INVESTIGATIONS ON THE OPTIMUM ACCELERATOR PARAMETERS FOR THE ULTRA-SHORT BUNCH OPERATION OF THE FREE-ELECTRON LASER IN HAMBURG (FLASH)*

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Abstract

In order to produce the shortest possible radiation pulses using free-electron lasers like FLASH, various possibilities have been proposed during the last decade. Probably the most robust method is the generation of electron bunches that in the most extreme case are as short as a single longitudinal optical mode of the SASE (Self-Amplified Spontaneous Emission) radiation. For FLASH this means that the bunch length has to be a few fs only. As a consequence, very low bunch charges (in the order of 20 pC) have to be used.

To achieve these extremely short bunch lengths, a new photo-injector laser has been installed, which allows for the generation of shorter electron bunches right at the cathode. Simulations of the electron bunches and their six-dimensional phase-space distribution have been performed to investigate the optimum accelerator parameters during injection and to determine how to realize them. First results are discussed in this contribution.

MOTIVATION

Many users of the FLASH Facility work on pump-probe experiments that allow for instance to study the dynamics of atomic and molecular reactions. The time-resolution of these experiments is determined by the XUV pulse duration. Users have therefore expressed a strong interest for being provided with shorter SASE pulses.

SASE radiation properties such as pulse length and peak power are determined by the electron distribution at the entrance of the undulator section.

At FLASH standard operation, SASE pulses between 50 and 200 fs [1] can be produced. These pulses consist of many longitudinal optical modes. Figures 1 and 2 show the spectrum and longitudinal power distribution of a typical short FLASH SASE pulse of about 50 fs (FWHM) at about 13 nm, simulated with the Genesis FEL code (for further information see [2]). For the simulation a normalized transverse emittance of 1.4 mm mrad, a rms bunch length of 10 μm and a peak current of 2.5 kA have been used.

To produce the shortest possible SASE pulses, the electron bunch length has to be as short as to excite only a single longitudinal optical mode of the radiation. The resulting SASE pulse would then be longitudinally coherent.

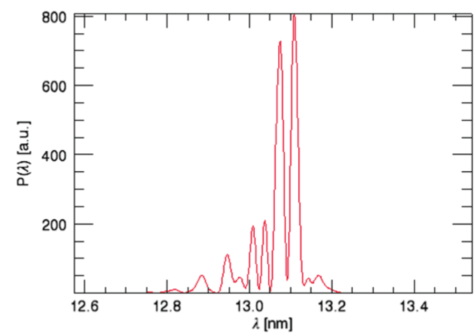

Figure 1: Genesis simulation of a spectrum of a typical short SASE pulse at FLASH (under standard FLASH operation conditions) at about 13 nm when applying an electron bunch with a rms bunch length of 10 μm.

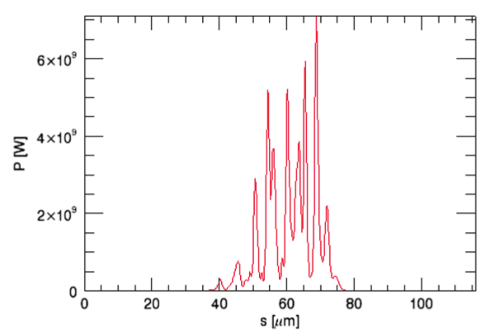

Figure 2: Genesis simulation of the longitudinal distribution of a typical short SASE pulse at FLASH (under standard FLASH operation conditions) at about 13 nm when applying an electron bunch with a rms bunch length of 10 μm.

Simulations of the spectrum and longitudinal distribution for a single mode SASE pulse at FLASH are displayed in Figs. 3 and 4. The simulated bunch parameters are identical to the case mentioned above, only the bunch length has been reduced to 1 μm. Consequently, to keep the peak current constant at 2.5 kA, the charge was reduced by a factor of 10. In this simulation, the optimum SASE pulse is reached after 19 m of the undulator section. Properties like the emittance have not been adapted in this simulation. As shown in the next sections, a clearly reduced emittance is expected, which will further improve the SASE performance. This paper focuses on the optimization of the injector parameters to reach optimum performance.

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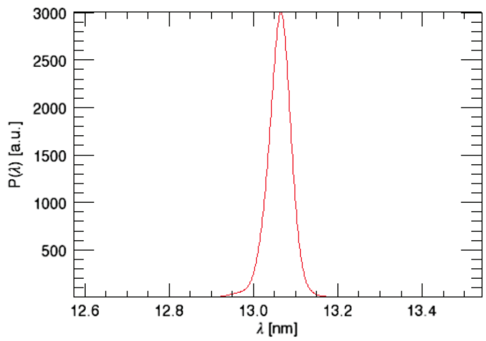

Figure 3: Simulated spectrum of a SASE pulse at about 13 nm, produced at FLASH when applying an electron bunch with a rms bunch length of 1 μm.

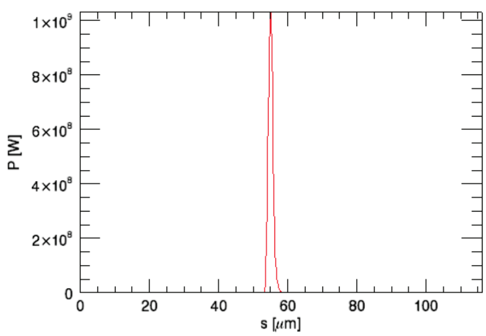

Figure 4: Simulated longitudinal distribution of a SASE pulse at about 13 nm, produced at FLASH when applying an electron bunch with a rms bunch length of 1 μm.

SHORT BUNCH OPERATION AT FLASH

FLASH features two bunch compressors to reduce the initial bunch length and to produce the high peak current needed for SASE operation. RF phase tolerances of the cavities scale linear with the bunch compression factor. This leads to a limitation of the achievable stable bunch compression. As a consequence, to produce very short bunch durations, shorter bunch lengths have to be produced already at the injector.

The initial bunch length is determined by the duration of the photo-cathode laser pulse, the RF-gun phase and by space charge forces. To reduce the duration of the photo-cathode laser pulse, a new photo-injector laser with a shorter pulse length has been installed at FLASH. To overcome the space charge forces, the bunch charge has to be reduced. Using a bunch charge of 20 pC instead of 500 pC would allow to reduce the laser pulse duration as well as the transverse beam size by a factor of about three ($25^{1/3}$) while keeping the space charge forces at the same level as at normal FLASH operation.

The particle tracking code ASTRA [3] has been used to perform simulations to study the influence of the laser and injector parameters on bunch properties such as bunch length and beam emittance and to optimize bunch injection using a shorter laser pulse directly at the photo-cathode.

FLASH INJECTOR

At FLASH, the high quality electron bunches required for the SASE process are provided by an RF photo injector [4]. A Cs_2Te photo-cathode is located at the back of the first half-cell of the RF gun. It is illuminated with laser pulses that create electron bunches by the photo-emission process.

While the FLASH standard laser [5] has a fixed rms pulse duration of 6.5ps, a new injector-laser in combination with a pulse stretcher allows for variable rms pulse durations from about 0.3 to 4.4 ps. The temporal pulse profile is Gaussian. Transversely, the beam is formed by an iris to be flat-top with variable spot size.

A system of main and bucking solenoid is used to compensate space charge induced emittance growth.

INFLUENCE OF LASER AND INJECTOR PARAMETERS ON BUNCH PROPERTIES

The properties of the created electron bunches are strongly determined by the parameters of the injector laser. This includes, amongst others, the bunch length, charge and bunch emittance. These parameters are of great importance for FEL operation. While the bunch length determines the SASE pulse duration, a small emittance is needed for the SASE process[6].

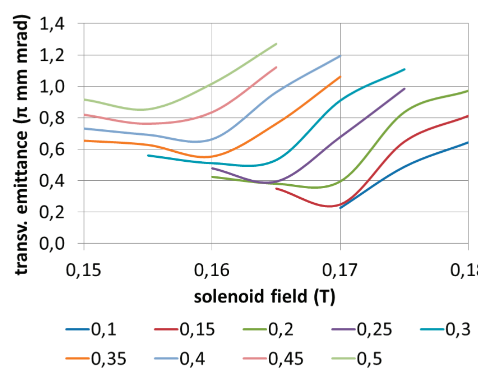

Figure 5: ASTRA simulation of the emittance for a 4.4 ps laser pulse (rms) as a function of the solenoid field for different rms spot sizes on the cathode (labeled with different colors, the unit is mm).

Astra simulations have been performed for a bunch charge of 20 pC. Figure 5 displays the influence of laser spot size and main solenoid focusing strength on the normalized transverse rms emittance at the end of the first accelerating module for a rms laser pulse duration of 4.4 ps. For a laser pulse length of 1.0 ps the resulting emittance is shown in Fig. 6. In both cases, the minimum achievable transverse emittance is at a similar level. This can be

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explained by the different contributions to the emittance. These scale as follows[7],[8]:

$$\epsilon_{\mathrm{x,th}} \propto T_{\mathrm{c}}^{1/2}\sigma_{\mathrm{x}} \quad \text{(thermal emittance)} \tag{1}$$

$$\epsilon_{\mathrm{x,sc}} \propto I_{\mathrm{bunch}}\mu_{\mathrm{x}}(A) \quad \text{(space charge)} \tag{2}$$

$$\epsilon_{\mathrm{x,RF}} \propto \sigma_{\mathrm{z}}^2\sigma_{\mathrm{x}}^2 \quad \text{(RF emittance)} \tag{3}$$

where T_{c} is a temperature indicating the initial spread in the transverse momenta of the photo-electrons at emission, I_{bunch} the charge of the bunch and $\mu_{\mathrm{x}}(A) = 1/(3A+5)$ a form factor depending on the form of the bunch and on $A = \sigma_{\mathrm{x}}/\sigma_{\mathrm{z}}$.

While space charge forces dominate at high particle densities, the RF emittance grows quadratically with the bunch length. In the cases of 1 and 4.4 ps these contributions lead to a balance in the total transverse emittance.

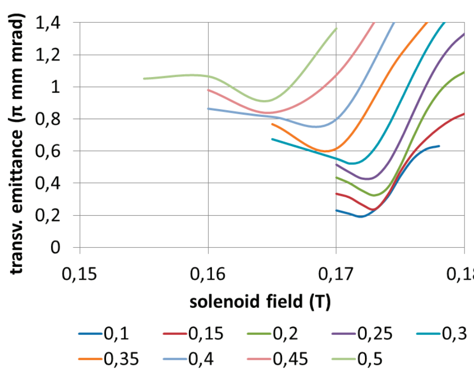

Figure 6: Simulated emittance for a 1.0 ps laser pulse (rms) as a function of the solenoid field for different rms spot sizes on the cathode (labeled with different colors, the unit is mm).

For the 1 nC standard operation at FLASH, the normalized transverse rms emittance has been measured to be 1.4 mm mrad for 90% beam intensity [9]. Thus the emittance predicted by the simulations for a bunch charge of 20 pC are about a factor of 7 less than those measured for standard 1 nC operation.

The influence of the laser spot size and pulse duration on bunch length and longitudinal emittance can be seen in Fig. 7. The shortening of the laser pulse duration from 4.4 to 1 ps does not lead to a shortening of the resulting bunch length by the same factor. This is due to space charge forces that dominate at high particle densities. The reduction of the longitudinal emittance due to the shortening of the laser pulse duration is more than could just be explained by the reduction of the bunch length. This is because in addition to the bunch length the energy spread is diminished.

CONCLUSIONS

The influence of shorter injector-laser pulses on bunch length and emittance has been investigated for a bunch charge of 20 pC using the ASTRA code.

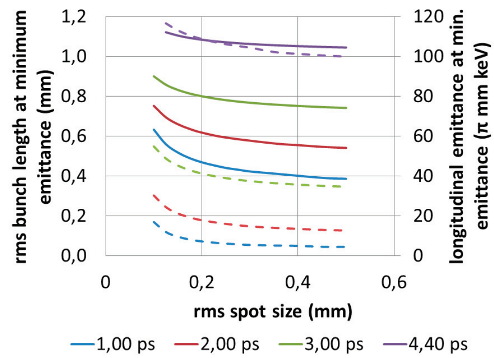

Figure 7: Simulated rms bunch lengths (solid lines, left scale) and corresponding longitudinal emittance (dashed lines, right scale) for different rms laser pulse durations (labeled with different colors) as a function of the spot size.

It has been found that the predicted minimum achievable transverse emittance is about 0.2 mm mrad for both the 4.4 and 1 ps case. This is about a factor of 7 smaller than the emittance for the standard 1 nC operation with a rms laser pulse duration of about 4.2 ps. This leads to a relaxation of the emittance criterion for FELs [6].

The simulations predict that it is possible to shorten the bunch length by more than a factor of 2 by reducing the laser pulse duration from 4.4 to 1.0 ps.

The simulation results will be verified by future measurements, using the new variable pulse length injector laser at FLASH.

REFERENCES

[1] S. Schreiber, et al., "Status of the FEL User Facility FLASH," 33rd FEL Conference (FEL2011), Shanghai, China.

[2] S. Reiche, Genesis 1.3, http://genesis.web.psi.ch/index.html

[3] K. Flöttmann, "ASTRA A Space Charge Tracking Algorithm," Manual, Version 3.0, Oct. 2011.

[4] M. Ferrario, et al., "Conceptual Design of the XFEL Photoinjector," TESLA FEL Report, 2001.

[5] I. Will, et al., "Photoinjector drive laser of the FLASH FEL," Optics Express 23770, Nov.8, 2011.

[6] P. Schmüser, M. Dohlus, J. Rossbach, "Ultraviolet and Soft X-Ray Free-Electron Lasers," Springer Tracts in Modern Physics, Volume 229, 2008.

[7] J.B. Rosenzweig, et al., "Generation of ultra-short, high brightness electron beams for single-spike SASE FEL operation," Nucl. Instr. and Methods A 593 (2008) 39-44.

[8] K.-J. Kim, "RF and space-charge effects in laser-driven RF electron guns," Nucl. Instr. and Methods A 275 (1989) 201-218.

[9] F. Löhl, et al., "Measurements of the transverse emittance at the FLASH injector at DESY," Phys. Rev. ST Accel. Beams 9, 092802 (2006).

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