SUPERCONDUCTIVE INSERTION DEVICES WITH VARIABLE PERIOD LENGTH

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IN MEMORY OF UDO RETZLAFF

Abstract

The tuning range and functionality of superconductive insertion devices can be enhanced significantly by period length switching. Period length switching can be achieved by employing two or more individually powerable subsets of superconducting coils.

In this paper the opportunities and restrictions of period length switching in superconductive undulators are discussed from a general point of view.

As a particular example, the design of a hybrid superconductive undulator/wiggler (SCUW) for ANKA based upon the period length switching technique is presented.

INTRODUCTION

The spectral range coverable with the harmonics of undulator radiation is determined by the undulator period length $\lambda_{\rm U}$ and the on-axis magnetic field amplitude $\tilde{B}_y$ according to the two basic undulator equations [1]

$$\begin{aligned} \lambda &= \frac{\lambda_{\rm U}}{2\gamma^2 k}\left(1+\frac{K^2}{2}\right) \\ K &= \frac{e}{2\pi m_e c}\lambda_{\rm U}\tilde{B}_y, \end{aligned} \tag{1}$$

where λ is the wavelength of the kth harmonic. Typically the undulator period is fixed and the photon wavelength is tuned by varying the field amplitude. Therefore the shortest photon wavelength or highest photon energy reachable with a given harmonic is determined by the undulator period and the relative electron energy γ only, while the actual tuning range is determined by the achievable field amplitude (see Fig. 1).

In this regard the demand for high photon energies on the one hand and wide gapless tuning ranges on the other hand pose contradicting requirements to the magnetic design as can be seen from Eq. (1): sustaining a tuning range given by a certain K-value for shorter and shorter period lengths requires a higher and higher field amplitude which, however, is the harder to achieve the shorter the period length gets. This might be addressed as a fundamental problem of undulator design motivating developments like cryogenic in-vacuum [2] or superconductive undulators [3].

Varying the period length rather than the field amplitude would be a way out of this dilemma [5] which is, however, technically not easy to realise. In the special case of superconductive undulators there is a particular solution: Combining the conventional field amplitude tuning with a stepwise period length switching. This switching can be achieved by reversing the current direction in a subset of the superconducting coils. The most simple example as proposed by [4] is scetched in Fig. 2. Here, the period length is doubled by reverting the current direction in the subset of superconducting windings displayed in yellow.

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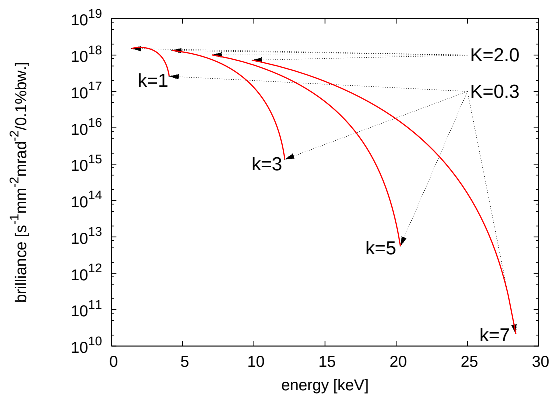

Figure 1: The “fundamental problem” of fixed-$\lambda_{\rm U}$ undulator design: tradeoff between short period length (high photon energies) and achievable field amplitude (overlaping of harmonics).

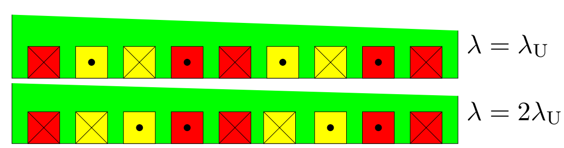

Figure 2: Period doubling as the most simple case of period length switching [4] using two independently powerable sets of superconductive windings. The period length is switched by reversing the current direction in the yellow winding.

BASIC CONSIDERATIONS

The potential and limitations of period length switching in superconductive undulators may be pointed out more specifically by answering the following questions:

- Which period length variation step widths can be realised?

Table 1: Fundamental parameters characterising a multi-$\lambda_{\rm U}$ undulator

$\lambda_{\rm U0}$	fundamental undulator period length
N_λ	number of period lengths
$N_{\rm W}$	number of independent wires
$\{l_1, ..., l_{N_\lambda}\}$	period lengths in units of $\lambda_{\rm U0}$
$\{K_1, ..., K_{N_\lambda}\}$	deflection parameters for each period length

- How many wires are required for a certain number of period length steps?
- Which conditions have to be fulfilled in order to cover a certain spectral range with a certain set of period lengths?

For convenience a set of fundamental parameters characterising undulators with switchable period length (in the following referred to as multi-$\lambda_{\rm U}$ undulator) is introduced in Table 1.

The first fact to note is that there is essentially no restriction to the period lengths that can be realised in a multi-$\lambda_{\rm U}$ superconductive undulator despite that they have to have a common divisor. This common divisor is the fundamental period length $\lambda_{\rm U0}$ of the underlying winding structure. Note that $\lambda_{\rm U0}$ does not necesserily have to be a period length of the undulator.

Period length variation step width and number of independent wires

Determining the number of independent windings required for a certain number of period lengths is a combinatorial problem treated in the following as exemplified by an undulator with three period lengths $\{l_1, l_2, l_3\} = \{1, 2, 4\}$ (see Fig. 3). Comparing the current direction patterns of the three cases three classes of windings can be identified: those in which the current direction stays the same for all period lengths (magenta), those in which the current with respect to $\lambda_{\rm U} = \lambda_{\rm U0}$ is reversed either for $\lambda_{\rm U} = 2\lambda_{\rm U0}$ or for $\lambda_{\rm U} = 4\lambda_{\rm U0}$ (cyan); this class contains two independent windings. The third class consists of those windings in which the current is reversed for both, the 2 and $4\lambda_{\rm U0}$ case. This class as well as the first class represents one independent winding.

Generalising this treatment to N_λ period lengths yields for the required number of independent windings

$$N_{\rm w} = \sum_{k=0}^{N_\lambda - 1} \binom{N_\lambda - 1}{k}, \qquad (2)$$

where the summation index k resembles the classes of windings discussed above. According to Eq. (2) the number of independent wires increases rapidly with the number of period lengths. Therefore superconductive undulators with more than three period lengths hardly seem to be technically feasible.

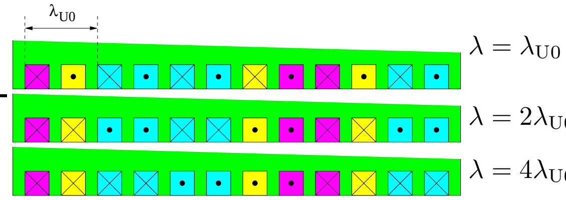

Figure 3: On the number of independent windings required for a particular set of $\lambda_{\rm U}$-variation steps, for example 1,2 and $4\lambda_{\rm U0}$: wires with current reversal neither for switching to 2 nor to $4\lambda_{\rm U0}$ are highlighted in magenta, wires with current reversal either for switching to 2 or to $4\lambda_{\rm U0}$ are highlighted in cyan, wires with current reversal for switching to 2 and to $4\lambda_{\rm U0}$ are highlighted in yellow.

Conditions for gapless tuning ranges

The main purpose of period length switching is to extend the tuning range of an undulator. A typical case will be a multi-$\lambda_{\rm U}$ superconductive undulator with the shortest period length matching the highest photon energy of the spectral range demanded but not providing an overlap between the harmonics. Switching to a longer period length now can be used to fill these tuning gaps.

General conditions for the overlap of the harmonics for *different period lengths* of the undulator can be derived from Eq. (1). Assuming two relative period lengths l_i, l_j with $l_i < l_j$ one gets

$$K_i \geq \sqrt{\frac{2l_j}{l_i} - 2} \qquad (3)$$

for overlap between harmonics of equal order and

$$K_j \geq \sqrt{\frac{2l_i k_j}{l_j k_i} - 2} \qquad (4)$$

for overlap between harmonics of different order k_i, k_j with $k_i < k_j$.

Fig. 4 shows as an example tuning curves from a case study for a possible 2-$\lambda_{\rm U}$ undulator. The electron beam parameters assumed in the simulation are those of BESSY. Here the fundamental period length is $\lambda_{\rm U0} = 4.88\,\rm mm$ and the two relative period lengths are $\{l_1, l_2\} = \{2, 3\}$. For this case Eq. 3 yields the condition $K_1 \geq 1$ for overlap between the first harmonics for both period lengths and Eq. 4 leads to the condition $K_2 \geq \sqrt{2}$ for overlap of the 3rd harmonic for $\lambda_{\rm U} = 2\lambda_{\rm U0}$ with fundamental for $\lambda_{\rm U} = 3\lambda_{\rm U0}$. Fulfilling these conditions makes possible a gapless tuning range from 1 to 23 keV in the first to nineth harmonics.

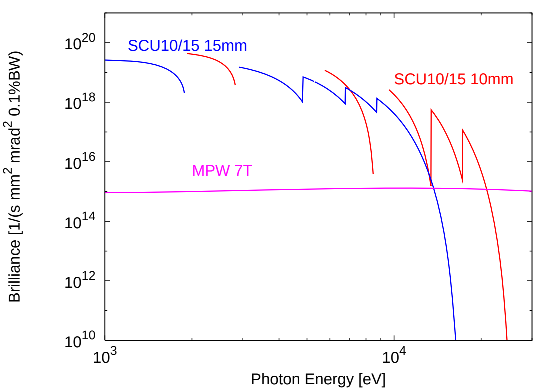

Figure 4: Case study for a 2-λ_U superconductive undulator with period lengths 9.76 and 14.64 mm. Tuning curves assuming $K_\mathrm{max}(\lambda_\mathrm{U} = 9.76\,\mathrm{mm}) = 1$ and $K_\mathrm{max}(\lambda_\mathrm{U} = 14.46\,\mathrm{mm}) = \sqrt{2}$ and the BESSY electron beam parameters. The brilliance of the BESSY 7T-multipole wiggler is displayed for comparison.

HYBRID SUPERCONDUCTIVE INSERTION DEVICES

An additional aspect of period length switching is the possibility to switch between an undulator and a wiggler operation mode of the superconductive insertion device in line with the period length variation. This technique will be applied for a hybrid superconductive undulator/wiggler (SCUW) which is planned for the ANKA IMAGE beamline. Switching between undulator and wiggler operation mode is achieved by period tripling employing the winding scheme scetched in Fig. 5. The design goal is to provide undulator radiation in a spectral range from 7 to 20 keV and to open a window to the hard X-ray range up to 100 keV in the wiggler mode. Fig. 5 shows the estimated brilliance of the radiation generated by this device, assuming the design parameters summarised in Table 2.

The technical realisation of the SCUW concept is one of the aims of an R&D collaboration between ANKA and Babcock-Noell (Würzburg, Germany) which started in October 2007.

Table 2: Design parameters of the hybrid superconductive undulator/wiggler (SCUW) for ANKA

	Und.	Wiggler
Period length [mm]	15	45
Gap width (cold bore) [mm]	7	7
Number of Periods	99	33
Max. Field Amplitude [T]	1.1	3.5
K_max	1.5	14.7

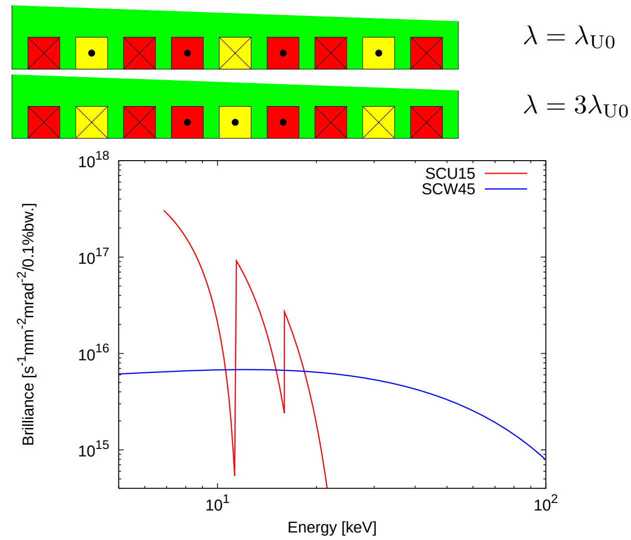

Figure 5: Winding scheme for period tripling foreseen for the planned SCUW for ANKA. Tuning curve and brilliance estimations for the undulator and the wiggler operation mode, respectively.

CONCLUSION

Period length switching may enhance both the spectral range and the functionality of superconductive insertion devices significantly. The switching technique relies on current reversal in a subset of the superconducting coils. The number of subsets required rapidly increases with the number of period length variation steps, technically limiting this technique. However, the rather free choice of period length ratios that can be realised in a multi-λ_U superconductive undulator gives a wide scope for design optimization. A first device involving period length switching, the SCUW for ANKA, is in the phase of detailled planning and will be built within the next years.

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