EVALUATION OF FEL PERFORMANCE WITH A LONGER INJECTOR DRIVE LASER PULSE AT THE LCLS*

F. Zhou+, Y. Ding, J. Duris. S. Gilevich, P. Hering, and S. Vetter, SLAC, Menlo Park, USA

Abstract

The X-ray Free Electron Laser (FEL) performance strongly depends on the beam emittance and peak current. Lengthening injector laser pulse can improve the injector emittance while compromising the injector peak current. With a longer laser pulse, stronger bunch compression through downstream bunch compressors is thus required to keep the same final peak current required by FEL process. This process may cause stronger micro-bunching effect. At the LCLS, we performed experiments with doubling injector laser pulse. In this paper, we present the simulation and preliminary experimental results of the injector emittance, microbunching effects and FEL performance with the long drive laser pulse.

INTRODUCTION

It is well known that the cost and performance of the x-ray free-electron-laser (FEL) depend critically on the emittance of the electron beam. The statement is particularly true for >20 keV, very hard x-ray FELs. The Linac Coherent Light Source (LCLS) can operate at about 25 keV FEL, much higher than the current 12.8 keV of FEL energy, with the shared LCLS-II variable-gap undulators starting 2019 [1]. Such harder x-ray FEL requires smaller emittance. The LCLS have efficiently preserved the electron beam emittance through acceleration. Consequently, it becomes important to extract electrons from a photoinjector with the lowest possible emittance.

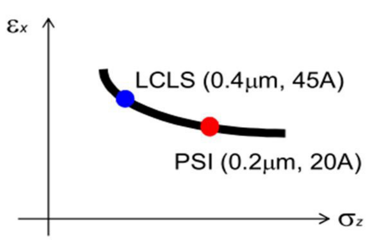

Figure 1: Pareto Front of emittance vs. bunch length.

Extensive worldwide photoinjector R&D aimed at emittance reduction has been performed for more than decades. Here, a simple approach is investigated for the emittance reduction without changing the LCLS injector beamline. According to the well-known Pareto-Front plot for the emittance versus bunch length, as shown in Figure 1, the emittance can be reduced by lengthening the bunch length (resulting in a lower peak current). For such an approach, the lower emittance is achieved mainly from suppression of the strong space charge force. A longer photocathode laser has to be applied to generate a longer electron bunch in the gun, requiring a stronger bunch compression through the downstream bunch compressors to keep a similar final peak current. This paper investigates the feasibility of the emittance reduction with this approach. First, we present simulations and measurements of the LCLS injector emittance with a longer drive laser pulse. Then, we discuss the measured and simulated longitudinal micro-bunching effect with the long modulated laser pulse after two stages of the bunch compression at the LCLS.

BEAM STUDIES FOR INJECTOR EMITTANCE REDUCTION

Simulations with a Longer Laser Pulse

Currently two 2-ps FWHM chirped s- and p-polarized laser pulses are stacked together in a Michelson interferometer to generating ~4 ps FWHM laser in routine FEL operations. We simulated 135 MeV injector beam performance with 11 ps FWHM laser, in comparison to the one using regular 4 ps laser, as shown in Figure 2 for 250 pC of bunch charge. The results show that the emittance with the 11 ps laser (red, left) can be improved about 50% but the peak current (red, right) is only about half the one with 4 ps photocathode laser (blue). It is verified in simulations that the emittance can be improved via compromising the peak current.

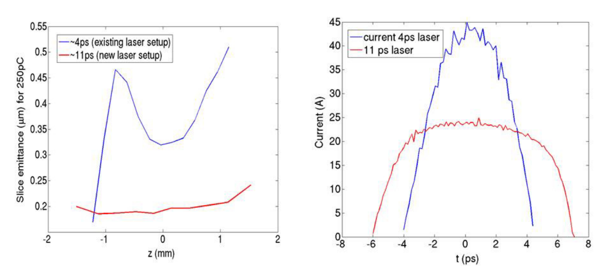

Figure 2: Comparison of beam simulations between 4 ps (blue) and 11 ps (red) FWHM laser pulse: emittance (left) and peak current (right) at 135 MeV.

Preliminary Measurements with a Long Laser Pulse

For this experiment, we are starting with a 1ps FWHM compressed UV laser pulse instead of the nominal 2ps chirped laser pulse.Using two birefringent α-BBO crystals (1.5 mm and 3 mm long respectively) placed in between Glan polarizers [2] , we are stacking 4-laser pulses to generate a ~4 ps pulse. We are then producing a ~8 ps FWHM laser pulse with the interferometric stacker. Beam emittance measurements were performed at the 135 MeV LCLS injector for 150 pC with a quad scan method using an OTR screen [3]. The projected emittance with the charge was firstly optimized. Then, with a transverse deflecting cavity located at the injector, the time-sliced

*The work is supported by DOE under grant No. DE-AC02-76SF00515.
+ zhoufeng@slac.stanford.edu

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emittance for the bunch charge is measured. Figure 3 shows the slice emittance with the stacked 8 ps laser, in comparison to the normal operation 4 ps laser (by stacking two 2-ps chirped laser pulses with the interferometric stacker). The measured time-sliced emittance is reduced by >30% and also the sliced emittance along the bunch is uniform for the case of 8 ps drive laser. This emittance improvement benefits from the reduced space charge effect with the longer laser pulse, in comparison to the one for 4 ps drive laser. The measured bunch length is about 30% longer than the one with 4 ps laser. These measurements are in reasonable agreement with the expectations.

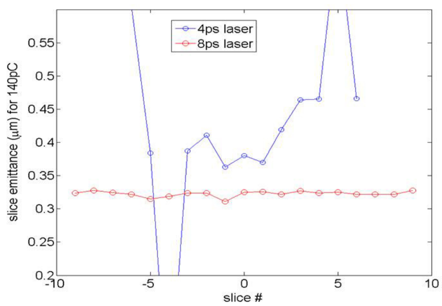

Figure 3: Comparison of the measured sliced emittance for the 4 ps (blue) and 8 ps (red) of photocathode lasers for 150 pC of bunch charge, at 135 MeV.

MEASURED AND SIMULATED LONGITUDINAL PHASE SPACE

When a few short pulses are stacked together to generate a long pulse, the final drive laser typically has density modulation on the flattop which cannot be totally avoided. This density modulation will further enhance the energy modulation due to longitudinal space charge force, and then transformed into stronger density/current modulation via downstream R_{56}. These modulations can significantly degrade the FEL performance. The following sections are to study the microbunching effect with the modulated longer laser pulse through the full LCLS machine.

Measured Longitudinal Effects with the Longer Laser

An X-band transverse deflector (XTCAV), located downstream of the undulator section, provides a direct diagnostic for this study [4]. This deflector includes two 1-m-long X-band rf deflecting structures, providing a time-dependent horizontal kick on the beam. It is followed by a vertically bending spectrometer magnet, and the beam is imaged on a downstream YAG screen. With this arrangement, the horizontal dimension of the measured image represents time while the vertical dimension represents energy. Thus, the XTCAV system provides a direct measurement of the electron beam time-energy phase space. Since the location of the measurement is downstream of the FEL lasing process, the lasing induced time-resolved energy spread growth and the microbunching structure can be measured. We conducted the following measurements with the same FEL conditions, at 1.5-keV photon energy (6 GeV of beam energy) with 2 kA of peak current. First, we use regular 4 ps laser by stacking two 2-ps pulses with the interferometric stacker for FEL lasing, and a 3.2 mJ of the FEL pulse intensity is observed. Figure 4 shows the XTCAV image with the FEL lasing (top left) and lasing off (top, right). Almost full beam gets lasing and the beam temporal distribution is reasonably smooth with the lasing off (no notable microstructure for the core beam). The measured sliced energy spread shown in Fig. 4 (bottom) is reasonably flat for core bunch with a regular laser heater setup.

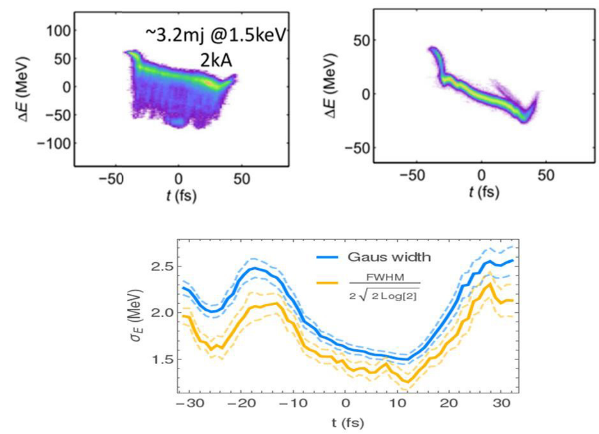

Figure 4: Measured XTCAV images with lasing (top, left), without lasing (top, right), and measured sliced energy spread along the bunch (bottom). Injector laser is from initial 2-ps pulse, then stacked to get a regular 4 ps pulse. Electron beam energy is 6 GeV.

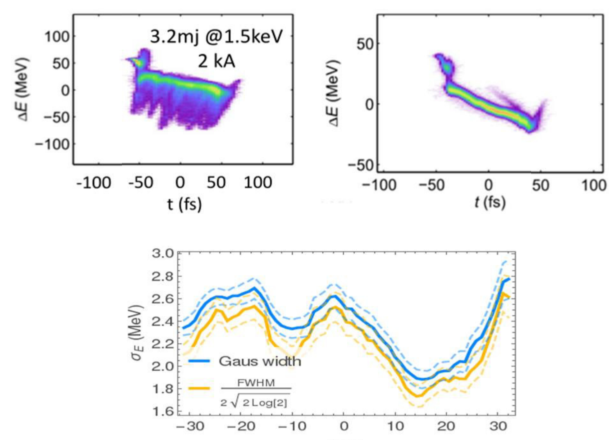

Figure 5: Measured XTCAV images with lasing (top, left), without lasing (top, right), and measured sliced energy spread along the bunch (bottom). Injector laser is from initial 1-ps laser, and then stacked with one BBO crystal followed by interferometric stacker to get 4-ps pulse. Electron beam energy is 6 GeV.

Then, we change laser initial pulse duration to 1-ps and stacked to ~4 ps FWHM pulse with one α-BBO crystal followed by an interferometric stacker. Figure 5 shows the XTCAV images with lasing (top, left), without lasing

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(top, right), and the sliced energy spread. In comparison to Fig. 4, the images look very similar to the above one except the sliced energy spread, which increases with one crystal (although the increased energy spread is not large enough to impact the FEL performance (3.2 mJ)). Lastly, we add another BBO crystal from the 2nd step to generate the 8-ps pulse. At a similar final current, the FEL lasing is almost totally suppressed, and scanning laser heater laser energy did not improve. Figure 6 shows some XTCAV images with lasing at different laser heater setup. The strong microbunching structures are observed. Several notable modulation periods on the bunch is clearly seen. We suspect the strong microbunching effect comes from the non-ideal photocathode laser modulation through the two crystals stacking and stronger downstream compression. Start-to-end simulations have verified these observations. In the simulations, with a 20% peak-to-peak modulation on the flattop of the injector laser, microbunching structure would appear with a laser heater induced energy spread of 10 keV but it is less important at laser heater above 20 keV with a price of increased final slice energy spread.

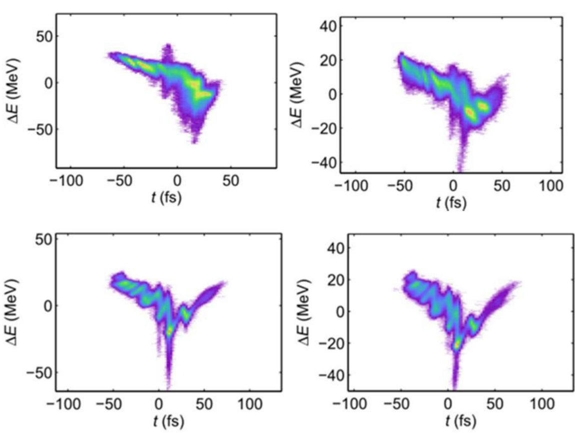

Figure 6: XTCAV images with different laser heater laser energy. Injector laser is from initial 1-ps laser, then stacked with two α-BBO crystals followed by the interferometric stacker to get 8-ps pulse. Beam energy is 6 GeV.

Solutions to Improve Longitudinal Phase Spaces

Lower emittance is critical for hard x-ray FEL operation especially pushing to shorter wavelength. The side effect of microbunching structures, on the other hand, needs to be treated carefully. Shorter wavelengths require higher electron beam energy, which is helpful for microbunching suppression. In this Section, we use final beam energy of 14 GeV as an example to investigate the microbunching problem. We looked into two possible solutions for alleviating the microbunching effect. One is to make the modulation period shorter by using shorter initial laser pulses [5]. This smaller period modulation in principle can be partially washed out by the laser heater. The other is to reduce the laser modulation amplitude on the flattop. The following examples use same final 8 ps FWHM drive laser but different laser modulations for generation of electron beam on the photocathode.

First, two crystals are used to stack initial 1 ps pulse with 20% peak-to-peak modulation. Figure 7 (top) shows the simulated final longitudinal phase space at 14 GeV with the modulation. Notable microbunching is seen. With the reduction of modulation from 20% to 10%, the microbunching effect is obviously better suppressed, as shown in Fig. 7 (middle). Usually maintaining 10% peak-to-peak laser modulation is challenging for 24/7 operations. Instead, stacking short initial pulse of 0.5-ps rather than 1-ps is relatively straightforward to suppress the microbunching effect. The laser heater can better suppress for the shorter period laser modulation. Figure 7 (bottom) shows results with stacking 0.5-ps initial pulse where 20% peak-to-peak modulation is assumed on the flattop and the microbunching becomes less.

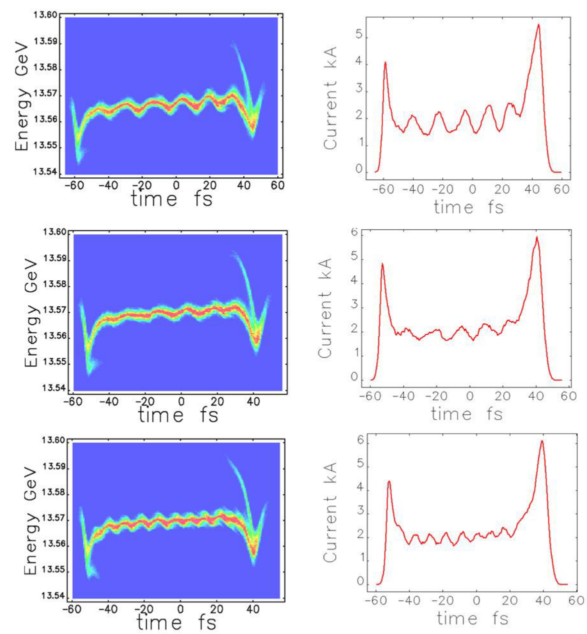

Figure 7: Simulated final longitudinal phase space with 20% peak-peak laser modulation and initial 1-ps laser (top), 10% peak-to-peak laser modulation and initial 1-ps laser (middle), and 20% peak to peak laser modulation and initial 0.5-ps laser for 150 pC of bunch charge.

SUMMARY

The injector emittance has been reduced by ~30% with 8-ps laser, comparing to a normal operation 4-ps laser setup. The strong microbunching effect is observed with the stacked 8-ps laser degrading the FEL performance. According to the simulations, the microbunching can be improved with reduced laser modulation and/or stacking a shorter laser pulses.

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