OPERATION OF FREE ELECTRON LASER FLASH DRIVEN BY SHORT ELECTRON PULSES

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Abstract

The program of low charge mode of operation is under development at free electron laser FLASH aiming in single mode radiation pulses. A short pulse photoinjector laser has been installed at FLASH allowing production of ultrashort electron pluses with moderate compression factor of the beam formation system. Here we present pilot results of free electron laser FLASH operating at the wavelength $\lambda = 13.1$ nm and driven by 70 pC electron bunches. Relevant theoretical analysis has been performed showing good agreement with experimental results.

INTRODUCTION

At the FEL2013 Conference we presented set of experimental results from free electron laser FLASH obtained in the framework of the program aiming production of ultra short radiation pulses [1–3]. We used all available techniques to derive parameters of the experiment. For the electron beam we took measurements of the energy, charge, emittance and longitudinal tomography. Dedicated tuning of the amplification process has been performed which provided good optical matching of the electron beam with focusing system of the undulator. For the radiation we performed set of spectral measurements, and statistical measurements of the radiation properties. At the next step of our studies, described in the present report, we took experimentally measured parameters of the electron beam as input parameters for the FEL simulation code FAST [4], produced many statistically independent simulation runs, and compared obtained results with experimental results containing similar data volume. Very good agreement has been observed without making additional assumptions (corrections) of the experimental results or simulation data.

EXPERIMENTAL METHODS

Experiment has been performed at FLASH at the electron energy of 689 MeV and bunch charge 70 pC. Radiation wavelength was equal to $\lambda = 13.1$ nm. FLASH undulator is fixed gap device with period length $\lambda_U = 2.73$ cm. It consists of 6 modules of 4.5 m length. FLASH facility has been described in details in several references [5, 6]. The only, but very important difference of our experiment is using of a short pulse photoinjector laser with 2.4 ps pulse duration (versus 20 ps standard pulse duration). A reduced photo injector laser pulse duration helps to reduce compression factor of the beam formation system thus relaxing the RF tolerances which scale linear with the compression factor. The commissioning of the new laser system is described in detail in [7, 8].

Table 1: Measured parameters of FLASH FEL operation

Transverse laser shape	Flat-top
Longitudinal laser shape	Gaussian
Injector laser pulse duration (FWHM)	2.4 ps
Electron energy	689 MeV
Bunch charge	70 pC
rms electron bunch length	78 fs
Radiation wavelength	13.1 nm
Linear regime (20 m):	
Radiation pulse energy	2.1 μJ
Fluctuations of pulse energy	40%
Number of modes	5.7
FWHM radiation pulse duration	40 fs
FWHM spectrum width	0.35%
Full length (30 m):	
Radiation pulse energy	25 μJ
Fluctuations of pulse energy	12.5%
FWHM radiation pulse duration	60 fs
FWHM spectrum width	0.42%

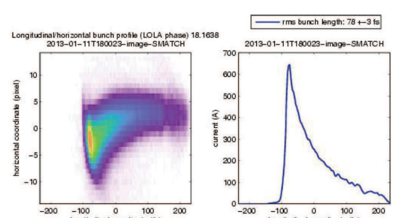

Figure 1: Measured longitudinal bunch duration using the transverse deflecting cavity during SASE performance for 70 pC. Bunch head is on the left-hand side.

The temporal bunch distribution was determined during the SASE performance by a transverse deflecting cavity (see Fig. 1). Additionally, the longitudinal distribution of the bunch was measured using a broadband THz spectrometer [9]. Both measurements show a peak current of 700 A and similar axial profile of the electron bunch. The emittance of the electron bunch has been measured for this setup after the first bunch compressor, and relevant simulation analysis has been performed [10]. Measured values of the projected emittance are 0.7 mm-mrad in vertical direction and 0.9 mm-mrad in horizontal direction. It does not differ strongly from the values derived from start-to-end sim-

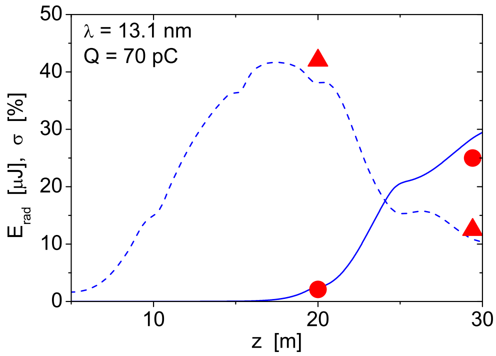

Figure 2: Average energy (solid line) and fluctuations of the radiation energy (dashed line) versus undulator length (simulations with code FAST). Circles (for energy) and triangles (for fluctuations) represent measured values after 4 and 6 undulator modules.

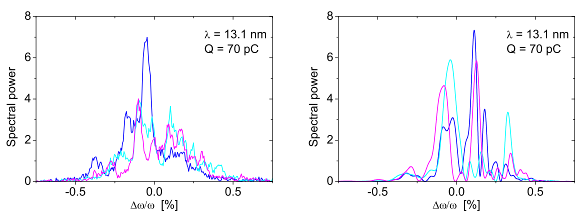

Figure 3: Single shot radiation spectra at full undulator length. Left and right plot refer to the measured spectra and simulation results with code FAST, respectively.

ulations used machine settings as input parameters: 1.26 mm-mrad (horizontal) and 0.8 mm-mrad (vertical).

Schedule of the experiment did not allow us to perform detailed measurements of all FEL properties along the undulator, and we performed extended set of measurements in the end of the exponential gain regime (4 undulator modules, undulator length 20 m, radiation pulse energy 2.1 μJ), and at full undulator length (6 undulator modules, undulator length 30 m, radiation pulse energy 25 μJ). Results of measurements are summarized in Table 1.

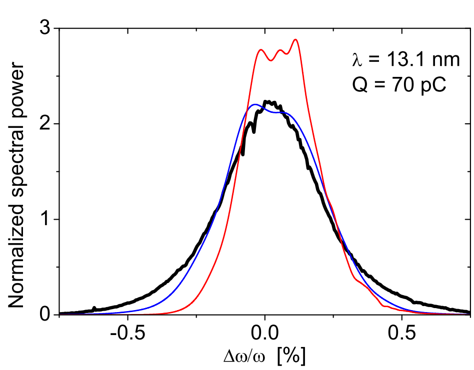

Figure 4: Averaged experimental spectra after 6 undulator modules (bold black curve). Blue and red curves represent averaged spectra calculated with simulation code FAST. Blue and red curve refer to 6 and 4 undulator modules, respectively.

Figure 2 shows gain curve with simulation and experimental results. Average pulse energy has been measured with gas monitor detector (GMD) [11], and statistical measurements have been performed with MCP detector [12, 13]. Saturation length of 25 m has been determined from quick statistical measurements. Radiation from SASE FEL operating in the linear regime holds properties of completely chaotic polarized light [14], and measurements of fluctuations of the radiation pulse energy, allows us to derive the number of modes by $M = 1/\sigma^2$, and radiation pulse duration following Ref. [15] as $L \simeq M \times \lambda_R \times L_{sat}/(5\lambda_U)$. Measured fluctuations in the linear regime are equal to 42% which corresponds to the number of modes $M = 5.7$, and FWHM radiation pulse duration 40 fs. Fluctuations drop to 12.5% at full undulator length (see Fig. 2), and radiation pulse stretches to about 60 fs FWHM.

Radiation spectra have been measured with Plane Grating Monochromator Beamline (PG2) [16]. Figures 3 and 4 show single-shot spectra and averaged spectra at full undulator length. Measured averaged FWHM spectrum width $d\omega/\omega$ is 0.35% for linear regime (after 4 undulator modules), and 0.42% at full undulator length (post-saturation regime).

NUMERICAL SIMULATIONS VERSUS EXPERIMENTAL RESULTS

We took experimentally measured parameters of the electron beam: bunch charge 70 pC, pulse shape from LOLA measurements with peak current of 700 A and energy chirp along the electron pulse of 10 keV/fs (see Fig. 1). We assume electron beam to be perfectly matched in the undulator. In this case average beta function (geometrical mean of periodic) is equal to 7.5 m. These data has been used for simulation of the FEL process with three dimensional, time-dependent FEL simulation code FAST [4].

With these initial conditions we performed statistically independent runs with FEL simulation code FAST (800 for linear regime, and 240 for full undulator length), and derived parameters for comparison with experiment. Figure 2 shows evolution of the radiation pulse energy and its fluctuations along the undulator. Measurements of the pulse energy and fluctuations after the 4th undulator module (20 m) give 2.1 μJ and 42%, respectively. Relevant simulation numbers are 2.3 μJ and 38%. Difference in terms of the number of radiation modes is 5.7 versus 6.9. Such an agreement can be considered as pretty good. The same quality of the agreement refers to the full undulator length, 25 μJ (30 μJ) and 12.5% (10%) for experimental (simulation) results.

Probability distributions of the radiation pulse energy have been derived form simulation data as well. One can see from Fig. 5 that perfect agreement of the details of probability distributions of the radiation pulse energy E takes place - gamma distribution in the linear regime [14]:

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

where $M = 1/\sigma^2$ is number of radiation modes.

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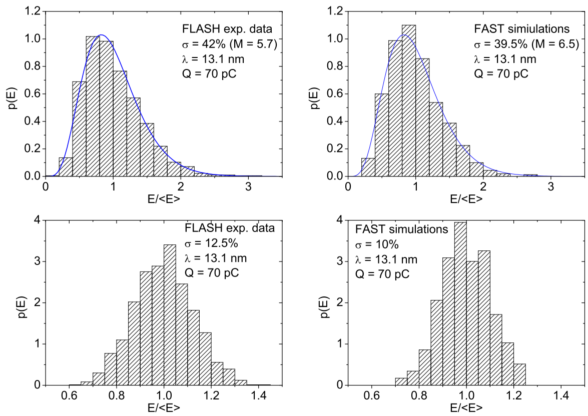

Figure 5: Probability distributions of the radiation energy after 4 and 6 undulator modules (top and bottom raw, respectively). Left and right column represent experimental and simulation results with code FAST, respectively. Blue curve is gamma distribution with parameter $M = 5.7$

Figure 3 shows single shot spectra from experiment (left plot) and from simulations (right plot). We see good qualitative agreement of spectra in terms of the number of spikes. Averaged spectra are presented in Fig. 4. Bold black curve shows experimental results at full undulator length. Relevant simulation results are presented by blue curve. Width of the spectra are pretty much close to each other. Bandwidth of the simulated spectra for the linear regime (red curve) is equal to 0.34% which agrees well with measured value of 0.35%. We note that spectrum bandwidth is close to the natural bandwidth of SASE FEL with monoenergetic electron beam. Thus, lasing part of the beam is not disturbed by a chirp, which is typically caused by beam formation procedures or collective effects. Due to the weak compression these effects could be avoided.

SUMMARY

Free electron laser FLASH with shot-pulse photoinjector laser demonstrated nearly perfect operation in terms of stability and quality of the radiation. It is important that measurements with both, electron and photon beam diagnostics are consistent between each other. Using of measured parameters of the electron beam as input parameters for the FEL simulation code allows to reproduce all features of the radiation. This gives us firm basis for future developments. The next steps are scheduled in the experimental program aiming improving technical reliability of the laser from one side, and demonstration in experiment the reducing of the radiation pulse length to the Fourier limit.

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