Study of the statistical properties of the radiation from a VUV SASE FEL operating in the femtosecond regime

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The Free-Electron Laser (FEL) at the TESLA Test Facility at DESY operates in the self-amplified spontaneous emission mode and generates sub-100-fs radiation pulses in the vacuum ultraviolet spectral region. During operation in the saturation regime, radiation pulses with GW peak power are produced. The statistical properties of the FEL radiation have been studied for different amplification regimes as well as behind a narrow-band monochromator and found to be in good agreement with the results of numerical simulations. Information about the spectral and temporal structure of the FEL radiation has been deduced from the statistical properties. The pulse duration of the FEL radiation can be varied by tailoring the electron bunch that drives the FEL.

1. Introduction

Free-Electron Lasers (FEL) based on the principle of Self-Amplified Spontaneous Emission (SASE) [1–4] produce powerful, transversely coherent radiation within a single pass of the electron beam through an undulator. The amplification process in a SASE FEL starts from shot noise in the electron beam and, hence, the SASE FEL radiation itself is of stochastic nature. Theoretical investigations [5] predict that the radiation from a SASE FEL operating in the high-gain linear regime incorporates all features of completely chaotic polarized radiation. Experimental studies of the statistical properties in this regime have been presented in Ref. [6].

In this paper, we present a comprehensive experimental and theoretical study of the statistical properties of the SASE FEL radiation covering the linear and nonlinear regime. The probability densities of the total energy in the radiation pulse as well as a small spectrally resolved fraction measured behind a monochromator are found to be in good agreement with the results from numerical simulations obtained with the code FAST [7]. We can infer information about the spectral and temporal structure of the SASE FEL radiation from the statistical properties.

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2. Experimental setup and data recording

The experimental results presented in this paper have been achieved at the TESLA Test Facility (TTF) FEL at the Deutsches Elektronen-Synchrotron DESY. The principal layout of the experimental setup and a detailed description of the TTF FEL is given in Ref. [8].

The energy in the radiation pulse has been monitored with a micro-channel plate (MCP) based detector consisting of a gold wire mesh that scatters a tiny fraction of the FEL radiation onto a MCP (for further details and method of calibration see Ref. [9]). During the data recording, the individual bunch charges and beam offsets at the undulator entrance – the most critical beam parameters influencing the FEL process – have been measured simultaneously. In order to exclude machine jitter contributions from the data analysis, only those pulses have been taken into account for which the bunch charge was within 1% (rms) of the average charge and the orbit deviation was less than 50 μm (rms) of the nominal orbit. After such a data selection, the measured pulse-to-pulse fluctuations of the energy in the radiation pulse are dominated by the statistical properties of the SASE FEL radiation.

The statistical behaviour of the pulse energy for a small spectral bandwidth has been studied using a narrow-band monochromator of an optical feedback system [10]. The monochromator consists of a spherical grating in Littrow mounting with a resolution of about $(\Delta\omega/\omega)_{\mathrm{M}} \simeq 10^{-4}$.

The full spectral distribution of the SASE FEL radiation has been measured with a commercial 1-m normal incidence monochromator (0.2 nm resolution) equipped with a fluorescent screen (P46) in the focal exit plane which was imaged with an intensified CCD camera [11]. Both, the short exposure times (down to 5 ns) of the ICCD camera and the imaged dispersive range (about 7 nm) enabled the recording of the full spectral distribution of single FEL pulses (single-shot spectra).

3. SASE FEL amplification process

The upper part of Fig. 1 shows the typical evolution of the average energy in the radiation pulse as a function of the active undulator length. The active length of the undulator has been varied by orbit deflections of the electron beam at the position z which were sufficient to inhibit the SASE process. Apparently, the amplification process passes three stages: start-up from shot noise (lethargy regime), exponential gain (i.e. high-gain linear regime), and saturation (nonlinear regime). The fluctuations of the pulse energy presented in the lower part of Fig. 1 are inherent in the SASE process. For a length $z < 5$ m the rms fluctuation is in the order of 4% and mainly given by the MCP-based detector. When the FEL radiation exceeds the level of spontaneous emission, the rms energy deviation increases rapidly to more than 60%. The growth of the intensity fluctuations in the high-gain linear regime ($z = 6 - 10$ m) is due to transverse mode selection along with the increase of the longitudinal coherence. A sharp drop of the energy fluctuations is observed when the energy in the radiation pulse approaches the saturation level in the nonlinear regime [12].

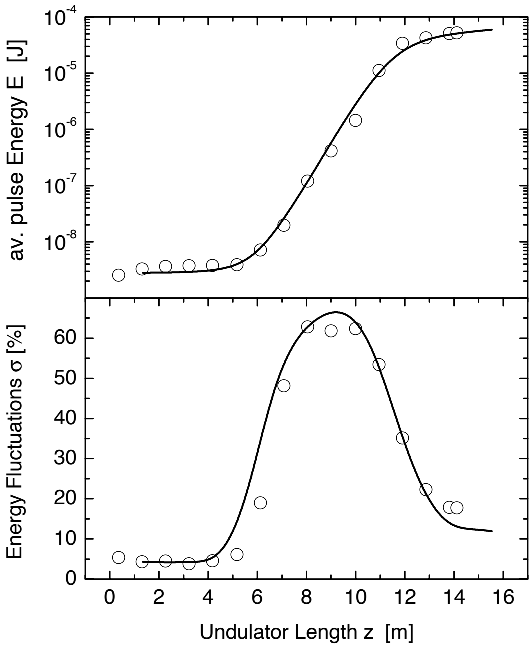

Figure 1. Average energy in the radiation pulse (top) and the rms energy deviation (bottom) versus the active undulator length. The wavelength of the FEL radiation was 98 nm. Circles: experimental results. Solid curves: numerical simulations with the code FAST [7].

4. High-gain linear regime

The fluctuations of the energy in the radiation pulse have been measured in the high-gain linear regime for two different electron beam parameters (Fig. 2). The radiation from SASE FELs operating in the high-gain linear regime possesses all the features of completely

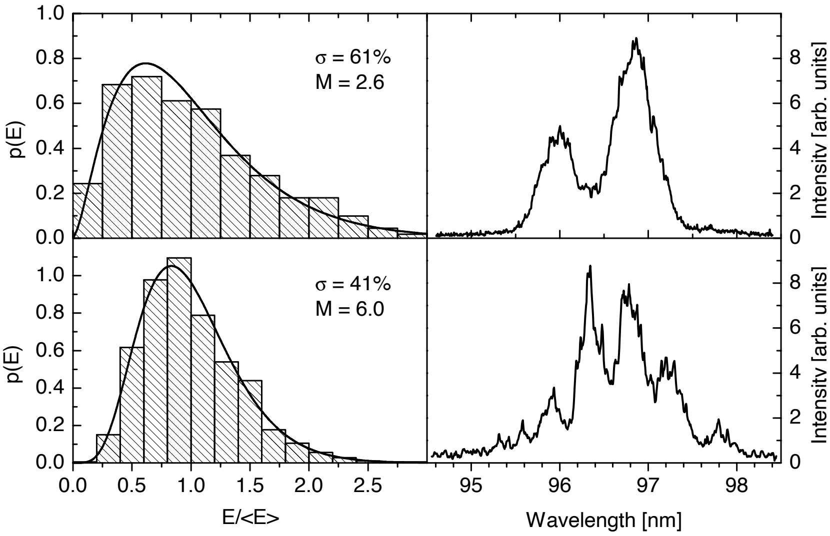

Figure 2. Left: Probability density distributions of the energy in the radiation pulse for different tailoring of the electron bunch. The FEL has been operated in the high-gain linear regime. Solid curves represent gamma distributions. Right: Single-shot spectra for the corresponding modes of operation.

chaotic polarized light [5]. In particular, fluctuations of the energy in the radiation pulse follow a gamma distribution:

$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{\langle E \rangle}\right)^{M-1} \frac{1}{\langle E \rangle} \exp\left(-M\frac{E}{\langle E \rangle}\right),$$

where $\Gamma(M)$ is the gamma function, $M = 1/\sigma^2$, and $\sigma^2 = \langle (E - \langle E \rangle)^2 \rangle / \langle E \rangle^2$. The parameter M can be interpreted as the average number of "degrees of freedom" or "modes" in a radiation pulse. In the high-gain linear regime the radiation from SASE FELs is almost completely transversely coherent [13], and the value of M is the typical number of spikes in the temporal and spectral distribution of the radiation pulse.

The left part of Fig. 2 shows the probability density distributions of the pulse energy together with the deduced number of modes $M = 2.6$ (top) and $M = 6.0$ (bottom). The measured probability density distributions perfectly match gamma distributions. Single-shot spectra, corresponding to these modes of operation, are presented in the right part of Fig. 2. The number of spikes in the spectra corresponds to the number of modes M derived from the statistical analysis. The typical duration of one spike in the time domain is given by the value of the coherence time t_c. The latter quantity is directly related to the gain length or to the averaged spectral width [14] and has been measured to be $t_c \simeq 20$ fs [15]. Finally, the pulse durations can be calculated by $\tau_{rad} \simeq M \cdot t_c$ and amount to $\tau_{rad} \simeq 50$ fs (top) and $\tau_{rad} \simeq 120$ fs (bottom). Furthermore, the width of the spikes in the spectra is reduced for larger values of M. The spectral width of the spikes is inversely proportional to the pulse duration.

The variation of the number of modes in the radiation pulse and, hence, the pulse duration has been achieved for different bunch compressor settings in combination with the correct matching of the phases of the accelerating modules (see Ref. [8]). Thus, the duration of the radiation pulse at the TTF FEL can be tuned depending on the tailoring of the driving electron bunch.

Another fundamental property of the radiation from SASE FELs operating in the high-gain linear regime is that the radiation energy of a narrow spectral band fluctuates according to the negative exponential distribution:

$$p(E) = \frac{1}{\langle E \rangle} \exp\left(-\frac{E}{\langle E \rangle}\right), \qquad (1)$$

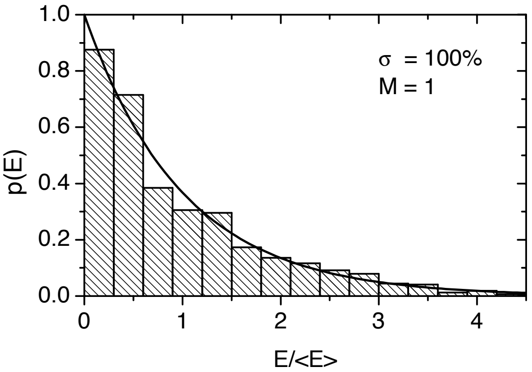

Figure 3. Probability density distributions of the pulse energy behind a narrow-band monochromator. The SASE FEL has been operated in the high-gain linear regime. The active undulator length was 9 m. The solid curve represents the negative exponential distribution.

where $\langle E \rangle$ is the average pulse energy. Measurements of the fluctuations of the radiation energy have been performed behind the narrow-band monochromator of the optical feedback system [10]. The resolution of the monochromator is of the order of a spike in the spectrum. The measured probability density distribution of the energy in the radiation pulse behind the monochromator is shown in Fig. 3. The solid curve represents the negative exponential distribution (Eq. (1)) and is in good agreement with the experimental results. That means, energy fluctuations amount to 100% for the fraction of the radiation behind a monochromator with a resolution in the order of a spike in the spectrum.

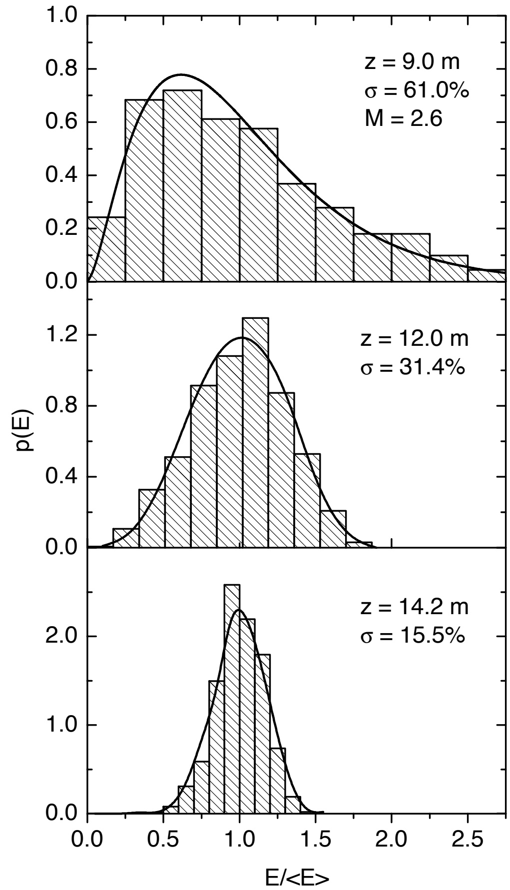

Figure 4. Probability density distributions of the energy in the radiation pulse at the undulator lengths $z = 9$, 12, and 14.2 m. The upper plot corresponds to the high-gain linear regime, the lower plots to the nonlinear regime. The solid curves are the results of simulations with the code FAST [7].

5. Nonlinear mode of SASE FEL operation

A detailed quantitative study of the statistical properties in the nonlinear regime has been performed for a pulse duration of about 50 fs ($M = 2.6$). The average energy in the radiation pulse presented in Fig. 1 has been recorded under these conditions. Figure 4 shows the evolution of the probability distribution of the energy fluctuations in the nonlinear regime. Energy fluctuations are presented for active undulator lengths $z = 9$ m, 12 m, and 14.2 m. In the nonlinear regime, the probability distribution no longer matches the gamma distribution and the number of modes M cannot be deduced anymore from the (rms) width σ of the probability distribution. The step from the high-gain linear to the nonlinear regime occurs abruptly within the order of a field gain length (≈ 1.4 m [15]). The evolution of the probability distribution is in good agreement with theoretical predictions and numerical simulations (solid curves).

Measurements of the energy fluctuations of the

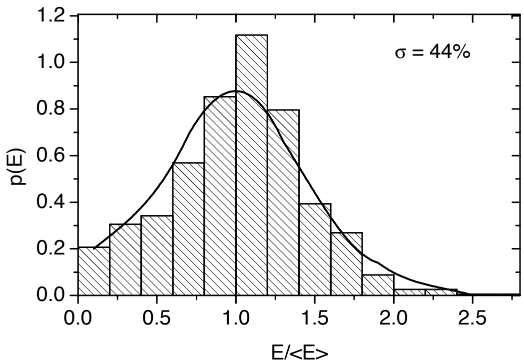

Figure 5. Probability density distribution of the pulse energy behind a narrow-band monochromator. The SASE FEL has been operated in the nonlinear regime; the active undulator length was 14.2 m. The solid curve represents simulations with the code FAST [7].

SASE FEL radiation in the nonlinear regime have also been performed behind a narrow-band monochromator (Fig. 5). The theory of SASE FELs predicts that the fluctuations should drop noticeably when the pulse duration τ_{rad} is such that $\rho\omega\tau_{\mathrm{rad}} \lesssim 3$ [12] with ρ being the FEL parameter. The fluctuations increase drastically for larger values of $\rho\omega\tau_{\mathrm{rad}}$ and approach quickly the 100% level. Since the radiation pulse length at the TTF FEL is about twice the coherence time ($\rho\omega\tau_{\mathrm{rad}} \simeq \tau_{\mathrm{rad}}/t_{\mathrm{c}} \simeq 2.6$) [15], we should expect a significant suppression of the fluctuations in the nonlinear regime. It can be seen from Fig. 5 that the measured fluctuations of the pulse energy are only $\sigma = 44\%$ for the nonlinear mode of operation. There is both qualitative and quantitative agreement of the experimental results with calculated probability density distribution. It is worth to mention that such a reduction of the fluctuations is a further, independent indication for very short pulse durations τ_{rad} [12].

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