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FIELD ERROR CORRECTION FOR A SUPERCONDUCTING UNDULATOR

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Abstract

To reach higher photon energies in the region of soft or hard x-rays from 1 to 10 keV with high photon beam brightness in low energy storage rings, superconducting undulators with very short period length and high magnetic field strength are required. Because undulator radiation comes in a line spectrum, photons up to the 7th harmonic are desired. This requires to correct the undulator for errors in period length and magnetic field strength. The photon brightness (or photon flux density) in such harmonics is strongly dependent on perfect periodicity of the magnetic field. Small changes in field strength and phase from period to period can cause destructive interference which reduces the photon intensity dramatically, especially at higher harmonics. Such imperfections also appear in conventional permanent material undulators, which can be corrected by well developed and efficient shimming. Unfortunately, this method cannot be applied to superconducting undulators. Therefore, we present a new approach to field corrections by modification of the magnetic field saturation in each pole. By this correction, not only the magnetic field error but also greatly improves phase (period length) errors from period to period. The proposed method works quite local with only small perturbations in neighbouring poles. The tunability is preserved for most of the field excitations and is reduced only at extreme parameters.

INTRODUCTION

Undulators are the desired sources of synchrotron radiation. The radiation is emitted at a quasi-monochromatic fundamental wavelength for low and in higher harmonics (i) at higher magnetic fields given by

$$\lambda_i = \frac{\lambda_\mathrm{p}}{2\gamma^2 i}\left(1+\frac{1}{2}K^2\right)$$

with $K = 0.934B[T]\lambda_\mathrm{p}[cm]$, By changing the magnetic field, a wide range of photon energies can be covered. For high photon energies either a high electron beam energy γ or short period length λ_p is required. A short period length less than the gap aperture causes a fast fall-off of the field. Therefore, superconducting undulators are being developed to reach practical field strengths. Significant photon intensities in higher harmonics requires a strength parameter of $K = 2$ to 3 as shown in Fig.1 showing the photon flux density in arbitrary units as a function of the K-parameter. Angular flux density [1] is given by

$$\left|\frac{d\dot{N}_i}{d\Omega d\omega/\omega}\right|_{\theta=0} = 1.744\times 10^{14} N^2 E^2[GeV] I[A] A_i(K)$$

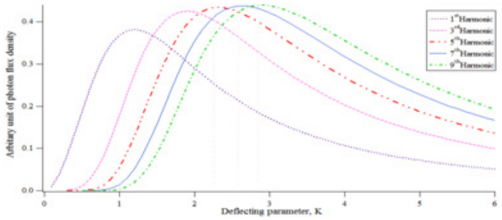

Figure 1: Amplitude of the harmonics i-th for each deflecting parameter K.

A superconducting undulator (SCU15) with 15 mm period length, number of periods of 20, magnetic gap of 5.6 mm and peak field strength of 1.4 T has been build [2] and tested at NSRRC in Taiwan. The magnetic field has been measured together with a correction method [3] used for permanent undulators at room temperature. Although this correction could not compensate the errors for the whole SCU15, we use these measurements to compare them with accuracy of numerical simulations. Agreement between the measurement and simulations, we use this simulation to develop a new field error correction which is localized errors compensation and turned out to be effective and practical.

MAGNETIC FIELD AND PHASE ERROR

Field and period length (phase) errors impact on photon radiation especially at high harmonics of the radiation. To investigate influence of these errors on angular flux density of the radiation, A real undulator field is expressed $B_{real} = (B_0 + \Delta B)\sin(kz + \Delta\varphi)$ with field error ΔB and phase error $\Delta\varphi = k\Delta\lambda_p$ Here, $k = 2\pi/\lambda_p$. Both errors can degrade the photon flux density significantly as shown in Fig.2.

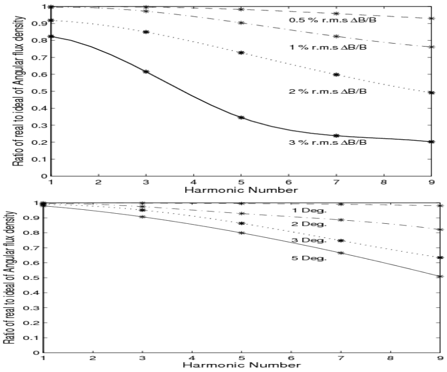

Figure 1: Reduction of angular flux density for i harmonics caused by peak field (a) and period length or phase (b) errors.

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To reach almost ideal angular flux density, r.m.s field $\Delta B / B_0$ and phase $\Delta\varphi$ errors should be kept to less than 0.5 % and 0.5 Deg, respectively.

MAGNETIC FIELD MAPPING

A superconducting undulator (SCU15) with period length of 15 mm, field strength of 1.4 T and magnetic gap of 5.6 mm was designed and tested [2,3] at NSRRC. We use this prototype as an example of field correction in a superconducting undulator. Magnetic field measurements were performed at 500 A, and the actual field and period length errors are shown in Figs. 3.

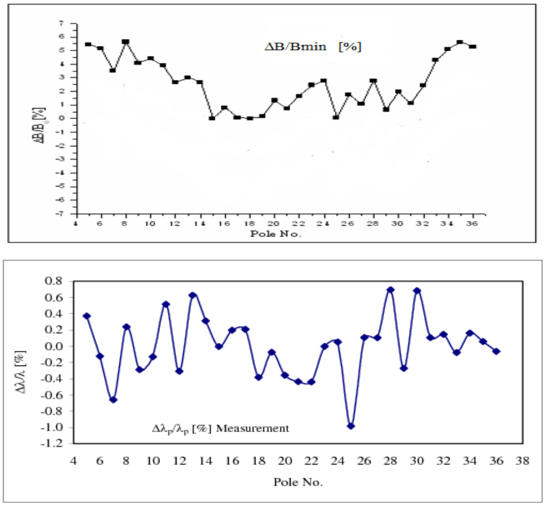

Figure 3: Field (upper) and phase (bottom) errors normalized to a minimum peak field of B_0 = 1.3521 T and average period length λ_p of 15.007 mm, respectively.

Due to relative rms field error of 3 % and rms period length (phase) error of 1.4°, A comparison of the angular flux density for the measured and ideal field of 1.352 T is shown in Fig. 4. The negative effect is obvious and field correction is required to regain close to ideal flux densities.

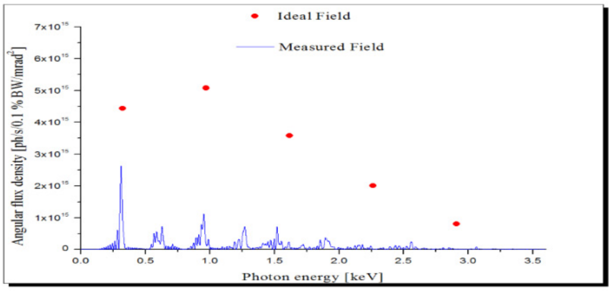

Figure 4: Comparison of angular flux density for measured (solid line) and ideal (dots) fields. Beam energy and current are 1.2 GeV and 0.2 A, respectively. Beam emittance and energy spread are assumed to be zero.

FIELD ERROR CORRECTIONS

First and Second Field Integral Correction

Both first and second field integrals should ideally are zero because the electron beam path should not be affected by more than 10 % of beam size outsize the undulator in order not to perturb electron beam orbit. From the field measurement, the first and second integrals which are determined by deflection angle and displacement are 285×10^{-6}rad and 85×10^{-6}m, respectively. There is an overall curvature within the ID which we correct with a long coil around the whole length of the ID poles (top and bottom). Then we activate two steering magnets, located before and after the undulator, to correct the position and angle of the electron path at the ID exit as shown in Fig. 5 in green.

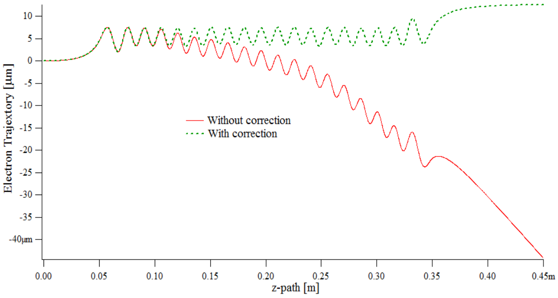

Figure 5: Electron path with (dash) and without (solid) field integral corrections and long coil.

A little improve only on the third harmonics of the radiation not higher one by the integral correction thus we must to apply suitable corrections within the undulat to improve the angular flux density of the radiation.

Peak Field Error Correction

Due to non-constructively interference of emitted radiation caused by field and phase errors within the undulator, the angular flux density is significantly reduced. To restore high flux density, we must correct the field and phases to near ideal conditions. To correct individual pole peak fields we make use of the fact that the iron of the magnet is close to saturation at 1.4T. The proposed method is based on a modification of the iron content in the poles, which are partially saturated and therefore sensitive to the iron content. This is done by machining hollow poles and backfilling the voids with magnetic iron as needed as indicated in Fig. 6.

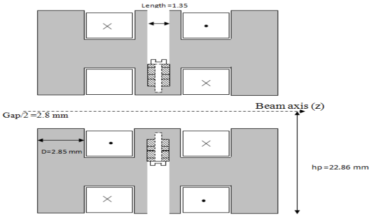

Figure 6: Cross-section of the SCU15 with indentations into the backside of the poles.

By implementing such indentations in the iron poles, we enforce a higher magnetic field density in the remaining iron such that the resulting field in the gap is reduced. Refilling partially the indentation with ferromagnetic iron we adjust the localized fields to desired values. To make this method effective, the field should change only in the pole under consideration. Figure 7 shows the small effect of an indentations (in pole #21) on the field in neighbouring poles (upper) and on the bottom we show the field change as a function of the depth of indentation. Each pole requires field correction ΔB to meet the minimum field of 1.352 T. This field change is composed by contribution from all other poles. Thus the changes of iron content in each pole determine the field changes for each pole and defined by $\Delta B_i = M_{ij}\Delta y_j$ where Δy_j is change in iron pole content in each pole j measured in terms of depth change of indentations. By matrix inversion, employing SVD method the Δy_j can be solved. Based on this correction, the rms field errors could be reduced from 0.042 T or 3 % to 0.0003 T or 0.021 % as shown in Fig. 8. This correction method improve quality of the undulator field both in amplitude and period length therefore the angular flux densities in all harmonics up the 9th are increased significantly as shown in Fig.9, in comparison with those from the ideal undulator.

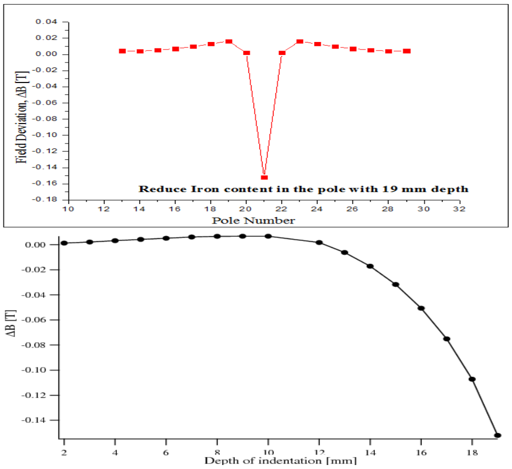

Figure 7: Field changes (upper) by an indentation into the backside of pole #21 in the SCU15 and change (bottom) in peak field for different depth of indentations.

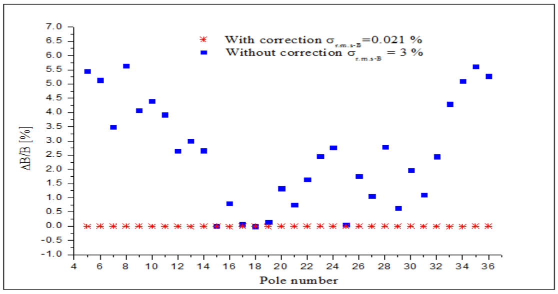

Figure 8: Effect of peak field corrections in the SCU15.

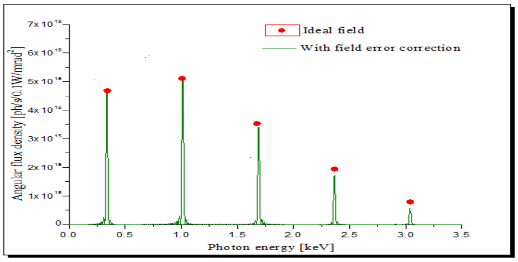

Figure 9: Angular flux density after field corrections as described.

This correction also impacts the phase without specific correction method for them. As the result, the rms phase error can be reduced from 1.4 ° to 0.086 ° .

RESULT AND DISCUSSION

A superconducting undulator with short period length and high field is used to produce short wavelength radiation up to the 9th harmonic for low energy storage ring. Angular photon flux densities at such high harmonics are severely reduced by even small manufacturing imperfections in the magnetic field and periodicity of the undulator. Although field integrals are corrected but it does not restore the ideal radiation angular flux density for high harmonic up to the 5th. By making the poles hollow and filling the hollow space with adjustable amounts of iron pieces, it works locally with only small perturbations in neighbouring poles. This correction method works only over a limit range in the strength or K of undulator. We determine the range of excitation permissible before the effect of field correction is lost and keep the angular flux density at the 5th, 7th and 9th harmonics of the radiation at least 90 % of the ideal values. Acceptable ranges in each harmonic in tern of the undulator strength K are shown in Fig. 10.

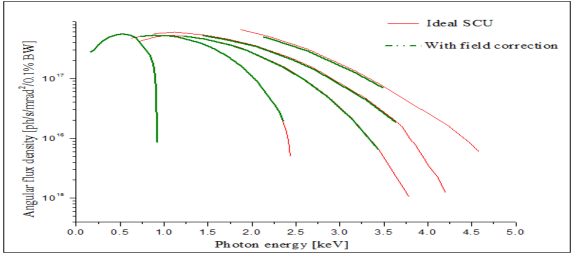

Figure 10: A comparison of angular flux density between ideal (red solid line) and corrected (green dash line) SCU15 with 200 periods.

REFERENCES

[1] H. Wiedemann, "Particle Accelerator Physics", Berlin, Springer, 2007.

[2] J.C. Jan, C.S. Hwang an et.al, "Design of Field Trimming by Iron pieces and Coils for Superconducting undulator", in *Proc*. ASC2008, 2008.

[3] J.C. Jan, C.S. Hwang and et.al, "Design and Improvement of a Mini-Pole Superconducting undulator at NSRRC", IEEE Trans. Appl. Supercond., vol. 18, No. 2, 2008.