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DETERMINATION OF THE SLICE ENERGY SPREAD OF ULTRA-RELATIVISTIC ELECTRON BEAMS BY SCANNING SEEDED COHERENT UNDULATOR RADIATION*

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Abstract

Modern high-gain free-electron lasers make use of the high-brightness ultra-relativistic electron beams. The uncorrelated energy spread of these beams is, upon creation of the beam, in the sub-permille range and below the resolution of state-of-the-art diagnostics. One method to determine the slice energy spread is to use an external seed laser to imprint a coherent microbunching structure that gives rise to coherent radiation processes different than radiation sources such as transition radiation, synchrotron radiation, or undulator radiation and others. Here, we present a method and show measurements to determine the slice energy spread using an external seed laser with a 266 nm wavelength to produce coherent undulator radiation at higher harmonics. The distribution of these harmonics allows to retrieve the electron beams slice energy spread with high precision.

INTRODUCTION

The invention of the high-gain x-ray free-electron laser has enabled the study of the dynamics and structure of matter on the atomic and molecular level and for time scales on the order of atto- and femtoseconds [1–4]. As these devices are driven by high-brightness ultra-relativistic electron beams, the operation requires sophisticated beam and bunch diagnostics in order to be able to measure and control the properties of the electron beam parameter. One of the crucial beam parameter for the performance of an FEL is the uncorrelated energy spread σ_E. Modern high-brightness electron sources are known to generate electron bunches with uncorrelated energy spread in the order of one keV. The direct measurement of this parameter is extremely challenging as typical diagnostic tools are resolution limited at a few keV. Nevertheless, processes which directly depend on σ_E can be used to indirectly determine this value. At the SDUV-FEL facility in Shanghai, a method using laser-seeded radiation with coherent harmonic generation (CHG) was used to determine the slice energy spread [5]. Here, the seed laser power and the longitudinal dispersion of the bunching chicane of the CHG setup was scanned in order to retrieve the local energy spread using the second harmonic of the initial seed laser wavelength. Similar to that, it is possible to scan the harmonic number instead of changing the dispersion and laser power. Fitting the measurements to simulation data by using the energy spread σ_E and modulation amplitude ΔE as free parameter, we are able to retrieve these values in a similar way. The measurements were performed at the experimental seeding setup sFLASH at the free-electron laser user facility FLASH at DESY.

METHOD

Imprinting a periodic modulation of the longitudinal current density to the electron bunches allows the production of coherent radiation at harmonics of the fundamental frequency. The radiating process can e.g. be synchrotron radiation from a dipole, diffraction or transition radiation from screens, or undulator radiation. By overlapping an external laser pulse (wavelength λ) with the electron beam of beam energy E_0 and with a slice energy spread σ_E inside an undulator, it is possible to induce a periodic modulation of the beam energy with modulation amplitude ΔE. Transporting this energy-modulated beam through a section with longitudinal dispersion (R_{56}), a periodic current modulation forms. A Fourier analysis of the current density is used to extract the bunching coefficients for higher harmonic orders [6]:

$$b_n = \exp\left[-\frac{1}{2}n^2B^2\right] \cdot J_n(-nAB) \qquad (1)$$

where $A = \Delta E/\sigma_E$ is the normalized modulation amplitude, $B = 2\pi\sigma_E R_{56}/(\lambda E_0)$ the normalized dispersive strength of the chicane, and n the harmonic number. For a laser pulse with an electric field envelope $\mathcal{E}(t)$, the modulation amplitude also will be a function of time $\Delta E(t)$. Assuming a constant energy spread along the modulated fraction of the electron bunch we can calculate the bunching distribution $b_n(t)$ after the chicane. Sending the electron beam with this bunching distribution through an undulator of length L_u tuned to the n^{th} harmonic will lead to the emission of coherent undulator radiation with a power profile proportional to $\rho_{FEL}|b_n(t)|^2L_u^2$ [7]. For simplicity, we assume that the initial bunch current is low enough to neglect exponential FEL amplification. Integrating the power profile over time we can now calculate the photon pulse energy from the coherent harmonic generation for different harmonic numbers.

SIMULATION

For accurate simulation of the CHG process, the time-dependent FEL simulation code *GENESIS1.3* has been used [8]. The simulation parameter are similar to the experimental settings summarized in table 1. Figure 1 exemplary shows the result of the simulated bunching distributions for different harmonic numbers n and for an energy spread of

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[*] Supported by the Federal Ministry of Education and Research of Germany under contract 05K13GU4, 05K13PE3, and 05K16PEA

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Table 1: Experimental Parameters

	parameter	**value**
modulator	period length	0.2 m
	effective length	1.2 m
	max. K_{peak}	10.8
radiator	period length	31.4 mm
	effective length	2 m
	max. K_{peak}	2.7
chicane C2	R_{56}	100 µm
electron beam	energy	680-700 MeV
	peak current	160 A
	charge	0.4 nC
seed beam	wavelength	266 nm
	pulse energy	<280 µJ
	NIR pulse duration	~50 fs (FWHM)
	UV pulse duration	250-280 fs (FWHM)
	UV Rayleigh length	1.6 m

σ_E = 20 keV and a modulation amplitude of ΔE = 495 keV. A set of 6552 time-dependent *GENESIS1.3* runs has been performed with a range of the slice energy spread from 2 to 25 keV (in steps of 1 keV) and modulation amplitude from 250 to 350 keV (in steps of 5 keV) and for the harmonic numbers $n = 7 \ldots 19$.

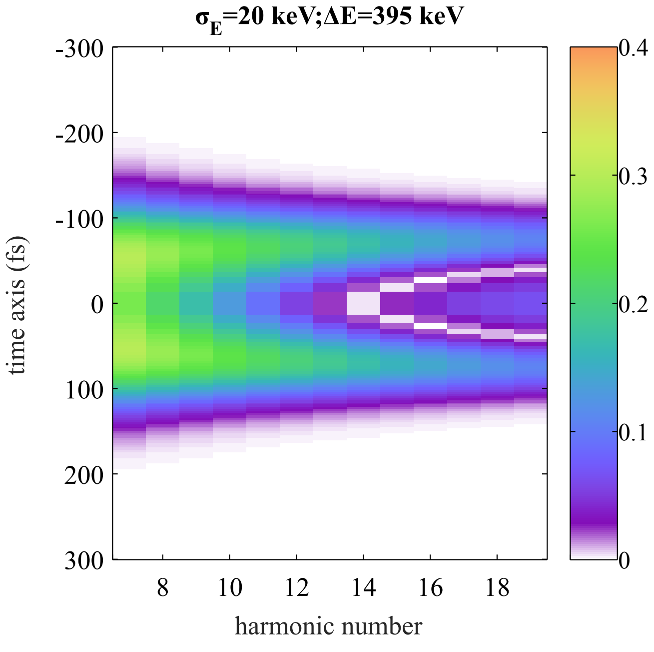

Figure 1: Distribution of the bunching factors (color coded) for different harmonic numbers $n = 7..19$.

EXPERIMENT

Setup and Procedure

The parameters of the experimental setup are summarized in Table 1. Figure 2 shows a schematic layout of the CHG seeding experiment with it modulator undulator, the chicane and one radiator undulator module. An XUV spectrometer as well as an micro-channel plate (MCP) based detector are used to measure the CHG pulse energy and spectrum. The 266-nm seed pulses are generated by third-harmonic generation (THG) of near-infrared (NIR) Ti:sapphire laser pulses. The electron bunch compression settings were chosen such that a sufficient CHG signal is detectable in the photon diagnostic section but without starting exponential FEL gain within 2 meters of undulator length. Once the laser-electron overlap has been established, the undulator gap is scanned and the generated radiation is recorded by the MCP detector and the spectrometer.

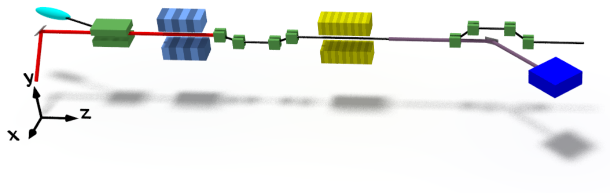

Figure 2: Schematic of the experimental setup. The seed laser is injected at the last dipole of the energy collimator section.

Measurements

Figure 3 shows the result of the scan of the undulator gap. The CHG pulse energy was recorded up to the 19th harmonic of the 267-nm seed laser for a fixed MCP gain voltage (blue data points). Extending the range of the gap scan towards even higher harmonics was performed for higher gain voltages (red data points). The inset of the figure shows the integrated spectrum for the maxima of the harmonics. The measurement proves that the MCP indeed shows radiation at the particular harmonic and is not effected by other signals.

RESULTS

The maxima of the CHG signal for each harmonic number n was used to compare the measurement with simulation data. Figure 4 shows the calibrated energy measurements for each harmonic as a function of n. A least square fit was used in order to find the $(\sigma_E, \Delta E)$-set of simulation which fits best to the measurement data. The red solid line corresponds to the best fit and the dashed lines indicate the 1-σ error band. The retrieved values for the energy spread the modulation amplitude are:

$$\sigma_E = 13 \pm 3\,\text{keV} \tag{2}$$

$$\Delta E = 315 \pm 10\,\text{keV} \tag{3}$$

The results are well in line with the predicted values for the energy spreads given by $\sigma_E = 100\,\frac{\text{keV}}{\text{kA}} \cdot I$ with I being the peak current in kA. As the compression factor for the experiment was about 8, we can conclude that the slice energy spread from the FLASH photo-injector is in the order of 1.5 keV. This value is also close the results measured

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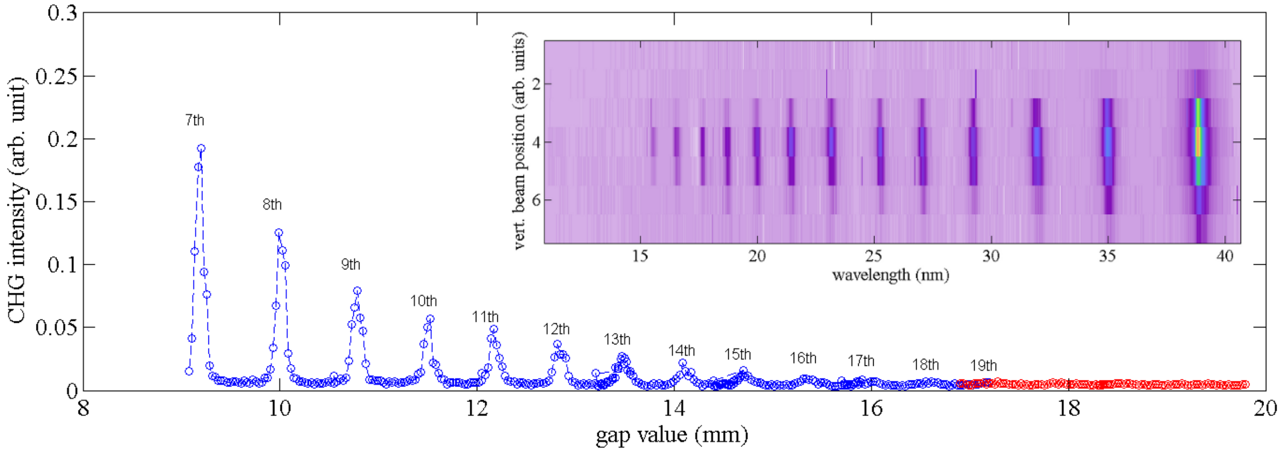

Figure 3: Coherent harmonic generation signal from a 2-m-long variable-gap undulator as a function of the gap value. By scanning the gap from 9 to 20 mm the undulator is resonant to the different harmonics of the 266 nm seed laser. The inset shows an integrated spectrum of the complete scan.

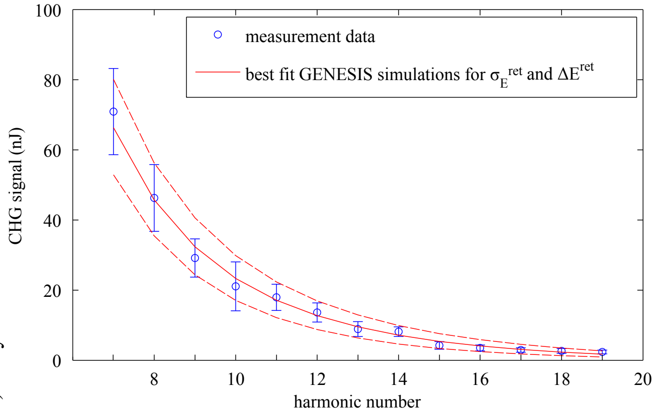

Figure 4: Measured energy maxima for scanning the hamrnonic number and the result of the best fit from the numerical model to the data.

at the DUV-FEL facility in Shanghai of 1.2 keV [5]. The modulation amplitude has been characterized independently using a transversely deflecting structure and fits within the measurement error to the retrieved values using this method.

SUMMARY

The slice energy spread of the FLASH electron beam has been retrieved by comparing simulation and measurements of seeded coherent undulator radiation by coherent harmonic generation. For a peak current of $I = 160$ A and a beam energy of 690 MeV we found the slice energy spread to be $\sigma_E = 13 \pm 3$ keV.

OUTLOOK

The measurements are planned to be repeated for several sets of bunch compressions and for varying laser-electron timings. That way the energy spread profile along the electron bunch distribution can be characterized.

ACKNOWLEDGMENTS

Without the help from many groups at DESY, the preparation and commissioning of all components of this experiment would not have been conceivable. Their support is gratefully acknowledged. This work is supported by the Federal Ministry of Education and Research of Germany within FSP-302 under FKZ 05K13GU4, 05K13PE3, and 05K16PEA and the German Research Foundation within GrK 1355.

REFERENCES

[1] W. Ackermann *et al.*, *Nature Photonics*, vol. 1, p. 336, 2007.

[2] E. Allaria *et al.*, *Nature Photonics*, vol. 6, p. 699, 2012.

[3] P. Emma *et al.*, *Nature Photonics*, vol. 4, p. 641, 2010.

[4] T. Ishikawa *et al.*, *Nature Photonics*, vol. 6, p. 540, 2012.

[5] C. Feng *et al.*, *Phys. Rev. ST Accel. Beams*, vol. 14, p. 090701, 2011.

[6] L.-H. Yu *Phys. Rev. A*, vol. 44, p. 5178, 1991.

[7] E. Jaeschke *et at.*, *Synchrotron Light Sources and Free-Electron Lasers*, (New York: Springer International Publishing, 2016), 207.

[8] S. Reiche, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, p. 243, 1999.

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