# SUB-FEMTOSECOND HARD X-RAY PULSE FROM VERY LOW CHARGE BEAM AT LCLS

V. Wacker*, University of Hamburg, Hamburg, Germany
Y. Ding, J. Frisch, Z. Huang, C. Pellegrini and F. Zhou, SLAC, CA 94025, USA

*Abstract*

The Linac Coherent Light Source (LCLS) is an x-ray free-electron laser (FEL) at SLAC National Accelerator Laboratory, supporting a wide range of scientific research with an x-ray pulse length varying from a few to several hundred femtoseconds. There is also a large interest in even shorter, single-spike x-ray pulses, which will allow the investigation of matter at the atomic length (Å) and time scale (fs). In this paper, we investigate the FEL performance using 1 pC and 3 pC electron bunches at LCLS, based on the start-to-end simulations. With an optimization of the machine set up, simulations show that single spike, sub-fs, hard x-ray pulses are achievable at such a low charge.

## INTRODUCTION

Self-amplified spontaneous emission (SASE) FELs provide tunable, high-power, coherent light sources in the x-ray wavelength range. Several FEL projects worldwide [1, 2, 3] provide users with high peak power, femtosecond long pulses. Nevertheless, a growing interest in even shorter, single-spike pulses with a full longitudinal coherence is evolving within the FEL user community. These ultra-short pulses could open undreamed-of possibilities for experiments in physics and other domains of science.
The generation of single-spike x-ray pulses in SASE mode can be obtained with very short electron bunches, produced by reducing the beam charge, or with using a laser or emittance-spoiling foil to manipulate the long electron bunches [4]. Reducing the bunch charge from nC to pC level is a simple way, as first studied in [5, 6]. At LCLS, a systematic study has been performed with 20 pC [7], and it works very well for providing users of x-ray pulses below 10 fs. In this operation mode, the x-ray pulses typically have a few spikes. It is possilbe to further optimize the machine set up, or to combine the emittance-spoiling foil and taper schemes to achieve a single-spike SASE FEL x-ray pulse at this 20pC charge [8], but the collective effects have to be carefully considered.

In this paper, we study the possibilities of further reducing the charge from 20 pC to 1pC/3pC for producing sub-femtosecond, hard x-ray pulses at LCLS, based on start-to-end simulations. However, the beam diagnostics for such small, low charged bunches are currently challenging topics at LCLS. At such a low charge, the collective effects from the space charge force, the coherent synchrotron radiation, and wake fields are expected to be much smaller. A schematic layout of the LCLS machine is shown in Fig. 1. The compression in the second bunch compressor (BC2) determines the final electron bunch length. By tuning the phase of the L2 linac the compression ratio was adjusted.
The start-to-end simulations were made using IMPACT [9] and ELEGANT [10] codes for the tracking of the electron bunch from the photocathode to the beginning of the undulator. From there on the FEL radiation was simulated with GENESIS 1.3 [11]. IMPACT covers the tracking of one million macro-particles from the photocathode to the end of the first dog-leg (DL1) at 135 MeV. The code includes 3D space charge forces allowing detailed modeling at low energies. To reduce the high-frequency numerical noise in the following ELEGANT simulations, the particle output from IMPACT was smoothed in longitudinal dimension [12]. ELEGANT includes a 1D model of incoherent and coherent synchrotron radiation (ISR, CSR) as well as longitudinal space charge (LSC) effects. The generation of the FEL radiation was simulated using GENESIS. This FEL simulation includes LSC effects in the undulator chamber. The influence of resistive wall-wakes is negligible and was not considered.

Our results show that a single-spike pulse with 5 GW peak power and 0.2 fs fwhm is achievable using a bunch charge of 1 pC. The simulations for a bunch charge of 3 pC resulted in about two spikes.

## ELECTRON BEAM OPTIMIZATION

In this section the required machine set up for single-spike operation at LCLS is studied. From the photoinjector down to the undulator, we aim for the shortest bunch, the highest current and the smallest transverse emittance possible. In this manner, we obtain high electron beam brightness, the key requirement for FELs.

The condition for the rms bunch length $\sigma_z$ under which the SASE FEL produces a single-spike pulse was found to be $\sigma_z \leq 2L_{coop}$ [6]. In case of LCLS, the cooperation length $L_{coop}$ is approximately 25 nm, dictating a rms bunch length

$$\sigma_z \leq 50\,\mathrm{nm}. \tag{1}$$

To obtain such a short bunch, shorter bunch length in the injector and almost full-compression in the linac and compression system have been applied, as discussed in the following sections.

### *Electron Beam Optimization for 1 pC*

The photoinjector set up was obtained by IMPACT simulations using one million particles and a bunch charge of 1 pC. The optimized bunch was achieved using a Gaussian

* violetta.wacker@desy.de



ISBN 978-3-95450-123-6

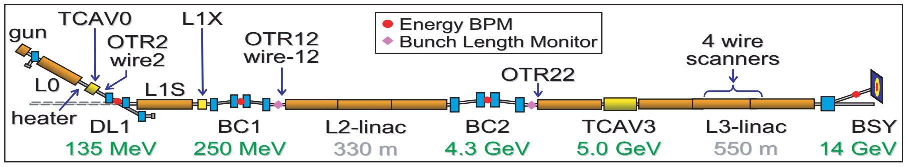


Figure 1: Schematic layout of the LCLS machine.

Table 1: LCLS Machine Parameters for 1 pC and 3 pC Simulations for Single-spike Generation

| Parameter | Value |
|---|---|
| Cathod laser length | 1.5 ps fwhm |
| Cathod laser iris | 0.3 (1pC), 0.4 (3pC) mm |
| Gun rf phase | -5 ° |
| L1 phase | -22 ° |
| LX phase | -160 ° |
| BC1 $R_{56}$ | -45.5 mm |
| L2 phase | -32.1° (1pC), -32.4° (3pC) |
| BC2 $R_{56}$ | -24.7 mm |
| L3 phase | on crest |

shaped UV laser pulse with a fwhm pulse length of 1.5 ps, an iris of 0.3 mm and a gun RF phase of -5°. These values are realizable at LCLS. At the end of DL1 the electron bunch produced has a rms bunch length of $\sigma_z = 66\,\mu$m and a normalized, transverse emittance of $\epsilon_n = 0.067\,\mu$m.

The parameters used for the ELEGANT simulations are listed in table 1. The values for the L1 and L2 phase were optimized based on LiTrack [13] simulations. The L2 phase was tuned to adjust the compression, while the BC2 $R_{56}$ was fixed. To generate a reasonable short electron beam with a sufficiently high peak current, the optimized L2 phase is -32.1°, which corresponds to the full

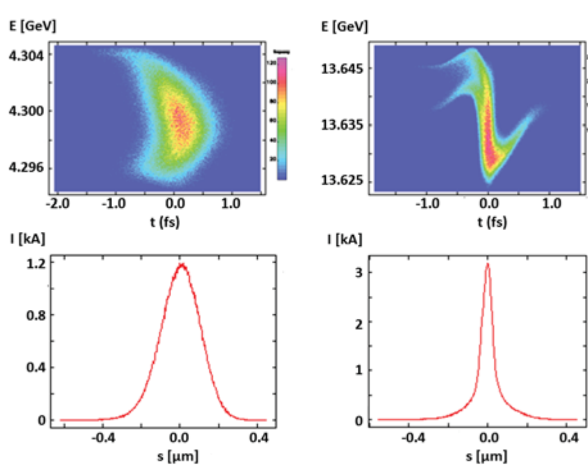


Figure 2: Longitudinal phase space distribution and current profile after BC2 (left) and at the beginning of the undulator (right), for full compression (L2 phase of -32.1°) and a bunch charge of 1 pC.

compressed bunch. The resulting electron beam after BC2 is 85 nm long (rms) and has a peak current of 1.2 kA (see the left plots in Fig. 2). After BC2 the bunch passes L3, accelerating it to 13.6 GeV. The longitudinal space charge effects in L3 stretch the bunch and generate a time-energy chirp with higher energy on the bunch head. Subsequently, a small positive $R_{56}$ within DL2 rotates the bunch and further compresses it. These effects lead to a final peak current of 3.2 kA and a rms bunch length of 38 nm (see the right plots in Fig. 2), which meets the requirement given by eq. (1). The vertical and horizontal normalized emittance are $\epsilon_{n,y} = 0.07\,\mu$m and $\epsilon_{n,x} = 0.14\,\mu$m, allowing to operate the FEL at full compression for single-spike generation though the slice energy spread is 5 MeV.

Other than nearly full-compression, operating at under or over-compression it only gets peak current in the range of ~100 A with 1pC charge, which is insufficient for FELs.

## *Collective Effects in BC2*

At BC2 we observed a broadening of the longitudinal phase space distribution for all compressions schemes investigated. This energy spread gain is mainly caused by the incoherent synchrotron radiation (ISR) effect. In this section we discuss the collective effects in BC2 by means of an under-compression scheme. For a full compression case the broadening due to the ISR effect is even stronger.

Figure 3 shows the longitudinal phase space distribution before and after BC2 for an under compression case obtained with a L2 phase of -29.8°. The bunch is compressed from 11.9 $\mu$m (rms) by a factor of 13 to 0.89 $\mu$m (rms). However, the slice energy spread increases from 5 keV by a factor of 44 to 220 keV. This discrepancy is caused by

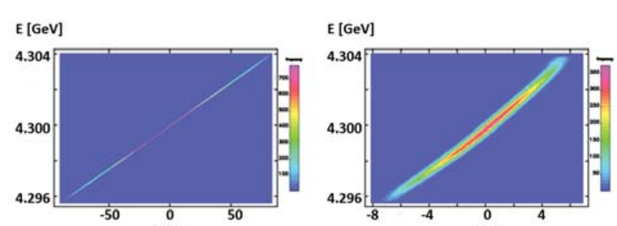


Figure 3: The longitudinal phase space distribution before (left) and after BC2 (right) for under compression (L2 phase of -29.8°) with a bunch charge of 1 pC. The phase space distribution is blown up due to ISR effects.

ISBN 978-3-95450-123-6

ISR. The effect can be estimated roughly with

$$\sigma_{E_{ISR}} = \frac{1}{L_B}\sqrt{(4.13 * 10^{-11})E^7|\theta_B^3|} = 12.5\,\mathrm{keV/BM},$$

where $L_B = 0.549$ m is the length of each bending magnet (BM) and $\theta_B = 0.0347$ rad is the bending angle. The beam energy $E = 4.3$ GeV at BC2. The ISR contribution to the energy spread of 12.5 keV per bending magnet is amplified by the compression process

$$\sigma_i = C_{BM_i}\sqrt{\sigma_{i-1}^2 + 12.5^2}\,\mathrm{keV},$$

where $C_{BM_i}$ is the compression factor of the BM. Therefore, the slice energy spread at the end of BC2 is approximately 252 keV. The result is slightly overestimated, because the approach neglects that the compression and the energy spread gain take place simultaneously. Nevertheless, it is well explained why the growth of the energy spread is much larger than the compression factor.

The coherent synchrotron radiation (CSR) effect is very small in comparison. The largest CSR contribution from the fourth bending magnet acounts about 20 keV.

## FEL PERFOMANCE

In this section we discuss the GENESIS simulations. We used the LCLS-I undulator line for the simulations. The line consists of 33 fixed gap, planar permanent magnet hybrid undulators and is ~130 m long including breaks. Each of the 3.4 m long undulator segments has a period length of 30 mm and a magnetic gap size of 6.8 mm. The effective K value is 3.5. The undulator magnet poles have canted angles to allow small adjustment of the field K for FEL gain optimization.

In order to use the ELEGANT output file for the GENESIS simulations, the $\alpha$- and $\beta$-function had to be matched to the beginning of the undulator based on the lattice file, and we used an average beta function of 30 m inside the undulator. To include LSC in the undulator we added an external energy loss of the electron beam to the beam file in FEL simulations. The loss is given by the derivative of the current profile. This model predicts a maximal energy loss of 150 keV/m due to LSC at this full-compression mode with 1pC charge.

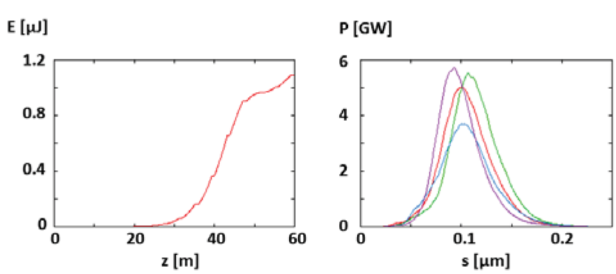


Figure 4: The total energy of the FEL pulse as a function of the distance along the undulator z, one typical case (left). Power profiles at 50 m for four different shot noises (right).

### FEL Simulations for 1 pC

Figure 4 shows the result of the simulations for the 1 pC bunch charge, full compression case. The left plot shows the total energy of the x-ray pulses as a function of the distance along the undulator z. Saturation is reached at around 50 m. After saturation the total energy rises again, because a second spike is generated. Hence, the undulator section has to end after 50 m for single-spike generation. At LCLS this could be realized by moving undulators out of the beamline. However, this would require a comprehensive study. The right plot in Fig. 4 shows the power profiles at saturation using four different initial shot noises. They all consist of a single spike. The average peak power is approximately 5 GW. The fwhm pulse length is about 0.2 fs.

## SIMULATIONS FOR 3 PC

One possibility to achieve a higher peak power is to increase the bunch charge. Therefore, we increased the charge to 3 pC and repeated the proceedings used for the 1 pC study.

### Electron Beam Optimization for 3 pC

The photoinjector set up was again optimized with 1 million macro-particles using IMPACT. The shortest bunch was generated for a Gaussian shaped photo-injector laser pulse with a fwhm pulse length of 1.5 ps, an iris of 0.4 mm and an RF phase of -5°. Only the size of the iris was changed compared to the set up for 1 pC. The electron bunch produced has a rms bunch length of $\sigma_z = 96\,\mu$m and a normalized transverse emittance of $\epsilon_n = 0.095\,\mu$m at the end of DL1. The parameters for the subsequent ELEGANT simulation are listed in table 1.

For a L2 phase of -32.4° the electron bunch is fully compressed in BC2. The resulting electron bunch is 1 fs fwhm long and has a peak current of ~3 kA. As discussed for the 1 pC bunch, LSC in L3 and the positive $R_{56}$ in DL2 lead to a shorter electron bunch with a higher peak current. Thus, we achieve a peak current of 8.9 kA and a rms bunch length of 34 nm at the beginning of the undulator (see Fig. 5). The vertical and horizontal normalized emittance are

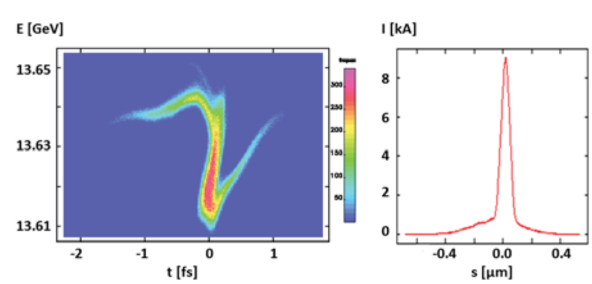


Figure 5: Longitudinal phase space disturbition (left) and current profile (right) at the beginning of the undulator for a full compression (L2 phase of -32.4°) with a bunch charge of 3 pC.



ISBN 978-3-95450-123-6

$\epsilon_{n,y} = 0.09\,\mu\text{m}$ and $\epsilon_{n,x} = 0.4\,\mu\text{m}$. This high peak current and small transverse emittance can compensate for the large slice energy spread of 10-14 MeV.

### *FEL Simulations for 3 pC*

The GENESIS simulations for the 3 pC bunch charge, full compression case were made using the same undulator line and simulation parameters as for the 1 pC case. We included the impact of LSC in the simulations as done for 1 pC. For a bunch charge of 3 pC, the model predicts a maximal energy loss of 300keV/m due to LSC effects in the undulator.

The results of the GENESIS simulations are shown in Fig. 6. The left plot shows the total energy as a function of the distance along the undulator. After $\sim$40 m a second spike is generated. From there the energy rises strongly until saturation is reached between 60 m and 80 m. At about $\sim$80 m the whole radiation pulse completely slipped out of the bunch. Hence, no deep saturation interaction is visible [6]. The right plot shows the power profile for four different shot noises at 60 m. The second spike is clearly visible. The average peak power is $\sim$10 GW, twice as much as for the 1 pC bunch charge simulations.

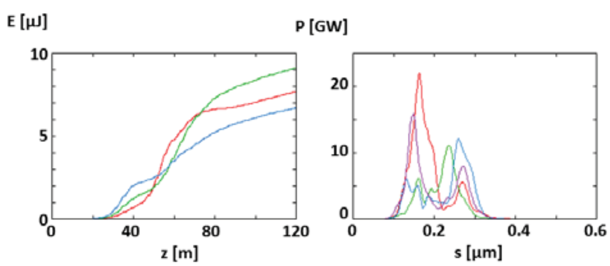


Figure 6: The total energy of the FEL pulse (left) as a function of the distance along the undulator z for three different shot noises. The power profiles (right) at 60 m for four different shot noises with a clear second spike.

In other GENESIS simulations we intentionally neglected the LSC effects to check the FEL performance. Those results show a sub-femtosecond (fwhm) single-spike pulse for a bunch charge of 3 pC with a peak power in the 10 GW range. Using a tapered undulator, which can compensate for LSC effects, it is expected to help generating a single-spike pulse for a 3 pC bunch charge [14]. However, this needs further study in the future.

## SUMMARY AND OUTLOOK

Based on start-to-end simulations we investigated the possibility of producing single-spike pulses at LCLS with 1 pC and 3 pC bunches, by operating the bunch at a full-compression mode.

Using a 1 pC bunch, we achieved a $\sim$0.3 fs long bunch with a peak current of $\sim$3 kA. The GENESIS simulation showed that this bunch can generate $\sim$0.2 fs fwhm long single-spike pulses with a peak power of $\sim$5 GW. A phase jitter in L2 of $\pm 0.1^\circ$ still gives reasonable FEL performance. In order to obtain more peak power we repeated our study for 3 pC bunch charge. The production of a $\sim$0.3 fs fwhm long bunch with a peak current of $\sim$9 kA is possible with a 3 pC bunch. Simplified GENESIS simulations neglecting LSC in the undulator chamber show a sub-fs long (fwhm) single-spike pulse with $\sim$10 GW peak power. However, in simulations including LSC a second spike was clearly visible.

Future work could include the optimization of the initial bunch parameters. Furthermore, a tapered undulator could be helpful to enhance the FEL performance for the 1 pC bunch and to suppress the second spike in the 3 pC case. The LSC model in Elegant is a simplified 1-D model, and more detailed studies using other codes would benefit to more understanding of this effect.

## ACKNOWLEDGMENTS

We would like to thank J. Rossbach and J. Rönsch-Schulenburg for the support and many suggestions for the work and the paper. This work was partially supported by the U.S. Department Of Energy under contract No. DE-AC02-76SF00515.

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