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MEASUREMENTS OF COMPRESSION AND EMITTANCE GROWTH AFTER THE FIRST LCLS BUNCH COMPRESSOR CHICANE*

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Abstract

The Linac Coherent Light Source (*LCLS*) is a SASE x-ray free-electron laser project presently under construction at SLAC [1]. The injector section from RF photocathode gun through first bunch compressor chicane was installed during the fall of 2006. The first bunch compressor is located at 250 MeV and nominally compresses a 1-nC electron bunch from an rms length of about 1 mm to 0.2 mm. Transverse phase space and bunch length diagnostics are located immediately after the chicane. We present preliminary measurements and simulations of the longitudinal and transverse phase space after the chicane in various beam conditions, including extreme compression with micron-scale current spikes.

INTRODUCTION

The first stage of electron bunch compression in the *LCLS* accelerator is a 4-dipole magnetic chicane (BC1) at 250 MeV in the SLAC linac. (A second compression stage will be installed in fall 2007.)

BC1 is motorized so that the center two dipoles can be translated on a stage to match the bend fields and electron energy. This allows the chicane to be switched off by ramping down the dipole fields and straightening out the chicane. A stripline beam position monitor (BPM), an OTR screen, and a pair of independently adjustable horizontal collimator jaws are included at chicane center.

The energy-time correlation (chirp) needed for compression in the dispersive chicane is established by accelerating the beam off the crest of the preceding three 3-m long S-band (f = 2.856 GHz) 'L1S' RF sections, which accelerate from 135 MeV to 250 MeV (Figure 2). To maintain the temporal distribution, an X-band 4th harmonic RF section (f = 11.424 GHz) slightly decelerates the beam by 20 MeV, removing the second order energy-time correlation. This not only linearizes the compression process, but also allows the final bunch length to be squeezed down to a few microns in length.

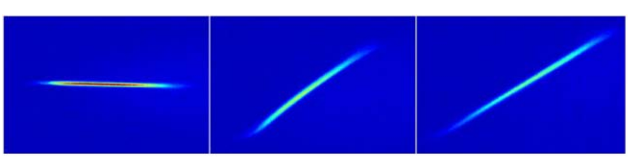

Figure 1: Energy chirp dispersed on BC1 OTR screen with transverse RF *OFF* (left), *ON* (middle), and *ON* with X-band RF also *ON* (right).

A transverse RF deflector (Figure 2) allows time-resolved bunch measurements by vertically streaking the beam across a screen. Figure 1 shows a beam image with a large energy chirp (off crest 'L1S' phase) horizontally dispersed on the BC1 OTR screen with RF deflector *OFF* (left), deflector *ON* (middle), and again with deflector *ON* but also with X-band RF *ON* (right). The X-band RF clearly linearizes the energy chirp.

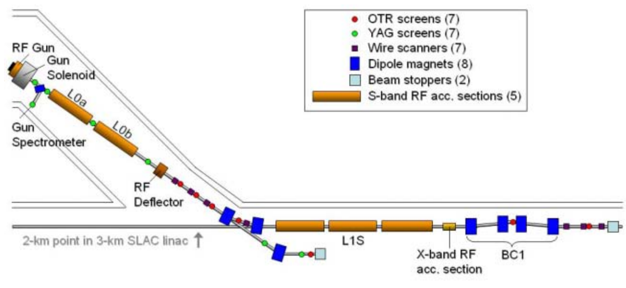

Figure 2: Layout of *LCLS* injector from gun to BC1.

Table 1: BC1 compressor parameters.

Parameter	symbol	value	unit
Electron energy	γmc^2	250	250
Nom. compression factor	R_{56}	39	mm
Hor. norm. rms input emittance	$\gamma\varepsilon_x$	1.8	μm
Bend angle of each dipole	$\|\theta\|$	4.98	deg
Magnetic length of each dipole	L_B	0.204	m
Distance between bend 1-3 & 3-4	ΔL	2.435	m
Distance between bend 2-3	ΔL_c	0.830	m
Beta function at bend-1 entrance	β_{x0}	24.7	m
Alpha function at bend-1 entrance	α_{x0}	3.65	
Bunch charge	Q	0.2	nC
Initial bunch length (rms)	σ_{z0}	0.7	mm
Correlated rel. energy spread	σ_E/E	1.5	%
Uncorrelated init. energy spread	$(\sigma_E/E)_u$	<4	10^{-5}

BEAM SIMULATIONS

The *Impact-T* and *Elegant* codes are used for start-to-end simulation. Impact-T, a 3D space charge code that has a parallel implementation [3], is used to model the injector beamline up to 135 MeV. Here we use a longitudinal Gaussian laser profile (as measured with the drive laser cross-correlator) with an rms length of 2.4 ps and a uniform transverse distribution with 1.2 mm radius to generate 200 pC of bunch charge, as listed in Table 1. The X-band RF was not included, since it was not operational during the experiment. All magnet settings follow the experimental configurations. The beam is

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accelerated on crest through the L0a and L0b accelerator sections (see Figure 2) to 135 MeV. The projected emittance in the simulation is 1.85 microns at this energy. In the central part of the bunch, the simulation shows that the slice emittance is about 0.75 microns and the slice energy spread is about 1 keV. The output beam distribution from *Impact-T* at the exit of L0b is used by *Elegant* [4] to simulate the beam dynamics in 'L1S' (see Figure 2) and BC1, including linac longitudinal wakefields and a 1-D model of coherent synchrotron radiation (CSR). To compare with the experimental results, we scan the 'L1S' RF phase while keeping the final energy at 250 MeV and BC1 R_{56} = −39 mm. With such a small slice energy spread, a current spike of more than 1 kA can be generated when the bunch is fully compressed. The projected emittance at the OTR12 location (after BC1) is calculated and compared to measurements (see next section). A verification run using the 3D code *CSR-Track* shows good agreement when no current spike is formed. (A very long, high-resolution run with the current spike was not available.)

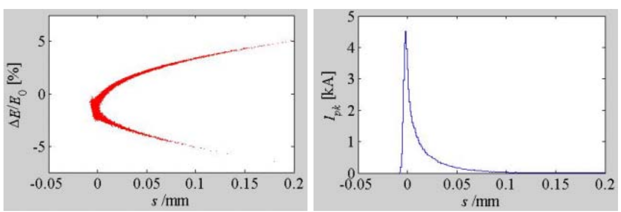

Figure 3: Longitudinal phase space and distribution after BC1 including 1D CSR model with parameters of Table 1 (X-band off). The spike width is just 4 μm wide (FWHM).

MEASUREMENTS

Residual Dispersion

The BC1 dipole field quality unfortunately includes a significant field gradient generating large horizontal dispersion beyond the BC1. The dispersion has been corrected using two small quadrupoles placed in the BC1 just for this purpose, but the effect is much larger than had been anticipated.

The dispersion is measured by scanning the beam energy before the chicane and correlating it with BPM readings after the chicane. No RF steering is observed upstream of the BC1, which might mimic dispersion.

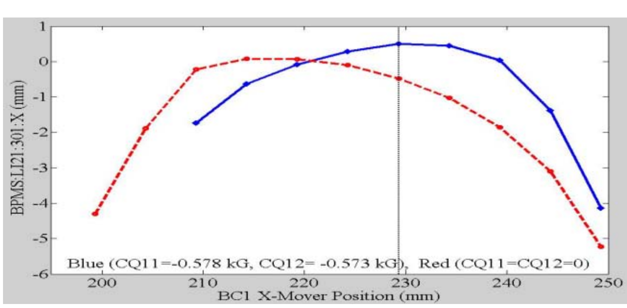

Figure 4: Measured effective field profile of center bends (dashed: no dispersion correction – solid with dispersion correction). The nominal BC1 position is 229 mm.

To confirm the dipole field quality, the motorized chicane position control is used to scan the dipole magnets horizontally while the beam is held stationary. The field roll-off with *x*-position leads to steering observed on a BPM downstream of the chicane, shown in Fig. 4 both with correction quadrupoles ON (solid) and OFF (dashed). The dipoles will need field shimming to correct the gradient, and perhaps nose pieces to compensate the sextupole term (a less significant effect).

Emittance

The horizontal emittance is measured using a quadrupole scan on an OTR screen. The screen is 2.5 m downstream of the quadrupole, with no optics in-between. The emittance is calculated by varying the spot size (50-200 μm rms) on the screen with 7 different quadrupole settings for each emittance measurement. The screen image is sampled 10 times for each quadrupole setting and the rms size is averaged (Figure 5). The RF phase of the S-band accelerator upstream of the BC1 is then varied in order to vary the final bunch length, while the voltage is adjusted to maintain the beam energy (verified with the chicane BPM). The dispersion is first corrected carefully in order to remove this source of emittance growth.

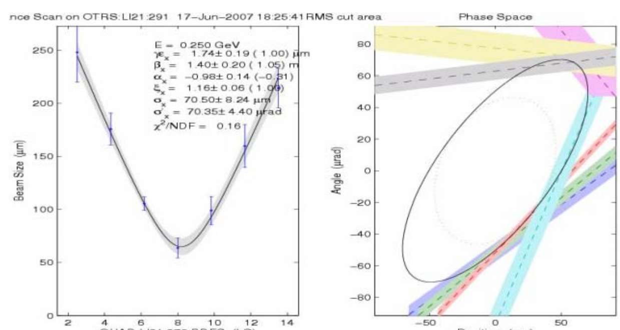

Figure 5: Emittance measurement after BC1 with beam size vs. quad setting (left) and phase space plot (right).

Energy Spread and Chirp

As the RF phase is varied, the energy chirp changes. This is measured by inserting the OTR screen at the center of the chicane and determining the rms horizontal spot size, as shown in Figure 1 (left).

Bunch Length

The initial bunch length, and its distribution, is measured in an absolute sense by switching on the RF deflector in the injector (see Figure 2). This streaks the beam vertically on a nearby OTR screen increasing the spot size by a factor of ten, thereby providing a sub-picosecond temporal resolution of the longitudinal bunch distribution. An example measurement is shown in Figure 6. Measurements during the full data acquisition showed an rms bunch length of 2.4 ps (0.72 mm).

Unfortunately, at this time, it was not possible to transport the beam to the second transverse RF deflector, 900 m downstream of BC1, so the final absolute bunch length could not be measured simultaneously. It can be inferred from the known compression factor, R_{56}, of the chicane, and the measured energy chirp and initial bunch distribution. Future studies will include an absolute measure of the final bunch length and distribution.

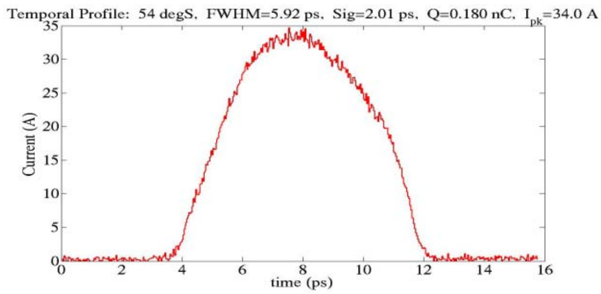

Figure 6: An example measured temporal profile at 135 MeV. The bunch was 0.72-mm rms in length (2.4 ps).

Beta Function

The horizontal beta function through the chicane is also an important factor for the CSR-induced emittance growth. This is determined from the emittance quadrupole scan, which also measures the beta and alpha functions just downstream of the chicane. Beta-matching was done prior to these measurements and the design beta functions through the chicane were established reasonably well (see Figure 5) and also used in the simulations.

Measurement Results

The emittance data are shown in Figure 7, along with simulation results, versus the 'L1S' RF phase setting. Bunch compression is in the direction of positive RF phase (with respect to crest at zero). This is confirmed by monitoring the relative bunch length signals using the microwave radiation from a ceramic gap after BC1, which is detected with two waveguide coupled diodes at 90 and 300 GHz to measure the bunch form factor at these two frequencies. These signals are shown in Figure 8, also versus the 'L1S' RF phase, indicating the bunch length begins rapidly to compress at an RF phase of >30°.

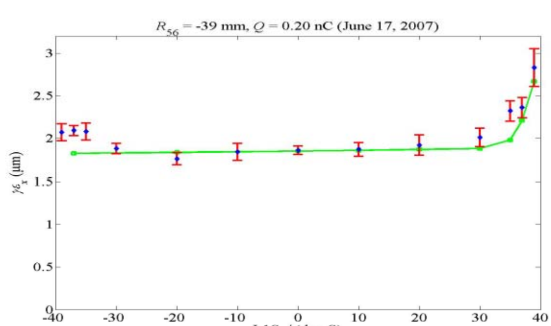

Figure 7: Horizontal emittance measured after BC1 vs. RF phase, with emittance growth near maximum compression point at right. Simulations in 1D are the green solid curve.

The 'L1S' RF phase (φ) was scanned in both the positive and negative directions from crest (φ = 0) in order to discriminate between emittance growth due to a large energy chirp ($\varphi < 0$) and emittance growth due to a short bunch ($\varphi > 0$). The simulations did not include the dipole magnet field imperfections, which might explain the small growth at $\varphi < -30°$. It is suggested here that the larger growth at $\varphi > 30°$ is due to CSR in the BC1 bends.

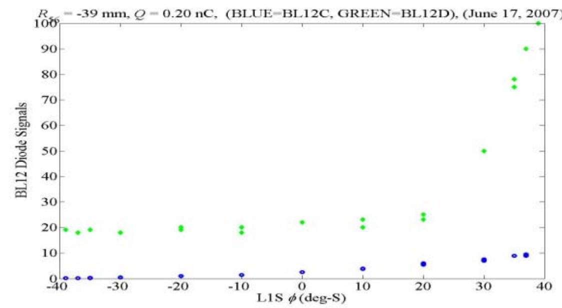

Figure 8: Diode signals (green: 300 GHz, blue: 90 GHz) from ceramic gap vs. RF phase, indicating compression as the phase is increased to >30º.

OTR Screen

It is worth noting that the OTR screen used to measure emittance demonstrates some unusual behavior with extremely short bunches. The total integrated optical signal seen by the camera increases by almost two orders of magnitude when the X-band RF is used and the bunch is compressed to its extreme (not the case in the above measurements). This effect is not understood yet, but could be coherent optical transition radiation due to the (expected) micron-scale current spike passing through the OTR foil. This effect (Figure 9) is just beginning to be examined. There may be some bias of the results shown in Figure 7 due to this mechanism. These results are therefore considered preliminary. Further study will certainly follow, likely with the second RF deflector used to monitor the final bunch length and its distribution.

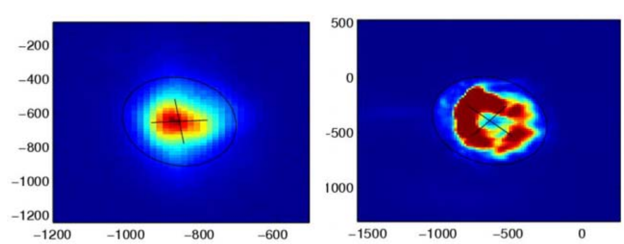

Figure 9: OTR image with no compression (left) and extreme compression (right). The total optical camera signal increases by up to 100-times for the case at right.

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