MEASUREMENT OF FEMTOSECOND LCLS BUNCHES USING THE SLAC A-LINE SPECTROMETER *

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Abstract

We describe a novel technique and the preliminary experimental results to measure the ultrashort bunch length produced by the LCLS low-charge, highly compressed electron bunch. The technique involves adjusting the LCLS second bunch compressor followed by running the bunch on an rf zero-crossing phase of the final 550-m of linac. As a result, the time coordinate of the bunch is directly mapped onto the energy coordinate at the end of the linac. A high-resolution energy spectrometer located at an existing transport line (A-line) is then commissioned to image the energy profile of the bunch in order to retrieve its temporal information. We present measurements of the single-digit femtosecond LCLS bunch length using the A-line as a spectrometer and compare the results with the transverse cavity measurement as well as numerical simulations.

INTRODUCTION

X-ray free electron (XFEL) lasers have ushered in a new era of ultrafast x-ray sciences [1]. These noval sources can provide a few fs and even sub-fs pulses but also pose tremendous challenges for both electron and x-ray temporal diagnostics. A notable example is that the compressed bunch length of the linac coherent light source's (LCLS) low charge operating mode is too short to be measured by the standard accelerator diagnostics. In order to reach a temporal resolution that approaches 1 fs, a longitudinal mapping technique following the work of Ref. [2] is further developed in Ref. [3], taking advantage of the XFEL accelerator configuration and into account the longitudinal wakefield of a long linac. In this paper, we report the preliminary results obtained using this technique to measure the temporal profiles of the ulrashort LCLS bunches.

DESCRIPTION OF THE METHOD

In a typical x-ray FEL such as the LCLS, after the electron bunch is compressed in the final bunch compressor (that we call BC2 at the electron energy $E_2 = \gamma_2 mc^2$), there is a final linac section (that we call L3) to accelerate the beam to the desired final energy. In addition to the nominal machine configuration, we add a diagnostic chicane right after BC2 and run the beam in the L3 linac on the rf zero-crossing phase (where there is no net acceleration). We sketch the setup in Fig. 1. Nominal setup parameters are given in black type, those changed for measurement mode are in red and have an over-bar. The head of the bunch is assumed at $z < 0$. A simple chicane has $R_{56} < 0$ with this convention.

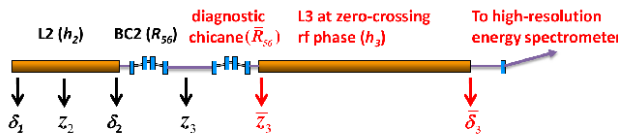

Figure 1: Schematic setup for short bunch measurement using a chicane and an rf linac. The arrows give the locations at which the various energy and position symbols apply. In red are parameters that are changed for the purpose of the bunch length measurement. Note that the diagnostic chicane is actually part of BC2, with its total strength changed to $R_{56} + \bar{R}_{56}$.

Suppose a diagnostic chicane strength is $\bar{R}_{56}$, and the rf-induced linear energy chirp in L3 is

$$h_3 = \pm\frac{2\pi}{\lambda_{rf}}\frac{eV_3}{E_2}\,, \tag{1}$$

where the rf wavelength $\lambda_{rf} = 10.5$ cm, V_3 the maximum accelerating voltage of L3, and $\pm$ refers to the two rf zero-crossing phases. Then the longitudinal phase space is transformed between the BC2 end and the L3 end according to

$$\begin{aligned}\begin{pmatrix}\bar{z}_3\\ \bar{\delta}_3\end{pmatrix} &= \begin{pmatrix}1 & 0\\ h_3 & 1\end{pmatrix}\begin{pmatrix}1 & \bar{R}_{56}\\ 0 & 1\end{pmatrix}\begin{pmatrix}z_3\\ \delta_2\end{pmatrix}\\ &= \begin{pmatrix}1 & \bar{R}_{56}\\ h_3 & 1+h_3\bar{R}_{56}\end{pmatrix}\begin{pmatrix}z_3\\ \delta_2\end{pmatrix},\end{aligned} \tag{2}$$

where z_3 and $\bar{z}_3$ are the longitudinal bunch coordinates after BC2 and the diagnostic chicane, δ_2 and $\bar{\delta}_3$ are the relative energy coordinates at the end of L2 and L3, respectively (see Fig. 1). To have a one-to-one correspondence between z_3 and the final energy coordinate $\bar{\delta}_3 = h_3 z_3 + (1 + h_3\bar{R}_{56})\delta_2$ requires that [2]

$$1 + h_3\bar{R}_{56} = 0\,. \tag{3}$$

Hence, to first order the final energy coordinate is independent of the initial energy coordinate

$$z_3 = \frac{\bar{\delta}_3}{h_3}\,, \quad \text{and} \quad \sigma_{z3} = \frac{\bar{\sigma}_{\delta 3}}{|h_3|}\,, \tag{4}$$

where $\bar{\sigma}_{\delta 3}$ is the final rms energy spread at the L3 end, and σ_{z3} is the rms bunch length after BC2. Thus, the final

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energy profile of the beam is a scaled image of its temporal profile after BC2, and an energy spectrum measurement yields the bunch profile. In the LCLS measurements shown below, the diagnostic chicane is actually part of BC2, with its total strength changed to $R_{56} + \bar{R}_{56}$.

The longitudinal wakefield in the 550-m long L3 linac can change the rf-induced energy spread. For a very short bunch, the linac wakefield mainly introduces a linear energy chirp and may be compensated for by adjusting the compression setting [3]. To restore the (almost) one-to-one mapping from z_3 to $\bar{\delta}_3$, one can shift the L2 phase by

$$\Delta\phi_2 \approx \sqrt{\frac{8\pi}{3}\frac{I_2}{I_A}\frac{\lambda_{rf}\cos^2(\phi_2)L}{2\pi\gamma_2 a^2 R_{56}|h_3|}}\,, \tag{5}$$

where $I_2/I_A = r_e N/(\sqrt{2\pi}\sigma_{z2})$ is the peak current in L2 (for a Gaussian bunch) in terms of the Alfvén current $I_A \approx 17$kA, a is the average radius of the iris, and L is the length of the L3 linac. Such a phase shift can also be found empirically as follows. In the LCLS, a coherent radiation detector after BC2 is used to monitor the bunch length; it can determine the L2 phase corresponding to full compression to $\pm 0.2°$ precision [4]. Thus, the necessary L2 phase shift can be obtained by comparing the energy spread minimum using this measurement technique with the coherent radiation signal maximum after the nominal BC2 setting.

An alternative way to compensate the wakefield effect is to change $\bar{R}_{56}$ instead of ϕ_2, since it can be a part of the compressor setting adjustment. The required change is [3]

$$\Delta\bar{R}_{56} \approx \sqrt{\frac{8\pi}{3}\frac{I_2}{I_A}\frac{R_{56}L}{\gamma_2 a^2|h_3|}}\,. \tag{6}$$

Therefore, in order to measure the compressed bunch length after BC2 under the nominal operating R_{56}, we can increase the BC2 strength by $|\bar{R}_{56} + \Delta\bar{R}_{56}|$ according to Eqs. (3) and (6), and run the beam in L3 at an rf zero-crossing phase ($-90°$). The measured energy profile at the end of L3 divided by $|h_3|$ gives the temporal bunch shape (or its mirror image) as it exists after BC2 at the original R_{56} setting. Alternatively, we can decrease the BC2 strength by $|\bar{R}_{56}| + \Delta\bar{R}_{56}$, and run the beam in L3 at the other rf zero-crossing phase ($+90°$) to obtain the same results. In the experiments discussed below, both the L2 phase shift and changes in R_{56} are used to compensate for the wakefield effect.

A-LINE ENERGY SPECTROMETER

The energy spread generated by a very short bunch (with $\sigma_{z3} \approx 1$ μm) through this technqiue is about $\bar{\sigma}_{\delta 3} = |h_3|\sigma_{z3} \sim 10^{-4}$. To measure such a small energy spread, a high-resolution spectrometer is necessary. The A-Line, one of the two original beam transport systems at SLAC, is designed to branch out electron beams from the linac end and has a high dispersion point in the middle of a 24-degree deflection section. The A-line was restarted for this purpose after several years of dormancy. A phospher screen profile monitor (PR18) near the highest dispersion location ($\eta_x \sim 6$m) can be used to image the beam's horizontal profile and size (x and σ_x). Assuming the screen resolution is much better than the beam size induced by the energy spread (about 700 μm in this example), we have

$$z_3 = \frac{x}{h_3\eta_x}\,, \quad \text{and} \quad \sigma_{z3} = \frac{\sigma_x}{|h_3\eta_x|}\,. \tag{7}$$

The dispersion at PR18 can be measured by correlating the horizontal position with the beam energy, while the chirp can be determined by the L3 linac setup and is not very sensitive to the exact phase near zero-crossing. An empirical calibration may be obtained by correlating the horizontal positiion with the beam phase in L3 (i.e., z_3). However, the L3 phase jitter (~ 50 fs rms) results in horizontal position jitter (~ 10 mm rms) on PR18, which makes the empirical calibration difficult. Therefore, we simply measure the dispersion (with the beam on L3 crest) and calculate the chirp from L3 on-crest energy gain. The bunch length measurement is based on single-shot images and is not sensitive to the L3 phase jitter as long as the beam is on the screen (PR18 screen is about 10 cm wide).

BUNCH LENGTH MEASUREMENT

Comparision with TCAV Measurements

To validate this technique, we compare the measurement results with the standard transverse deflector method when the charge is not too low (40 pC) and the bunch length is not too short. At the nominal BC2 setting (with $R_{56} = -24.7$ mm), we first measure the bunch length using an rf deflector (TCAV3), located after BC2, as a function of the L2 phase [4]. We then set BC2 $R_{56} = -34$ mm to provide the strength for the diagnostic chicane as well as to compensate for the L3 wakefield. An energy feedback based on a BPM near PR18 is used to hold the L3 phase (near zero-crossing). Averaged PR18 rms beam size (over a few shots) yields the post-BC2 bunch length for the nominal BC2 setting as a function of the L2 phase. A comparison of the rms bunch length (both using the asymmetric Gaussian fit) is shown in Fig. 2. When the bunch is either under or over-compressed with the rms bunch length longer than 3 μm, the two methods are in reasonable agreement. Near the full compression phase, TCAV3 reaches its resolution limit and yields scattered results, while the PR18 measurements shows a smooth curve with the minimum rms bunch length slightly above 1 μm. This minimum is believed to be limited by the resolution of the very old PR18 screen.

Measurements with the Upgraded Screen

A new phospher screen (ZnS) of 0.1 mm thickness was installed to replace the old screen in order to improve the PR18 resolution. The target inscribed on the new screen suggests that the resolution is about 125 μm in y and about 250 μm in x (a factor of 2 due to the 60-degree viewing angle). We will subtract this estimated horizontal resolution

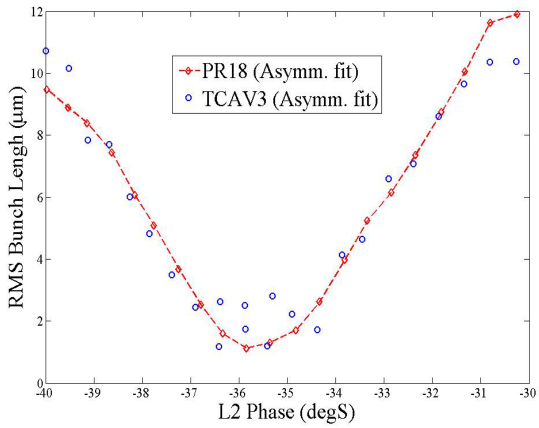

Figure 2: Comparison of 40 pC bunch length measured from PR18 and from the deflecting cavity (TCAV3).

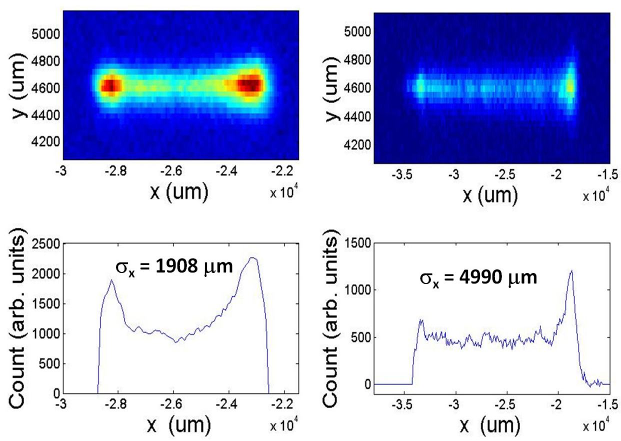

Figure 3: Two single-shot images on PR18 (upper plot) for 40 pC under-compressed bunches. The lower plots are the projections onto x that show the double-horn bunch profiles. RMS cut area method is used to obtain the rms beam size shown in the plot. The head of the bunch is to the right.

from the rms beam size in quadrature. The detailed bunch temporal structures show up on the new screen as in Fig. 3 and Fig. 4 for 40 pC and 10 pC compressed bunches respectively, very similar to those obtained in simulations. The microbunching structure observed for the 40-pC overcompressed bunch (Fig. 4, left plots) supports the screen resolution at 250 μm in x. The measured dispersion at PR18 is $\eta_x = -6.13$ m. The total on-crest energy gain in L3 is 9.92 GeV. At a -90° L3 phase, the chirp is $h_3 = 126$ m^{-1} for a beam with its energy at 4.7 GeV (BC2 energy).

To make a quantitative comparison with simulations , we note that the double-horn shape shown in Fig. 3 can not be fitted by a Gaussian function. Thus, we use the “RMS cut area” method (applying 5% cut in head and tail part of the bunch signal) to calculate the rms bunch length for both experimental and simulated results. In *LiTrack* [5] simulations, we set up the initial beam conditions that correspond to the measured injector and post-BC1 bunch lengths. Figure 5 shows the simulated rms bunch length vs. L2 phase

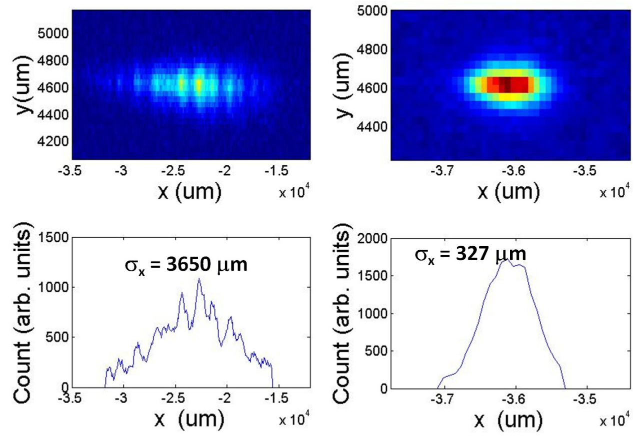

Figure 4: Two single-shot images on PR18 (upper plot) for 40 pC over-compressed bunch (left) and 10 pC fully-compressed bunch (right). The lower plots are the projections onto x that show the Gaussian-like bunch profiles.

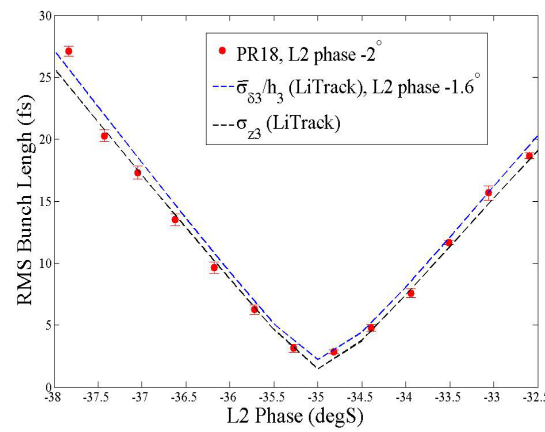

Figure 5: Comparison of 40 pC bunch length measurement with *LiTrack* simulations.

when BC2 $R_{56} = -24.7$ mm (black dashed line). Then we set $R_{56} = -35$ mm and L3 at $-90°$ as in the measurement setup to simulate $\bar{\sigma}_{\delta 3}$ at the linac end (green dashed line). The L2 phase is shifted by $-1.6°$ to compensate for the wakefield effect and R_{56} adjustment. The experimental data (red points) are shifted by $-2°$ in the L2 phase in order to match the simulations. The agreement between the measurements and simulations is good.

The smallest horizontal rms beam size measured on PR18 is 327 μm (Fig. 4 right plots) for a 10-pC bunch. After subtracting the screen resolution of 250 μm, we get a minimum rms bunch length of ~ 0.27 μm or 0.9 fs.

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