OPTICAL AFTERBURNER FOR A SASE FEL: FIRST RESULTS FROM FLASH

M. Först, Max Planck Research Group for Structural Dynamics,
Center for Free Electron Laser Science, University of Hamburg, Hamburg, Germany
M. Gensch, Helmholtz-Zentrum Dresden-Rossendorf e.V., Dresden, Germany
R. Riedel, F. Tavella, Helmholtz-Institut-Jena, Jena, Germany
E.A. Schneidmiller, N. Stojanovic, M.V. Yurkov, DESY, Hamburg, Germany

Abstract

Radiation pulse from a Self-Amplified Spontaneous Emission Free Electron Laser (SASE FEL) consists out of spikes (wavepackets). Energy loss in the electron beam (averaged over radiation wavelength) also exhibit spiky behavior on a typical scale of coherence length, and follows the radiation pulse envelope. These modulations of the electron beam energy are converted into large density (current) modulations on the same temporal scale with the help of a dispersion section, installed behind the x-ray undulator. Powerful optical radiation is then generated with the help of a dedicated radiator (afterburner). We have recently demonstrated this principle at the Free Electron Laser in Hamburg (FLASH), and this paper present the first experimental results.

INTRODUCTION

An afterburner allowing production of optical replica of VUV/x-ray pulses from SASE FEL has been proposed in [1]. It consists of a dispersive section and a radiator installed after the main undulator. FEL amplification process is accompanied by energy loss in the electron beam. On the top of density and energy modulations in the electron beam on the scale of a resonant wavelength λ, there are long-scale energy modulations on the scale of coherence length, $l_c \simeq \lambda/(2\pi\rho)$, where ρ is FEL parameter [2]. When electron beam leaves the main undulator, it passes dispersion section which converts long-scale energy modulations to the modulations of the electron beam current. Short-scale energy and density modulations are completely smeared out due to the energy spread in the electron beam. Then modulated electron beam passes radiator and produces radiation pulse. Significant enhancement of the radiation power takes place on the wavelengths around the values corresponding to the coherence length. Two main applications of this effect were proposed in [1]: production of the optical pulse perfectly synchronized with an x-ray pulse from a SASE FEL to be used for jitter-free pump-probe experiments; and on-line monitoring of x-ray pulse duration since the optical pulse from the afterburner is a replica of an x-ray pulse. Both applications are being worked out at FLASH, and the results will be published elsewhere. In this paper we present and discuss first observations of the afterburner effect at FLASH.

EXPERIMENT

Experiment has been performed at the FLASH facility at DESY, Hamburg [3, 4]. It consists of 1.2 GeV accelerator and a free electron laser operating in the wavelength range from 4.2 nm up to 47 nm. The FLASH facility is equipped with five beam lines for user experiments [4]. The electron beam is produced in a radio frequency gun and brought up to an energy of up to 1200 MeV by seven superconducting accelerating modules operating at a frequency of 1.3 GHz. At intermediate energies of 150 and 450 MeV the electron bunches are compressed in the bunch compressors. The electron beam formation system is based on the use of linearized longitudinal compression realized with the help of an accelerating module operating at a frequency of 3.9 GHz [5]. After acceleration to the target energy (450 to 1200 MeV), electron beam produces powerful coherent radiation during a single pass through the long undulator (planar, hybrid, 12 mm fixed gap, magnetic length 27 m, period 27.3 mm, peak magnetic field 0.48 T).

FLASH facility is equipped with electromagnetic undulator for generation of powerful pulses of far infrared (FIR) radiation precisely synchronized with the x-ray pulses coming out of main undulator [6, 7]. FIR undulator is installed after the main undulator. Outcoupling of the FIR radiation is performed by the mirror with the hole. Well collimated x-ray pulse passes through the hole and is transported to the experimental hall via x-ray beamline. FIR pulse is reflected by the mirror and is directed to the dedicated optical beamline transports the FIR radiation to the experimental area [8]. Both pulses can be recombined in the experimental chamber for performing pump-probe experiments. Parameters of the FIR undulator are: period length is 40 cm, number of regular periods is 9, and value of the peak magnetic field can be changed from 0 to 1.2 T (maximum value of the undulator parameter $K = 49$). Its wavelength range spans from sub-μm up to 200 μm depending on the electron beam energy. The net compaction factor of the undulator is equal to $R_{56} = 2N\lambda$, where N is the number of undulator periods and λ is the resonant wavelength. Thus, the R_{56} of the FIR undulator can be tuned from 0 to a few mm depending on the value of resonance wavelength.

Experiment has been performed at the electron energy of 890 MeV. Radiation wavelength from the SASE FEL

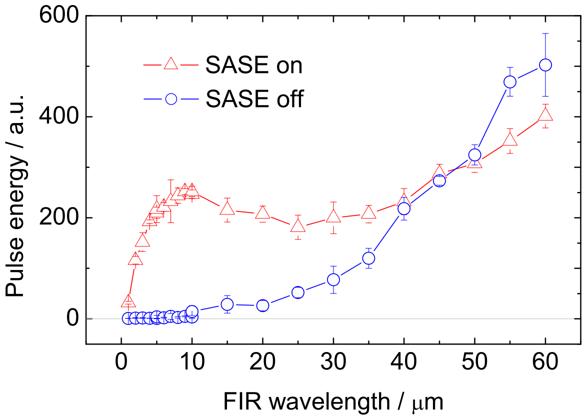

Figure 1: Intensity of the afterburner signal versus resonance wavelength of the FIR undulator. Triangles and circles corresponds to the case of SASE saturation and SASE ”off”, respectively. Numbers on the vertical axis correspond to the signal of Si photodiode in mV. Radiation wavelength of SASE FEL is equal to 7.9 nm.

was 7.9 nm. FEL process has been tuned to the saturation regime with the average energy in the radiation pulse of 100 microjoles. The value of the bunch charge was 0.8 nC. FIR undulator has been used as a dispersion section and a radiator at the same time. At the electron energy of 890 MeV FIR undulator can be tuned to the radiation wavelength up to 80 μm which corresponds to maximum value of the net compaction factor R_{56} of about 1.4 mm.

In principle, there are several sources of the radiation capable to produce afterburner pulse. The first one is FIR undulator. Electron beam passing FIR undulator gains density modulation and simultaneously produces radiation at the fundamental and higher harmonics. The second source of radiation is edge radiation which can be produced behind this undulator. There is a few meter drift between the undulator and the beam dump, so that there is enough space for formation of such radiation in visible and near-infrared range. Also, coherent synchrotron radiation from the dump dipole can give some contribution to the total radiation pulse energy.

Radiation pulse energy has been measured by Si photodiode. Detected band of the radiation is defined by the bandwidth of the optical elements and photodiode, and spans from 0.4 μm to 1.1 μm. Measurements have been performed by means of the field scan of the FIR undulator. Relevant results are presented in Fig. 1 in terms of the resonance wavelength of the FIR undulator. The measurements cover the range of R_{56} from 0 to about 1.1 mm. Two sets of measurements have been taken in each point. Triangles present the case when SASE FEL produces full radiation power in the saturation with the average energy in the radiation pulse of 100 μJ. The second set of measurements (shown by circles) has been performed under conditions when FEL amplification process has been suppressed by means of an angle kick in front of the main undulator. In both cases electron beam passes the same way from the photocathode to the undulator entrance and is subjected to the same electromagnetic fields (accelerating and focusing), and possible collective instabilities as well. The only difference was small deviation of the trajectory in the undulator which excludes difference in any other noticeable collective instability in the undulator except of the FEL instability.

The main concern before starting this experiment was the microbunching instability of high-brightness electron beams in linacs [9, 10] that may occur in the optical range. If the amplitudes of the beam modulation due to such an instability would be comparable to the amplitudes due to the effect under study, one would have difficulties distinguishing between these effects. We performed two types of measurement: when SASE is at saturation, and when it is ”off”, as described above. It is clearly seen from Fig. 1 that in the range of FIR wavelengths around 10 μm and below the photodiode signal disappears when SASE is off. It means that the beam modulations due to the microbunching instability are negligible in this range of R_{56}, and one can study and use a clear FEL afterburner effect. For large values of R_{56} the microbunching instability takes place, but the analysis of its nature is beyond the scope of this paper. It is only important that this effect is well separated from an FEL afterburner effect, and in the case of FLASH is negligible in the region of interest for an afterburner operation.

NUMERICAL SIMULATIONS

Despite parameters of the electron beam are not well known, information we have is sufficient to perform reliable physical estimations of the effect. This happens because of slow evolution of the coherence time with the electron beam parameters. Experiment has been performed at the bunch charge of 0.8 nC. Phase space distribution of the electron beam is rather complicated, and not all electron bunch contribute to lasing. We estimate lasing part of the electron bunch to bring 0.5 nC charge. This number serves just for consistency - the result we are looking for refers to the relative behavior of the bunch form factor which does not depend on bunch charge. Estimates for other essential beam parameters are: the peak electron beam current is about 2000 A, slice normalized electron beam emittance is between 1.5 mm-mrad and 2 mm-mrad depending on tuning of the beam formation system, and slice energy spread is 0.3 - 0.4 MeV. For the further studies we take the value of the normalized rms emittance of 2 mm-mrad. FEL parameter ρ is equal to 1.4×10^{-3}.

The simulations of the FEL process were performed with three-dimensional, time-dependent FEL code FAST [11]. Then particles’ positions in the bunch were changed in accordance with their energies and applied value of R_{56}. An example of the electron bunch structure after dispersion section is shown in Fig. 2. It has pronounced spiky structure of the beam current and of the beam form factor as well. The pattern change from shot-

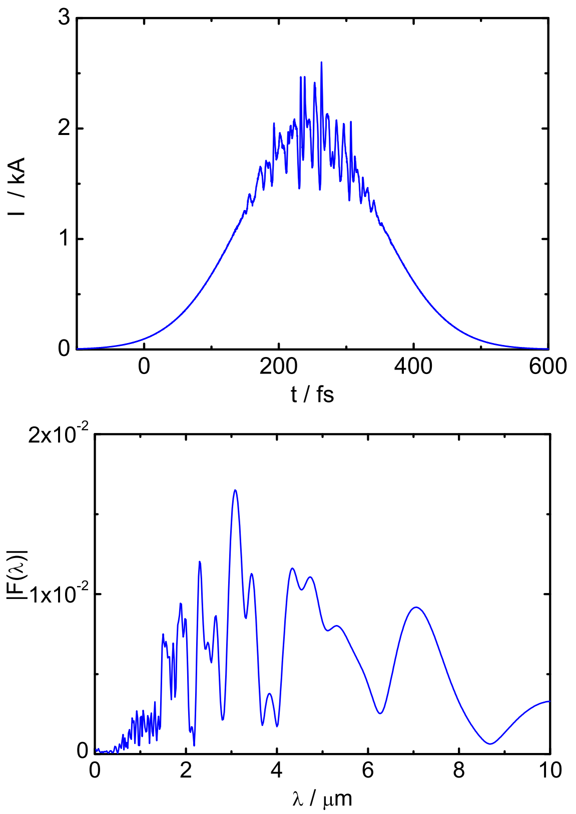

Figure 2: Beam current (upper plot) and form-factor (bottom plot) of the electron bunch after passing dispersion section with net compaction factor $R_{56} = 200$ μm. SASE FEL operates in the saturation regime. Radiation wavelength of SASE FEL is equal to 7.9 nm.

to-shot since SASE is stochastic process. For smaller values of the R_{56} the pattern remains the same but the amplitude reduces proportionally. For larger values of the R_{56} the pattern gets strongly modified, and "red" shift of the bunch spectrum takes place [1]. Spectral density of radiation produced by a bunch in any radiator is $p(\lambda) = p_1(\lambda)\left[N_e + N_e(N_e-1)|F(\lambda)|^2\right]$, where $p_1(\lambda)$ is the energy spectral density produced by a single electron, and N_e is the number of electrons in the bunch. Linear in N_e term gives usual incoherent radiation (spontaneous emission). Thus, a modulated bunch radiates by a factor $N_e|F(\lambda)|^2$ more energy at a given wavelength than an unmodulated bunch. Here we consider the bunch with the charge of 0.5 nC ($N_e = 3.1 \times 10^9$), so that one can expect an enhancement over spontaneous emission by many orders of magnitude.

The next step of our study is simulation of the experimental conditions. We take into account that the region of detection in our case is pretty narrow, from 0.4 μm to 1.1 μm. We calculate $|F(\lambda)|^2$ for 0.8 μm and 1 μm (see Fig. 3) and present plots in the same units of the FIR resonance wavelength as on the plot in Fig. 1. One can see rather good qualitative agreement of experimental and simulation results at small values of the net compaction factor. In both cases signal grows up to the value of the FIR resonance wavelength about 10 μm (R_{56} about 200 μm), and then falls down. As we mentioned above, growth is connected with the growth of the beam modulation at small values of R_{56}. When R_{56} reaches values about $\lambda/(2\pi\rho^2)$, this process saturates. Moreover, "red" shift of the bunch spectrum becomes to be important at some point [1], and intensity of the radiation within detection band falls down.

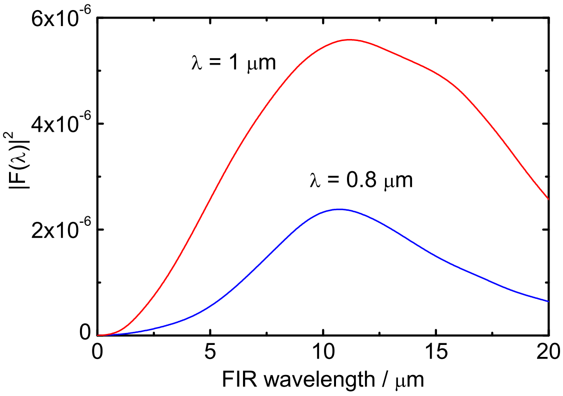

Figure 3: Squared value of the beam form-factor versus FIR resonance wavelength at wavelengths 0.8 and 1 μm. SASE FEL operates in the saturation regime. Radiation wavelength of SASE FEL is equal to 7.9 nm.

ACKNOWLEDGMENTS

We would like to thank A. Al-Shemmary, A. Cavalieri, S. Duesterer, B. Faatz, I. Grguras, T. Laarmann, D. Nicoletti, and W. Seidel, for their assistance in preparation of experiment. We are grateful to FLASH staff for providing smooth and reliable operation of the hardware during experiment.

REFERENCES

[1] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13 (2010) 030701.

[2] R. Bonifacio, C. Pellegrini and L.M. Narducci, Opt. Comm. 50 (1984) 373.

[3] W. Ackermann et al., Nature Photonics 1 (2007) 336.

[4] K. Tiedtke et al., New Journal of Physics 11 (2009) 023029.

[5] E. Vogel et al., Proc. IPAC'10 Conference, Kyoto, Japan, 2010, THPD003.

[6] B. Faatz et al., Nucl. Instrum. and Methods A 475 (2001) 363.

[7] O. Grimm et al., Nucl. Instrum. and Methods A 615 (2010) 105.

[8] M. Gensch et al., Infrared Physics & Technology, 51 (2008) 423.

[9] M. Borland et al., Nucl. Instrum. and Methods A 483 (2002) 268.

[10] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods A 483 (2002) 516.

[11] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods A 429 (1999) 233.