BEAM DYNAMIC STUDIES FOR THE GENERATION OF SHORT SASE PULSES AT FLASH*

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Abstract

Many users at FLASH work on pump-probe experiments, where time resolution is determined by the duration of the SASE pulses. Therefore users have expressed the strong wish for shorter XUV pulses. The shortest possible pulse is a single longitudinal optical mode of the SASE radiation. The most direct way to realize this at FLASH would be to reduce the electron bunch length to only a few μm at the entrance of the undulator section. A bunch charge of 20 pC is sufficient for the generation of such short bunches. Such a small bunch charge reduces space charge in the injector area drastically and thus makes it possible to shorten the bunch duration directly at the photo-cathode [1]. This in turn helps to overcome technical limitations of the bunch compression due to RF induced non-linearities and minimizes collective effects during the compression process. Beam dynamic studies are being performed to optimize the parameters of the photo injector laser, of the accelerating modules, and of the bunch compression. This includes particle tracking starting from the cathode through the accelerating modules with the ASTRA code and through the dipole chicanes using CSRtrack. The expected SASE pulses are being simulated with the Genesis code.

INTRODUCTION

FLASH is a Free Electron Laser user facility in the XUV regime that offers SASE pulses within a wavelength range from 4.1 to 45 nm. At FLASH standard operation, electron bunches with a charge of 0.1 to 1.5 nC produce SASE pulses with pulse durations between 50 and 200 fs (FWHM) [2]. These SASE pulses consist of many optical modes, resulting in a spiky spectrum and temporal distribution.

The time-resolution of pump-probe experiments is determined by the duration of the radiation pulses. Thus in order to be able to time resolve even faster physical and biological processes, one needs to go to shorter SASE pulses. The shortest possible SASE pulse would be of the length of a single longitudinal optical mode. At FLASH this length is in the scale of a few μm. Beam dynamic studies are being done to find out the parameters needed for single spike operation. This paper focusses on a preliminary start-to-end simulation as a starting point for further optimization.

For more information on the progress towards single spike operation at FLASH see also [3].

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SINGLE SPIKE CONDITION

The length of a longitudinal optical mode is determined by the cooperation length L_c [4, 5, 6]. It is the distance spanned by the emitted radiation in its slippage over the electron bunch over one gain length,

$$L_{\rm c} = \frac{\lambda_r}{4\pi\sqrt{3}\rho} * (1+\eta) \quad (1)$$

where λ_r is the wavelength of the emitted radiation, given by

$$\lambda_r \cong \frac{\lambda_{\rm u}}{2\gamma^2}(1+{\rm K}^2) \quad (2)$$

and η is a degradation factor that takes into account 3D effects like radiation diffraction, beam emittance and energy spread, as first introduced by M. Xie [6]. The 1D parameter ρ is the FEL gain parameter, which is a measure of the beam quality. It is defined as

$$\rho = \left[\frac{{\rm JJ}^2{\rm K}^2 I_{\rm p}}{8{\rm I_A}{\rm k_u}^2\gamma^3\sigma_{\rm tr}}\right]^{1/3} \quad (3)$$

with the undulator parameter K and ${\rm k_u} = 2\pi\lambda_{\rm u}$, $\lambda_{\rm u}$ being the undulator period length. JJ is the coupling factor between the emitted radiation and the bunch. For planar undulators like FLASH it is just a little below unity. ${\rm I_A} \approx 17$ kA is the Alfven current. The gain parameter also depends on bunch parameters. Here $I_{\rm p}$ is the peak current, γ the beam energy in terms of the electron rest mass energy, and $\sigma_{\rm tr}$ is the transverse beam size.

Another property determined by the gain parameter is the gain length $L_{\rm g}$ with

$$L_{\rm g} = \frac{\lambda_{\rm u}}{4\pi\sqrt{3}\rho}(1+\eta) \quad (4)$$

It determines the distance until SASE radiation power reaches saturation.

Thus by choosing the bunch properties one can control the SASE radiation properties. A bunch with a length of $\sigma_z \leq 2\pi L_{\rm c}$ would excite only a single longitudinal optical mode [4]. The emitted radiation pulses would not only be extremely short, but also longitudinally coherent.

Due to the wishes of the users to go towards shorter pulse durations, this operation scheme is highly appealing for FLASH.

SHORT BUNCH OPERATION AT FLASH

FLASH uses a two-stage bunch compression scheme to reach the bunch lengths needed for SASE operation. A

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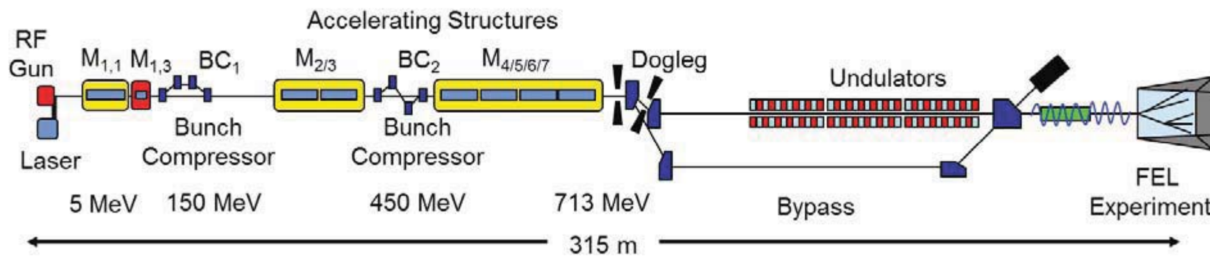

Figure 1: Schematic layout of FLASH (not to scale), including the beam energies used for the start-to-end simulation discussed in this paper. Generally, beam energies up to 1.25 GeV can be reached at FLASH.

third-harmonic cavity is used to linearize the longitudinal phase space distribution before the first bunch compressor. The schematic layout of FLASH is shown in fig. 1.

The standard FLASH photo-injector laser [7] has a fixed rms pulse duration of 6.5 ps. The resulting initial bunch length for standard operation is about 2.3 mm rms for 1 nC [8]. To reach the length of a single optical mode at 13 nm, the bunch would have to be compressed down to less than 3μm, resulting in a compression factor of about 560 instead of a factor of 48 used for standard SASE operation with 2.5 kA [8].

The bunch compression in magnetic chicanes is highly sensitive to small deviations of the longitudinal phase space distribution. The achievable stable bunch compression is thus limited by RF induced non-linearities of the phase space distribution as well as by collective effects. A main challenge of single spike operation at FLASH is to overcome these limitations of the bunch compression.

One way to help overcome these limitations is to start with shorter electron bunches right at the cathode. In order to allow for this, an additional photo-injector laser has been installed that features a variable pulse duration, adjustable from about 0.3 to 4.4 ps rms. Beam dynamic simulations for a bunch charge of 20 pC, as discussed in [1], suggest that using this laser it should be possible to produce short bunches down to 0.35 mm at the injector (e.g. for an rms spot size of 0.2 mm) and emittances below 0.3 mm mrad. Choosing a different aperture allows to go to even shorter bunch lengths, or, alternatively, to smaller emittances. Velocity bunching as an option has not been taken into account so far. It will be investigated in the future.

START-TO-END SIMULATION

Based on the injector studies, a preliminary start-to-end simulation has been performed for electron bunches with a charge of 20 pC. For these simulations the particle tracking code ASTRA [9] has been used for the linac and CSRtrack [10] for magnetic chicanes. The aim was to find a starting point for start-to-end simulations for single spike operation of FLASH.

The FLASH parameters used for this first simulation are shown in table 1. They are based on an existing start-to-end simulation for 100 pC [11]. The pulse duration of the injector laser has then been scaled down with the charge to about 0.9 ps rms, while keeping the laser spot size constant. This approach was chosen to keep the space charge forces at the same level while producing a shorter bunch length at the photo-cathode.

Table 1: FLASH parameters used for the single-spike start-to-end simulation at about 13 nm, using a bunch charge of 20 pC.

parameter	value
laser pulse duration	0.9 ps (rms)
laser spot size	0.2 mm (rms)
gun phase	$-2.0°$
$M_{1,1}$, phase	$6.3°$
3rd harmonic module, phase	$-137.5°$
1st. BC, R_{56}	-228 mm
$M_{2/3}$, phase	$-25.6°$
2nd. BC, R_{56}	-42.0 mm
$M_{4/5/6/7}$, phase	on crest

Bunch Compression

For bunch compression, the bending radius in the first bunch compressor is chosen at 1.932 m, leading to a compression factor of 7.5. A low compression factor has been chosen as in [8] to minimize space charge effects between the two bunch compressors. This also reduces CSR effects in the first bunch compressor. The bending radius in the second bunch compressor can be chosen between 5.3 and 16.8 m. It has been adjusted for compression to the bunch lengths needed for single spike operation. The phases of the cavities remain fixed for this first study. Under these conditions the minimum bunch length is reached at a bending radius of 8.1 m. The bunch length, energy spread and transverse emittance as a function of the bending radius in the second bunch compressor are displayed in fig.2.

The initial horizontal emittance is 0.265 mm mrad. The massive growth of the horizontal emittance in the bunch compressor is due to coherent synchrotron radiation (CSR). The emittance growth due to CSR in the last bending mag-

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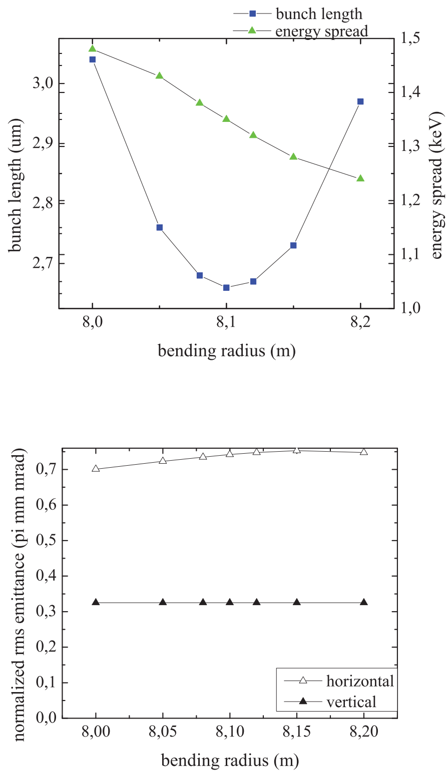

Figure 2: Simulated bunch length and energy spread (top) as well as horizontal and vertical normalized rms emittance (bottom) after the second bunch compressor as a function of its bending radius. The phase of the cavities is fixed.

net of the chicane can be estimated at [12] as

$$\frac{\varepsilon_f}{\varepsilon_i} = \sqrt{1 + \frac{0.22^2 \mathrm{r_e}^2 N^2}{36\gamma\varepsilon_i\beta}\left(\frac{|\theta|^5 \mathrm{L_B}}{\sigma_z^4}\right)^{2/3} * A(\alpha,\beta)} \quad (5)$$

with the initial normalized rms emittance ε_i, the classical electron radius $\mathrm{r_e}$, the dipole length $\mathrm{L_B}$ and the angle of deviation θ. N is the number of electrons per bunch, σ_z the rms bunch length and

$$A(\alpha,\beta) = \left[\mathrm{L_B}^2(1+\alpha^2) + 9\beta^2 + 6\mathrm{L_B}\alpha\beta\right] \quad (6)$$

where α and β are the Twiss parameters. The gaussian rms bunch length σ_z is assumed to be constant during the passage through this last dipole. This estimation gives an emittance growth of 213% in the last dipole. This very big growth of emittance is due to the bad focussing for the given bunch parameters. It can be reduced by optimization of the focussing, thus reducing α and β.

The initial bunch length is 57.8 μm. Maximum compression corresponds, for the given phase of $-25.6°$, to a compression factor of 22 in the second bunch compressor. Compared to the standard FLASH injector laser, which has a fixed pulse duration of 6.5 ps, the total compression factor can thus be reduced by a factor of 3.4. This helps to reduce the problem of tight tolerances for strong compression at the bunch compressors. Choosing an even shorter laser pulse duration and a larger spot size on the photo-cathode compared to those used for the present simulations would allow to reduce the total compression factor even more, while increasing the transverse emittance. The growth of emittance in the bunch compressors may be reduced by optimization of the focussing. The results of the SASE process simulations discussed in the next section of this paper indicate that this is an option.

Relaxing the compression factor by going towards slightly under-compressed bunches would also reduce the energy spread. This is important for SASE operation, as shown below.

SINGLE SPIKE SASE PULSES AT FLASH

FLASH I uses fixed gap undulators. Thus the active undulator length cannot easily be adjusted for the specific needs of single spike operation. Also tapering of the undulators is not an option. This constitutes a challenge for single spike SASE operation at FLASH. A way of operation has to be found where the radiation pulse doesn't slip out of the bunch before the end of the undulator section. This would lead to the development of a second (or more) radiation spike and thus ruin single mode operation.

Simulations of the SASE process have been performed using the Genesis code [13] and a gaussian longitudinal bunch profile. The aim was to find out the electron bunch properties required for single spike SASE pulses at the end of the FLASH undulator section. As a starting point bunch and machine parameters have been used that lead to good SASE lasing at 200 pC at FLASH. The bunch length was reduced down to $2\pi L_c$ and the peak current adjusted to 20 pC. This results in single spike lasing, but saturation was reached early and the single spike nature of the radiation lost before the end of the undulator. Increasing the emittance helps to increase the gain length and thus shift the reaching of saturation towards the end of the undulator. This can e.g. be achieved by choosing a bigger aperture of the injector laser. This has the additional benefit of allowing to start with even shorter electron bunches at the cathode and thus further reduce the bunch compression.

As a second approach, the SASE process of the present start-to-end simulation has been studied to learn how the bunch parameters have to be modified for single spike operation. For the simulation the transverse emittance growth after the dogleg was neglected. The Twiss parameters at the beginning of the undulator were set to standard FLASH values. Since the present simulation was not yet optimized in terms of energy spread, an energy spread of $7 * 10^{-4}$ rel. was adopted as a conservative assumption based on previous FLASH simulations. The resulting simulated SASE pulse is shown in figs. 3 to 5. The single spike SASE pulse at 12.6 nm is Fourier-limited and has a pulse duration of 11.3 fs (FWHM). As seen from fig. 4, saturation is not yet reached in the present single spike arrangement. Further optimization of the scenario is under way to see what has to be done that the single-spike property of the radiation

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can be conserved while the saturation level is reached.

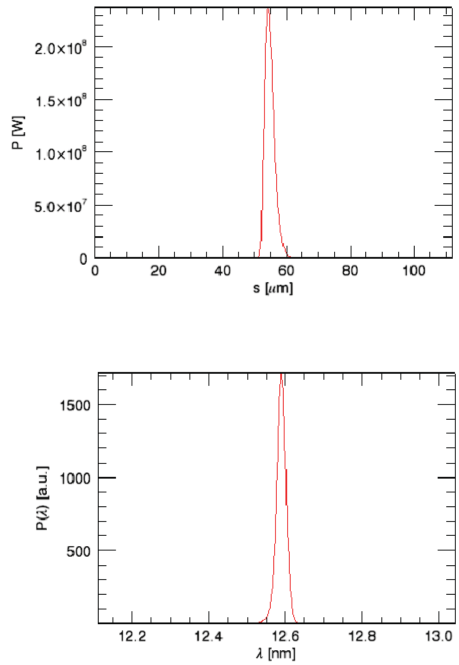

Figure 3: Simulated longitudinal SASE pulse distribution (top) and SASE spectrum (bottom) at the end of the FLASH undulators.

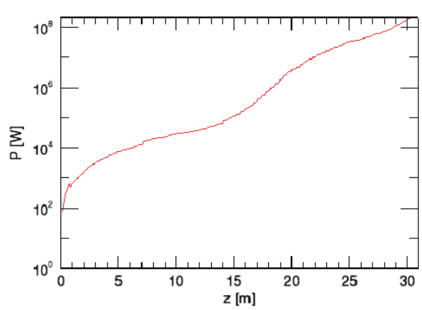

Figure 4: SASE radiation power vs. distance along the undulator.

CONCLUSIONS AND OUTLOOK

A start-to-end simulation for single spike operation at FLASH, using a new short-pulse injector laser has been done. It is shown that using an injector-laser pulse duration of 0.9 ps rms and a spot size on the photo-cathode of about 0.2 mm rms reduces the required bunch compression for single spike operation by a factor of 3.4 compared to the standard injector laser. Optimization of the focussing throughout the accelerator is necessary to avoid extensive emittance growth in the magnetic chicanes as well as for optimum SASE operation.

Simulations of the SASE process show that a comparatively large transverse emittance helps to shift the reaching of saturation towards longer distances and thus preserve

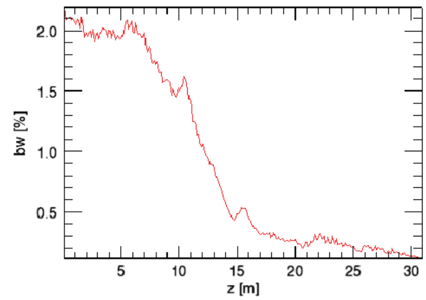

Figure 5: Bandwidth of the simulated SASE pulse.

single spike radiation until the end of the FLASH undulators. As a consequence it is possible to optimize the injector laser settings for minimum bunch compression instead of minimum transverse emittance.

The energy spread resulting from the preliminary start-to-end simulation was found to be too big for SASE radiation. It can be reduced by optimization of the accelerating phases, starting at the gun. Optimization of the gun phase for minimum energy spread has the additional benefit of producing shorter electron bunches and thus further reduce the required bunch compression.

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