TIME-RESOLVED IMAGES OF COHERENT SYNCHROTRON RADIATION EFFECTS IN THE LCLS FIRST BUNCH COMPRESSOR

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Abstract

The Linac Coherent Light Source (*LCLS*) is an x-ray Free-Electron Laser (FEL) facility now in operation at SLAC. One of the limiting effects on electron beam brightness is the coherent synchrotron radiation (CSR) generated in the bunch compressor chicanes, which can significantly dilute the bend-plane (horizontal) emittance. Since simple emittance measurements [1] do not tell the full story, we would like to see the time-dependent CSR-kicks along the length of the bunch. We present measured images and simulations of the effects of CSR seen on an intercepting beam screen just downstream of the *LCLS* BC1 chicane while powering a skew quadrupole magnet near the center of the chicane [2]. The skew quadrupole maps the time coordinate of the pre-BC1 bunch onto the vertical axis of the screen, allowing the time-dependent CSR-induced horizontal kicks to become clearly visible.

INTRODUCTION

The effects of CSR can degrade the brightness of an electron bunch, especially as it is being compressed in a magnetic chicane and begins to radiate coherently at wavelengths which are long compared with the shrinking bunch length. The CSR wake tends to kick the head and tail of the bunch in different bend-plane directions due to the CSR-altered head and tail energies which arise during passage of the bunch through the chicane bends. The net effect is typically an increased bend-plane emittance, usually characterized by the spot size projection onto an intercepting screen. In fact, it will also be very useful to time-resolve these kicks along the length of the bunch.

With this goal in mind we have installed a skew quadrupole magnet [2] (rotated by 45° wrt a standard quadrupole magnet) near the center of the BC1 chicane, which couples the x-position of an electron at chicane center to a y-position after the chicane. The *LCLS* BC1 layout [3] is shown in Figure 1 with parameters in Table 1.

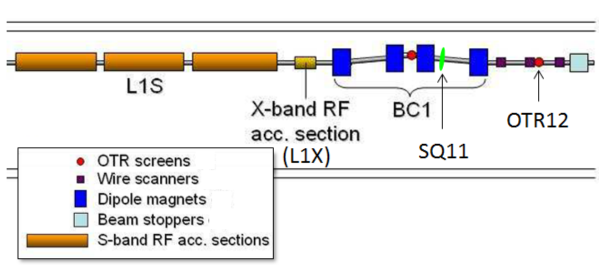

Figure 1: Layout of *LCLS* injector in the BC1 area. The 9-m long S-band linac section (L1S) is followed by a 60-cm long X-band RF section (L1X) feeding the BC1 chicane at 220 MeV. The "SQ11" skew quad and "OTR12" screen are also shown.

Table 1: LCLS Injector and BC1 Parameters

Parameter	sym.	Value	Unit
Bunch charge	Q	0.25	nC
BC1 Momentum Compaction	$\|R_{56}\|$	45.5	mm
Electron energy at BC1	E	220	MeV
Pre-BC1 bunch length (rms)	σ_z	0.62	mm
Focal length of skew quad	f	14	m

In order to compress the bunch length in BC1, the bunch must be energy chirped (linearly correlated energy along bunch length) by operating the L1S RF (nominally accelerates from 135 MeV to 239 MeV) off its accelerating crest phase by −25 degrees (sets head of bunch at lower energy than tail). The chicane then delays the low-energy bunch head ($\gamma >> 1$) and advances the high-energy bunch tail, compressing the bunch.

Since the accelerating RF wave is sinusoidal and the pre-compressed bunch length (~0.6 mm rms) is not insignificant compared to the S-band (2.856 GHz) RF wavelength (105 mm), there is also a significant 2nd-order chirp on the bunch induced by the RF. If not corrected, this 2nd-order chirp can generate a sharp temporal spike on the bunch if enough compression is applied. This very short, intense spike generates even more CSR power and can amplify the emittance growth.

To remove this 2nd-order chirp, and also to compensate the slight 2nd-order compression effect of the chicane, a short harmonic RF section [4,5] is installed just before the chicane and operated at the *decelerating* crest phase (decelerates from 239 MeV to 220 MeV at −180° here). At *LCLS* this is a 4th harmonic RF section (wavelength of ~26 mm) at X-band frequencies (11.424 GHz). When the X-band peak RF voltage, V_{L1X}, is set properly (typically about 19 MV at *LCLS*), the bunch compression process is quite linear, producing an unchanged temporal distribution, except shorter (*i.e.*, no temporal spikes develop). If the X-band voltage is set too low, the 2nd-order chirp will persist (negative 2nd derivative of energy with time) and a spike will first begin to develop at the *head* of the bunch as the compression is further increased (by setting the L1S phase to more negative values). If the X-band voltage is set too high, the 2nd-order chirp will flip sign (positive 2nd derivative) and a spike will begin to develop, first at the *tail* of the bunch. If the L1X voltage is set at the ideal voltage, no spikes will develop.

In order to see the effects these spikes have on the CSR-induced kicks as a function of the compression level and in a time-resolved way, we have carried out an experiment using the 'SQ11' skew quad and the 'OTR12' screen (see Figure 1), where the L1X voltage is varied

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over three settings (weak, strong, and ideal) and the L1S RF phase is scanned over nine settings per L1X setting in order to explore the progression of bunch compression and gradually watch the CSR effects develop on OTR12.

When switched on, the BC1 skew quad (SQ11) converts the large horizontal beam size at the chicane center (induced by the large L1S energy chirp and horizontal BC1 dispersion) into a large vertical beam size on OTR12. Since the large beam size is due to the energy chirp, which is highly linearly correlated to the pre-BC1 bunch length coordinate, the OTR screen then clearly reveals the pre-BC1 bunch length as a vertical streak (see images in Figure 2). This configuration allows a linear mapping of the pre-BC1 bunch length coordinate onto a simple beam screen, allowing time-resolved beam measurements after BC1. For this experiment the bunch charge was 250 pC and the transverse normalized *x* and *y* emittance values (before BC1) were each about 0.5 µm.

MEASUREMENTS

Figure 2 shows 27 measured electron beam images on the OTR12 screen (using optical transition radiation), which is located 3.6 meters after the exit of the BC1 chicane, where the SQ11 skew quad is switched *on* (14-m focal length) generating the vertical time-streak seen in each image. Each column in this figure represents one of three L1X RF voltage settings (16, 19, and 22 MV, left to right), and each row corresponds to one L1S RF phase setting (about an 8º range from top to bottom centered near −31º). The 220-MeV electron energy at OTR12 is preserved at all settings here by adjusting the L1S RF voltage, which is controlled by a feedback loop reading a beam position monitor (BPM) in BC1, but the L1X voltage and phase are both constant within one column.

As the reader scans the images from top to bottom, starting on the left column (V_{L1X} = 16 MV), the images are seen to blow up horizontally, with the blow-up starting at the top of the image (the pre-BC1 bunch *head*) and quickly progressing along the beam core to the bottom of the image (the pre-BC1 bunch *tail*). The last images show the CSR blow-up beginning to relax since the bunch is now over-compressed (getting longer) and not radiating strongly. It is important to note that the skew quad maps the *pre-BC1 bunch length* coordinate onto the screen, not the post-BC1 bunch length. Therefore the time scale along the screen's vertical axis is always the same here (~6 ps FWHM) and does not flip sign, even though the post-BC1 bunch is compressing and eventually flipping *head* with *tail* (over-compression).

The reader might now scan the images from top to bottom again, examining the center column (V_{L1X} = 19 MV). This shows the CSR-induced horizontal blow-up no longer crawling along the bunch (head to tail), but now exploding almost uniformly (near −31º) and then relaxing similarly. This is the linearized L1X voltage setting producing no spikes.

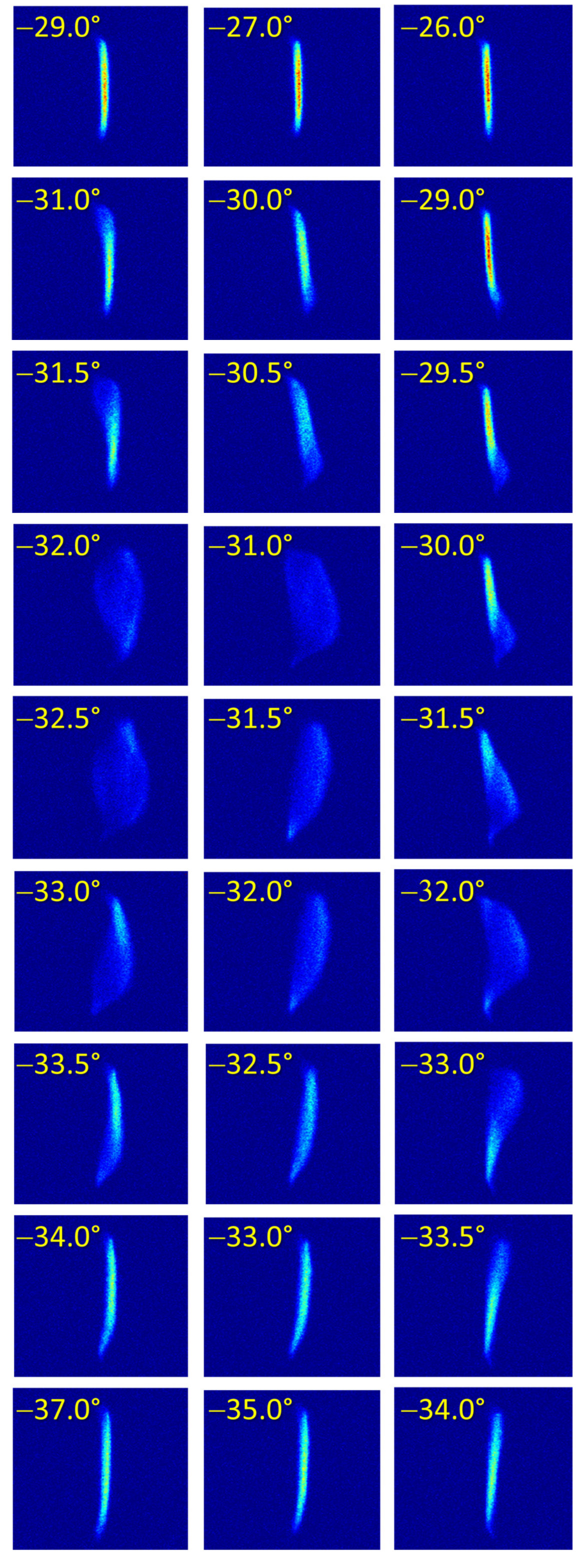

Figure 2: OTR screen images with the X-band RF set at 16 MV (left column), 19 MV (center), and 22 MV (right). The bunch length (vertical streak) here is ~6 ps FWHM with the pre-BC1 bunch *head* at the top of each image. Energy loss in the final BC1 bend kicks to the right here.

The final (right) column has the L1X voltage set too high, at 22 MV. Here the opposite behavior occurs (with respect to the left column at 16 MV). Now the beam

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begins to blow up (when images are observed from top to bottom again) starting at the bunch *tail* (bottom of each image), rather than the bunch *head* (top of each image). This CSR-induced horizontal blow-up is seen to crawl along the pre-BC1 bunch from *tail* to *head* now, rather than *head* to *tail*. The evolution of these images is explained graphically in Figure 3 (post-BC1 bunch *head* at left here), showing longitudinal phase space with the sign of the 2nd-order chirp set by the L1X voltage. A negative 2nd-order chirp ($V_{L1X} < 19$ MV, top six plots) generates a temporal spike starting at the pre-BC1 bunch *head* (top-left plot pair) and evolving toward the pre-BC1 bunch *tail* (top-right plots), whereas a positive 2nd-order chirp ($V_{L1X} > 19$ MV, bottom six plots) generates a temporal spike starting at the pre-BC1 bunch *tail* (bottom-left plot pair) evolving toward the pre-BC1 bunch *head* (bottom-right plot pair).

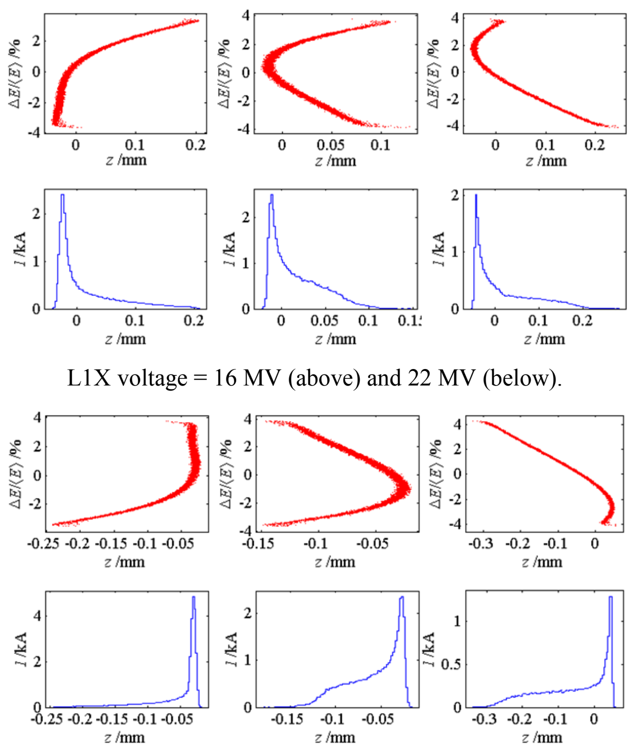

Figure 3: Simulation explaining evolving images in Figure 2 with two L1X voltage settings (top six plots at 16 MV and bottom six at 22 MV). Each of the three plot columns are for different L1S phases. Parameters are approximate here simply to help explain the effect.

It is also worth pointing out that a broad-band pyroelectric radiation detector is located at the end of BC1, and is normally used in a feedback loop to measure the relative post-BC1 bunch length, based on the CSR power of the last chicane dipole magnet [6]. Although this bunch length feedback loop was switched off during these experiments (leaving only the BC1 BPM-based energy loop operating), the pyro-detector was monitored during the data acquisition and the peak signal is seen to correspond to the largest blown-up image in each column of Figure 2 (*i.e.*, –32.5° at $V_{L1X} = 16$ MV, –31.5° at $V_{L1X} =$ 19 MV, and –32.0° at $V_{L1X} = 22$ MV). Figure 4 shows the pyro-detector reading vs. the L1S RF phase at $V_{L1X} = 16$ MV, which confirms the maximum CSR at –32.5° as also seen in Figure 2 (left column). The fused silica vacuum window attenuates much of the CSR at $\lambda < 100$ µm so the response is somewhat flat near the peak compression.

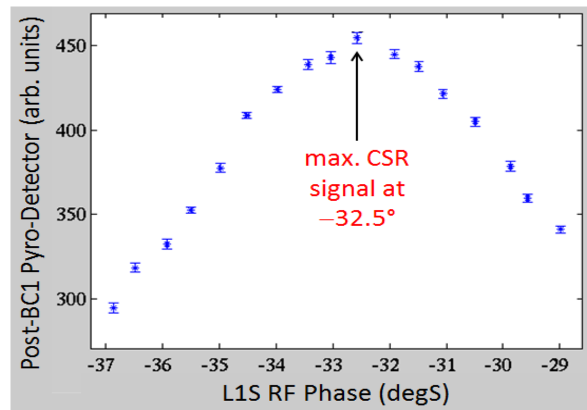

Figure 4: Post-BC1 pyroelectric CSR detector reading vs. L1S RF phase at $V_{L1X} = 16$ MV with maximum at –32.5°.

To enhance the spike even further, the L1S RF phase was varied again, but now with the L1X RF system switched *off*. Figure 5 shows the OTR12 measurement (left) and accompanying simulations (right) using *Elegant* [7], with the L1S RF phase set at –37° (but at –39° in the simulation) corresponding approximately to the top-center plot pair in Figure 3.

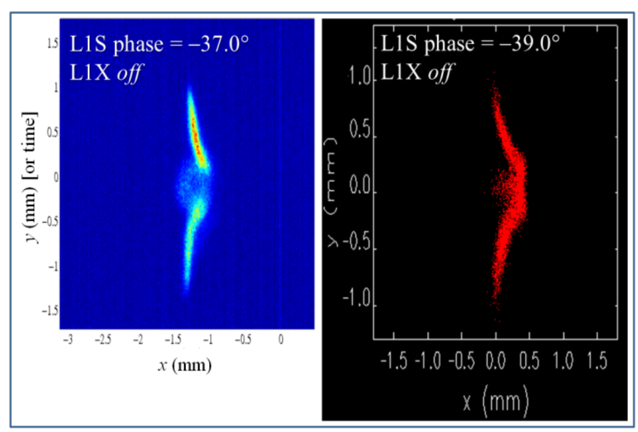

Figure 5: Measured image (left, at –37°) and simulated (right, at –39°) with L1X RF switched *off*. The L1S phase differs between measurement and simulation by 2°.

A horizontal deflection (to the right here) corresponds to an energy loss just prior to, or within the final BC1 bend. This is where a spike appears along the center of what was the pre-BC1 bunch length coordinate, generating a clear CSR-induced horizontal kick that is quite well localized (with laser heater off [8]) due to the extreme case with L1X off (no linearization and large spike).

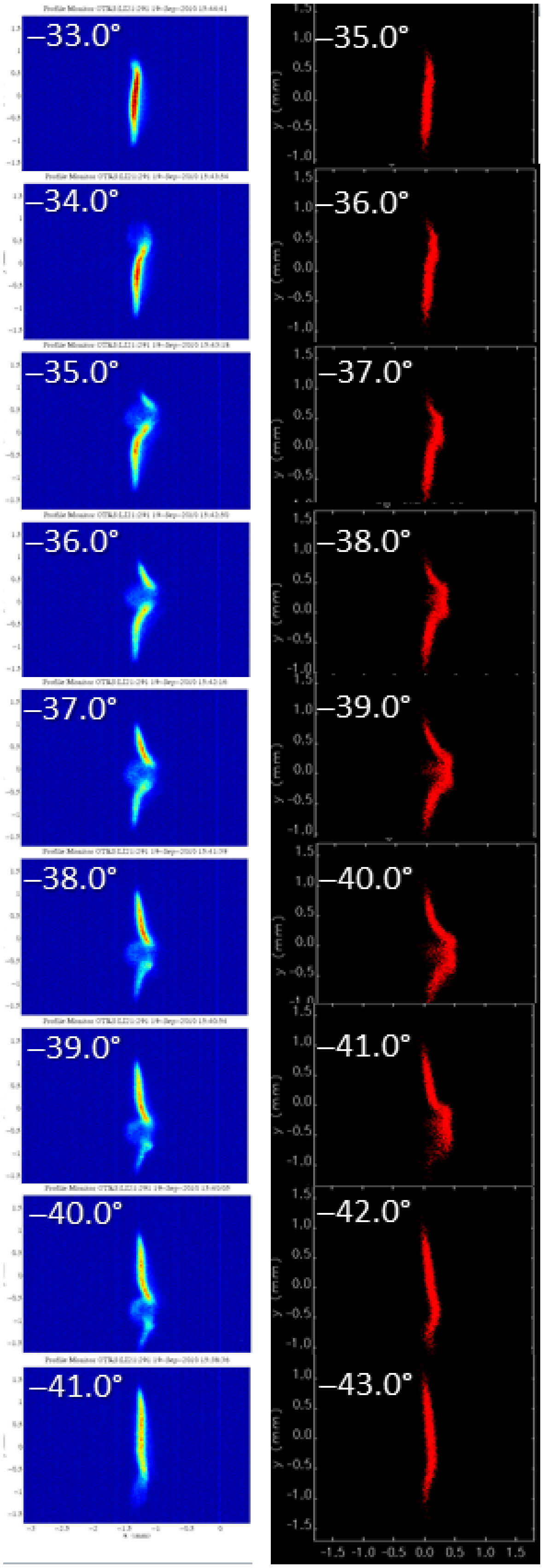

Figure 6: Measurements (left) and simulations (right) with X-band RF switched off. The L1S phase settings differ between measurement and simulation by 2°.

The simulations agree quite well except for a 2° difference in the absolute RF phase between measurement and simulation, which is difficult to know with better accuracy. The middle of the beam appears to be losing more energy as we observe closer to the spike, where the peak current is highest, but some small part of the beam at the spike is clearly exploding and may actually be slightly accelerated by the CSR (steered to the left).

Finally, Figure 6 shows similar images, all with the L1X RF off, but each row here is a new setting of the L1S RF phase (measurements in left column and *Elegant* simulations at right). The CSR blow-up again crawls along the pre-BC1 bunch length coordinate (still vertical here, from top to bottom) and remains quite localized at the sharp temporal spike produced with the L1X RF switched off.

CONCLUSIONS

The skew quadrupole trick used here [2] is a simple way to examine time-resolved CSR effects of a bunch compressor chicane, and these measurements provide some confidence that our simple line-charge, transient field modeling of CSR [7] is reasonably accurate, including the time-dependent character. It is also worth noting that the measured bend-plane emittance (at 220 MeV and 250 pC) after BC1 was increased by CSR by about a factor of 10 when the most extreme BC1 compression conditions were applied (as shown in Figure 2 with L1S RF phase at −31.0 deg and the L1X voltage at 19 MV). We thank Joe Bisognano for motivating these time-resolved measurements and Oleg Shevchenko for suggesting the diagnostic possibilities of a skew quadrupole magnet.

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