ELECTRON BEAM DIAGNOSTICS AND FEEDBACK FOR THE LCLS-II*

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Abstract

The LCLS-II is a CW superconducting accelerator driven, hard and soft X-ray Free Electron Laser which is planned to be constructed at SLAC. It will operate with a variety of beam modes from single shot to approximately 1 MHz CW at bunch charges from 10 to 300 pC with average beam powers up to 1.2 MW. A variety of types of beam instrumentation will be used, including stripline and cavity BPMs, fluorescent and OTR based beam profile monitors, fast wire scanners and transverse deflection cavities. The beam diagnostics system is designed to allow tuning and continuous measurement of beam parameters, and to provide signals for fast beam feedbacks.

LCLS-II

The LCLS-II uses a 4 GeV, CW superconducting LINAC to drive two variable gap undulators to generate soft and hard X-rays (see Fig. 1). The hard X-ray undulator and some of the electron beam line are shared with the LCLS-I room temperature LINAC in order to allow operation with either accelerator. The SC LINAC will operate at bunch rates up to approximately 1MHz, and uses fast kickers ("beam spreader") to direct selected bunches to each undulator, or to the beam dump.

The LCLS-II includes a low rate (120Hz) diagnostic line at an energy of 100 MeV. A kicker can select single bunches for diagnostics without interfering with the rest of the bunch train.

The LCLS-II can operate in a variety of modes with varying bunch charge and pulse structure, a representative operating mode is shown in Table 1.

Table 1: LCLS--II Electron Beam Parameters (Nominal)

Beam energy	4 GeV
Bunch Charge	10 – 300 pC
Bunch rate	< 0.93 MHz
Average beam power	<1.2 MW
Peak current	500-1500 A
Bunch length (RMS)	0.6 – 52 μm
Energy spread	125-1500 keV
Energy stability RMS	<0.01%
Emittance (at 100pC, normalized)	~0.3 μm

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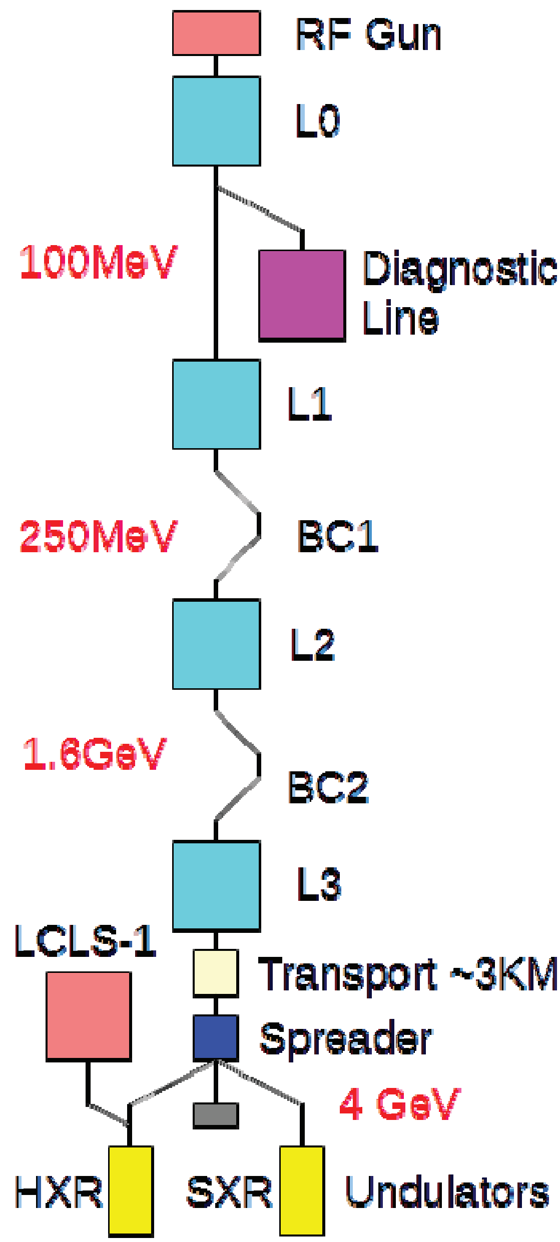

Figure 1: LCLS-II Layout.

DIFFERENCES FROM LCLS-I

Beam Rate / Average Power

The single bunch properties for LCLS-II are similar to those for the existing LCLS-I; however the high average bunch rate and beam power result in new requirements for

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the diagnostics systems. The high average power prevents the use of continuously intercepting beam diagnostics in the main beam lines. However, OTR and YAG profile monitors can be used in the lower rate diagnostic line. High speed wire scanners can be used in the full 1MHz rate beam provided they operate above a minimum scan velocity.

The high beam rate results in high data rates and necessitates the use of processing in FPGAs. Feedbacks which operate at or near full beam rate will also require FPGA processors. In addition some devices with slow response times (for example cavity BPMs) will require additional signal processing to isolate individual bunch signals.

Low Charge / Short Bunch Operation

The LCLS-II will operate with bunch charges as low as 10pC with pulse lengths as short as 600nm RMS. The requirement for high position resolution for low bunch charges will require the use of cavity BPMs in locations where single bunch resolution below 20 microns is required.

At the shortest bunch lengths (600nm) the temporal structure of the bunch will have significant frequency components in the visible spectrum. This will result in substantial optical coherent emission that is strongly dependent on details of the bunch temporal profile, and prevent the use of optical imaging diagnostics for the compressed beam.

DIAGNOSTICS CONTROLS

Common Platform

The beam diagnostics system will largely be built from a common controls hardware / firmware / software platform. The same platform is expected to also be used for the LLRF system (see Fig. 2).

- Analog Front End: This converts raw sensor signals into a bandwidth and amplitude that can be directly digitized. An example would be the variable gain amplifiers and RF downmixers for a cavity BPM.
- A-D: The specifications have not been finalized but this is expected to be a commercial high performance A-D, roughly 150Ms/s, 16 bit.
- FPGA: This converts raw data from the A-D into “physics” parameters such as X, and Y position at the 1 MHz beam rate.
- Timing Network: This provides beam time clock and pulse ID with <1ns stability
- EPICS Network: Conventional TCP/IP network for communication and configuration
- MPS Network: Machine protection network to provide low latency (<100usec), high reliability beam trip signals if pre-defined beam limits are violated
- Fast Feedback Network: A low latency (~5 μsec + cable speed) network to transmit data from sensors to feedback actuators.
- DAC: The specifications have not been finalized but this is expected to be a commercial high performance D-A, roughly 100Ms/s at 16 bits. Note that the D-A is not required for many diagnostics devices but may be included on the FPGA board for commonality of parts.
- Analog Driver: This converts the D-A output to the signal levels / types required to drive the beam actuator (kicker, deflection cavity etc.).

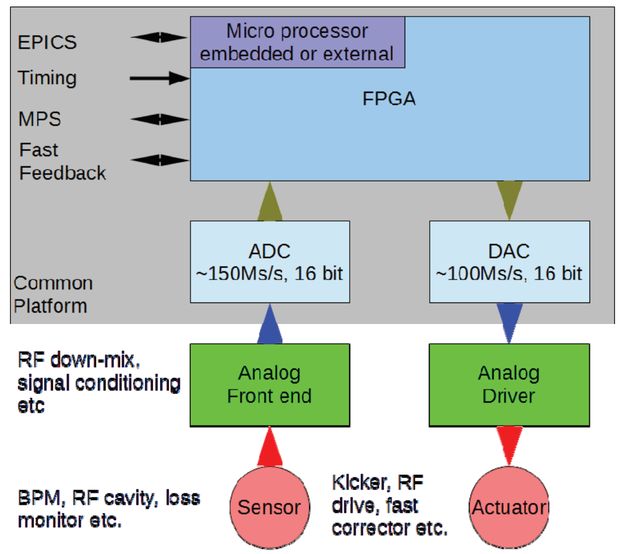

Figure 2: Common controls platform.

Other Devices

Some devices, including profile monitors and wire scanners, which cannot operate at the 1MHz beam rate will be controlled directly through EPICS rather than the “common platform”. These will be triggered to operate on specific beam pulses by the timing system.

BEAM POSITION

The LCLS-II contains approximately 360 BPMs of a variety of types:

Stripline BPMs

Standard strips: Most of the LCLS-II uses 12cm strips in a 2.5 cm diameter pipe

Bypass Line: The LCLS-II uses the existing PEP-II 2-kilometer bypass line. This line has stripline BPM pickups with 61cm long strips in a 7.3cm diameter pipe.

The stripline BPM electronics will be similar to that used for LCLS-I: the strip signals will be bandpass filtered, then digitized. A strip-to-strip calibration system will correct for variations in channel gains (see Fig. 3). LCLS-II will use a 300MHz BPM processing frequency compatible with both strip lengths. The high beam rate will require processing in an FPGA to extract single bunch data. Note that for installations with long cables, reflections from previous bunches may interfere with measurements and so will need calibration and correction.

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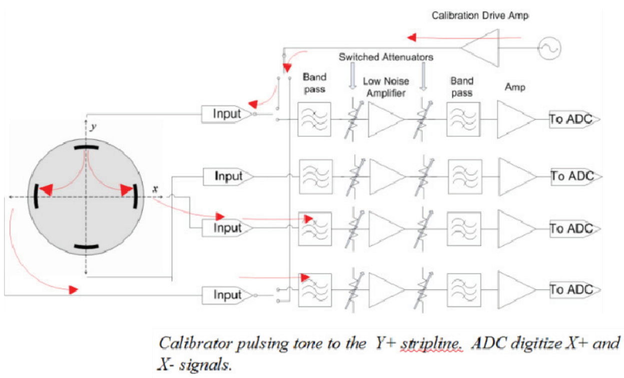

Figure 3: Stripline BPM front end electronics.

Cavity BPMs

Cavity BPMs are used in locations where high resolution is required. Three different types of cavity BPMs will be used:

- Undulator BPMs: These are required to provide a resolution of <1µm at a 10pC charge. They will operate at X-band (11.424 GHz).
- LINAC Feedback BPMs: These are used in locations where single bunch resolution that is better than that which can be obtained with striplines is required. The design has not been finalized but will likely be S-band in order to provide sufficient aperture.
- Dispersion Region BPMs: The bunch compressors and dispersive regions in the beam transport system require large aperture (~100 mm) with high resolution (20µm) at 10pC. This will require low frequency (L-band) cavity BPMs.

The cavity BPM front end electronics will use a conventional filter and downmix to an IF frequency that can be digitized. The IF frequency has not been selected yet, but is probably near 50MHz.

All of the cavity BPMs will be high "Q" and single bunch measurements will be performed by subtracting the vector amplitude of the fields that are present in the cavity from the previous bunch time. In the simulation in figures 4, and 5, the fields for measurement time "B" from bunch "A" in the absence of a bunch in "B" are subtracted from the measured "B" signal. The subtraction is done on the vector amplitudes of the RF signals. Note that the simulation was done at 10X the real bunch rate in order to exaggerate the effect that needs correction.

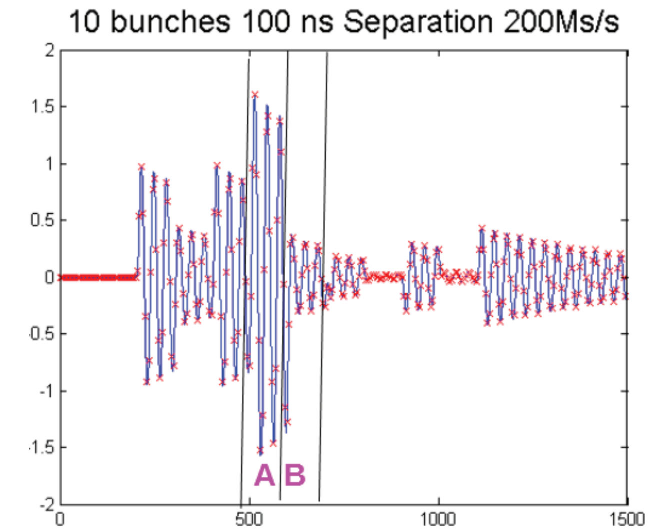

Figure 4: Simulation: The signal for bunch "B" is corrected for the ringing signal for bunch "A".

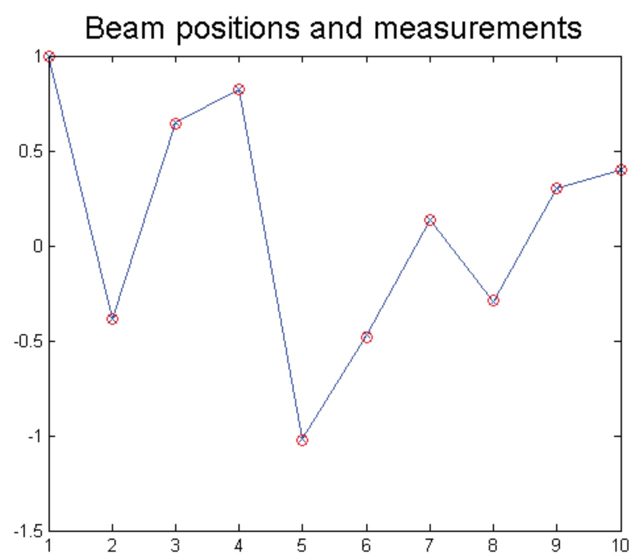

Figure 5: Simulation: Corrected BPM position (red circles) plotted with the correct beam position (blue line).

Cold Button BPMs

The cryo-modules will use button BPMs: the single bunch resolution requirements are 100 µm RMS at 10pC, with multi-bunch averaging to obtain better resolution. The buttons will be similar to the XFEL design with 20mm diameter buttons in a 70mm beampipe (see Fig. 6). Processing electronics will operate below beampipe cutoff and will downmix ~1GHz button signals to an IF that is digitized by the standard controls digitizer.

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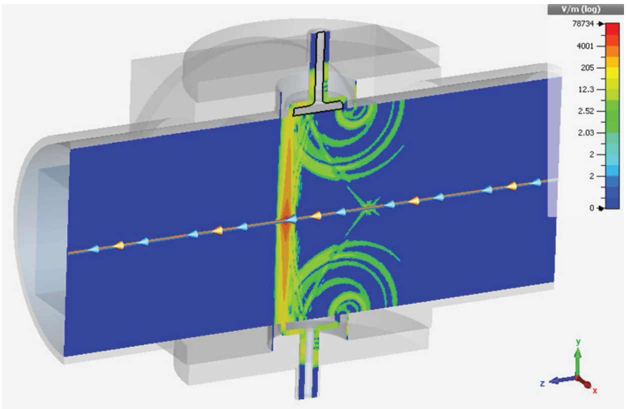

Figure 6: Cryo button BPM based on European XFEL design.

Note that LCLS-II has chosen a somewhat simpler but lower performance processing scheme than that used by XFEL [1].

HOM BPMs

The signals from the SC cavity HOM ports are brought out to room temperature. The first cavity in the injector and possibly others will be instrumented with HOM based position readouts similar to those described in [2].

TRANSVERSE PROFILE

Profile Monitors

The short bunch operating modes (0.6um RMS) of LCLS-II will result in substantial enhancement of optical emission from the longitudinal bunch form factor in addition to the coherent emission from CSR induced current modulation. This is expected to make imaging based on optical radiation impractical in the fully compressed beams.

OTR type profile monitors will be used in the injector at reduced beam rates, and in the low rate diagnostic line (120Hz, 100MeV). We are investigating the use of a profile monitor design developed at PSI using YAG:Ce crystals that is less susceptible to coherent emission than standard designs [3].

OTR profile monitors will also be used in the dump lines. The OTR foils will be located away from the main beam axis and the beam will be kicked onto the foil at low rate for energy spread measurements.

Wire Scanners

The LCLS-II will rely on wire scanners for most beam profile measurements. Wire scanners can be used on the full rate beam as long as the scan rate is high enough to prevent overheating of the wires. Calculations were done to estimate the wire temperature rise under varying beam conditions and scan rates [4]. For uncooled carbon wires, 34um in diameter (same as for LCLS-I wire scanners), and 100pC and a 600kHz beam with a 40µm spot size, a scan speed > 250mm/s is required to avoid thermal damage. A prototype fast wire scanner based on a linear motor has been tested at SLAC and operates at and above that speed (see Fig. 7).

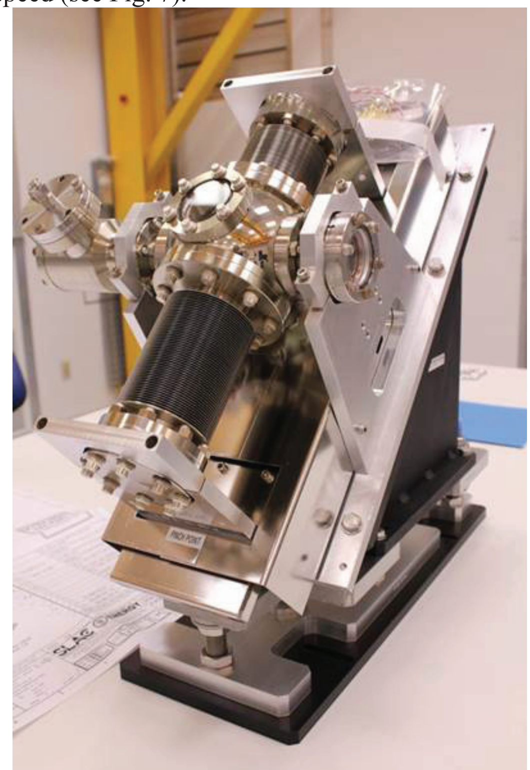

Figure 7: Fast wire scanner tested at SLAC.

Thermal radiation does not provide significant cooling; however heat diffusion along the length of the wire can substantially reduce the wire temperature. Figure 8 shows the reduction in temperature rise as a function of thermal diffusivity in the range of values expected for different carbon wire types.

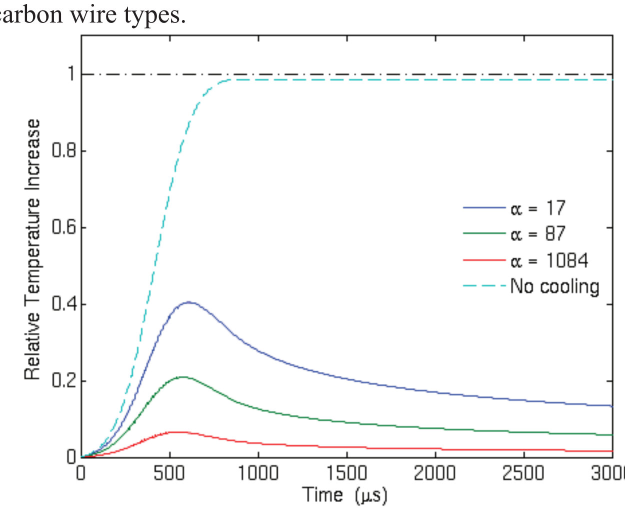

Figure 8: Wire temperature rise (normalized) as a function of wire thermal diffusion in mm^2/sec.

The signals from the wire scanners will be detected by measuring the degraded energy particles lost from the beam. The wire scanner data will be correlated with beam position data from one or more nearby cavity BPMs to correct the scans for beam position jitter.

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Halo Monitors

The high average beam power in LCLS-II requires measurements of the beam halo to prevent beam loss. The wire scanners will include thick wires that can be moved close to, but not in the main beam to allow sensitive halo measurements.

LONGITUDINAL MEASUREMENTS

Beam Energy / Energy Spread

BPMs in locations with known dispersion are used to measure the beam energy. BPMs in nearby non-dispersive regions are used in combination with the optics model to correct for incoming beam orbit variations.

Due to the requirement for high energy resolution (<0.01% single bunch), and the large aperture requirements (several cm), cavity BPMs are used for the energy measurements.

Wire scanners are used in the dispersive regions to measure the beam energy spread. As with other wire scanners, the average beam position is measured and corrected with BPMs to remove beam jitter.

Bunch Length – Relative

The electron bunch length is measured with coherent radiation monitors in the bunch compressors. This measurement is not calibrated but is used for bunch length control feedback. The concept is similar to LCLS-I however there are additional technical challenges:

- The wide range of operating charge and bunch length requires a large dynamic range from the detectors.
- The high beam rate can result in high average powers on the detectors.
- The high beam rate requires firmware to correct for multi-bunch effects in the detectors.

For BC2, pyroelectric detectors similar to the LCLS-I design will be used. As the maximum average coherent radiation power could exceed 10 Watts, and the detector average power limit is estimated at 25mW, the beam will be attenuated. The maximum allowed single bunch energy on the detector at a 1MHz beam rate is 25nJ. However the estimated detector noise is 6nJ which only provides a very limited single bunch signal to noise. In addition the charge amplifiers used for the LCLS-I bunch length monitors do not have sufficient bandwidth to measure a 1 MHz beam. This is an area of active development and several approaches are being considered:

- Cooled pyroelectric detectors that can be used at higher average power
- Improved charge amplifiers designed for lower noise and higher bandwidth
- Use of alternate detector technology

For BC1 at low charges and long bunch lengths the signals can be as low as 1.5nJ. Here the bunch lengths are longer so the coherent emission peak frequency is in the 100s of GHz. High sensitivity millimeter wave diodes are available commercially in this frequency range [5]. High frequency diodes measuring signals from a ceramic gap have been tested successfully as bunch length monitors in the first bunch compressor in LCLS-I.

Bunch Length Monitor – Transverse Cavity

Calibrated bunch length and longitudinal profile measurements will be performed with transverse deflection cavities similar to those used on LCLS-I. Transverse deflection cavities will be installed in the following locations:

- Injector 100MeV diagnostics line, combined with a spectrometer bend: S-band
- After BC1: S-band
- After BC2: X-band
- After each undulator, combined with a spectrometer bend: X-band

The transverse cavities will use room temperature structures operated at a maximum of 120Hz. The fill time of the structures is substantially shorter than the 1 microsecond bunch spacing so the deflectors can be used to measure single bunches without disturbing the remainder of the 1MHz bunch train.

Downstream of the undulators the combination of a TCAV and spectrometer bend allows a measurement of the E vs. T profile of the electron bunch after the lasing interaction (see Figs. 9 and 10).

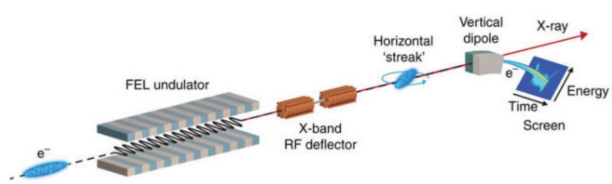

Figure 9: Transverse deflection cavity and spectrometer.

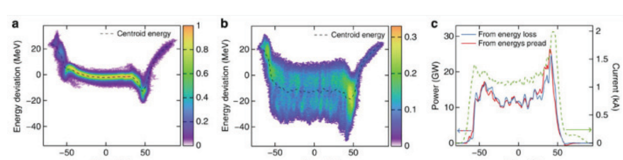

Figure 10: TCAV measurements at LCLS-I showing energy spread / change from FEL interaction.

The X-band transverse deflection structure at LCLS-I has used time-dependent energy loss to measure X-ray pulses with a temporal resolution of 3 femtoseconds FWHM [6].

Arrival Time Monitor

The X-ray experiments performed at LCLS-II will require measurement and control of the bunch arrival time. A RF cavity based bunch length monitor similar to

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that used at LCLS-I will provide pulse by pulse bunch timing information.

Electron bunches excite a longitudinal cavity whose output is down-mixed and digitized. The measured RF phase is then corrected for cavity frequency drifts (primarily due to temperature changes) by using the cavity frequency measured on each pulse.

The existing LCLS-I monitor operates at <10fs RMS jitter and 40fs drift [7]. Based on initial tests, improvements to the processing algorithm are expected to improve the measurement jitter to <7fs RMS.

FEEDBACK

Slow Feedback

The measurements from all diagnostic devices are available through EPICS channel access. The diagnostics electronics firmware will provide data averaged by beam destination as well as single pulse data selected by pulse-ID. The beam control devices (magnets, kickers and RF stations) are controllable through EPICS, with control of pulsed / fast devices available on a pulse-ID or beam destination aware fashion.

Feedbacks will be programmed in Matlab [8] operating through channel access in a similar fashion to that used in LCLS-I. Based on LCLS-I experience, loop speeds of up to approximately 5 Hz are expected, sufficient for beam drift correction.

Transverse beam feedbacks will control the trajectory throughout the accelerator / FEL systems. Most of the controls will be slow correctors, but fast (1MHz) correctors are available upstream of the undulators and feedbacks can control the kickers used for the diagnostic line and beam spreader. A total of 15 transverse feedbacks are planned.

Longitudinal feedbacks use the measured beam energy and bunch length at various locations to control the RF fields in the SC cavities in a manner similar to that used for LCLS-I. A total of 11 longitudinal feedbacks are planned.

The LCLS-II uses a single SC linac to drive two variable gap undulators. Undulator gap tuning is used for wavelength changes; however there is a need for fine independent control of the operating wavelength of the two undulators.

A single SC structure at the end of the LINAC will be operated off frequency so that the electron bunches directed to the two undulators see opposite phase accelerating fields. The amplitude of this structure controls the difference in the X-ray energies while the remainder of the RF controls the sum allowing for independent X-ray energy feedback in both undulators.

Fast Feedback

The LLRF systems for the SC structures are expected to control the fields to maintain short term variations below 0.01% amplitude and 0.01 degrees phase. Slow variations will be corrected by the slow beam feedbacks described above. This is expected to meet the LCLS-II beam stability requirements.

There may be high frequency beam disturbances that are not controlled by the RF system, including:

- Interference in cavity probe signals from beam fields
- Mechanical vibration of the SC structures
- The microbunching instability can cause variations in the longitudinal profile which will result in variations in CSR energy losses
- Variations in drive laser pointing

The LCLS-II will include a fast feedback system that allows selected devices to be attached to a low latency feedback network. Initial design studies suggest that a latency of 5 μs in addition to the cable delays is practical.

The final design and implantation of the fast feedback system will be finished after early beam commissioning when the requirements are understood.

The "common platform" FPGA interface described earlier will include a SFP (small form pluggable transceiver) port that can be connected to the low latency feedback network.

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