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Revision History

Revision	Date Released	Description of Change
R0	6/23/2014	Original Release.

1 Purpose

This document describes the physics requirements for the LCLS-II longitudinal beam-based feedback systems. These feedbacks control the beam charge, energy, bunch length and timing in the LCLS-II to provide stable operation of the X-ray sources for user experiments.

2 Definitions

Slow Feedback	Feedback loops operated at low (<10Hz) rates, through high level applications interacting with EPICS.
Fast Feedback	Feedback loops operated at high rates (>10KHz) operating in FPGAs, communicating through a low latency network.
I and Q vectors	The In-phase (accelerating) and out-of-phase (90 degree) components of the RF field in a structure. Amplitude = sqrt(I^2 + Q^2). Phase = atan(Q/I).
CC1	Name for the single cavity cryomodule located in the injector. This module is not baseline, but may be included in the design.
LEM	Linac Energy Measurement – refers to how accurately the electron beam energy gain profile along the LINAC matches the lattice design energy.

3 References

LCLSII-2.7-PR-0066	Controls System Requirements PRD
LCSLII-2.2-PR-0086	Injector Laser Heater Requirements PRD
LCLSII-2.2-PR-0084	LCLS-II SCRF Injector System PRD
LCLSII-2.4-PR-0068	Post-LH Diagnostic Beamline Requirements PRD
LCLSII-2.4-PR-0041	Linac Requirements PRD
LCLSII-2.4-PR-0040	BC2 Bunch Compressor Chicane Requirements PRD

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LCLSII-2.4-PR-0039	BC1 Bunch Compressor Chicane Requirements PRD
LCLSII-1.1-PR-0133	LCLS-II Parameters

4 Responsibilities

Jose Chan	Accelerator System Manager
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5 Feedback Algorithms

This section provides a general description of the operation of the feedbacks, but the implementation of the algorithms will be described in the engineering specification documents.

5.1 Feedback states

This calculation takes a set of measurements, for example BPM positions, and converts them to physical states, for example beam energy. In some cases, the feedbacks may operate on a single state, such as beam charge. In others, a set of states, for example, energy and bunch length, may be controlled by a single feedback loop.

In some feedback loops, the measurements will represent single readings from beamline devices. In others, the feedbacks will operate on averages of a series of measurements to reduce the measurement noise.

Some slow feedbacks will use the response of measurements to the dithering of actuators, or analysis of imaging devices to calculate states.

5.2 Cascading

Feedbacks will include a communication mechanism to allow downstream feedbacks to have information about the actuator changes made by upstream feedbacks. This allows multiple feedbacks to interact correctly.

5.3 Time response

In the LCLS-I system, there is minimal “dynamics”; the properties of each pulse are not determined by the properties of the previous pulse. In the LCLS-II, the energy storage times in the accelerator cavities (accelerating and HOM modes) are longer than an inter-pulse period, so the system may have complex time dependence. The feedbacks will use an algorithm that allows stable operation with tunable frequency response.

5.4 Beam code and ID awareness

The measurement data and feedback states will be tagged with the associated beam pulse ID and beam code. Pulse ID tagging ensures that feedbacks are able to operate on sets of data from measurements all taken on the same beam pulse. Beam code tagging allows feedbacks to provide actuator control that depends on the beam code. An example of this from LCLS-I is the time-slot difference feedbacks which provide different actuator setting for beams on different 60Hz time slots.

Note that fast feedback loops with fast actuators need to account for the variable delay time of the beam to each actuator as well as the variable delay time from the measurements.

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5.5 Actuators

The majority of the longitudinal feedbacks use RF phase and amplitude control as actuators. For the SCRF structures, a number of effects need to be considered in the design of the feedbacks

- Bandwidth: The SC cavity bandwidth is approximately 30 Hz. This does not however limit the small signal bandwidth of a SC cavity based feedback, which is instead limited by the time delays in the system which are expected to be less than a microsecond. The cavity stored energy does limit the slew rate (change in vector amplitude / second) from the available RF power to approximately 0.1% vector amplitude in 10 microseconds. This is not expected to limit the operation of feedbacks.
- Lorentz Detuning: The RF fields in a SC structure produce a radiation pressure proportional to RF power. In the LCLS SC structures, this pressure is sufficient to detune the cavity frequency by approximately 7 line-widths. The LLRF system normally controls this detuning by the use of piezo-electric actuators to control the cavity length. Any change in the RF field amplitude in the cavity will change the detuning force, and thereby the cavity frequency, which will result in a RF phase change and will require a change in the piezo actuators. The result of these effects on the small signal bandwidth of the cavities for amplitude detuning needs to be evaluated.
- Beam Loading: When the phase of an RF structure is changed, the amount of RF power absorbed by the beam will change, resulting in a change in the required RF drive power to maintain the RF amplitude. The possible bandwidth for phase changes will depend on the design of the LLRF system.
- RF power amplifier, power slew rate limit: Some RF power amplifier designs use a variable voltage DC power supply to drive the output transistors, and these may be limited in the rate at which they can increase RF output power. Depending on the design of RF amplifier chosen for LCLS-II this may limit the response time of the RF amplitude.

Due to the uncertainties in the response of the SCRF to changes in amplitude and phase, the feedback system design must allow for a variety of RF control schemes. For accelerator sections with only a single RF cavity (for example CC1), the only option is to control amplitude and phase directly with the amplitude and phase of the cavity. For accelerator sections which have multiple cavities (L0, L1, L2, and L3), there are the options listed below. Further simulation and testing will be required to determine which control method is optimal for each feedback, so the feedback infrastructure must allow for any of the following:

- Direct control of the phase and amplitude of all cavities. This is the most straightforward and is preferred if the effects described earlier in this section do not limit the bandwidth. This is used in LCLS-1 L1-S.
- Phase modulation of all individual cavities to change the net phase and amplitude of the accelerator section. This reduces LEM errors, but requires the accelerator phases to be known with good accuracy.
- Phase modulation of the last two cavities to change the net phase and amplitude of the accelerator section. This is used in LCLS-1, L2.

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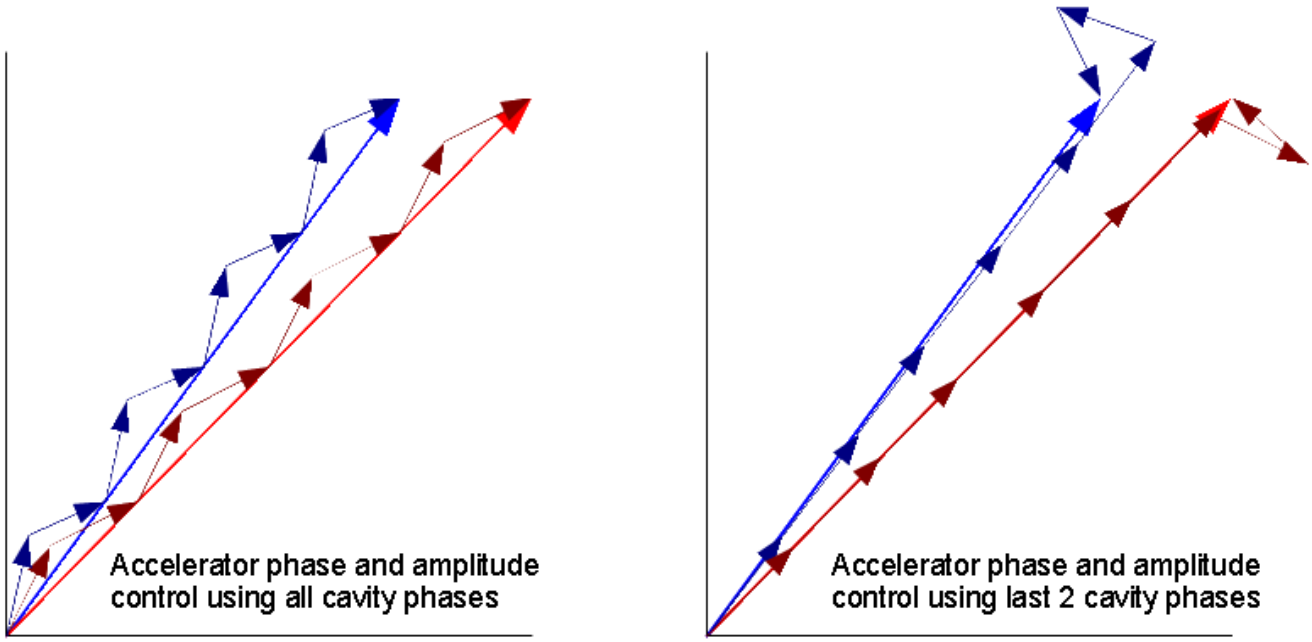

Two methods of structure amplitude and phase control described in section 5.5

In addition to the above requirements, the feedback algorithms must incorporate the time response of the actuators. This may be included in the time-response calculation in the feedback, or in an intelligent actuator controller.

6 Slow Feedbacks

Slow feedbacks are operated by high-level languages (Matlab, Python, etc.) which communicate with measurements and actuators through EPICS channel access. The loop speed of these feedbacks is typically limited to < 10Hz.

The use of high-level languages makes it possible for accelerator operators and physicists to create new feedbacks as needed. It also allows the use of more complex algorithms than the linear matrix algorithms used by the fast feedback system.

Some slow feedbacks will need to operate independently on data tagged with different beam codes, and may control pulsed actuators in a manner similar to what is used for the LCLS-I energy / bunch-length feedbacks. Slow feedbacks may also use data that is averaged over multiple (beam code aware) pulses in the measurement device.

Software support for slow feedbacks is required for CD4, but which specific feedbacks are required will depend on the results of measurements during accelerator commissioning.

7 Fast Feedbacks

Fast feedbacks are operated by firmware in FPGAs connected to a low latency network. In general, the response time will be determined by cable delays in the low latency network and the FPGA computation time, probably < 5 microseconds. The loop speed of these feedbacks is typically limited to < 100KHz.

The fast feedback loops will use linear algorithms designed so that the measurements, actuators, and feedback matrices can be changed by high level applications without modifying the FPGA firmware.

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This will allow accelerator operators and physicists to modify and create new fast feedbacks as required by machine development.

Fast feedbacks are not required for CD4, but will be required to reach the full machine design performance for science experiments

8 Feedback effects on subsystem specifications

Feedback loops reduce the stability and low frequency noise requirements for systems that affect the accelerator beam, including RF and magnets. A full accelerator model will be required to determine the frequency response of the feedbacks. Until that analysis is completed, we make the following assumptions:

- Slow feedback loops will completely correct any noise on their measurements at frequencies below 0.1 Hz. Specifically at frequencies below 0.1Hz, the feedback measurements can be assumed to be at their set points.
- Fast feedback loops will completely correct any noise on their measurements at frequencies below 1/100 of the beam rate.

Determining the detailed interaction between feedbacks and drifts requires simulation or experiments. Initial estimates are that the use of fast beam based feedbacks relax the requirements on the LLRF systems to +/-1 degree phase and +/-1% amplitude for variations on 10-second timescales and longer.

9 List of feedbacks

This is a list of feedback loops to be available for LCLS-II operation at startup. Additional feedback loops may be added after beam stability studies are performed on the operating machine. All of these feedback loops will initially be commissioned as slow loops, but some may need to be converted to fast loops based on beam measurements. Feedbacks listed as “FAST” may be operated as “SLOW” for CD4. Note that while software must provide support for these feedbacks, not all will be required for CD4.

Name	Ref	States	Measurements	Actuators	FAST / SLOW	Comments
Bunch Charge	9.1	Bunch Charge	Post BC1 BPM TMIT.	Laser Intensity (AO modulator)	Fast	
Buncher	9.2	Pre CC1 bunch length	CC1 bunch length monitor	Buncher amplitude	Fast	Interacts with 9.3
CC1 compressio n	9.3	Post CC1 bunch length	Post CC1 bunch length monitor	CC1 RF Q component	Fast	Interacts with 9.2
Laser heater energy	9.4	Laser heater energy	Laser heater BPMs	L0 RF I component	FAST	Set point controlled by 9.5

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Injector diagnostic line	9.5	Injector diagnostic line bunch length and energy	Diagnostic line BPM and TCAV	L0 I and Q components	Slow	Controls set point of 9.4
BC1	9.6	Energy, Bunch length	BC1 BPM, Post-BC1bunch length monitor	L1 I and Q components	Fast	Phases adjusted opposite directions?
3.9 GHz	9.7	Beam Profile	TCAV + dispersion screen	3.9 GHz I and Q components	Slow	Interacts with 9.6
BC2	9.8	BC2 energy, “final” bunch length	See notes	L2 I and Q components	Fast	Measurements depend on operating mode. May interact with 9.6
Final beam energy	9.9	Beam energy	See notes	L3 I component	Fast	Measurements depend on operating mode
Energy dither	9.10	X-ray monocromator throughput	X-ray power detector	L3 I component	Slow (dither)	Changes set point for 9.9
Arrival Time	9.11	Beam timing	Beam Arrival Time monitor	See notes	Fast	

9.1 Bunch Charge

The bunch charge measured in the injector is used to control the laser intensity on the photocathode gun. The feedback will normally use the first BPM after BC1 to avoid measuring dark current, but will fall back to upstream BPMs if beam stops are inserted. Fast feedback is possible using an electro-optical or accousto-optical intensity modulation of the gun laser.

9.2 Buncher

The bunch length measured at the first compression monitor (gap monitor) upstream of CC1 will be used to control the amplitude of the injector buncher cavity.

Note that there is insufficient information to control the phase and amplitude of the buncher in feedback. It may be necessary to regularly measure the bunch phase by scanning phase vs beam energy or bunch length.

This feedback interacts with and may be combined with 9.3

Depending on the stability of the bunch RF system, this feedback may not be required

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9.3 CC1 Compression

The bunch length measured on the (Gap monitor) compression downstream CC1 will be controlled by adjusting the phase of CC1. Note that if CC1 is not installed, this feedback will not be used.

Note that there is insufficient information to control the phase and amplitude of CC1 in feedback and it may be necessary to regularly measure the phase of CC1 relative to the beam by scanning the phase vs beam energy.

9.4 Laser Heater Energy

The beam energy measured in the laser heater will be controlled through the energy gain of the L0 structure. Note that a slow feedback in 9.5 will be used to adjust the set point of this feedback. (FAST)

9.5 Injector Diagnostic Line

The beam energy and bunch length in the injector diagnostic line will be controlled by a vector modulation of the L0 RF. This feedback will control the set point of the laser heater energy feedback 9.4. The bunch length will be measured with the TCAV and the energy by a BPM. (SLOW)

9.6 BC1

The beam energy and bunch length in BC1 will be controlled by vector modulation of the L1 RF. (FAST)

9.7 3.9GHz (may not be required)

A TCAV and kicker downstream of BC1 are used to measure the longitudinal profile of the beam after BC1. A slow feedback is used to adjust the 3.9GHz vector amplitude. This feedback is not required for CD4. (SLOW)

9.8 BC2

This feedback controls the beam energy and bunch length in BC2 using vector modulation of the L2 structures.

The bunch length inputs for this feedback will be selectable from multiple sources depending on the accelerator operating mode, listed here: (FAST)

- BC2 relative bunch length monitor
- BC3 relative bunch length monitor (if BC3 is installed and operating)
- CSR induced beam deflection downstream of BC2. This deflection is related to the bunch length at the exit of BC2.
- CSR induced beam deflection downstream of BC3. (if BC3 is installed and operating)

9.9 Final Beam Energy

The final beam energy is controlled by the energy gain in the L3 accelerator. The measurement for the L3 energy feedback will depend on the operating mode: (FAST)

- LINAC extension dog leg energy if the beam is not in the LTU
- BC3 energy (if BC3 is installed and operating)
- Beam energy measured in the dispersive regions downstream of the spreader

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- Beam energy in the SXR or HXR dump
- Photon energy signal from the SXR or HXR

Note that independent feedback of the e-beam or photon energy in the HXR and SXR is not possible in the baseline design unless there is sufficient time to change the RF fields between pulses to the two undulators, see section 5.5.

9.10 Beam Energy Dither

When a seeder or monocromator is in use, the beam energy can be dithered with a 2nd order feedback to maximize the throughput. Note that this can only be used if only one undulator is being driven by the LCLS-II linac, or if the other undulator does not have tight X-ray energy constraints. The dither feedback is SLOW but the energy dither may be performed using the FAST feedback network.

9.11 Beam Arrival Time (not in current baseline scope 4/2/2014)

The beam arrival time measured after each undulator will be used to control the beam time in the accelerator. As with the energy feedback, in gen eral only one undulator can be controlled, however with the expected small difference in R56 between the two undulator lines, stabilizing the arrival time at one undulator should also stabilize the time at the other. (FAST)

The Bunch Arrival Time monitors will be used to measure the arrival time of the electron beam after each undulator.

There are a variety of possible actuator schemes for the feedback:

- Change the phase of all RF systems (including the gun laser) to correct the beam arrival time. This method will result in minimal disturbance of beam parameters but requires the simultaneous change of many RF stations. This capability is supported by the fast feedback system
- Change the beam energy in BC2 using the L2 LLRF system, and then correct the energy with a change in the L3 energy gain. This results in a small orbit change in BC2 and requires good knowledge of the energy gain calibration of the structures, but requires fewer actuators to be changed.

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