COMMISSIONING EXPERIENCE WITH THE LINAC COHERENT LIGHT SOURCE FEEDBACK SYSTEMS*

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Abstract

The Linac Coherent Light Source (LCLS) is a SASE x-ray Free-Electron Laser (FEL) project under construction at SLAC. The machine commissioning includes the injector, the first and second bunch compressor stages, the linac up to 14 GeV, and the various beam diagnostics. To ensure the vitality of FEL lasing, it is critical to generate and preserve the high quality of the electron beam during acceleration and compression. The final beam quality can be very sensitive to system jitter. To minimize the accumulated jitter effects on the electron beam and therefore on the FEL light, various transverse and longitudinal feedback systems are required. Here, we report the commissioning experience with these systems during the two phases of commissioning in 2007 - 2008.

INTRODUCTION

For the past two years, the world's first x-ray Free Electron Laser (FEL) project – Linac Coherent Light Source (LCLS) [1] – has been commissioning: from the injector, through the SLAC LINAC system with two bunch compressors (BC1 and BC2), to the entrance of the "virtual" undulator [2, 3]. Excellent beam parameters and stable machine operation have been successfully demonstrated. Many RF and beam-based feedback loops have been established to stabilize the electron beam over longer time periods. The injector RF [drive-laser, gun, L0, L1S, Transverse RF deflector (TCAV), and X-band cavity (L1X)] employs RF-based phase and amplitude feedback loops to maintain these critical parameters [4]. In addition, there are presently seven electron beam-based loops, plus two drive-laser loops. Five of the electron loops maintain beam trajectory by reading Beam Position Monitors (BPM) and adjusting steering coils at five locations. These loops maintain: gun launch angle, injector trajectory, position at L1X, trajectory after BC1, and trajectory after BC2. A sixth loop holds the bunch charge constant by reading a BPM sum-signal and adjusting a drive-laser waveplate angle. A special seventh loop [5] maintains six critical longitudinal parameters: 1) DL1 energy, 2) BC1 energy, 3) BC1 peak current, 4) BC2 energy, 5) BC2 peak current, and 6) Beam Switch Yard (BSY) energy. Here we report commissioning experience of the beam-based feedback systems.

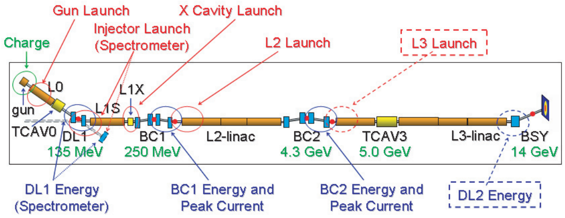

Figure 1: LCLS accelerator system layout with feedback.

BEAM-BASED FEEDBACK

The LCLS accelerator system layout with beam-based feedback loops are shown in Fig. 1. These loops drawn in solid circles have been commissioned. Those in dashed circles are planned to be commissioned in the next commissioning phase starting from November of this year 2008.

At the up front end, there is a control of the laser power, which then maintains the electron bunch charge pulse-to-pulse. Along the accelerator beam line, in sequence, there are Gun launch, Injector launch, X Cavity launch, L2 launch, and L3 launch (planned) to control the electron bunch trajectory. These controls are in the electron bunch transverse planes. In the longitudinal planes, the electron bunch centroid energy and the rms bunch length (therefore the electron bunch peak current) are being controlled.

The transverse trajectories are being controlled by adjusting the correctors so to minimize the difference between the chosen BPM readings and the reference orbit which the operator/user sets up. The electron bunch centroid energy is controlled by adjusting the RF cavity amplitude (and phase) so to maintain the BPM reading in a dispersive section at the reference number which the operator/user chooses. The longitudinal rms bunch length is controlled by adjusting the RF cavity phase (and amplitude) so to maintain the Bunch Length Monitor (BLM) reading at the reference number specified by the operator/user.

Currently, the beam-based feedback systems are constructed with high-level Matlab code controlling the underlayer EPICS systems with Beam Synchronous Acquisition. The Graphic User Interface (GUI) front page is shown in Fig. 2. The boxes next to each feedback loop being green indicates the alarm system status being good. When the feedback system detects some problem in the accelerator system, that box will turn into red. For example, these situations can be that the electron bunch does not go through the BPMs and/or the BLMs. Similarly, the system will alarm for cases when the actuators have been maximized out. The alarm status of the feedback system is integrated

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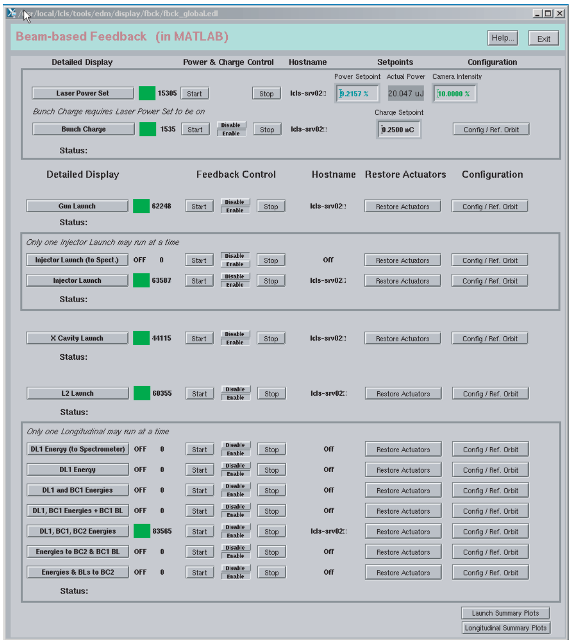

Power Setpoint 9.2157 %
Actual Power 20.047 uJ
Camera Intensity 10.0000 %
Charge Setpoint 0.2500 nC

Figure 2: Beam-based Matlab-EPICS feedback front page.

into the entire LCLS alarm status. The states of the feedback system can be running, *i.e.*, the calculated correction will be applied to the actuators so that the measurement will approach to the reference orbit. Or the state can be computing only, *i.e.*, the feedback is still taking measurement data and calculating the amount of correction, but it does not apply to the actuators. This is needed when other part of the machine is being scanned or optimized.

The feedback system is designed so that the operator/user can configure the setup. The operator/user can choose actuators from a pre-selected pool. He/she can also choose measurement from a pool. He/she can further define the limits for the operation range for the actuators and the measurement. With these all setup, the feedback matrix can be computed and be stored for the feedback operation. It is assumed that the feedback will maintain the electron bunch phase space parameters according to the designed values; however, when the operator/user does machine study, he/she can tune the accelerator system to a certain state, and the feedback system can collect the reference orbit, and store it in the memory. Then the feedback will maintain the electron bunch parameters at this operator/user defined state.

One example is in the X-cavity area. The X-cavity is introduced to linearize the electron bunch longitudinal phase space. The electron bunch is accelerated close to on-crest through L0 accelerator cavities as shown in Fig. 1. A correlation between the electron longitudinal internal coordinate z and the electron energy deviation $\delta = (\gamma - \gamma_0)/\gamma_0$ is introduced in the L1S S-band accelerator cavity. However, since the electron bunch temporal duration is on the order of a few ps, in the S-band cavity L1S, this means that the electron bunch spans for a few degree on the RF waveform. Hence, the correlation is not linear, that will affect the compression in the following two bunch compressors. To overcome this, a harmonic cavity (X-cavity) is introduced, which runs at the 4-th harmonic of the S-band cavity. It turns out that the transverse wakefield and coupler effects of the L1X can easily increase the emittance when the beam is not at a certain position through L1X. For example, the x-emittance is sensitive to the x-offset of the electron bunch centroid passing through L1X. As shown in Fig. 3, an x-offset of about 250 μm is needed to achieve the best emittance for the electron bunch passing through the L1X. Hence, a non-zero x-offset is introduced in the reference orbit, and the feedback is configured to maintain this non-zero orbit.

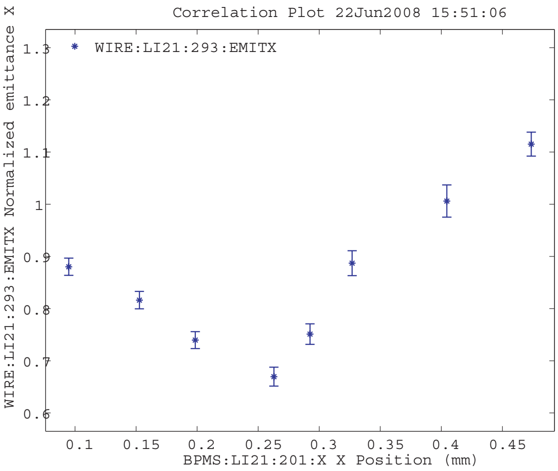

Figure 3: Optimization of the electron bunch x-offset in L1X to minimize the x-emittance degradation.

As explained in above, the main function of the feedback system is to maintain the right amount of charge coming out of the cathode, to keep the electron bunch following the reference orbit, to have the right energy at various locations, and to have the right bunch length after the two bunch compressors. Besides these, the feedback system can also be used to optimize the accelerator-FEL system.

For this purpose of optimization, the feedback system is designed so that the operator/user can scan the feedback states. For example, for LCLS accelerator and bunch compression system, there are two bunch compressors. The first one is located in the beam line where the electron beam is accelerated to a centroid energy of $E = 250$ MeV, and the second one is located at the electron beam energy of $E = 4.3$ GeV. Assuming that the final FEL calls for a peak current of $I_{pk,2} = 3,400$ Amp, then the peak current after the second bunch compressor $I_{pk,2}$ is fixed, but leaving the peak current after the first bunch compressor $I_{pk,1}$ as a parameter to be optimized. In Fig. 4, the BC1 peak current $I_{pk,1}$ is shown as the scan parameter on the horizontal axis, the estimated FEL power is shown in the vertical axis. It is seen that maintaining the BC2 peak current $I_{pk,2} = 3,400$ Amp fixed, the accelerator, bunch compressor, and FEL system prefers the BC1 peak current to be around $I_{pk,1} = 250$ Amp.

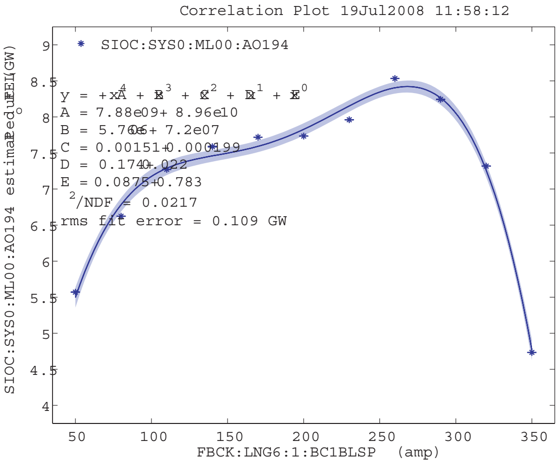

Figure 4: Optimization of the BC1 peak current $I_{pk,1}$ to maximize the pseudo-FEL power.

BUNCH LENGTH MEASUREMENT AND BUNCH PEAK CURRENT CALIBRATION

The electron bunch length is measured by two approaches for the LCLS accelerator system. The absolute measurement is done by using the TCAVs [6]. The initial bunch length is precisely determined by using the low-energy TCAV (TCAV0) at 135 MeV as shown in Fig. 1, upstream of BC1. There is no TCAV right after the first bunch compressor BC1, and there is one TCAV (TCAV3) after the second bunch compressor BC2 as shown in Fig. 1. This approach of using a TCAV can measure the electron bunch length precisely in an absolute sense; yet, it is invasive and will destroy the electron bunch after measurement. Hence, for the planned 120 Hz operation, this absolute bunch length measurement can only be done in a pulse-stealing mode, and should be done only occasionally. Therefore, for the pulse-to-pulse beam-based feedback, we need a non-invasive approach, which is the second approach we use for the LCLS. This non-invasive approach is to use the coherent emission power of the electron bunch passing through the bunch compressor [7, 8]. Due to the complication of the coherent emission and propagation of the coherent light through the imaging and detector system, we fit the coherent emission power P_{ch} to the following scaling law

$$P_{ch} \propto C^2 \sigma_z^{-4/3}, \tag{1}$$

where C is the total charge in the electron bunch, and σ_z is the electron bunch rms length. We assume that the total signal flux S_{BLM} detected by the bunch length monitor is linearly proportional to the coherent emission power P_{ch}. Then the electron bunch rms length follows the scaling as

$$\sigma_z \propto C^{3/2} S_{BLM}^{-3/4}. \tag{2}$$

Experimentally, this scaling law is valid in the feedback operation range as shown in Fig. 5. In that plot, the electron bunch rms length is measured by using TCAV3 after BC2 and shown on the horizontal axis. The scaling combination of $C^{3/2}S_{BLM}^{-3/4}$ is shown as the vertical axis. The linearity of the data supports the scaling law in Eq. (2).

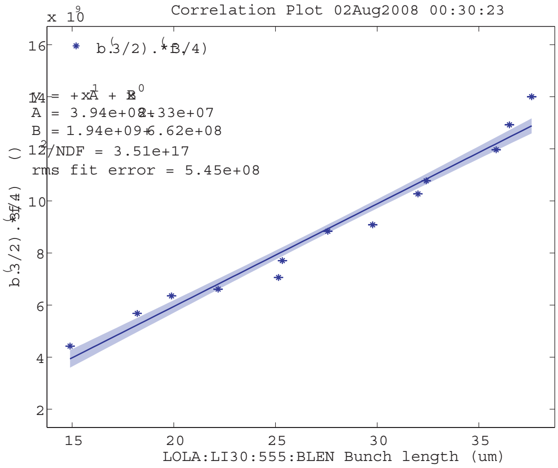

Figure 5: BLM signal calibration against the bunch length.

We define the electron bunch peak current as $I_{pk} \equiv Cc/(\sqrt{12}\sigma_z)$ with c being the speed of light in vacuum. Then the scaling in Eq. (1) gives a functional relation between the peak current I_{pk} and the BLM signal S_{BLM} as

$$I_{pk} \propto S_{BLM}^{3/4} C^{-1/2}. \tag{3}$$

This functional dependency is implemented in the feedback system with the fitting coefficient obtained from the calibration mentioned above.

ISSUES AND DISCUSSION

The transverse launch feedback loops as illustrated in Fig. 1 are running independently of one another, but not cascaded. The way to reduce the interference among them is to set them at different time scale. For example, the Gun launch loop is making correction on a much slower rate than the Injector launch feedback loop does. In general speaking, the transverse betatron oscillation can be mistaken by the energy feedback loops as energy error in a dispersive region. So, in principle a complete loop with the 6-dimensional phase space information incorporated seems to be a good solution after all. Right now, the transverse feedback loop is designed to make correction much faster than the longitudinal feedback loop does. This will reduce the effect from the betatron oscillation in a dispersive region. Furthermore, the dispersion function η_x at the energy feedback BPM location is very large, so the orbit error is dominated by the $\eta_x\delta$ term, *i.e.*, $\eta_x\delta \gg x_\beta$ where x_β is the betatron oscillation term.

Due to the coherent emission of the electron bunch passing through the bunch compressor, the electron bunch loses some energy after the fourth magnet of the bunch compressor. The longitudinal energy feedback is based on the BPM reading at the middle of the bunch compressor, so even though the energy is corrected at the middle of the bunch compressor, the electron bunch energy after the bunch compressor can still be low. This results in both an trajectory offset and an angular deviation. The transverse feedback loop after the bunch compressor will pick this up and correct it as shown in Fig. 6. In this plot, the horizontal axis is the peak current after BC1. Hence a larger peak current indicates higher compression and more coherent emission, therefore the corrector strength shown as the vertical axis has to increase to correct it.

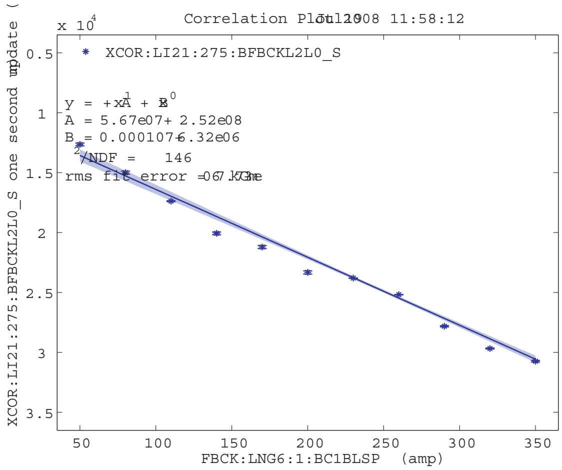

Figure 6: L2 launch feedback corrects the trajectory and angular error due to energy loss at bunch compressor BC1.

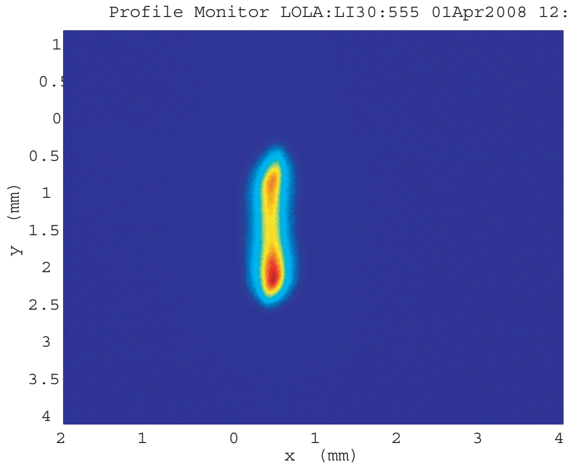

Figure 7: Double-horn temporal structure after BC2.

The electron bunch after BC2 has a double-horn temporal structure as in Fig. 7. Since the TCAV3 introduces a correlation between the electron bunch internal coordinate z and y, the the y-axis image down stream of TCAV3 is a map of the z-coordinate, therefore gives temporal information. This double-horn structure is due to the geometric LINAC wake between the first bunch compressor and the second bunch compressor [7]. This geometric wake introduces a nonlinear energy profile on the electron bunch. After compression at BC2, the electron bunch has double-horn temporal structure. The double-horn structure produces high-frequency spectrum and can bias the bunch length measurement. Furthermore, the electron bunch can have some microstructure on the optical wavelength range [9]. This has two effects on the bunch length monitor signal. First, the microstructure again introduces high-frequency components in the total flux going into the BLM detector, that can bias the bunch length measurement. Second, since the microstructure varies from pulse-to-pulse, this high-frequency content jitters from pulse-to-pulse. Hence, the BLM has to have low-pass filter to reject this high-frequency component from the double-horn structure and some possible microstructure [7]. For the BLM after BC2, there are two low-pass (LP) filters: the first one is a 30 μm LP filter and the other is 100 μm LP filter. The BC2 BLM signal with either filter is shown in Fig. 8, where the red dots indicate the BLM signal with the 100 μm LP filter inserted, and the blue dots are with the 30 μm LP filter inserted. It is clearly seen that with the 100 μm LP filter, the signal is more stable indicating the less pulse-to-pulse variation of the electron bunch high-frequency contents.

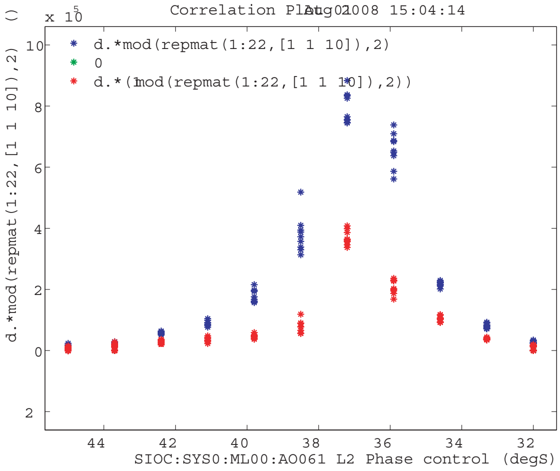

Figure 8: BC2 BLM signal with different LP filter.

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