Analysis of magnetic properties of the European XFEL undulator prototype

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Abstract. In this contribution, we present an analysis of the experimentally measured magnetic field data from the planar hybrid 40 mm period undulator prototype for the European XFEL, and a simulation of expected radiation properties. Because of manufacturing errors, the magnetic field data include a small horizontal component, as well as some irregularities in its vertical (leading) component. A Fourier harmonics analysis was carried out. It was found that the vertical component of the measured magnetic field includes a sufficiently noticeable (about 6 percent relative to the fundamental) third harmonic component in addition to the fundamental harmonic. The spontaneous radiation properties are simulated from the experimentally measured magnetic field. Relying on computed radiation distributions, the effective magnetic field amplitude, the effective undulator period and deflection parameter are calculated.

1. Introduction

The European X-Ray Free-Electron Laser (XFEL) is a new international scientific project which is being built in Hamburg. The purpose of the facility is to generate extremely brilliant (peak brilliance ~ 10^{33} photons/s/mm^2/mrad^2/0.1%BW), ultra-short (<100 fs) pulses of spatially coherent x-rays with wavelengths 0.05 - 5 nm [1], and to exploit them for revolutionary scientific experiments in a variety of disciplines spanning physics, chemistry, materials science and biology. The 1.7 km long accelerator, located in an underground tunnel, can provide electrons up to 17.5 GeV with repetition rate 27000 pulses/sec (other main working points are 10.5 GeV and 14 GeV [2]).

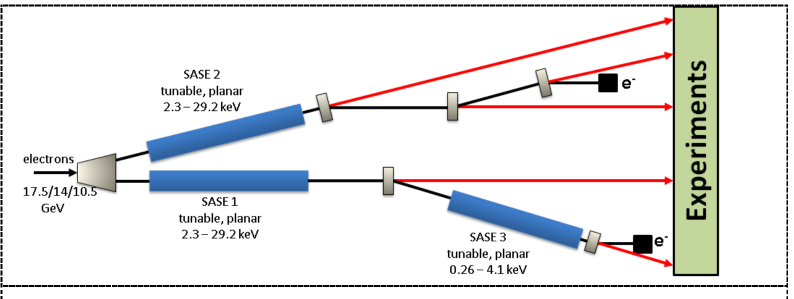

Figure 1. Schematic layout of the electron and photon beam distribution [2, 3].

The three undulator systems SASE1, SASE2 and SASE3 will be used to produce photon beams at the project start-up stage (see Fig. 1). Due to the undulator length and to the small gap one needs to superimpose an external focusing SASE lattice to the undulator sections. The undulator is therefore, designed as a collection of 35 cells for a total magnetic length 175 m for SASE 1 and SASE2. One cell consists of a 5 m long undulator segment and a 1.1 m long intersection.
Main parameters of the electron beam are summarized in Table 1 [3].

Table 1. Main parameters of electron beam.

Parameter	Value
Max. electron energy	10.5 - 17.5 GeV
Charge of electron beam	0.02 - 1 nC
Slice energy spread	4.1 - 2 MeV
Norm. slice emittance	$0.32 – 0.97 \cdot 10^{-6}$ m·rad

2. Undulator parameters

No alternative to permanent magnet (PM) technology is available for large-scale use in undulator systems, such as the European XFEL Facility. The hybrid design uses NdFeB permanent magnets and soft iron parts, which concentrate the magnetic flux. Usually, the following equation is used for estimating the magnetic field amplitude dependence on material constants a_1, a_2, a_3, magnetic gap g and undulator period λ_u:

$$B_{\max}(T) = a_1 \times \exp\left[a_2 \frac{g}{\lambda_u} + a_3 \left(\frac{g}{\lambda_u} \right)^2 \right], \quad (1)$$

where $a_1 = 3.000$, $a_2 = -4.052$, $a_1 = 0.551$ (European XFEL undulator prototype U40-X001-K001).
The main undulator parameters (with computed magnetic field amplitudes) are shown in Tables 2.

Table 2. Parameters of undulator U40.

Parameter	Value
Period length	40 mm
Number of periods	124
Gap distance	10 mm
Maximum magnetic field	~1.1 T
Deflection parameter	3.964

3. Undulator performance

We will analyse the measured magnetic field of an undulator prototype with emphasis on radiation properties. The measured horizontal and vertical components of the undulator's magnetic field are shown in Fig. 2. The horizontal component of the magnetic field includes a stochastic component as a result of manufacturing errors. The maximal amplitude of B_x is 2 mT. The amplitude of the vertical component of the field is 1.121-1.132 T, and the variation of the magnetic field amplitude is a result of manufacturing errors as well. It should be noted that expression (1) gives an amplitude value $B_{\max}$ of 1.127 T. Undulators are engineered following the anti-symmetric scheme ½ -1, 1, -1,…, 1, -½, which can't make the second field integral equal to zero.
The computed horizontal and vertical trajectories of an electron with initial conditions $x = y = 0$, $x' = y'$ = 0 in the measured field are shown in Fig. 3. Simulation is carried out at 17.5 GeV.

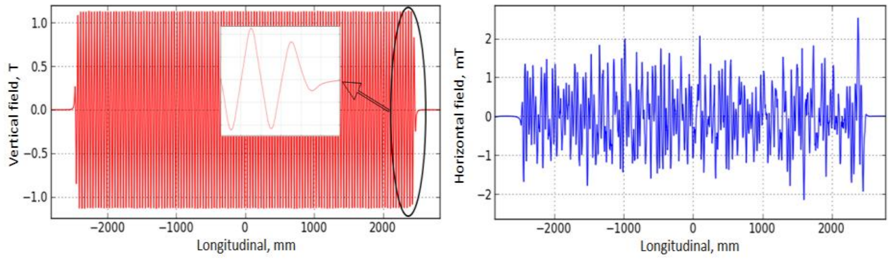

Figure 2. Measured magnetic fields of undulator, gap=10 mm.

Here we assume that air coils are set in such a way that first and second field integral equal zero, meaning that we consider air coils with their magnetic field integrals $C_x = 10\cdot10^{-3}$ T·mm, $C_y = 22\cdot10^{-3}$ T·mm (upstream coil) and $C_x = 57\cdot10^{-3}$ T·mm, $C_y = 38\cdot10^{-3}$ T·mm (downstream coil). These values seem very small compared with the maximum possible integral of air coil, corresponding to 0.6 T·mm.

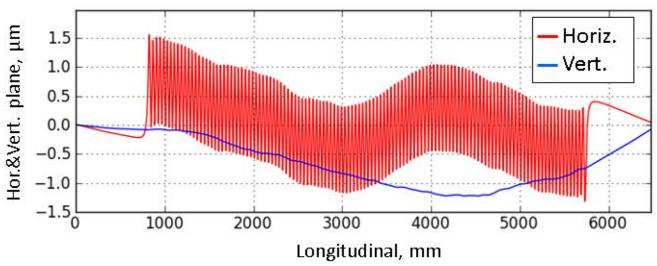

Figure 3. Horizontal and vertical trajectories of the electron.

3.1. Fourier analysis of the magnetic field

Fourier analysis of magnetic field was carried out. In order to simplify it, we cut off ending poles thus extracting the periodical part of the magnetic field. As a result we expect to see the main harmonic and harmonics induced by manufacturing errors, but not the harmonics resulting from the ending poles. The spectrum of the Fourier transform of the magnetic field is presented in Fig. 4. As we can see there are mainly first and third harmonic components, with the third harmonic amplitude ~ 6.6% of the fundamental. It should be noted that the average period of the undulator is 40.002 mm, thereby the accuracy of manufacturing is $5\cdot10^{-5}$. Further we will set the period $\lambda_u = 40.002$ mm.

The following equation can be easily derived for the effective deflection parameter K [4,5]:

$$K = \sqrt{\sum_n \frac{K_n^2}{n^2}}, \qquad K_n = \frac{eB_n\lambda_u}{2\pi mc^2} \tag{2}$$

where n is the number of the harmonic. From (2) we obtain $K = 3.963$. We can therefore expect that the first harmonic of the radiation ε_1 will be at 8212.3 eV. In case of neglecting the third harmonic of the field, ε_1 would equal 8215.9 eV.

3.2. Radiation properties

To check our expectations we carried out computer simulations of the radiation characteristics by using the measured magnetic field. Trajectories and spontaneous radiation properties were calculated using a new computer code written in C++ for dealing with the complex geometry of the European XFEL facility. Details of the code will be presented elsewhere. The fundamental harmonic of the radiation is presented in Fig.5. The vertical axis shows the spectral flux density (ph./s/mrad^2/0.1%BW) for an average current of the electron beam equal to 1 mA at the electron beam energy of 17.5 GeV.

As we can see our estimation in the section 3.1 is very close to the simulation output, see Fig.5, with an accuracy ~ $6\cdot10^{-4}$. We can also estimate the effective magnetic field as $B_{eff} = 1.0614$ T.

Finally, in Table 3 we present results from the study of four different cases. In the first three cases the magnetic field amplitude was reconstructed by using the first and the third harmonic (case 1) or the first harmonic only (case 2) or first harmonic but with the amplitude equal to B_{eff} (case 3). The figure of merit is the position of the first harmonic, which is obtained by computer simulation of the emitted spontaneous radiation.

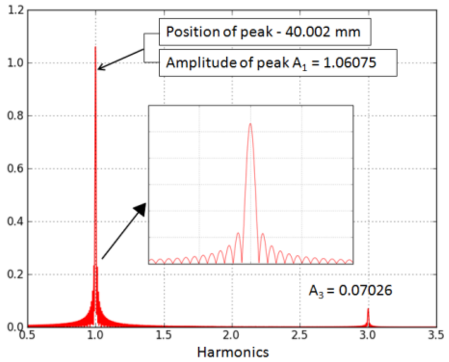

Figure 4. Magnetic field spectrum.

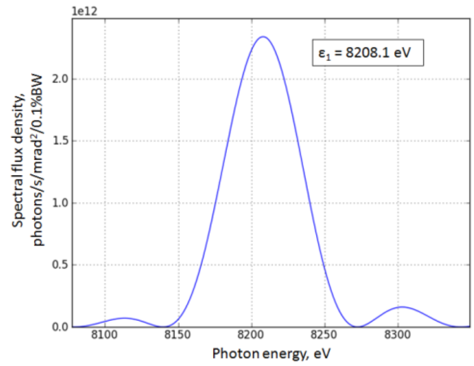

Figure 5. Fundamental harmonic of radiation from the zero-emittance e-beam.

Table 3. Undulator parameters for the U40 prototype

λ_u, mm	Harmonics, T		Magnetic field amplitude, T	ε_1 (code), eV
	A_1	A_3		
40.002	1.06075	-0.07026	0.9905	8212.3
40.002	1.06075	-	1.06075	8215.9
40	1.0614	-	1.0614	8208.2
Real magnetic field			1.121-1.132	8208.1

Analyzing Table 3 we can notice that the position of fundamental harmonic of radiation from the real magnetic field (case 4) and one from reconstructed magnetic field (case 1) are very close to each other. Thereby Fourier analysis may be useful for estimating the position of the first harmonic. Indeed, in the case 1 the magnetic field amplitude is less than one in the case 2 because of the negative sign of the third harmonic. At the same time, in accordance with Eq.(2), the *K*-value for the case 1 is higher than in the case 2. As a consequence, the fundamental harmonic energy in the case 1 is less. Also, Eq. (2) agrees with results of computer simulation (see Table 3). Finally, we conclude that the influence of manufacturing errors on position of fundamental harmonic is small ($\sim 5 \cdot 10^{-4}$) for this prototype.

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