is known and is described by $g(s)$. This constraint may be a sum of several different constraints, including the electron beam "stay-clear", impedance, heat load and possibly other constraints. E.g. the electron beam "stay-clear" constraint in the vertical plane can be expressed as a function proportional to vertical size of electron beam at a given longitudinal position s:

$$g(s) = N_{\sigma}\sqrt{(s^2 + \beta_{y0}^2)\varepsilon_y / \beta_{y0}}\,, \qquad (1)$$

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where β_{y0} is the vertical beta-function value at the electron beam waist, corresponding to the longitudinal position $s = 0$, ε_y is the vertical electron beam emittance, N_σ is the ratio between the allowable insertion device gap (or inner size of the vacuum chamber) and the vertical RMS size of electron beam. At NSLS-II, with $\varepsilon_y \approx 8$ pm, $\beta_{y0} \approx 1.06$ m in the Low- and $\beta_{y0} \approx 3.4$ m in High-Beta straight section, the vertical "stay-clear" constraint is defined by Eq. (1) with $N_\sigma \approx 1000$.

Consider then an insertion device consisting out of N adjacent to each other segments with longitudinal coordinates of edges: $s_0 < s_1 < \ldots < s_N$ and gaps g_i (constant within each segment) satisfying the constraint:

$$g_i \geq \max\left[g(s_{i-1}), g(s_i)\right], \; i = 1, 2, \ldots, N \qquad (2)$$

In order for all these segments to work as one undulator, the fundamental photon energy E_1 of undulator radiation in these segments should be the same:

$$E_1 = \frac{2hc\gamma^2}{(1 + K_i^2/2)\lambda_{ui}}, \qquad (3)$$

where h is the Plank's constant, c is the speed of light, γ is the reduced electron energy, λ_{ui} the magnetic period and K_i the effective deflection parameter in i-th segment.

Definition of the periods $\{\lambda_{ui}\}$ in the AGU segments can be done as far as magnetic performance, expressed e.g. as dependence of the deflection parameter, or directly the fundamental photon energy, on undulator gap and period $E_1 = E_1(g, \lambda_u)$ is known, e.g. from magnetic calculations [9]. This relation can then be "inverted" numerically, using interpolation, allowing one to determine the set of periods $\{\lambda_{ui}\}$ for a given set of gaps $\{g_i\}$ (resulting from Eq. (2)) as functions of the fundamental photon energy.

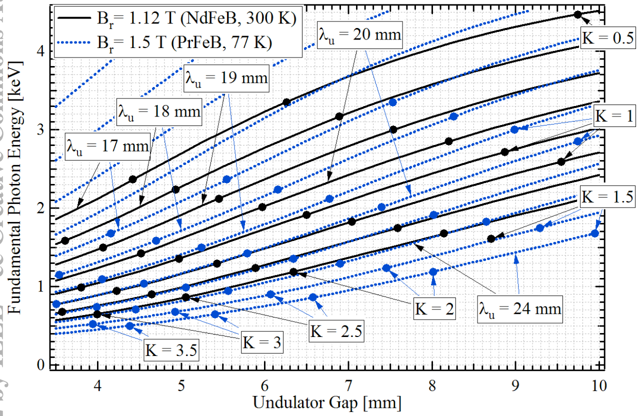

Figure 1: Calculated fundamental photon energy vs gap and period of room-temperature and cryo-cooled hybrid undulators for magnetic models considered for NSLS-II.

Examples of the fundamental photon energy dependences on undulator gap and period, calculated using Radia [9] for two types of hybrid in-vacuum undulators - one with NdFeB magnets, 1.12 T remanent magnetization, operating at room-temperature, and one with PrFeB magnets, 1.5 T remanent magnetization, cryo-cooled, operating at 77 K - are given in Fig. 1 for 3 GeV electron energy.

Approximate parameters of some AGUs, calculated assuming different magnet technologies, are given in Tables 1, 2. Table 1 shows possible parameters of AGU for the NSLS-II Inelastic X-ray Scattering (IXS) beamline to be located in High-Beta straight section. This beamline requires highest possible flux at ~ 9.1 keV photon energy, and doesn't require a large tuning range. All these AGU structures are composed out of seven 1 m long segments; the minimal gap among all segments, ~5.25 mm, is reached in the segment (#4) located in the middle of the structure. Table 2 suggests possible parameters of AGU for Low-Beta straight sections of NSLS-II. These AGU are also composed out seven segments, of 0.64 m length. In this case, the minimum gap value in the segment located in the middle of the structure is ~3.5 mm, which is by ~0.5 mm larger than the stay-clear constraint value at the center of the Low-Beta straight section. The fundamental photon energy for these AGU was chosen to be the same as for the baseline in-vacuum undulator IVU20: $E_{1\min} \approx 1.6$ keV.

Table 1: Possible AGU Parameters for NSLS-II IXS Beamline to be Located in High-Beta Straight Section.

Technology:		Room-Temp.	Room-Temp.	Cryo-Cooled	SC
$E_{1\min}$ [keV]:		1.82	3.04	3.04	3.04
N of Periods:		331	394	423	482
Segm.#	g_i [mm]	λ_{ui} [mm] / $K_{i\,\max}$			
1, 7	7.46	22.5/1.47	18.8/0.994	17.6/1.10	15.4/1.28
2, 6	6.45	21.3/1.55	17.9/1.07	16.6/1.18	14.6/1.36
3, 5	5.68	20.2/1.62	17.1/1.14	15.8/1.24	14.0/1.42
4	5.25	19.6/1.66	16.7/1.17	15.4/1.29	13.6/1.46

Table 2: Possible AGU Parameters for NSLS-II Low-Beta Straight Section.

Technology:		Room-Temp.	Cryo-Cooled	SC
N of Periods:		224	245	286
Segm.#	g_i [mm]	λ_{ui} [mm] / $K_{i\,\max}$		
1, 7	6.72	22.5/1.66	20.5/1.79	17.4/2.04
2, 6	5.20	20.4/1.80	18.6/1.94	15.9/2.18
3, 5	3.93	18.4/1.95	16.9/2.08	14.5/2.32
4	3.50	17.8/2.0	16.2/2.14	14.1/2.37

In Tables 1,2 maximal deflection parameter values in undulator segments are given, assuming that it may be possible to vary these parameters in different segments, while keeping them always tuned to the same fundamental photon energy. This implies the necessity of separate motorization of gap motion in permanent-magnet / hybrid AGU, and separate variation of currents in coils of different segments of a superconducting AGU.

SPECTRAL CALCULATIONS

To compare spectral performances of the segmented AGU with that of conventional undulators, we have performed a series of calculations of single-electron beam intensity and the spectral flux from finite-emittance (and energy spread) electron beam, collected through a fixed aperture, for the AGU detailed in Tables 1, 2. The conventional undulator parameters used for the comparison were obtained by optimization [7].

Figure 2 shows the results of calculations, performed using SRW code [10] for the "candidate" sources of the IXS beamline (see Table 1). As one can see from Fig. 2-b, spectral flux of the room-temperature AGU is even higher than that of the conventional cryo-cooled in-vacuum undulator (cIVU); spectral flux of the cryo-cooled AGU (cAGU) is comparable to that of the "conventional" superconducting undulator (SCU); super-conducting AGU (scAGU) provides further gain over the SCU.

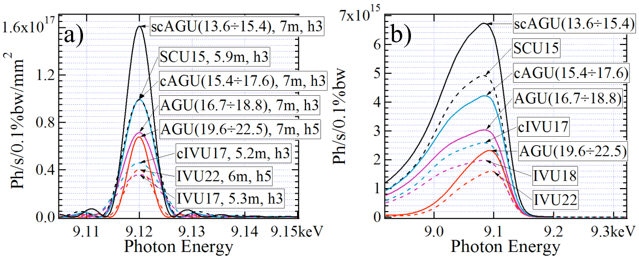

Figure 2: On-axis single-electron intensity at 20 m observation distance, normalized by 0.5 A current (a), and finite-emittance electron beam flux collected in 100 μrad (hor.) x 50 μrad (vert.) angular aperture (b) of radiation from AGU detailed in Table 1, in comparison with that of conventional undulators.

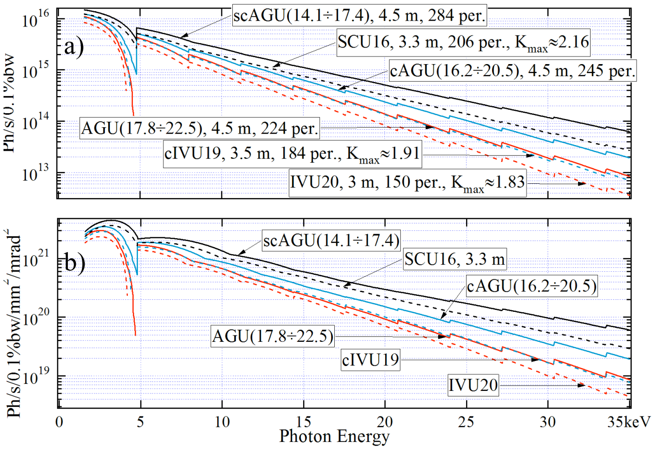

Figure 3: Approximate spectral flux (a) and brightness (b) tuning curves for odd harmonics of AGU detailed in Table 2 (solid lines) and conventional undulators (dashed lines), considered for NSLS-II Low-Beta straight section.

We also present (in Fig. 3) the results of approximate calculations of the spectral flux and brightness tuning curves for odd harmonics of the AGU described in Table 2 and the corresponding conventional undulators. These calculations take into account the finite emittance and energy spread of the electron beam and beta-function values in Low-Beta straight section of NSLS-II.

Quite expectedly, the AGU can be seen to dominate in spectral flux and brightness over the conventional undulators at all harmonics in the full spectral range covered by the undulators. This gain is stronger at higher harmonic numbers and higher photon energies, thanks to smaller gaps and larger deflection parameter values in segments located in the middle of AGU, compared to those of conventional undulators.

CONCLUSION

Segmented adaptive-gap undulators with different period lengths in segments promise significant gain in spectral performance (by factor of 1.3 to 2 and higher in hard X-ray range) compared to conventional in-vacuum undulators, profiting from large length of straight sections in 3rd generation synchrotron sources. This concept is applicable to all popular undulator magnet technologies. Future development will address transitions at junctions between segments to control steering and phasing errors.

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