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# EXPERIENCE WITH MCP-BASED PHOTON DETECTOR AT FLASH2

S. Grunewald, E. Mueller, E. A. Schneidmiller, K. Tiedtke, M. V. Yurkov, DESY, Hamburg, Germany
O. I. Brovko, A. Grebentsov, E. M. Syresin, JNR, Dubna, Russia

*Abstract*

We present recent experimental results on statistical measurements of amplification process in FLASH2 SASE FEL. Micro-channel plate (MCP) detector is used for precise measurements of the radiation pulse energy. DAQ based software is used for cross-correlation of the SASE FEL performance and electron beam jitters. Analysis of machine jitters essential for SASE FEL operation has been performed. Application of gating strategy with measured machine parameters allows us to isolate machine jitters from fundamental SASE fluctuations. Subsequent application of statistical techniques for characterization of SASE FEL radiation allows to derive such important quantities as gain length, saturation length, radiation pulse duration, coherence time, and degree of transverse coherence.

## INTRODUCTION

VUV and soft x-ray free electron laser FLASH is in operation at DESY since the year 2000 [1–3]. Several upgrades of the facility have been performed, and currently FLASH covers a wavelength range from 3.5 nm to 100 nm in the fundamental. Two beamlines operate in parallel, FLASH1 with fixed gap undulator (period length $\lambda_w = 2.73$ cm), and FLASH2 with variable gap undulator (period length $\lambda_w = 3.14$ cm). FLASH is equipped with a set of detectors for measurements of the energy in the radiation pulse: gas monitor detectors (GMD), micro channel plate (MCP) based detectors, photodiodes, and thermopiles [4, 5]. MCP detectors are installed in front of all other detectors and are used for precise measurements of the radiation pulse energy of single pulses. The MCP detector measures the radiation scattered by a metallic mesh placed behind an aperture. The electronics of MCP-detector has low noise, about 1 mV at the level of signal of 100 mV which provides a 1% relative accuracy of the radiation pulse energy measurement.

Measurements have been performed in the framework of the experimental program at FLASH2 aiming at development of statistical techniques for characterization of SASE FEL process. In February, 2019 we recorded status of FLASH2 operation corresponding to typical conditions of user run during last months. One of the features during user run was sporadic appearance of machine jitters affecting stability of the SASE FEL output. There were several goals of our studies. Main goal was to include MCP detector into the DAQ system recording essential machine parameters. The next step was to measure FEL gain curve and derive essential parameters of the radiation from these measurements . Final step was to analyze correlation data of SASE output and essential parameters of the electron beam (jitters of orbit and beam formation system) and localize origin of the jitters. It turned out that frequency of sporadic machine jitters during our shift was pretty big, which moved the last planned goal (jitter correlation studies) to the first priority.

Analysis of experimental results shows that the main jitter problem is sporadic orbit jitter which develops from the very beginning of the accelerator. An important feature of this jitter are correlated x-y orbit kicks. Bunch compression system also contributes to the SASE FEL output, but at a smaller level. We also applied gating strategy for cleaning experimental results with subsequent application of statistical techniques for determination of essential parameters of the SASE FEL: gain length, saturation length, coherence time, radiation pulse duration, number of radiation modes in the pulse (longitudinal and transverse), degree of transverse coherence [6–8].

## RAW DATA AND MACHINE JITTERS

Measurement of the radiation pulse energy (average and dispersion) provides reliable way for determination of key parameters of the SASE FEL process. In practical situation there are always machine jitters (orbit, beam formation system, sporadic failures of subsystems, etc) which contribute additionally to fluctuations of the SASE FEL output, so relevant technique for gating of the experimental results with measured parameters of the machine has been developed [2, 6–8]. FLASH is modern facility with global computer control of machine operation, electron and photon

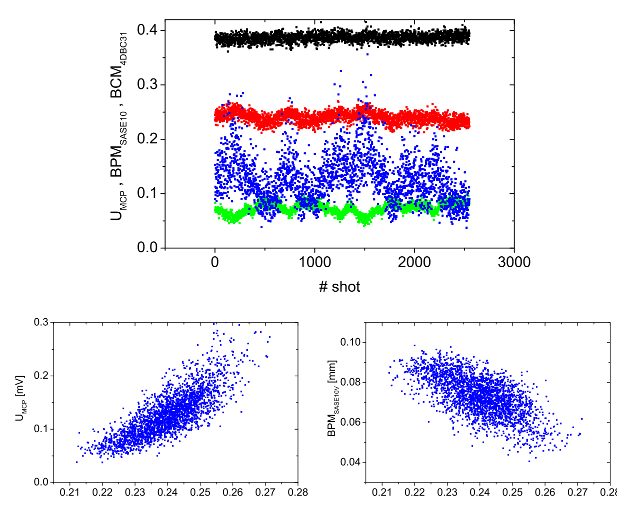


Figure 1: Top: raw signal of MCP detector (blue), BPM 3FL2SASE10 (x - red, y - green), and BCM 4DBC31 (black). Bottom: correlation plots of MCP signal versus BPM 3FL2SASE10H (left), and x and y positions of BPM 3FL2SASE10 (right). Measurements are performed after 7 undulator modules. Radiation wavelength is 10 nm.

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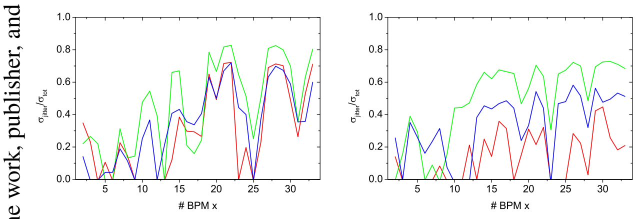

Figure 2: Contribution of the machine jitters seen by BPMs to total fluctuations of the radiation pulse energy. BPMs are numbered according to Table 1. Left: horizontal BPMs, right: vertical BPMs. Red, green, and blue curves refer to measurements after 6, 7, and 8 undulator modules, respectively. Radiation wavelength is 10 nm.

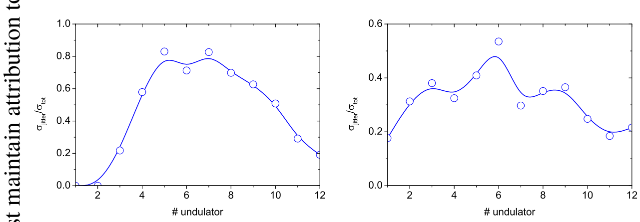

Figure 3: Contribution of machine jitters to total fluctuations of the radiation energy seen by BPM 3FL2SASE10H (left) and BCM 4DBC31 (right) along the undulator. Radiation wavelength is 10 nm.

beam parameters. Each shot of accelerator has unique time stamp, and all essential parameters of the accelerator, electron bunch, and photon pulse related to a specific shot are stored in the data base. For each shot we record signals from MCP and GMD detectors (radiation pulse energy), from the beam position monitors (BPM) along the accelerator and undulator (32 horizontal and 32 vertical listed in Table 1), four signals of beam compression monitors (BCM) installed after BC2 and BC3 compressors, and three signals of bunch charge monitors (gun, FLASH2 extraction section, and undulator entrance). Figure 1 shows data taken for the radiation pulse energy (MCP detector), horizontal beam position in the undulator (3FL2SASE10H), and BCM signal after BC3 stage (4DBC31). Correlation plot in this

Table 1: List of BPMs at FLASH2

| | | | | | |
|---|---|---|---|---|---|
| 1 | 1GUN | 11 | 3DBC3 | 21 | 3FL2SASE3 |
| 2 | 3GUN | 12 | 11ACC7 | 22 | 3FL2SASE4 |
| 3 | 2UBC2 | 13 | 15ACC7 | 23 | 3FL2SASE5 |
| 4 | 1DBC2 | 14 | 19ACC7 | 24 | 3FL2SASE6 |
| 5 | 3DBC2 | 15 | 4FL2EXTR | 25 | 3FL2SASE7 |
| 6 | 5DBC2 | 16 | 5FL2EXTR | 26 | 3FL2SASE8 |
| 7 | 7DBC2 | 17 | 8FL2EXTR | 27 | 3FL2SASE9 |
| 8 | 11DBC2 | 18 | 3FL2SEED1 | 28 | 3FL2SASE10 |
| 9 | 1UBC3 | 19 | 3FL2SEED4 | 29 | 3FL2SASE11 |
| 10 | 2UBC3 | 20 | 3FL2SEED7 | 30 | 3FL2SASE12 |
| 31 | 3FL2SASE13 | 32 | 3FL2SASE14 | | |

Figure clearly demonstrate sporadic jitter which happened during measurements. Our analysis show that machine jitters, essential for SASE FEL operation, appear at the very beginning of the accelerator, and reach maximum values at the undulator entrance. An important observation is that x-y orbit kicks are correlated (see Fig. 1). This feature is clearly detected already after the first accelerating module ACC1.

It is important do derive figure of merit for quantitative description of an effect of machine jitters on SASE FEL operation. Fundamental SASE fluctuations and machine jitters are statistically independent, so total fluctuations are: $\sigma^2_{tot} = \sigma^2_{SASE} + \sigma^2_{jitter}$, and required figure of merit is ratio of machine induced fluctuations to total fluctuations, $\sigma_{jitter}/\sigma_{tot}$. The value of $\sigma_{jitter}$ is calculated after gating of the experimental results. Application of gating procedure sequentially for each measured machine parameter allows to trace evolution of the jitter along accelerator. Relevant plots for the beam position monitors are presented in Fig. 2. We note that some machine jitters are already detected with BPMs in the gun area, then they become pronouncing after the first accelerating module ACC1, and gradually increase along the accelerator. Influence of machine jitters on SASE FEL output also depends on the stage of amplification process. Maximum contribution of the machine jitters is obtained in the end of the high gain linear regime, and becomes less pronouncing in the saturation regime as it is illustrated in Fig. 3. Correlation signals of MCP-BPM (related to orbit jitters) are clean, but correlation signals MCP-BCMs (reflecting jitters of the beam formation system) are not co clear due to larger noise in BCM devices.

## SASE FEL CHARACTERIZATION

Characterization of SASE FEL with statistical methods is based on the analysis of the gain curve with application of basic knowledge on statistical properties of the SASE FEL radiation [1, 2, 6–10]. Radiation from SASE FEL operating in the linear regime holds properties of completely chaotic polarized light, and inverse value of the dispersion of the radiation pulse energy is the number of modes in the radiation pulse, $M = 1/\sigma^2$. Point where fluctuations reach maximum value corresponds to the end of high gain exponential regime with minimum photon pulse length $\tau_{\mathrm{phot}}$. Saturation (corresponding to maximum brilliance of the radiation) occurs when fluctuations of the radiation pulse energy fall down by a factor of 3 with respect to the maximum value. Parameter range of SASE FELs operating in the VUV and x-ray wavelength range is such that the number of field gain lengths to saturation is about 10 [9]. Practical estimates for the field gain length $L_g$, the FEL parameter $\rho$, radiation pulse duration $\tau_{\mathrm{phot}}$, coherence time $\tau_{\mathrm{c}}$, and rms length of the electron beam lasing fraction $\sigma_z$ are [6–8]:

$$L_g \simeq L_{sat}/10 , \quad \rho \simeq \lambda_{\mathrm{w}}/L_{\mathrm{sat}} , \quad \tau_{\mathrm{c}} \simeq \lambda L_{\mathrm{sat}}/(2\sqrt{\pi} c \lambda_{\mathrm{w}}) .$$

$$\tau_{\mathrm{phot}} \simeq \sigma_z \simeq (M \lambda L_{\mathrm{sat}})/(5 c \lambda_{\mathrm{w}}) .$$

Measurements has been performed at FLASH2 at the electron energy of 1130 MeV and bunch charge 280 pC. We tune

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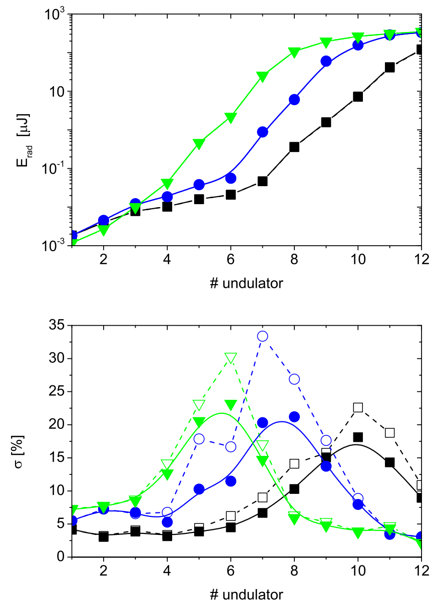


Figure 4: Gain curve of SASE FEL at FLASH2: average energy in the radiation pulse (top) and its fluctuations (bottom). Dashed and solid curves correspond to raw and gated data. Black, blue and green colors correspond to the radiation wavelength 7 nm, 10 nm, and 15 nm.

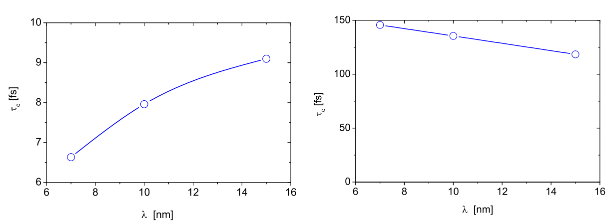


Figure 5: Coherence time (left) and radiation pulse duration (right) derived from the gain curves shown in Fig. 4.

SASE FEL to the maximum signal at full undulator length (12 undulator modules). Then, keeping fixed all machine parameters, we gradually open undulator sections and record all essential machine and photon beam parameters as it has been described in the previous section. Plots in Fig. 4 show experimental results for the gain curve at three radiation wavelengths: 15 nm (closed undulator gap), 10 nm (intermediate gap position), and 7 nm (open undulator gap still providing saturation in the end of the undulator).

In our case sporadic machine jitters contribute significantly to fluctuations, and the next step is to isolate fundamental SASE fluctuations. To do this, we apply gating strategy using measured parameters of the machine. Sensitivity analysis of machine jitters (see previous section) tells us that the most sensitive diagnostics elements are BPM 3FL2SASE10H (orbit) and BCM 4DBC31 (beam compression). Using double discrimination with these parameters we reject 80% of the shots subjected to jitters, and get good quality of the gain curve governed mainly by fundamental SASE FEL fluctuations (see Fig. 4). A strong argument

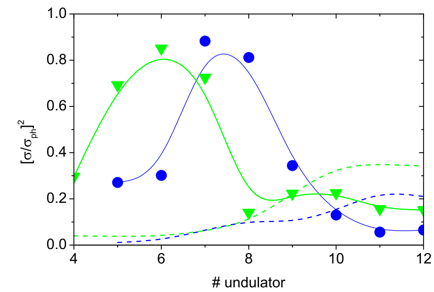


Figure 6: Ratio of dispersions of the full radiation pulse energy to that filtered by a pinhole, $\sigma^2/\sigma^2_{ph}$ (solid lines). Dashed curves show relative fraction of the radiation power passed through a pinhole. Blue and green colors correspond to the radiation wavelength 10 nm and 15 nm.

in favor of this statement is that values of the rms electron pulse duration $\sigma_z$ derived from gated data agree with good accuracy for all measurements (see Fig. 5).

For the radiation wavelengths 10 nm and 15 nm we performed measurements with a pinhole in order to derive the number of longitudinal modes and degree of transverse coherence. Measurements at 7 nm has not been done due to lack of an appropriate aperture much smaller than photon beam spot. In the linear regime, inverse value of the dispersion of the radiation energy after pinhole gives us the number of longitudinal modes, $M_{long} = 1/\sigma^2_{ph}$. Ratio of dispersions of the full radiation energy to that filtered by a pinhole gives the value of the degree of transverse coherence, $\zeta = \sigma^2/\sigma^2_{ph}$ [7, 8]. We see from Fig. 6 that maximum value of the degree of transverse coherence is about 0.8 which is in agreement with theoretical expectations for FLASH2 SASE FEL [10].

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