Segmented Adaptive-Gap In-Vacuum Undulators - Potential Solution for Beamlines Requiring High Hard X-Ray Flux and Brightness in Medium Energy Synchrotron Sources?

O Chubar\(^1\), J Bengtsson\(^1\), A Blednykh\(^1\), C Kitegi\(^1\), G Rakowsky\(^1\), T Tanabe\(^1\) and J Clarke\(^2\)

\(^1\)Photon Sciences Directorate, Brookhaven National Laboratory, Upton NY, USA
\(^2\)ASTeC, STFC, Daresbury Laboratory, UK

E-mail: chubar@bnl.gov

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. Placing together undulator segments with different periods may introduce small kicks to electron trajectories at the segment junctions, which can be easily compensated, without introducing any significant radiation phase error, by active correction magnets or by special design of terminating magnets in the segments. Thanks to this, the entire multi-segment structure can operate as one long undulator. On the other hand, since the vertical gaps in segments located close to straight section center can be smaller than at extremities, such structure can offer better magnetic performance, compared to the case of a standard undulator with constant gap (and period) over its length. We present magnetic field, radiation flux and brightness calculation results for such segmented adaptive-gap in-vacuum undulators if used in low-beta straight sections of NSLS-II, and demonstrate their gain in spectral performance, especially in hard X-ray range, over standard room-temperature and even cryo-cooled in-vacuum 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 UV 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 Insertion Devices (ID), because this may violate electron beam "stay-clear" constraint and 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 works and subsequent large-scale efforts made at 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, the 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.

Determinating 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 \( s \):

\[
g(s) = N_o \sqrt{(s^2 + \beta_{s0}^2)\varepsilon_y / \beta_{s0}},
\]

where \( \beta_{s0} \) is the vertical beta-function value at the electron beam waist, corresponding to the longitudinal position \( s = 0 \), \( \varepsilon_y \) is the vertical electron beam emittance, \( N_o \) is the ratio between the allowable insertion device gap (or the inner size of vacuum chamber) and the vertical RMS size of electron beam. At the National Synchrotron Light Source II (NSLS-II), which is currently under construction at Brookhaven National Laboratory, \( \varepsilon_y \approx 8 \) pm, \( \beta_{s0} \approx 1.06 \) m in the Low- and \( \beta_{s0} \approx 3.4 \) m in High-Beta straight section, the vertical "stay-clear" constraint is defined by Eq. (1) with \( N_o \approx 1000 \).

Consider 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:

\[
g_i \geq \max\{g(s_{i-1}), g(s_i)\}, \quad i = 1, 2, \ldots, N.
\]

\(2\)
In order for all these segments to work as one undulator, the fundamental photon energy $E_1$ of the undulator radiation in these segments should be the same:

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

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

The choice of periods $\{\lambda_{ui}\}$ in the AGU segments can be done as far as magnetic performance, i.e. dependence of the fundamental photon energy on undulator gap and period $E_1 = E_1(g_i, \lambda_{ui})$ is known. Approximately, this dependence can be estimated using the Halbach's formula [9] combined with Eq. (3). However, for taking into account special features or constraints of magnetic design and materials, series of magnetostatics calculations for different undulator gaps and periods have to be performed [10], [7]. Once this is done, the period values in the segments $\{\lambda_{ui}\}$ can be determined for the corresponding gap values $\{g_i\}$ (satisfying Eq. (2)), for a required minimal fundamental photon energy $E_1$, by interpolation. Note that each segment will have a different gap dependence vs. fundamental photon energy, therefore independent gap control is required to synchronize all segments while tuning the photon energy. Of course, the final gap vs. photon energy tables for the segments must be determined from magnetic measurements.

Table 1 suggests possible parameters of AGU for Low-Beta straight sections of NSLS-II, calculated assuming different magnet technologies: room-temperature, cryo-cooled and superconducting (SC). These AGU are all composed out of seven 0.64 m long segments. The minimum gap 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 NSLS-II in-vacuum undulator IVU20: $E_{1\text{min}} \approx 1.6$ keV (the maximal deflection parameter values $K_{i \text{max}}$ in Table 1 correspond to that fundamental photon energy).

**Table 1. Possible AGU Parameters for NSLS-II Low-Beta Straight Section.**

| Technology:         | Room-Temp. | Cryo-Cooled | SC       |
|---------------------|------------|-------------|----------|
| Num. of Periods:    | 224        | 245         | 286      |
| Segm. # $g_i$ [mm]  | $\lambda_{ui}$ [mm] / $K_{i \text{max}}$ |
| 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 |

Spectral calculations

To compare spectral performances of the segmented AGU with that of conventional undulators, we have performed a series of calculations of the spectral flux and brightness from finite-emittance (and finite energy spread) electron beam, for the AGU detailed in Table 1. For comparison, parameters of the baseline NSLS-II IVU20 [7], and possible cryo-cooled and superconducting undulators, optimized for Low-Beta straight section, were taken. Figure 1 shows the results of these calculations, performed using SRW code [11]. As one can see from figure 1-a and 1-b, the spectral flux and brightness of the room-temperature AGU are even a bit higher than those of the conventional cryo-cooled in-vacuum undulator (cIVU19); spectral flux and brightness of the cryo-cooled AGU (cAGU) is comparable to that of the "conventional" superconducting undulator (SCU16); super-conducting AGU (scAGU) provides further spectral performance gain over the SCU.
Figure 1. Spectral flux (a) and brightness (b) tuning curves for odd harmonics of AGU detailed in Table 1 (solid lines) and conventional undulators (dashed lines), considered for Low-Beta straight sections at NSLS-II.

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 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. This concept is applicable to all popular undulator magnet technologies. Future development will address design of transitions at junctions between segments to control steering and phasing errors.

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