Statistical properties of SASE FEL radiation: experimental results from the VUV FEL at the TESLA Test Facility at DESY

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Abstract

This paper presents an experimental study of the statistical properties of the radiation from a SASE FEL. The experiments were performed at the TESLA Test Facility VUV SASE FEL at DESY operating in a high-gain linear regime with a gain of about 10^6. It is shown that fluctuations of the output radiation energy follows a gamma-distribution. We also measured for the first time the probability distribution of SASE radiation energy after a narrow-band monochromator. The experimental results are in good agreement with theoretical predictions, the energy fluctuations after the monochromator follow a negative exponential distribution.

1 Introduction

The correct design of a self-amplified spontaneous emission free electron laser (SASE FEL) and the planning of the equipment and experiments of FEL users depend strongly on an understanding of the radiation amplification process in the

[1] V. Ayvazyan, N. Baboi, I. Bohnet, R. Brinkmann, M. Castellano, L. Catani, P. Castro, M. Dohlus, H.T. Edwards, B. Faatz, A.A. Fateev, J. Feldhaus, K. Flöttmann, A. Gamp, T. Garvey, C. Gerth, V. Gretchko, B. Grigoryan, U. Hahn, C. Hessler, K. Honkavaara, M. Hüning, R. Ischebeck, M. Jablonka, T. Kamps, M. Körfer, M. Krassilnikov, J. Krzywinski, J. Lewellen, M. Liepe, A. Liero, T. Limberg, H. Loos, C. Magne, J. Menzel, P. Michelato, M. Minty, A. Mosnier, U.-C. Muller D. Nölle, A. Novokhatski, C. Pagani, F. Peters, J. Pflüger, P. Piot, L. Plucinski, K. Rehlich, I. Reyzl, A. Richter, J. Rossbach, E.L. Saldin, W. Sandner, H. Schlarb, G. Schmidt, P. Schmüser, J.R. Schneider, E.A. Schneidmiller, H.J. Schreiber, S. Schreiber, D. Sertore, S. Setzer, S. Simrock, R. Sobierajski, B. Sonntag, B. Steeg, F. Stephan, K.P. Sytchev, K. Tiedtke, M Tonutti, R. Treusch, D. Trines, D. Türke, V. Verzilov, R. Wanzenberg, T. Weiland, H. Weise, I. Will, K. Wittenburg, M.V. Yurkov, K. Zapfe

SASE FEL and the knowledge of the properties of the output radiation. The amplification process in the SASE FEL starts from the shot noise in the electron beam. This implies that the SASE FEL radiation itself is of a stochastic nature. Theoretical investigations [1] predict that the radiation from a SASE FEL operating in the linear regime possesses all the features of completely chaotic polarized radiation. In particular, the probability density function of the energy in the radiation pulse should follow the gamma distribution, and the intensity after a narrow-band monochromator should fluctuate in accordance with a negative exponential distribution.

2 Theoretical background

In the linear mode of operation the SASE FEL can be treated as a narrow band linear device which filters a wide band random input signal – shot noise. A general property of such devices is that an output signal is a Gaussian random process. The properties of SASE FEL radiation can be adequately described in terms of statistical optics: time and spectral correlation functions, probability distributions of finite-time integrals of the radiation power (i.e. energy in the radiation pulse), and probability distributions of the radiation energy after a monochromator. The radiation from a SASE FEL operating in the linear regime falls into the category of statistical optics called completely chaotic polarized light [2]. A detailed study of the statistical properties of the radiation from a SASE FEL is presented in [1]. Here we summarize some results relevant to the SASE FEL operating in the high-gain linear regime:

- The distribution of the instantaneous radiation power P is a negative exponential distribution:

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

  where $\langle P \rangle$ is the average power.
- Finite-time integrals of the instantaneous power (i.e. energy in the radiation pulse) follow a gamma distribution:

$$p(W) = \frac{M^M}{\Gamma(M)} \left(\frac{W}{\langle W \rangle} \right)^{M-1} \frac{1}{\langle W \rangle} \exp\left(-M \frac{W}{\langle W \rangle} \right) , \tag{2}$$

  where $\Gamma(M)$ is the gamma function, $M = 1/\sigma_W^2$, and $\sigma_W^2 = \langle (W - \langle W \rangle)^2 \rangle / \langle W \rangle^2$. 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 FEL is almost completely transversely coherent [3], and the value of M is the typical number of spikes in the radiation pulse. When M tends to unity, the distribution (2) tends to a negative exponential distribution (1). When $M \gg 1$, the distribution (2) tends to a Gaussian distribution.

- The probability density distribution of the radiation energy after a monochromator, $p(W)$, is also described rather well by a gamma probability density function. When transversely coherent radiation is filtered by a monochromator, the number of modes gradually decreases with increasing of the monochromator resolution. When the latter value becomes narrower than the width of a spike in the spectrum, the number of modes in the filtered radiation approaches unity, and the fluctuations of the radiation energy are distributed in accordance with a negative exponential distribution (1).

3 Description of the FEL facility

The experimental results presented in this paper have been achieved at the TESLA Test Facility (TTF) Free-Electron Laser at the Deutsches Elektronen-Synchrotron DESY. The goal of the TTF FEL is to demonstrate SASE FEL emission in the VUV and, in a second phase, to build a soft X-ray user facility [4].

The injector is based on a laser-driven $1\frac{1}{2}$-cell rf gun electron source operating at 1.3 GHz [5–7]. The gun section is followed by a 9-cell superconducting cavity, boosting the energy to 16 MeV. Two superconducting accelerating modules accelerate the electron beam up to an energy of 300 MeV [8]. A bunch compressor is inserted between the two accelerating modules, in order to increase the peak current of the bunch.

The undulator is a fixed 12 mm gap permanent magnet device using a combined function magnet design with a period length of λ_u = 27.3 mm and a peak field of B_u = 0.46 T, resulting in an undulator parameter of $K = 1.17$ [9]. The undulator system is subdivided into three segments, each 4.5 m long. There is a spacing of 0.3 m between adjacent segments for diagnostics. The total length of the system is 14.1 m. The beam orbit straightness in the undulator is determined by the alignment precision of the superimposed permanent-magnet quadrupole fields which is better than 50 μm in both vertical and horizontal direction.

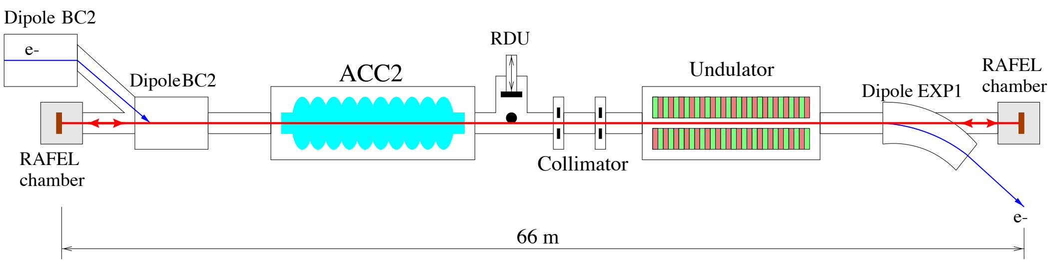


Fig. 1. General layout of the experimental facility. Here BC2 is the bunch compressor, Acc2 is the second accelerating module (120 to 240 MeV), RDU denotes the radiation detector unit (see Sec.4.2 for details). RAFEL chamber downstream the undulator houses a plane SiC mirror, and the chamber in the BC2 area hoses a grating. Both RAFEL chambers are equipped with MCP-based radiation detectors

Table 1
Main parameters of the VUV FEL at TESLA Test Facility

Parameter	Measured value
beam energy	180-270 MeV
rms transverse beam size	100 ± 30 μm
electron bunch charge	1-3 nC
peak electron current	400-600 A
bunch spacing	0.444 ns
number of bunches in a train	24
repetition rate	1 Hz
undulator period, λ_{u}	27.3 mm
undulator peak field	0.46 T
effective undulator length	13.5 m
radiation wavelength, λ_{ph}	80-180 nm
FEL gain	10^6
spectrum bandwidth (FWHM)	0.6%
FEL radiation pulse energy	10-15 μJ
FEL radiation pulse length	0.5-1 ps
FEL radiation peak power	10-20 MW
FEL radiation peak brilliance	10^{27} phot./sec/mrad^2/mm^2/(0.1% BW.)

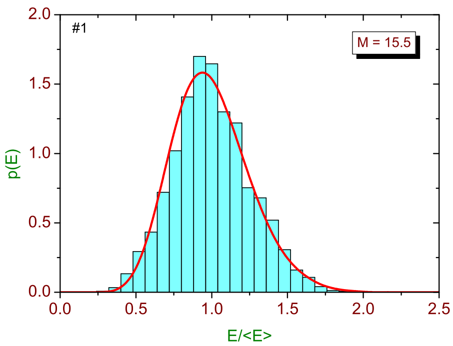
4 Experimental study of statistical properties of SASE FEL radiation

The main parameters for FEL operation are compiled in Table 1. Since the first lasing of the SASE FEL at DESY (February 2000) its performance has been gradually improved. The radiation wavelength is continuously tunable in a wide range from 80 to 180 nm [10]. At present the SASE FEL gain is tuned to the value of about 10^6, of about one order of magnitude below the gain at saturation. This is a significant improvement compared to the FEL gain of about 3×10^3 obtained last year [11]). The energy in the radiation pulse is about 10-20 μJ, the pulse duration is 0.5-1 ps, the peak and average radiation power are about 20 MW and 0.2-0.3 mW, respectively. The peak brilliance is about 10^{27} phot./sec/mrad^2/mm^2/(0.1% BW.).

The stable operation of the facility has enabled us to perform detailed studies of the statistical properties of the radiation from the SASE FEL operating in the high-gain linear regime. The FEL radiation has been monitored with an MCP-based detector consisting of a thin gold wire scattering a tiny fraction of the SASE FEL radiation onto a micro-channel plate (MCP) [12]. The dynamic range of the detector is about eight orders of magnitude which covers the whole operating range of a SASE FEL (from spontaneous emission up to saturation). The scheme of experiment is presented in Fig. 1.

Measurements of the energy in the radiation pulses have been performed by the MCP-based detector installed downstream the undulator in the RAFEL chamber (see Fig. 1). The accelerator has been operated with 24 bunches in a train (1.8 nC bunch charge, 0.444 ns bunch separation) at 1 Hz repetition rate. The radiation detector measured energy for every bunch with relative accuracy of better than 5%. Fluctuations of the output radiation energy occur from train-to-train and bunch-to-bunch within a train. In general they may be caused not only by statistical fluctuations of the SASE FEL radiation, but also by unstable operation of the accelerator. During the experiment we performed simultaneous measurements of individual bunch charges and offsets at the undulator entrance, the most critical beam parameters influencing the FEL process. The analysis of the results shows that the machine fluctuations were small and we did not find a significant correlation between a variation of the above mentioned parameters and the output radiation energy. Thus, we conclude that the measured fluctuations of the radiation energy in the bunch are dominated by the statistical properties of the SASE FEL radiation. During the experiment we stored information on 2000 macropulses and plotted the probability distributions of the radiation energy. Figure 2 illustrates relevant distributions for different bunch positions in the train. The solid curves represent the gamma-distribution (2). The parameter $M = 1/\sigma_W^2$ has been calculated from the experimental data. It is seen that there is good agreement of the measurements with theoretical predictions. Figures 3 and 4 shows the average radiation energy and parameter M along the train.

The determination of the parameter M gives us valuable information about the properties of the radiation pulse in time domain which can not be measured directly. Indeed, typical pulse duration of SASE FELs is about a fraction of a picosecond. The resolution time of modern fast photoelectric detectors is much larger than this value, about a fraction of nanosecond, which allows to measure only total energy



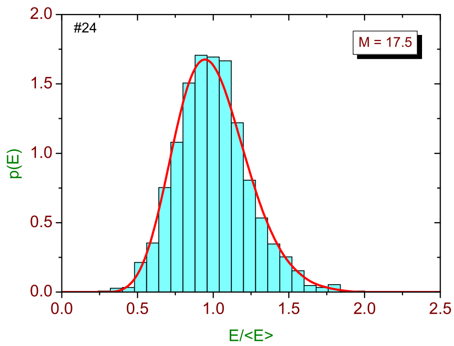


Fig. 2. Probability distribution of the energy in the radiation pulse. Left and right plots correspond to the first and the last bunch in the train, respectively. Solid curves: gamma-distribution.

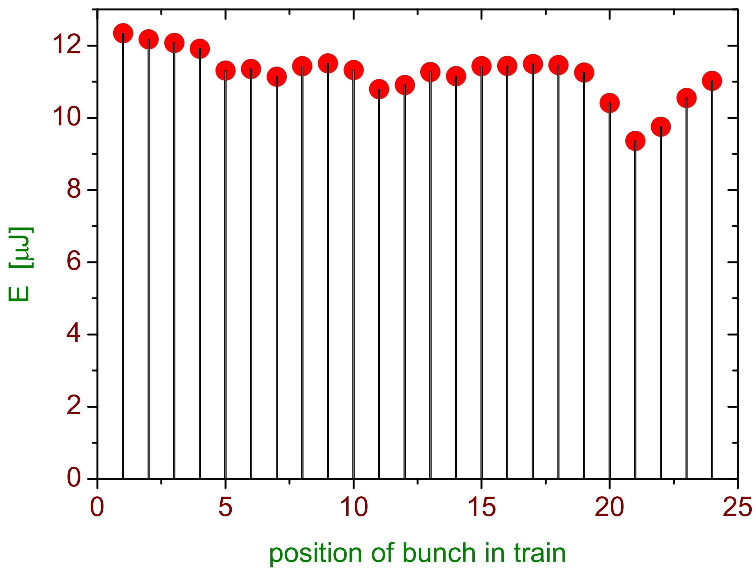


Fig. 3. Average energy in the radiation pulses versus position of the bunch in the train

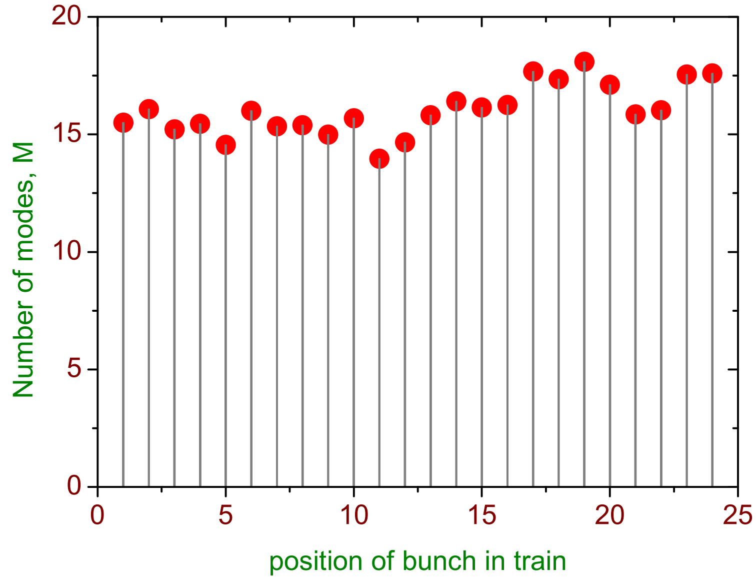


Fig. 4. Number of radiation modes, M, versus position of the bunch in the train

of the radiation pulse. For the SASE FEL operating in the high-gain linear regime the value of M has a direct physical meaning, namely it is about (in average) the number of modes (or spikes) in the radiation pulse in time (or spectral) domain. The typical scale of a spike in the frequency domain is the inverse value of the radiation pulse duration T. The spectral width $\Delta\omega$ of the radiation from a SASE FEL

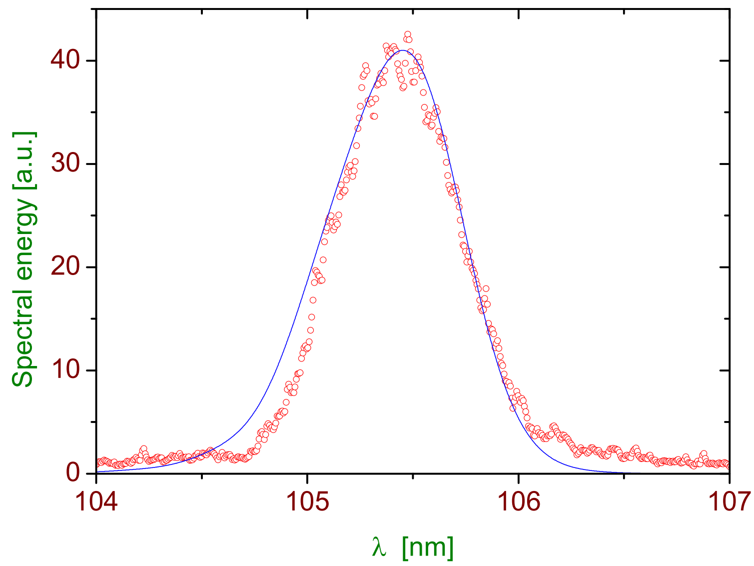


Fig. 5. Single-shot spectrum from TTF SASE FEL (circles). Spiky structure are not seen due to low resolution of monochromator. The solid curve presents the theoretical prediction for the averaged spectrum

can be measured without problems. A relevant measurement for our experiment is presented in Fig. 5. Thus, the radiation pulse length is given by $M/\Delta\omega$. Using the data presented in Figs. 4 and 5, we conclude that the radiation pulse length is about 0.5 ps.

4.2 Fluctuations of the energy after narrow-band monochromator

Measurements of fluctuations of the radiation energy after the monochromator have been performed using a narrow-band monochromator of the RAFEL (Regenerative Amplifier FEL [13]) optical feedback system. The scheme of the experiment is explained in Fig. 1. The SASE FEL radiation emitted by the electron beam is back-reflected by a plane SiC mirror (RAFEL chamber at the right side of the scheme) onto monochromator (RAFEL chamber at the left side of the scheme). The RAFEL monochromator is a spherical grating in Littrow mounting which disperses the light in the direction of the radiation detector unit (RDU) installed 27 meters downstream. The RDU is equipped with an MCP-based radiation detector with a thin (200 μm) gold wire which plays the role of an exit slit of the monochromator. The design of a spherical grating in Littrow mounting guarantees a resolution of about $(\Delta\omega/\omega)_{\mathrm{M}} \simeq 10^{-4}$ which is less than typical scale of the spike in spectrum $\Delta\omega/\omega \simeq 3 \times 10^{-4}$ (this value is given by the SASE radiation spectrum width divided by the number of modes M). The experimental procedure is the same as being described in the previous section. We stored information on 300 radiation pulses passed monochromator and plotted a histogram of the probability distribu-

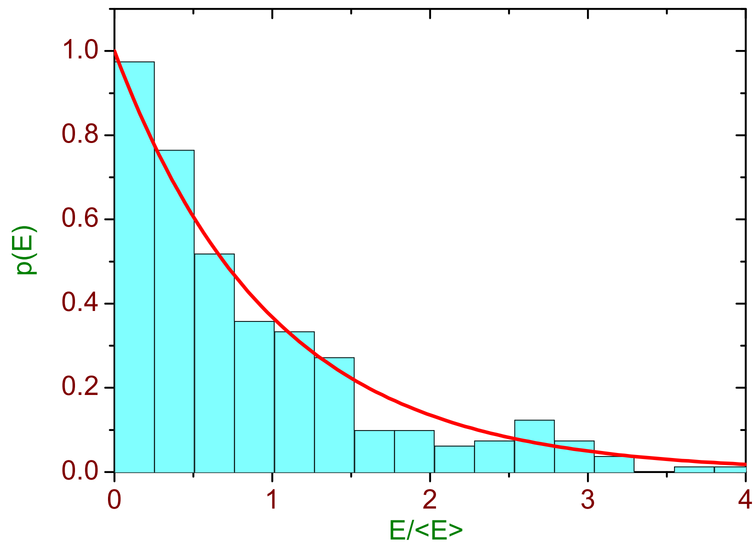


Fig. 6. Probability distribution of the energy in the SASE radiation pulse after narrow-band monochromator. Solid line: negative exponential distribution

tion of the radiation energy in the pulse. The solid curve in Fig. 6 represents the negative exponential distribution (1). It is seen that there is good agreement between experimental and theoretical results.

References

[1] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Opt. Commun. **148**(1998)383

[2] J. Goodman, Statistical Optics, (John Willey and Sons, New York, 1985)

[3] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opt. Commun. **186**(2000)185

[4] J. Rossbach, Nucl. Instr. and Meth. **A 375,** 269 (1996)

[5] J.-P. Carneiro, et al., Proc. 1999 Part. Acc. Conf., New York, 2027-2029 (1999)

[6] P. Michelato, et al., Nucl. Instr. and Meth. **A445,** 422 (2000)

[7] I. Will, S. Schreiber, A. Liero, W. Sandner, Nucl. Instr. and Meth. **A445,** 427 (2000)

[8] H. Weise, Proc. 1998 Linac Conf. Chicago, 674-678 (1998)

[9] J. Pflüger, Nucl. Instr. and Meth. **A445,** 366 (2000)

[10] J. Rossbach et al., report at FEL2000 Conference, Nucl. Instr. and Meth. A, in press

[11] J. Andruszkow et al., Phys. Rev. Lett. **85**(2000)3825

[12] B. Faatz et al, "Use of micro-channel plate for nondestructive measurement of VUV radiation from SASE FEL at the TESLA Test Facility", Presentation at FEL2001 Conference

[13] B. Faatz et al., Nucl. Instrum. and Methods **A429**(1999)424