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OPTIMIZATION FOR SINGLE-SPIKE X-RAY FELS AT LCLS WITH A LOW CHARGE BEAM*

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Abstract

The Linac Coherent Light Source is an x-ray free-electron laser at the SLAC National Accelerator Laboratory, which is operating at x-ray wavelengths of 20-1.2 Angstrom with peak brightness nearly ten orders of magnitude beyond conventional synchrotron radiation sources. At the low charge operation mode (20 pC), the x-ray pulse length can be <10 fs. In this paper we report our numerical optimization and simulations to produce even shorter x-ray pulses by optimizing the machine and undulator setup at 20 pC charge. In the soft x-ray regime, with combination of slotted-foil or undulator taper, a single spike x-ray pulse is achievable with peak FEL power of a few 10s GW.

INTRODUCTION

Linac Coherent Light Source (LCLS), the world's first hard x-ray Free electron laser (FEL), has started operation since 2009 [1]. With nominal operation charge of 250 pC, the generated x-ray pulse length is from 70 fs to a few hundred fs. This marks the beginning of a new era of ultrashort x-ray sciences. In addition, a low charge (20pC) operation mode has also been established. Since the collective effects are reduced at the low charge mode, we can increase the compression factor and still achieve a few kA peak current. The expected electron beam and x-ray pulses are less than 10 fs [2].

There are growing interests in even shorter x-ray pulses, such as fs to sub-fs regime. One of the simple solutions is going to even lower charge. As discussed in [3], single-spike x-ray pulses can be generated using 1 pC charge. However, this charge level is out of the present LCLS diagnostic range. 20 pC is a reasonable operation charge at LCLS, based on the present diagnostic system.

At 20 pC in the soft x-ray wavelength regime, we have experimentally demonstrated that FEL can work at under-compression or over-compression mode, such as 1 degree off the full-compression; at full-compression, however, there is almost no lasing. In hard x-ray wavelength regime, we observed that there are reasonable photons generated even at full-compression mode, although the photon number is less than that from under-compression or over-compression mode. Since we cannot measure the x-ray pulse length at this time scale, the machine is typically optimized for generating maximum photons, not minimum pulse length.

In this paper, we study the methods of producing femtosecond (or single-spike) x-ray pulses at LCLS with 20 pC charge, based on start-to-end simulations. Figure 1 shows a layout of LCLS. The compression in the second bunch compressor (BC2) determines the final e-beam bunch length. However, the laser heater, dog-leg after the main linac (DL2) and collective effects also affect the final bunch length. To adjust BC2 compression, we can either change the L2 phase or BC2 R_{56}. In this paper we only tune L2 phase while keep BC2 R_{56} fixed.

For the start-to-end simulations, we used IMPACT-T [4] and ELEGANT [5] tracking from the photocathode to the entrance of the undulator, after that the FEL radiation was simulated with GENESIS [6]. IMPACT-T tracks about 10^6 particles in the injector part until 135 MeV, including 3D space charge force. The output particles from IMPACT-T are smoothed and increased to 12×10^6 to reduce high-frequency numerical noise for subsequent ELEGANT simulations, which include linear and nonlinear transport effects, a 1D transient model of CSR, and longitudinal space charge effects, as well as geometric and resistive wake fields in the accelerator. In GENESIS part, the longitudinal wake field from undulator chamber and longitudinal space field are also included.

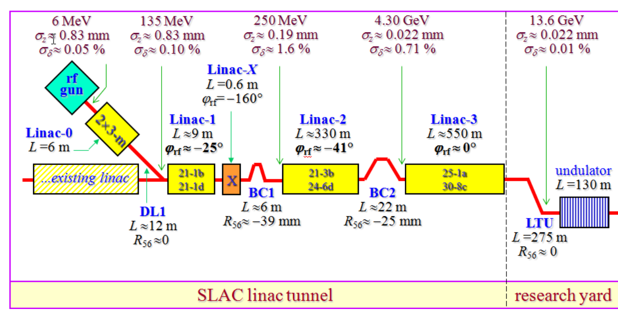

Figure 1: Layout of the LCLS machine.

ELECTRON BEAM OPTIMIZATION

In this section, we study the electron beam vs. L2 phase, laser heater and DL2 R56, with the final beam energy of 4.3 GeV (for soft x-ray generation).

Table 1: The Main Parameters Used in Simulations

Bunch charge	20 pC
Laser heater	6 keV or off
L1 phase	-22 deg
BC1 R56	-45.5mm
L2 phase	-33.3 deg
BC2 R56	-24.7 mm
DL2 R56	0.133mm or 0

Using the parameters listed in Table 1, L2 phase at 32.1° is close to the full compression, which gives a maximum peak current but the phase space is strongly distorted after BC2 by the downstream longitudinal space charge force at this 4.3 GeV energy. To generate a reasonable short e-beam, the optimized L2 phase is 33.3°

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which is at the over-compression mode (Fig. 2). Heating the energy spread to 6keV with the laser heater is effective to smooth the phase space. Note the present laser heater at LCLS is limited to work at this small heating level due the "trickle heating" effect [7]. If the laser heater is turned off, as show in Fig. 2, the current is much higher with a very narrow current profile at this L2 phase. However, this is too short for soft x-ray FEL generation, and we can slightly tune the L2 phase (going further over-compression) to broaden the spike during operation.

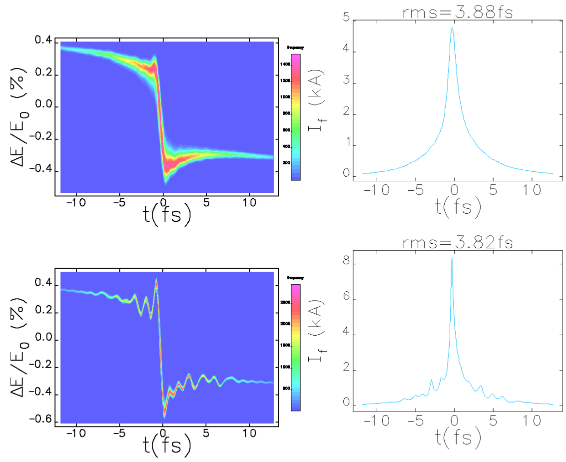

Figure 2: Laser heater effect on longitudinal phase space at undulator entrance with L2 RF phase -33.3°: with laser heater 6keV (top) and without laser heater (bottom). The computation uses 12M particles and 500 bins for longitudinal space charge calculation. DL2 R_{56} = 0.133 mm.

There is a small residual R_{56} of 0.133mm at the DL2 in the normal operation setup. The R_{56} and dispersion can be varied by changing the quadrupole strength as shown in the Fig. 3. Note the sign of this residual R_{56} is different with that from a chicane-type compressor. This R_{56} will further compress the e-beam with a chirp generated in the over-compression mode, or stretch the under-compressed beam. Figure 4 shows the longitudinal phase space and current profile at the undualtor entrance, with setting DL2 R_{56}=0. All other parameters are same as those in Fig.2 (laser heater 6 keV case). We can see that in Fig. 2 the residual R_{56} actually helps generate a higher peak current due to an additional compression in the DL2. The phase space can be optimized by changing L2 phase and R_{56} together. For example, there is even higher peak current (~7kA) with L2 RF phase of 34.3° and DL2 R_{56} of 1mm (Fig. 5). Apparently, more over-compressed bunch after BC2 (therefore a longer bunch with weak space charge effect) with a larger positive DL2 R_{56} can increase the final peak current at the undulator entrance. New DL2 Tweaker Quadrupole magnets have been installed to control both R_{56} and dispersion [8]. Strong dependence of the FEL performance (total photon number) on the quads strength has been observed in experiments. Simulations show much weaker effect of DL2 R_{56} for the high-energy hard x-ray case.

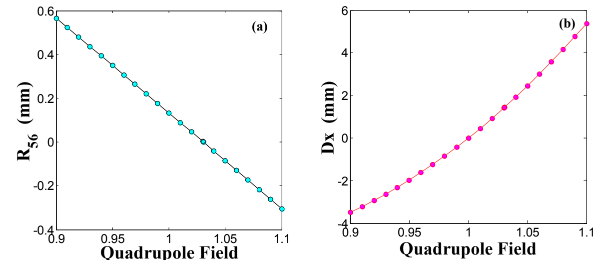

Figure 3: Dependence of the DL2 R_{56} (left) and dispersion (right) on the Quadrupole magnetic field.

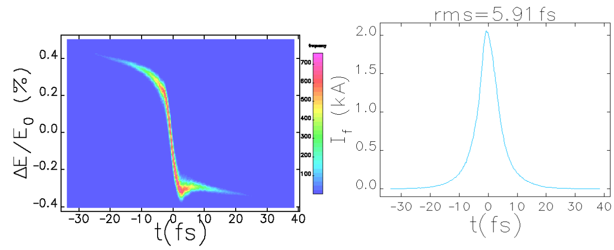

Figure 4: Longitudinal phase space at the undulator entrance with zero R56 at DL2. The L2 RF phase is -33.3° and the heater is 6keV.

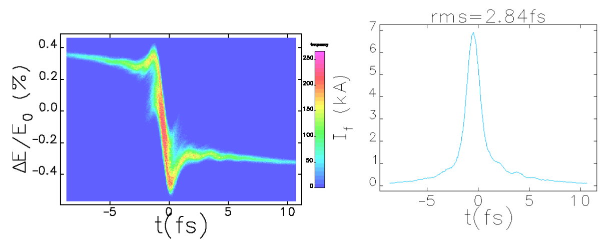

Figure 5: Longitudinal phase space at the undulator entrance with L2 RF phase of -34.3°, DL2 R_{56} of 1*mm* and laser heater of 6keV.

SINGLE-SPIKE SOFT X-RAYS

Slotted foil was proposed to spoil most of the e-beam emittance but leave a small fraction to pass through which will produce a much shorter x-ray pulse compared with the length of the e-beam [9]. Here we combine the low charge with a slotted foil to further shorten the x-ray pulses. An aluminium foil with the slot-width of 0.8mm has been used in the simulations. Figure 6 shows an example of the longitudinal phase space at the undulator entrance, with and without slotted foil. Using the dumped particles we did FEL simulations at 1.5 nm wavelength. Figure 7 shows the X-ray pulse at 50m of the undulator. A clean single spike is obtained with the slotted foil.

Since we have a pretty linear energy chirp in the core part of the e-beam, a linear negative taper should be also helpful for generating shorter x-ray pulses [10]. Figure 8 shows the x-ray pulse with different tapers, using the un-spoiled e-beam as shown in Fig. 6. A linear taper of a few percent (3~5% in 100m) is required for this soft x-ray case. The X-ray pulse still has a small side bump in this simulation example (Fig. 8), which is due to the slow variation of the chirp in the e-beams.

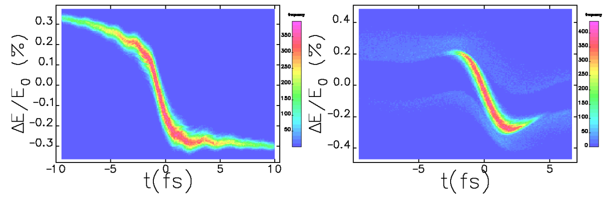

Figure 6: Longitudinal phase at the beginning of the undulator with L2 RF phase -33.5°, Laser heater 6 keV and DL2 R56 = 0.133 mm. (left)without slotted foil; (right) with 0.8mm width foil.

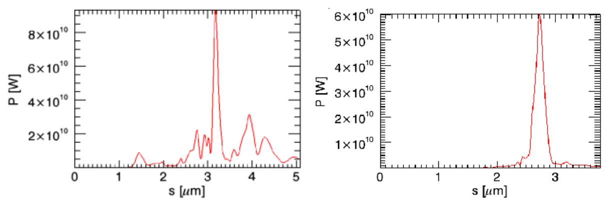

Figure 7: Simulated FEL power profile at undulator z=50m from electrons shown in Fig.6, without foil (left) and with 0.8mm width slotted foil (right).

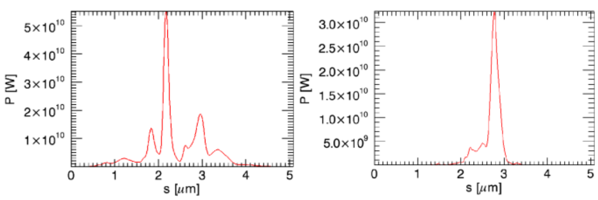

Figure 8: The FEL power profiles at undulator z=30m, vs different undulator taper: without taper (left); with 3.8% taper in 100m (right). The e-beam is operated at under-compression mode, L2 phase = -33.5°, laser heater 6 keV, DL2 R56=0.133mm, without slotted foil.

SUB-FEMTOSECOND HARD X-RAYS

For the hard x-ray case, the required taper in undulator is too large to select the core part. With the slotted-foil scheme, if we use a narrower slot to generate shorter x-ray pulses, there could be particle loss and making lower peak current. Simulations with LiTrack code find that the peak current doubles with a L1 phase of -17° comparing with the nominal phase of -22° while the L2 phase is adjusted to work at full compression at BC2 [8]. Our studies with ELEGANT code also confirm this. For instance, the peak current is 20kA with L2 phase of -34.95° for an initial bunch length of 220mm after injector (L1 phase is -17°). For an initial bunch length of 270mm, the optimized L2 phase is -34.65° with L1 phase -17° and the peak current is 25kA (see Fig. 9). Simulation with Genesis shows a short single-spike x-ray pulse of 0.1μm as shown in Figure 10. To compare, there are typically several (4~5) spikes over 0.5μm width with nominal L1 phase (-22°) and BC2 full compression.

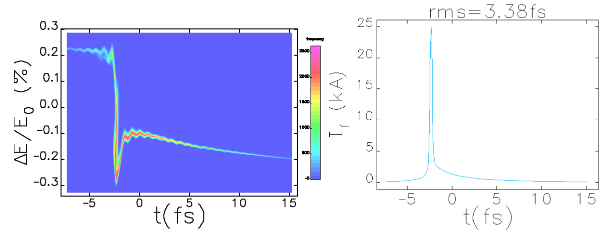

Figure 9: Phase plot and current profile at the beginning of the undulator. The RF phase 17° and 34.65° at L1 and L2, respectively.

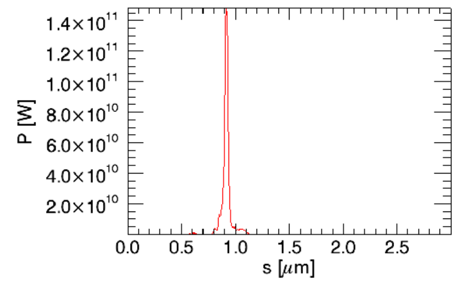

Figure 10: FEL power at the undulator distance of 52.2m with RF phase 17° at L1 and 34.95° at L2.

SUMMARY AND DISCUSSION

Preliminary studies have been done to optimize the low charge operation mode in order to get single spike X-ray pulses. Single spike x-ray can be obtained for both soft and hard X-rays. A small laser heater (few keV) helps in soft X-ray case. Both slotted foil and undulator taper can be used to obtain single spike X-ray pulses. Slotted foil has a better result and is easy to be implemented. The residual R_{56} at DL2 plays an important role for soft x-ray case.

For the hard X-ray, it is possible to produce peak current of 25kA and single spike X-ray pulses with setting L1 phase of -17°. The optimized L2 phase is sensitive to the beam parameter, such as the initial bunch length. More detail study is required for taper.

Many parameters can be optimized in the LCLS machine setup. Present optimization has been done manually, which is really time-consuming. An automatic optimization code is desired for a systemic optimization.

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