HIGH POWER SUB-FEMTOSECOND X-RAY PULSE STUDY FOR THE LCLS

J.P. MacArthur*, J. Duris, Z. Huang, A. Marinelli,
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

The desire to resolve sub-femtosecond electron dynamics has pushed FEL facilities to shorter pulse lengths. However, current short-pulse schemes provide low pulse energy and a gain-length limited lower bound on the pulse duration. The X-ray Laser-Enhanced Attosecond Pulses (XLEAP) project at SLAC is designed implement an Enhanced Self Amplified Spontaneous Emission (ESASE) scheme, which produces sub-fs current spikes by modulating and compressing the electron beam. We show through a series of Genesis simulations that the current spike is capable of producing sub-fs pulses with a peak power well above 100 GW. Space-charge induced beam chirp can decrease pulse lengths below 400 as, and multi-stage schemes can increase peak x-ray powers to around 1 TW.

INTRODUCTION

X-ray free-electron lasers typically produce x-ray pulses of 10s to 100s of femtoseconds in duration, matching the electron beam duration. In Self-Amplified Spontaneous Emission (SASE) operation, x-ray pulses are composed of short temporal spikes. Efforts to isolate or produce single temporal spikes, like emittance spoiling [1], low charge operation [2], spectral selection, and dechirper induced betatron oscillation [3], have been demonstrated. While these schemes have produced fs-level pulses, they also produce proportionally fewer photons per pulse.

In 2004, Zholents proposed an Enhanced SASE (ESASE) operation mode for FELs to produce high power, single spike FEL pulses. In the ESASE scheme, a visible wavelength energy modulation is imparted on the electron beam in a short modulator. This energy modulation is converted into a density modulation in a chicane. If the electron beam has a suitably small energy spread, the resultant high current spike produces a single photon spike. The evolution of the phase space is shown in Figure 1. The transverse phase space before the modulator (a), after the modulator (b), after the chicane (c), and after lasing (d) are shown.

The ESASE scheme is being implemented at LCLS with a 2 micron laser and modulator upstream of the undulator hall. This project, dubbed X-ray Laser Enhanced Altosecond Pulse Generatio (XLEAP), is being commissioned this year. The modulating laser is not a single cycle in duration, so the emittane spoiling technique will be combined with ESASE to isolate a single lasing slice.

There are a number of variables that affect ESASE, including the modulation amplitude, the R_{56} of the chicane, the undulator taper, and the post-compression drift distance.

* jmacart@slac.stanford.edu

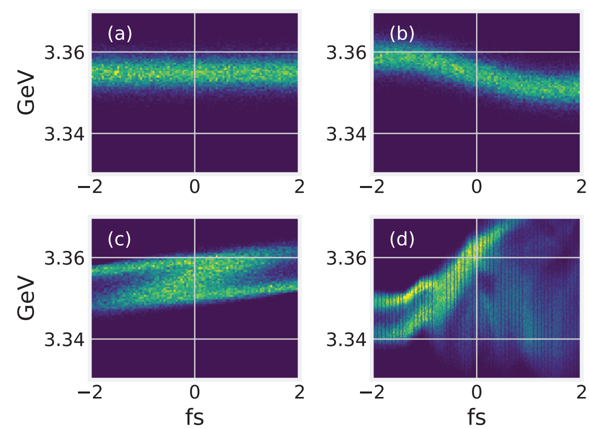

Figure 1: The transverse phase space evolution in an electron beam in the ESASE scheme. In this setup, a 2 micron laser generates a 4.0 MeV energy modulation in an initially uniform the electron beam (a-b). A chicane with an R_{56} of 0.45 mm stands up a current spike (c), which lases efficiently. In (c), the beam is slightly overcompressed. The phase space after 6 LCLS-like undulator segments is shown in (d). Lasing increases the energy spread, and a substantial space charge force also creates a slice-dependent energy change.

Here we find the conditions that minimize the x-ray pulse duration and maximize the x-ray pulse power in anticipation of LCLS commissioning of the XLEAP project.

SIMULATION RESULTS

We have performed a series of simulations with version 2 of the FEL code Genesis 1.3. The simulations used the conditions shown in Table 1. The soft x-ray self seeding chicane on girder 9 in the LCLS undulator line, which has a maximum R_{56} of 0.5 mm, is used to compress the electron beam. The remaining undulators on girders 10 - 33 may be used to produce a short x-ray pulse. The hard x-ray self seeding chicane on girder 16 may also be used for multi-staged operation, described later. A number of schemes to minimize the pulse duration and pulse power are discussed in the following sections.

Single Stage Optimization

In the simplest scheme the six undulators following the soft x-ray chicane, undulators 10-15, are used to produce a saturated x-ray pulse. To locate the optimum modulation amplitude, chicane R_{56}, and undulator taper, the sample space described in Table 1 was explored using the differential evo-

Table 1: LCLS-Like Simulation Parameters

Parameter	Value
Beam energy	3.55 GeV
Beam energy spread	2.54 MeV
Initial peak current	4 kA
Photon energy	500 eV
Emittance	0.4 µm
R_{56}	0 mm - 0.5 mm
Modulation	0 MeV - 17 MeV
Undulator taper	−2 % - 2 %

lution algorithm [4]. This optimization algorithm minimizes the pulse duration while searching through the sample space. At each optimization step, the fitness is calculated as the median fwhm duration of 16 time-dependent simulations, with a penalty for pulses below a threshold peak power of 20 GW.

The results of the optimization are shown in Figure 2. In this figure, the median peak x-ray pulse power and medianfwhm x-ray width (b) are plotted as a function of the R_{56} and modulation amplitude. The differential evolution algorithm samples the search space more densely where the pulse duration is short.

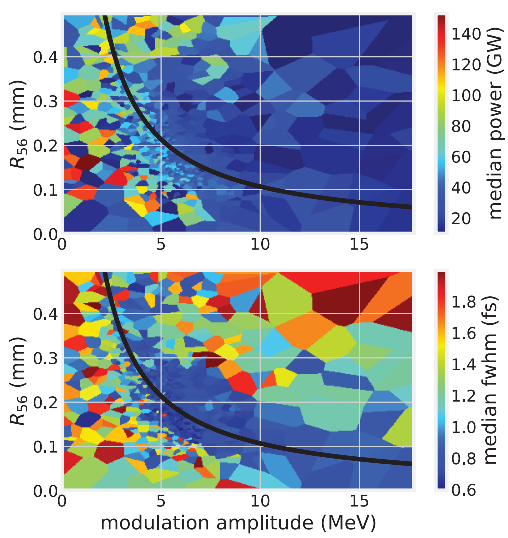

Figure 2: The peak power (top) and fwhm duration (bottom) are shown for a 6 undulator segment optimization. The undulator segment taper was also part of this optimization, though this axis is not shown explicitly. In this plot the non-uniform sampling of the sample space results the optimization algorithm's search through parameter space. The black line indicates the R_{56} required to stand the slice up vertically.

The pulse duration is minimized in areas where the beam is fully compressed. Full compression, defined as the point at which the slice is vertical in transverse phase space, is represented by the black line in Figure 1. Near full compression, the pulse width reaches a minimum of 60 as. Powers exceeding 100 GW are also possible with this scheme. The optimal taper slope is nearly zero is this 6 undulator scheme.

Space Charge Pulse Shortening

Since the peak current in the ESASE scheme is so large, only about six undulators are required to reach maximum powers. In the previous section, the first undulators after the compression are used. However, the final undulators may be used instead. In this scheme, the space charge from the current spike acts to give a chirp to the electron beam.

Using a 1D space charge formulation [5], we can allow the electron beam to drift for 50 meters prior to lasing. in Figure 3 (left) we display the longitudinal energy loss of an optimally overcompressed beam. The resultant x-ray pulse, shown in Figure 3 (right), is even shorter in duration than those seen in the previous section. The overcompressed beam was seen to be optimal after an optimization over the modulation amplitude, r_{56} and taper following a 50 m drift.

A reverse taper is also applied in this undulator line. The reverse taper is required to maintain resonance as photons slip forward into slices with a high beam energy. Eight undulators were used in these simulations.

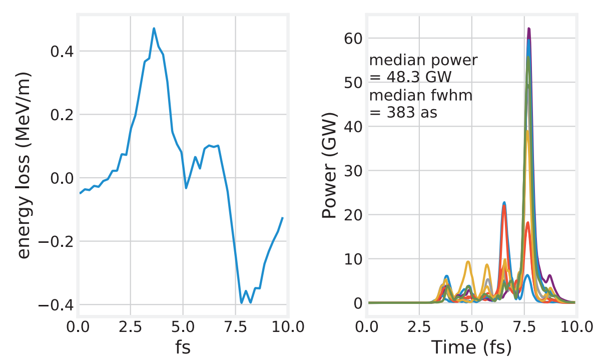

Figure 3: The longitudinal energy loss due to space charge in an overcompressed beam (left), and the resultant x-ray pulses (right) from eight simulations. This space charge force chirps the beam. A reverse taper is applied to the undulator in order to match the positively chirped parts of the electron beam.

Two Stage, Non-Fresh Lasing

Another scheme to improve the baseline single stage ESASE performance is to use a multi-stage lasing approach. In this scheme, two adjacent high current spikes generate x-rays in the six undulators between the soft x-ray chicane and hard x-ray chicane. The electron beam is then delayed by approximately 2 microns in the hard x-ray chicane, so that in the following six undulators, the rear x-ray pulse is amplified by the front electron beam spike.

The power evolution in this scheme is shown in Figure 4 (bottom). Here we begin with a 90 GW seed from the first stage, chosen from the single stage optimization. The delay from the hard x-ray chicane and the taper of the second stage

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are then scanned to find optimal conditions for lasing. The power grows over 6 undulators to 350 GW, a significant improvement over the single stage results.

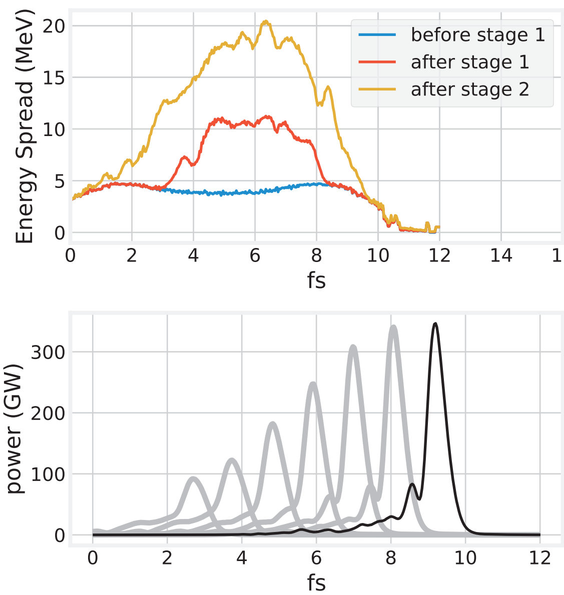

Figure 4: The energy spread (top) of an electron beam before the first stage, before the second stage, and after the second stage in the non-fresh slice scheme. With an optimal delay, the peak power increases from 90 GW to 350 GW (bottom) after a six undulator second stage. The power before the first undulator and after each of the six undulators is shown, with the black trace indicating the power after the last undulator.

This scheme is successful because the rear half of each current spike in the electron beam is unspoiled after a single stage, as seen in Figure 4 (top). If the delay is set so that the seed photons line up with the unspoiled electrons, rapid field growth is observed, even though the 2 micron delay washes out the microbunching developed in the first stage. The energy spread after the second is large throughout the whole slice, so a third stage would not help.

Two Stage, Fresh Slice Lasing

The recently developed fresh slice lasing technique allows LCLS to amplify a single photon pulse with multiple, fresh slices in the electron beam [3]. If a fresh current spike is used in the second section, the power after the second stage can be nearly 1 TW. The power evolution in this scheme is shown in Figure 5. Note that the simulation in Figure 5 is for a photon energy of 800 eV.

CONCLUSION

We have shown that at LCLS, ESASE can generate 100 GW, 600 as pulses with a single lasing stage. Pulse durations below 400 as are possible with space charge enhanced operation, and powers approaching 1 TW may be possible with multi-staged operation. With the commissioning of the XLEAP project in the next few months, we expect LCLS will soon provide short, high power pulses to users.

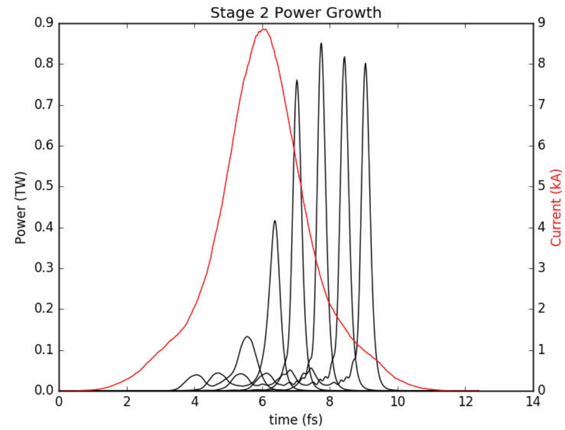

Figure 5: The power growth (black) and current (red) in the second stage of a fresh slice, two stage simulation. The power after each of the six undulators is shown. With fresh electrons to lase with, the x-ray power approaches 1 TW after the second stage. This simulation was conducted at 800 eV.

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