BEAM DYNAMIC SIMULATIONS FOR SINGLE SPIKE RADIATION WITH SHORT-PULSE INJECTOR LASER AT FLASH*

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Abstract

This paper discusses the generation of single spike SASE pulses at soft x-ray wavelength at the free-electron laser FLASH by using very short electron bunches of only a few micrometer bunch length. In order to achieve these extremely short bunch lengths, very low bunch charges (in the order of 20 pC) and short electron bunches exiting the photo-injector are required. For this, a new short-pulse injector laser with adjustable rms pulse duration in the range of 0.7 ps to 1.6 ps and bunch charges up to 200 pC was installed, extending the electron beam parameter range before bunch compression in magnetic chicanes. Beam dynamic studies have been performed to optimize the injection and compression of low-charge electron bunches by controlling the effect of coherent synchrotron radiation and space-charge induced bunch lengthening and emittance growth. Optimization includes the pulse parameters of the injector laser. The simulation codes ASTRA, CSRtrack and Genesis 1.3 were employed.

MOTIVATION

The Free-Electron Laser in Hamburg (FLASH) is a high-gain SASE FEL user facility offering highly brilliant radiation pulses in the XUV- to soft x-ray range with a typical pulse duration between <50 and 200 fs (FWHM) [1]. Amongst the variety of user experiments that are performed at FLASH there are many pump-probe experiments where the time resolution is limited by the XUV pulse duration. These experiments would greatly benefit from being provided with shorter SASE pulses. In principle, the shorter the SASE pulses that can be offered to the users, the shorter the time scales that can be studied and the better the time resolution for a given process to be investigated. FEL facilities around the world are investigating on the generation of extremely short SASE pulses. A relatively straight-forward method is the generation of SASE pulses from very short electron bunches (see e.g. [2–4]).

Due to the relatively low energies of only a few mega electron volt, space charge forces still play a major role at the injector. Therefore the high peak current and short bunch duration required for the production of short SASE pulses cannot be created at the injector. Instead bunch compression is achieved at higher energies, typically in magnetic chicanes. Strong compression in magnetic chicanes requires very tight RF tolerances in the accelerating structure used to apply the required energy chirp on the bunch. The main challenge for the generation of very short electron bunches is therefore the tolerance of the accelerating RF fields.

At FLASH an additional injector laser has been installed to produce shorter bunches already at the injector. This short pulse injector laser reduces the bunch compression required in the magnetic chicanes for low charge electron bunches, relaxing the RF tolerances for short pulse SASE operation [5].

SASE pulses typically consist of many longitudinal optical modes in the power distribution and spectrum. These individual spikes are typically separated by the cooperation length L_{coop} [6]. The shortest possible SASE pulse consists of only a single mode. This single spike operation constitutes a special mode of operation for FELs. For single spike radiation the bunch length σ_z has to approximately obey $\sigma_z \le 2\pi L_{\text{coop}}$ [2, 6]. At FLASH this means that the bunch length has to be in the order of only a few micrometers.

Beam dynamic simulations have been performed to achieve a detailed understanding of single spike operation at FLASH. A start-to-end simulation for single spike radiation with the short-pulse injector laser is presented that is very close to machine settings used for standard short pulse operation at FLASH.

SHORT PULSE OPERATION AT FLASH

FLASH has an RF photo-injector consisting of a 1.5 cell L-band gun and two solenoids for emittance compensation. Seven superconducting accelerating modules accelerate the bunch to energies of up to 1.25 GeV. Four third harmonic cavities upstream of the first bunch compressor are used to linearize the longitudinal phase space distribution. Two magnetic bunch compressors situated at 150 MeV and at 450 MeV are used to longitudinally compress the bunch to peak currents and bunch lengths required for SASE operation. Recently FLASH has been upgraded to have a second undulator beamline (FLASH2) that is currently being commissioned [1]. A schematic overview of FLASH is given in Fig. 1. The simulations presented in this paper have been performed for the original undulator beamline, FLASH1.

In order to adjust the SASE pulse duration to the needs of each specific user experiment, the bunch length at the undulator section is set accordingly. This is done by a combination of two methods. First, the bunch length can be scaled by adjusting the bunch compression applied in the magnetic chicanes. Second, especially for the shortest SASE pulses, the bunch length is additionally reduced already at the injector. This is done be scaling of the bunch charge

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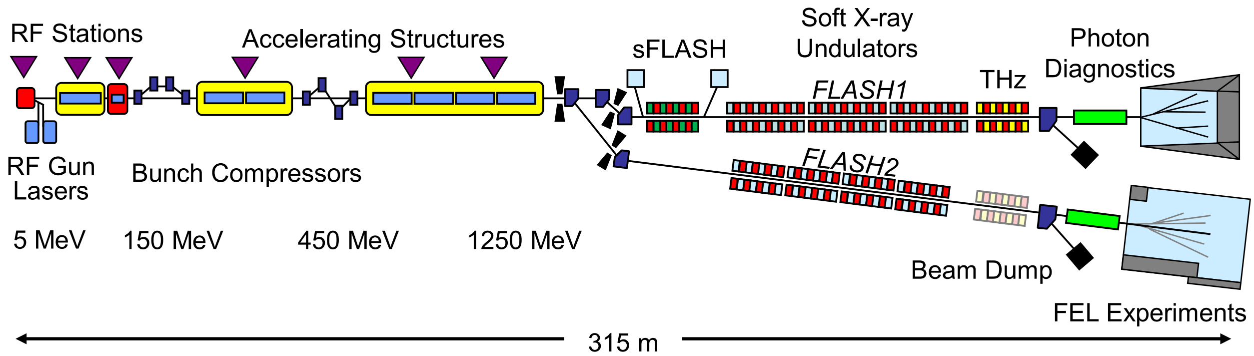

Figure 1: Schematic overview of FLASH. The simulations presented here have been performed for FLASH1.

and thus of the space charge forces that act on the electron bunch at the low energies present at the injector. Thus a small bunch charge in combination with a very strong bunch compression is used to produce the shortest SASE pulses of less than 50 fs (FWHM).

The initial bunch length of very low charge electron bunches where longitudinal space charge forces do not play a role any more at RF photo-injectors is given by the pulse duration of the injector laser. Bunch compression in magnetic chicanes is limited by RF tolerances. Thus a limit is given for the minimum SASE pulse duration that can be reached by this means and for stable SASE operation.

Short Pulse Injector Laser

While the standard injector laser at FLASH has a fixed pulse duration of 6.5 ps (rms), the pulse duration of the short-pulse injector laser can be adjusted between 0.7 ps and 1.6 ps (rms). By this means, the total bunch compression that has to be applied to the bunch for single spike radiation can be reduced by a factor 3–5.

Bunch charges of up to 200 pC can be produced with the short-pulse laser. The transverse spot size on the photocathode can be chosen by selecting a specific aperture from a set with different radii that can be imaged onto the cathode. The parameters laser pulse duration, bunch charge and spot size on cathode can be set independently for each laser.

START-TO-END SIMULATION

A start-to-end simulation for an example of standard short pulse operation at 13.5 nm can be found at [7]. The simulation is based on a machine setting from March 2012 that was used to produce SASE pulses with a pulse duration of 50 fs (FWHM) for a dedicated comparison of various different techniques for SASE pulse characterization. The bunch charge was 150 pC. This simulation has been used as a basis for a start-to-end simulation with the short pulse laser that is demonstrated in this paper.

It is important to note that no theoretical design optics was used but instead the optics used for the simulations is the exact optics that was in use in the machine during this specific run.

A combination of the particle tracking codes ASTRA [8] and CSRtrack [9] has been used for the simulations to include collective effects such as space charge forces and coherent synchrotron radiation (CSR). Wakefields have been added analytically.

Start-to-end Simulation with Short Pulse Injector Laser

A start-to-end simulation has been performed based on machine settings for standard short pulse operation at FLASH, but now for the short pulse injector laser. For the simulation, only parameters that are independent for each laser have been altered and the RF phase of the first accelerating module after the gun has been scanned for optimum bunch compression. Apart from this the machine setting is exactly the same for both simulations.

The bunch charge has been chosen to be 20 pC in order to be suited for single spike radiation at FLASH. The laser-dependent parameters for both simulations are given in Table 1.

Table 1: Laser-dependent parameters used for the start-to-end simulation for standard short pulse operation at FLASH [7] (standard laser) and the simulation with the short-pulse injector laser based on it that is presented in this paper.

parameter	standard laser	short-pulse laser
pulse duration	15 ps FWHM	2.8 ps FWHM
spot diameter	1.2 mm	1.0 mm
bunch charge	150 pC	20 pC

A comparison of the longitudinal current profile after the gun for both simulations is given in Fig. 2. The parameters chosen for the short pulse injector laser result in a reduction of the bunch duration by a factor 4 to 0.41 mm rms. The core slice emittance is 0.26 mm mrad and the slice energy spread 1.6 keV. The focussing strength of the solenoid has not been optimized for emittance compensation but is fixed to the value from the specific machine run described above.

The RF phase of the first accelerating module (ACC1) after the gun has been adjusted by 0.6° for optimum bunch

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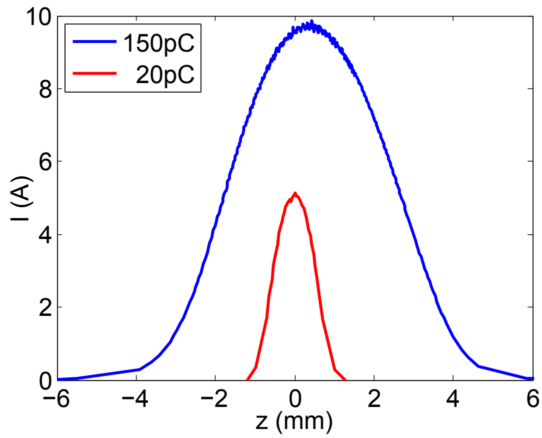

Figure 2: Longitudinal current profile after the gun for the standard injector laser (150 pC) and for the short pulse injector laser (20 pC) corresponding to the parameters in Table 1. The head of the bunch is to the right.

compression. Non of the other phases or gradients have been altered. The longitudinal phase space distribution of the bunch is well linearized upstream of the first magnetic chicane. The bunch is slightly over-compressed in the second bunch compressor.

Space charge forces acting on the bunch after compression lead to a double structure in the longitudinal current profile of the bunch, as can be seen in Fig. 3 at the beginning of the undulator. The rms bunch length at the undulator is 3.6 μm, while the individual widths of the two spikes can be fitted by a Gaussian to be 0.5 μm (trailing spike) and 0.6 μm (leading spike). The slice emittance is 0.8 mm mrad (horizontal) and 1.2 mm mrad (vertical) for the trailing and 0.2 mm mrad (hor.) and 0.5 mm mrad (ver.) for the leading spike, while the energy spread is $1.6 * 10^{-3}$ and $5.1 * 10^{-4}$ respectively.

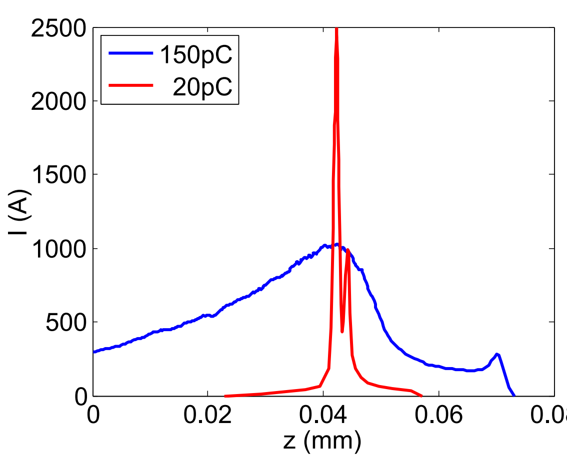

Figure 3: Longitudinal current profile at the beginning of the undulator section for the standard injector laser (150 pC) and for the short pulse injector laser (20 pC). The head of the bunch is to the right.

SASE Simulation

The SASE process has been simulated with the 3D time dependent code Genesis1.3 [10]. Longitudinal space charge forces have not been taken into account in the SASE simulation.

The longitudinal SASE profile and spectrum after 15 m of the undulator section is shown in Fig. 4 for four different statistical seeds. The SASE pulse duration is 2–3 fs FWHM corresponding to the individual seeds. 2–3 modes are visible in the spectrum of the SASE simulation, indicating that the SASE pulse shown is not yet a perfect single spike.

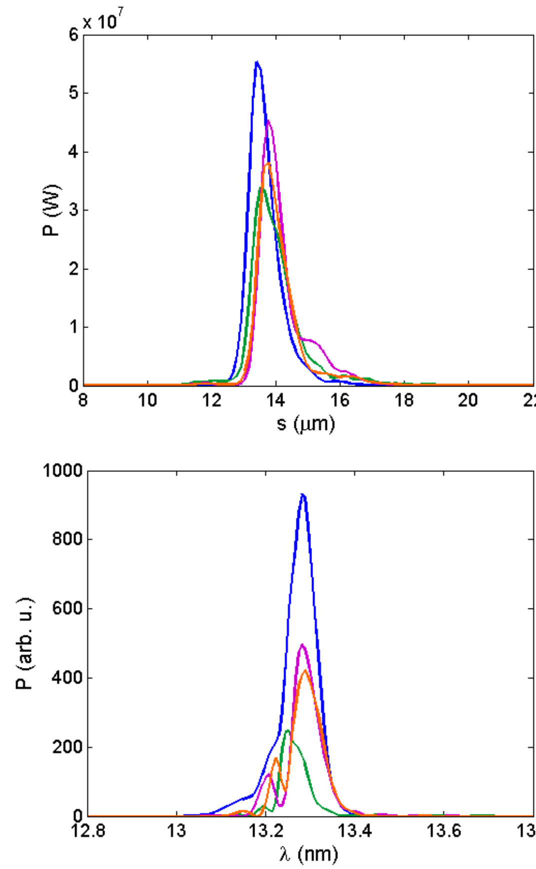

Figure 4: Longitudinal SASE profile (top) and spectrum (bottom) at 15 m of the undulator section for four different statistical seeds.

The double structure from the current profile of the bunch is not visible in the longitudinal SASE profile. This is due to the difference in the slice parameters of the two current spikes. While the trailing spike of the bunch has the highest peak current of 2.5 kA, its slice emittance and slice energy spread are much worse than those of the leading spike. The trailing spike therefore doesn't contribute much to the lasing process. Instead the single spike that is seen in the longitudinal current profile is produced by the smaller leading spike. The peak current of the leading spike of 1.1 kA is still high enough for SASE operation. It is comparable to the peak current for the case of standard short pulse operation as described above and in [7].

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CONCLUSION

Start-to-end simulations demonstrate that single spike SASE FEL radiation can be achieved with the short-pulse injector laser for machine settings that are almost identical to standard short pulse operation (with the standard injector laser) at FLASH.

The machine parameters that have to be adapted to achieve this are only those that solely depend on the injector laser that is in use – laser pulse duration, spot size and bunch charge – and the RF phase of one single accelerating module to optimize bunch compression.

As a result, if the machine is well set up, very little time is needed to switch between standard short pulse operation and single spike operation mode by switching between the standard and short-pulse injector laser.

Recently very short SASE pulses with only one to four spikes in the spectrum (an average of only 1.5 spikes within the FWHM) have been achieved with the short pulse injector laser at FLASH (see [5]).

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