FIELD OPTIMIZATION IN SUPERCONDUCTING UNDULATORS

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Abstract

Highest photon beam brightness or angular flux density can be achieved in radiation from undulators. Very short period length and high fields, reached only in superconducting undulators, are desired to produce hard x-rays. For lower energy storage rings the radiation at higher harmonics (7th and up) are desirable. This is possible only if the undulator fields and periods are near perfect. Shimming methods as applied for room temperature permanent magnet undulators cannot be used for such superconducting magnets. The effect of field and period tolerances on the photon flux density of higher harmonics will be presented and limiting tolerances will be discussed. A variety of different field optimization techniques together with some measurements on a test magnet will be discussed and evaluated to their usefulness as sources for high photon energies with high angular flux density.

INTRODUCTION

Most undulators producing hard x-rays are installed in high energy not low energy storage rings. Here a short period length and high field of a superconducting undulator (SCU) is required because the photon energy is related directly to the period length of the undulator defined as

$$\varepsilon_n[eV] = \frac{950nE^2[GeV^2]}{\lambda_p[cm](1+\frac{1}{2}K^2)} \qquad (1)$$

where ε_n is the photon energy at the n^{th} harmonic, λ_p is the period length of the undulator and the deflection parameter K is defined by $K=0.934\cdot\lambda_p[cm]\cdot B[T]$ with B the field strength along the beam axis. A photon angular flux density in practical unit is given by

$$\frac{d^2F}{d\theta d\psi}\Big|_{\psi=0} = 1.327\times10^{13}E^2[GeV]I[A]\left(\frac{\varepsilon}{\varepsilon_c}\right)^2 K_{2/3}^2\left(\varepsilon/2\varepsilon_c\right) \qquad (2)$$

where the K_i are modified Bessel functions of the second kind and ε_c is the critical photon energy defined in practical unit defined by ε_c [keV]=$0.665E^2$[GeV]B[T].

Construction tolerances generate field and phase errors which strongly affect the photon angular flux density, especially at high harmonics. To meet high flux density from the SCU, a technique must be developed to correct magnetic field and phase error to equalize all undulator periods resulting in an almost ideal angular flux density even at high harmonics of radiation.

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Shimming is used for permanent magnet undulators but for superconducting magnets a different method of magnetic field correction must be applied. In this paper, three concepts simulated with RADIA [1] and POISSON [2] are discussed and applied to an actual superconducting undulator (SCU15) with a period length of 15 mm and field strength of 1.4 T designed and tested [3] at NSRRC. During magnetic field measurements at NSRRC an iron piece, called trim pole, is placed on the SCU15 pole in an attempt to modify magnetic fields for correction (see Fig. 5). Other options are, for example, to wind an additional coil around each pole or to modify the pole saturation by removing some iron material from the pole. This last method can be accomplished, for example, by adjusting magnetic screws inside the pole material or adding/removing internal pieces of the pole.

MAGNETIC FIELD ERROR

To define an acceptable field and phase errors to obtain more than 90 % of the ideal photon angular flux density a real field is introduced by

$$B_{real} = B_0(1+\Delta B)\cdot\sin(kz) \text{ and } B_{real} = B_0\sin(kz+\Delta\varphi) \qquad (3)$$

The ΔB and Δφ are randomly fluctuations in peak field and phase respectively generated with MATLAB by $\Delta B = randn\cdot\left(\frac{\Delta B}{B}[\%]\cdot\frac{1}{100}\right)$ and $\Delta\varphi = randn\cdot\left(\frac{2\pi\cdot\varphi[^\circ]}{360}\right)$.

Reductions of the angular flux density calculated by B2E code [4] of the real field with different ΔB/B[%] and Δφ[°] are shown in Fig. 1. To reach almost ideal photon flux densities at high harmonics (9th), the acceptable field and phase errors should be less than 1% to avoid more than 10% decrease in the flux density.

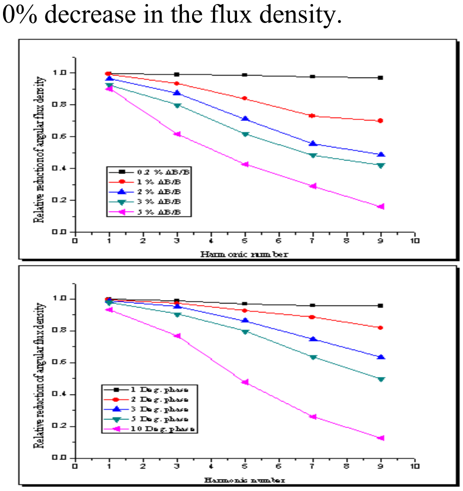

Figure 1: Reduction of the angular flux density calculated with B2E code for different ΔB/B (a) and Δφ (b).

MAGNETIC FIELD MEASUREMENT

The magnetic field of the superconducting undulator SCU15 at NSRRC was calculated with the code RADIA. After 21 training cycles a peak field of 1.4 T at 510 A was reached and the field was measured in a vertical test dewar designed for use at Liquid helium temperatures of 4.2 K. The magnetic field was measured at an excitation of 500 A with a mini-Hall probe sensor (AREPOC Ltd, HMP-MP type) and calibrated and tested against a NMR probe is shown in Fig. 2. The actual field measurement shows phase (period length) and amplitude (field strength) errors as shown in Fig. 3 from the average value of $\lambda_0 = 15.007$ mm and minimum measured peak field of B_0=1.352 T with a measured $\sigma_{B\text{-rms}}$=0.043 T and $\sigma_{p\text{-rms}}$=0.056 mm corresponding to 0.22 Deg The $\sigma_{B\text{-rms}}$ and $\sigma_{p\text{-rms}}$ are

$$\sigma_{B-rms} = \sqrt{\sum_{i=1}^{N}(B_i - B_0)^2 \Big/ N} \;,\; \sigma_{p-rms} = \sqrt{\sum_{i=1}^{N}(\lambda_i - \lambda_0)^2 \Big/ N} \quad (4)$$

where N is the number of undulator poles. We use the minimum field as the design field because some of the correction methods can only reduce the field. The angular flux for the measured undulator is shown in comparison with the ideal undulator in Fig. 4. The reduction in flux density is considerable and must be corrected to be useful for experimentation. All errors should be less than 1%. Several techniques have been introduced such as using the trim poles, additional coils and variation of pole saturation to reduce the peak field deviations to values as small as possible. The impact of phase errors, however, has not yet been addressed and must be evaluated after field correction.

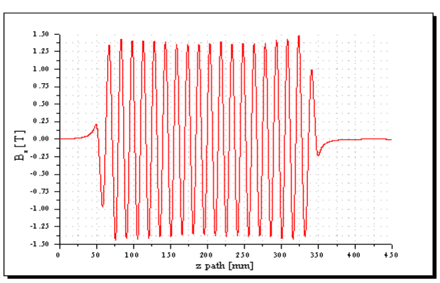

Figure 2: Measured field of the SCU15 along the beam axis using the Hall probe sensor.

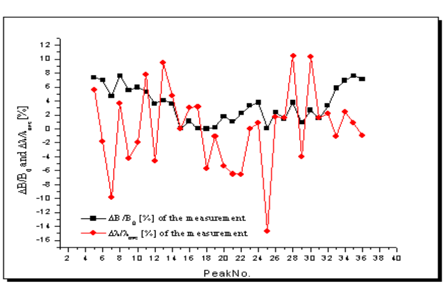

Figure 3: Field (black) and phase (red) error normalized to B_0 of 1.3521 T and λ_{ave} of 15.007 mm in percentage of the measured field of the SCU15.

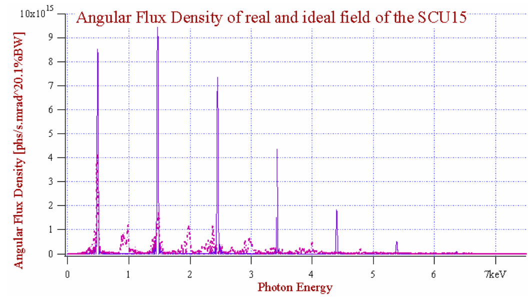

Figure 4: Comparisons of the angular flux density for measured and ideal field. The ideal field is 1.3521 T and the period length is the average measured value of 15.007 mm. The beam energy and beam current are 1.5 GeV and 0.2 A respectively.

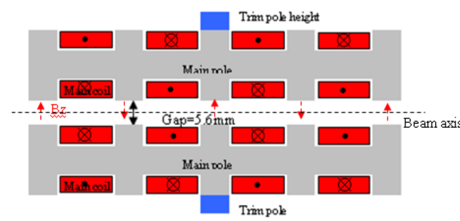

Figure 5: Cross section of the SCU15 with main coils (red), poles (gray) and a trim pole (blue).

FIELD ERROR COMPENSATION

Trim Pole

An iron pieces placed on the upper part of the pole as shown in Fig. 5 is used to function as a trim pole [5] to study changes in the peak field with the code RADIA. The trim pole reduces the peak field of the pole where the trim pole is located. However, the field in close-by poles are also affected significantly such that an individual correction of single peak fields is difficult to achieve.

Additional Coil

Additional coils wound around the pole close to the beam create field changes which are calculated with the RADIA code and are shown in Fig. 6. Such a trim coil obviously affects almost exclusively the peak field in question. From the localized peak field changes of the trim coil, the field errors can be compensated, although at a high price. A comparison of the field changes normalized to the average field with and without correction by the trim coils is shown in Fig. 7.

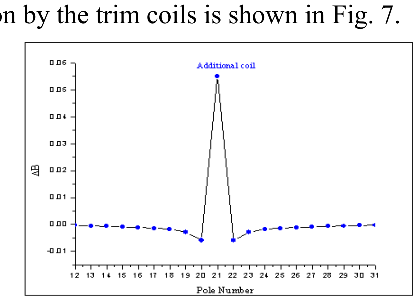

Figure 6: Peak field changes with an additional coil wound around the 21st pole with a current of 59 Ampere.

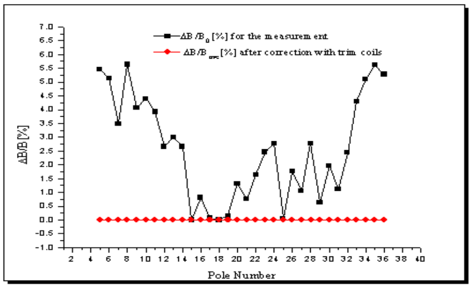

Figure 7: Comparison of peak field deviations related to the average measure peak field B_0 = 1.3521 T with and without correction by the trim coils.

Variation of Pole Saturation

The last concept is base on a modification of the iron content in the poles. This can be accomplished by varying the depth of magnetic screws or the addition/deletion of screwed-on iron at the back of the poles. Peak fields are calculated again with the code POISSON changing as a function of the iron content in the pole. This was simulated by the insertion of slits into the backside of the poles with a constant width (x) and length (z) but varying depth (y) as shown in Fig. 8. After applying the slits to the measured field, the field error can be reduced. A comparison of the field changes normalized to the average field with and without correction by adjusting the iron content in poles as shown in Fig. 9. Correction can be done only by lowering the field and therefore the fields are adjusted to the lowest value in the undulator. The corrected magnetic field distributions along the undulator for both concepts are recreated with the code RADIA by changing the current through the coils to match the field deviations as the field differences after correction. Finally the ratio of calculated angular flux density can be improved up to high harmonics as shown in Table.1 and defined by

$$\left(d^2F/d\theta d\psi\right)_{B-corrected,B-measured} \Big/ \left(d^2F/d\theta d\psi\right)_{B-ideal} \qquad (5)$$

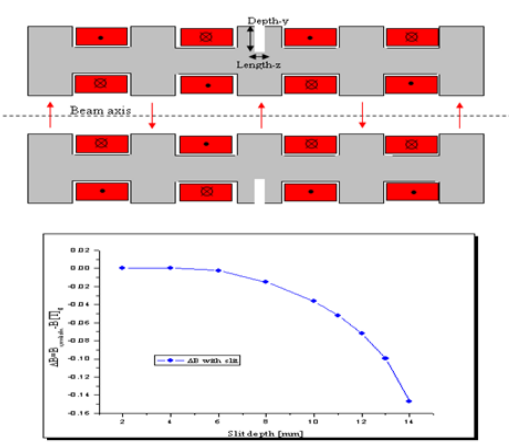

Figure 8: Cross-section of the SCU15 with inserted slit into backside of the poles (upper) and varying depth of inserted slit into the poles as a function of the changes in field (lower).

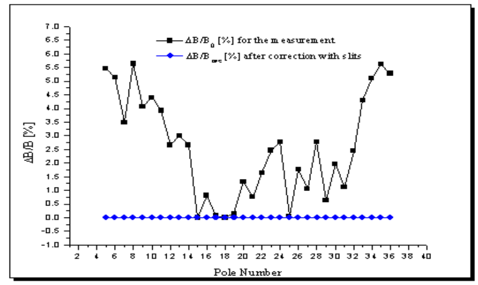

Figure 9: Comparison of peak field deviations related to the average measure peak field B_0 = 1.3504 T with and without correction by the slits in the poles.

CONCLUSION

After compensation of peak field errors by trim coils or varying the saturation in the poles, the photon flux density in all harmonics up to 9th-order are increased significantly. Much work has to be done still. Variation of the saturation, for example, works for one excitation only. During further studies the tuning range of such correction will be evaluated. Furthermore, the possibility of correcting also phase errors must be evaluated in more detail.

Table 1: Angular flux density each harmonic

Harmonics	Angular Flux density [%]		
	B_{meas}	$B_{corr-coils}$	$B_{corr-slit}$
1	63.0	99.9	99.8
3	23.4	99.9	99.3
5	30.3	98.8	97.2
7	18.5	92.3	88.8
9	-	86.5	80.9

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