PEAK CURRENT, ENERGY, AND TRAJECTORY REGULATION AND FEEDBACK FOR THE LCLS ELECTRON BUNCH*

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Abstract

The Linac Coherent Light Source is an x-ray Free-Electron Laser (FEL) project being commissioned at SLAC. The very bright electron beam required for the FEL is subjected to various sources of jitter along the accelerator. The peak current, centroid energy, and trajectory of the electron bunch are controlled precisely at the highest repetition rate possible with feedback systems. We report commissioning experience for these systems.

INTRODUCTION

For the past three years, the world's first x-ray Free Electron Laser (FEL) project – Linac Coherent Light Source (LCLS) [1] – has been commissioning: from the injector, the SLAC LINAC system with two bunch compressors (BC1 and BC2), through the LINAC-to-undulator (LTU) new beam line to the entrance of the undulators, and the undulators themselves [2, 3, 4]. First lasing and saturation at 1.5 Å is achieved [4]. Excellent electron and photon 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 and so the photon beam over longer time periods. The RF system [drive-laser, gun, L0, L1S, Transverse RF deflector (TCAV), X-band cavity (L1X), L2, and L3] employs Low Level RF (LLRF)-based phase and amplitude feedback loops to maintain these critical parameters [5]. In addition, there are presently eleven electron beam-based loops, plus three drive-laser loops. Nine of the electron loops maintain beam trajectory by reading Beam Position Monitors (BPM) and adjusting steering coils at nine locations. These loops maintain: gun launch angle, injector trajectory, position at L1X, trajectory after BC1, trajectory after BC2, trajectory in BSY, position in DL2, trajectory in LTU, and trajectory into the undulators. A tenth loop holds the bunch charge constant by reading a BPM sum-signal and adjusting a drive-laser waveplate angle. A special eleventh loop [6] 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) or DL2 energy. Acronyms are illustrated in Fig. 1. Here we report commissioning experience of the beam-based feedback systems.

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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. That in dashed circle is planned to be commissioned in the future after enough EPICS-based BPMs are brought on-line.

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, Injector, X Cavity, L2, L3 (planned), BSY, DL2, LTU, and Undulator launch loops to control the electron bunch trajectory, or simply the angle or the position for some of them as mentioned before. 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.

Currently, the beam-based feedback systems are constructed with high-level *Matlab* code controlling the underlayer EPICS systems with Beam Synchronous Acquisition. Based on the measurements on the electron bunch, the beam-based feedback calculates the set points for the magnetic kickers, the RF klystrons' phase and amplitude. For the RF part, the underlayer EPICS system has its own LLRF feedback, which maintains the set points provided by the beam-based feedback. The LLRF changes the I and Q directly via phase and amplitude controllers (PAC). The Graphic User Interface (GUI) front page is shown in Fig. 2. The boxes next to each feedback loop being green indicates the system is working well, and no alarm is registered. 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 into the entire LCLS alarm system 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. Right now, the *Matlab*-based feedback runs at a few Hz repetition rate. In the future, the beam-based feedback will be running at high repetition rate. The lon-

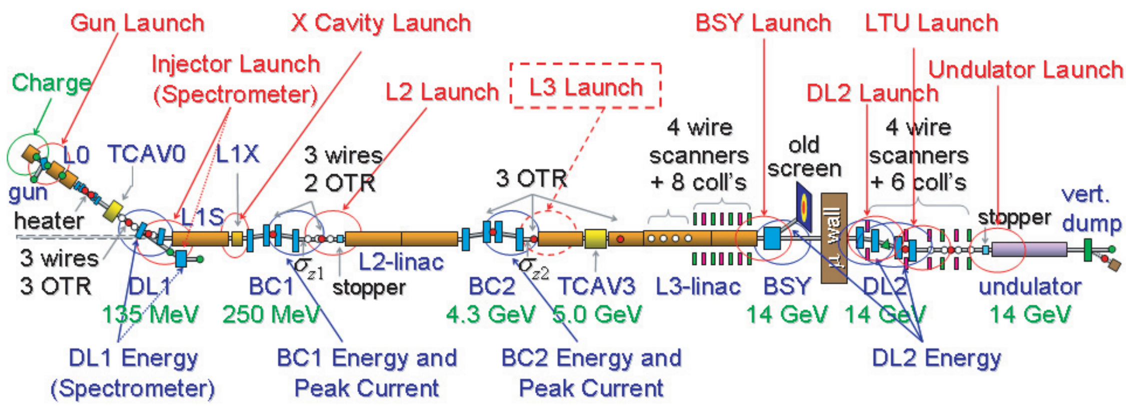

Figure 1: LCLS accelerator system layout with feedback.

gitudinal and the undulator launch will be running as high as 120 Hz. In that configuration, *Matlab* is no longer suitable. A dedicated network is needed for this fast feedback system. Additional architecture to recognize time slots is being designed as well.

The transverse trajectories are being controlled by adjusting the magnetic correctors so to minimize the difference between the chosen BPM readings and the reference orbit values which the operator/user sets up. The minimization is for the overall rms reading difference between the current value and the reference orbit value for all the BPMs chosen. So each BPM reading can be different from the reference orbit value, if a perfect agreement between the current value and the reference orbit value can not be achieved for all the BPMs. For the longitudinal feedback system, 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 specified by the operator/user. Similarly, 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 which the operator/user chooses. During the commissioning, we find that the bunch length signal relative fluctuation and the energy relative fluctuation differ largely, we then form orthogonal actuators to decouple the bunch length signal fluctuation from the energy fluctuation. Such orthogonal actuators are a particular combination of the RF phase and amplitude, so that one particular combination will only change the electron centroid energy, but not the bunch rms length. The other will just do the opposite. We then set different gain for the feedback on these orthogonal actuators to decouple them.

The electron bunch length is measured by two approaches for the LCLS accelerator system. The absolute measurement is done by using the TCAVs [7]. 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)

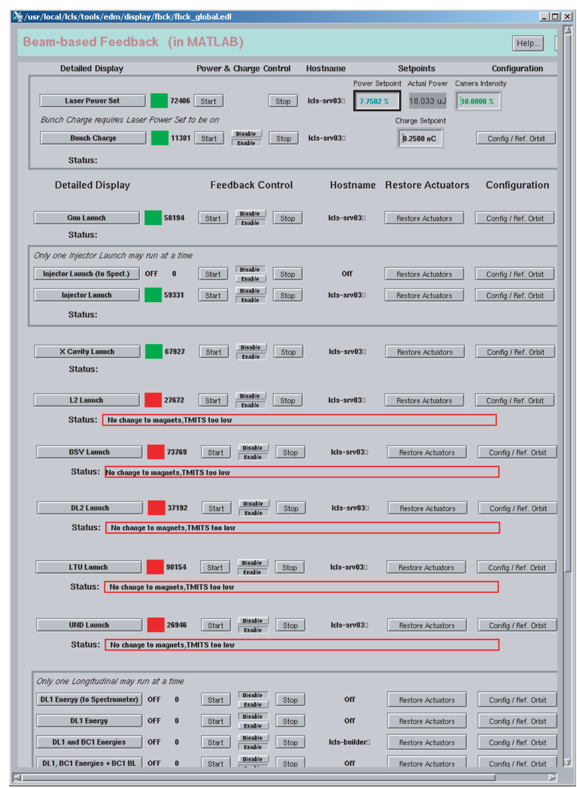

Figure 2: Beam-based Matlab-EPICS feedback front page.

after the second bunch compressor BC2 as shown in Fig. 1. 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 [8, 9]. 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 as function of charge and bunch rms length. We then define the peak current as function of charge and bunch rms length so that to set up a fitting formula of the peak current I_{pk} as function of the BLM reading S_{BLM} and the charge C, $I_{pk} \propto S_{BLM}^{3/4} C^{-1/2}$ [10]. This functional dependency is implemented in the feedback system with the fitting coefficient obtained from the calibration mentioned above.

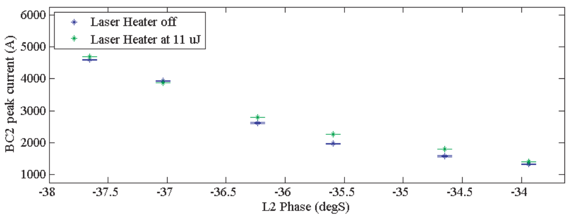

Figure 3: Peak current after BC2 as function of L2 phase with Laser Heater on (11 μJ) or off.

For the longitudinal loop, there are dedicated LINAC sections in L2 and L3 for the use of feedback on the electron centroid energy and the peak current [10]. Between BC1 and BC2 the electron bunch is accelerated from 250 MeV to 4.3 GeV, while the dedicated klystrons (24-1 and 24-2) can provide up to about 500 MeV acceleration, hence in case of klystron cycling, the feedback can run out of its limit. A different solution has been tested during this commission phase III of 2008-2009. The longitudinal feedback actuators are generalized to use the entire L2 phase in addition to the two dedicated klystrons: 24-1 and 24-2. Similarly, for L3, between the BC2 and DL2, the actuators are generalized to use the entire L3 phase in addition to the dedicated klystrons in section 29 and 30. This way the feedback scheme in L2 and L3 are almost the same at that in L1. This scheme works just fine during this commissioning phase. The other alternative is to increase the dedicated klystron numbers, for example, increase the total number of dedicated klystrons in L2 to 4 to better compensate for klystron cycling.

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 similarly prepared pool. He/she can further define the limits for the operation range for the actuators and the measurement. With all these setup, the feedback matrix can be computed and be stored for the feedback operation. During this phase III commissioning, the feedback is updated to use the XAL model, a high-level application framework which was originally developed by Spallation Neutron Source (SNS), and has been now adopted by the LCLS project [11].

The main function of the feedback is to maintain the electron bunch phase space parameters according to the designed values, or the operator/user defined particular state. In addition, 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. The final FEL calls for a peak current of $I_{pk,2} = 3$ kA, 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. It is tested that maintaining the BC2 peak current $I_{pk,2} = 3$ kA fixed, the accelerator, bunch compressor, and FEL system prefers the BC1 peak current to be around $I_{pk,1} = 250$ Amp.

The electron bunch after BC2 has a double-horn temporal structure [10]. 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]. A Laser Heater [12] is introduced to partially suppress the microstructure. The microstructure again introduces high-frequency components in the total flux going into the BLM detector, that can bias the bunch length measurement. Also, 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 [8]. 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. As shown in Fig. 3, with the 30 μm LP filter, the high-frequency component is highly suppressed, hence Laser Heater on and off does not change the bunch length signal much.

One important task in the undulator commissioning is the beam-based alignment [13], which requires setting the undulator for a few different electron beam energies. Hence, some of the transverse launch feedback loops, in particular the undulator launch loop has to be configured to recognize cases with different electron beam energies.

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