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<th>LCLS Physics Requirements Document # 1.1-304</th>
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<th>Revision 1</th>
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### Controls Requirements for LCLS Feedback Systems

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<tr>
<th>Name</th>
<th>Title</th>
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<tbody>
<tr>
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**Brief Summary:** This specification describes the number of beam-based feedback loops, and their locations throughout the accelerator, that need to be incorporated into the LCLS control system. The functionality of the loops is summarized and a table is listed for each loop’s readback and actuator devices. Performance requirements are given in terms of diagnostic device resolution and beam stability. Requirements are also imposed on the control system layout to ensure 120-Hz response time and interaction between the loops.
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Brief Summary: This specification describes the number of beam-based feedback loops, and their locations throughout the accelerator, that need to be incorporated into the LCLS control system. The functionality of the loops is summarized and a table is listed for each loop’s readback and actuator devices. Performance requirements are given in terms of diagnostic device resolution and beam stability. Requirements are also imposed on the control system layout to ensure 120-Hz response time and interaction between the loops.
The software feedback control loops for providing fast, single-pulse stabilization of electron beam parameters at rates up to 120 Hz are listed together with their locations. The broad categories of the feedback loops and their locations are:

1. Beam energy
   a. at DL1
   b. (or) injector energy spectrometer
   c. BC1
   d. BC2
   e. DL2 (in LTU)
   f. (or) BSY with 50B1 bend switched on (beam on SL-2 slits)
2. Trajectory position and angle, $x$ and $y$
   a. L1 launch
   b. L2 launch
   c. L3 launch
   d. LTU launch
   e. Undulator launch
3. Bunch length just downstream of chicane (and energy) at
   a. BC1
   b. BC2
4. RF phase of the diagnostic transverse deflecting cavity
   a. injector
   b. L3
5. Injector bunch charge
6. Injector laser steering
7. RF phase based on laser pulse timing

Description of the feedback loop function

1. Longitudinal Feedback

Beam energy is maintained at 4 locations along the LCLS linac: DL1, BC1, BC2, and DL2. The first and last locations (DL1 and DL2) are simple energy feedback loops, where the $x$-position reading of one or more BPMs (with at least one at a high dispersion location) are used to control one or more klystron amplitude levels to maintain the BPM reading (the relative energy) to a constant level. The
klystron effective amplitude may be controlled in one of two ways. The klystron may be operated below saturation in the linear regime and have its drive varied in order to change the output amplitude. This method is required when only one klystron is available to control the energy in the region of interest. In regions where multiple klystrons are available the preferred method is to use two klystrons that are phased symmetrically with opposite phases about the RF crest and vary their phases equally and oppositely to alter the effective acceleration amplitude. This has the advantage of leaving the klystrons in saturation and avoiding the cross coupling problems of amplitude to phase when a single klystron is used in the unsaturated mode. The first method will be used in L0 and L1 and the klystron pairing method will be used in L2 and L3. Figure 1 does not distinguish between amplitude changes designated by the symbol $V$ and effective amplitude changes when pairs of phases are adjusted.

The BC1 and BC2 locations include energy feedback, but also use a relative bunch length monitor just after each chicane to control the RF phase prior to the linac (see Fig. 1). So in these two cases both the phase and voltage are controlled independently by reading relative energy (BPM) and relative bunch length, as described in Ref. [1]. The bunch length measurement will be made using a coherent synchrotron radiation (CSR) detector which is sensitive to a particular frequency band suited to the local bunch length, as described in Ref. [2].

It may also be possible to use two different bunch length signals at each chicane, one in the low frequency band and one in the high frequency band, to differentiate whether the bunch is over or under compressed by using the ratio of these signals. However, this possibility has not yet been confirmed.

Energy and bunch length feedback has been tested at the SPPS bunch compressor chicane described in Ref. [4]. In this test the energy and bunch length loops were decoupled and operated independently of each other. The energy measurement in this test used a BPM in the middle of the chicane as will be done in the LCLS, but the relative bunch length was measured from the coherent radiation generated from transition radiation rather than from CSR.

![Figure 1: Schematic layout of energy, $\delta$, and bunch length, $\sigma_z$, feedback loops along LCLS linac. The relative bunch length is measured after BC1 and BC2, while the relative energy is measured at DL1, BC1, BC2, and DL2. The net voltage is controlled for each linac section (L0, L1, L2, L3) while the S-band RF phase is also controlled in L1 and L2.](image-url)
The longitudinal feedback loops will operate at up to a 120-Hz rate and be ‘cascaded’ so as to work as one loop, rather than as several independent conflicting loops. The cascade functionality requires the knowledge of all off-diagonal transfer coefficients so that a change in any RF phase or amplitude has a known impact on energy and bunch length at all downstream loop locations, as described and simulated in Ref. [1]. The loop transfer coefficients can be taken from theoretical coefficients, or empirically by making a number of prescribed step changes in the all actuator setting and measuring the change in energy and bunch length.

The feedback controls software will allow a number of beam pulses (specified by the user) to be integrated for each measurement (nominal=1). The feedback gain of the loop can also be user-specified (nominal=1). The feedback package will buffer the last ~1000 beam pulses and display them so that the user can observe the performance of the loop. The display will calculate the rms variation in the buffered sample and this number will be logged at specified intervals (e.g., every few minutes). Additional loop information is listed in Table 1.

2. Transverse Feedback

Transverse trajectory feedback is used at five locations along the linac, where the launch into the downstream section is important. The trajectory feedback also provides a convenient method of generating small localized trajectory distortions for emittance tuning purposes. The beam position at several locations is read on each pulse and a best-fit trajectory is calculated (around some previously saved reference trajectory) yielding an initial position and angle in both planes at a reference location. Two upstream steering correctors are specified in each plane and are chosen with suitable betatron phase advance so as to provide independent correction of position and angle at the reference location. The transfer coefficients (R-matrices) between correctors and BPMs, taken from the online optics model, are used to derive the trajectory position and angle in physical units. However, the loop may also be calibrated with experimentally measured transfer matrices.

As in the longitudinal case above, the software will allow a number of beam pulses to be integrated for each measurement, will allow a user chosen feedback loop gain, and provide rms data logging. Additional loop information is listed in Table 1.

3. RF Phase of Diagnostic Transverse Deflecting Cavity

The RF transverse deflecting cavities (one in L0 near sector-21 and one in L3 at sector-25) are used to time-streak the beam vertically in the accelerator so that a downstream transverse profile monitor image can be used to measure the bunch length. The phase of the beam with respect to the RF field in the deflecting cavity needs to be kept precisely at (or near) the zero phase crossing, otherwise large vertical deflections of the beam will result and the beam may move off the edge of the profile monitor.

A fast feedback loop similar to the trajectory feedback systems described above is used to monitor the vertical beam position (BPM) downstream of each deflecting cavity to calculate the effective kick to the beam originating at the cavity. Instead of using a steering magnet to correct the trajectory, this
loop uses the RF phase shifter for the deflecting cavity to apply the correction, maintaining the BPM reading and therefore the beam position on the profile monitor screen.

The loop is empirically calibrated by measuring the response of the BPM(s) to a change in the actuator phase shifter. Nominal settings are specified for loop averaging and loop gain. This loop is presently implemented at the transverse cavity test implementation at klystron 29-4 in the SLAC linac. Additional loop information is listed in Table 1.

4. Injector Bunch Charge

A beam current toroid near the RF gun measures the total charge of each bunch for each beam pulse. The laser intensity at the cathode is adjusted to maintain a constant bunch charge. The laser intensity is adjusted by using the attenuator consisting of the attenuation plate, which changes the polarization of the laser beam and polarizer, which transmits only vertical polarization. The attenuation unit is placed at the output of the laser system. The angular position of the attenuation plate determines the polarization of the laser beam upstream of the polarizer and therefore the laser system output energy. The feedback loop will regulate the position of the attenuation plate, according to the bunch charge. Two power meters, placed at the output of the drive laser system and the output of the cathode launch system, monitor laser energy. Nominal settings are specified for loop averaging and loop gain. Additional loop information is listed in Table 1.

5. Injector Laser Steering

The bunch charge loop above is sensitive to the position where the drive laser light hits the photocathode. Optimum operation of the injector is only possible if the position of the laser light is controlled independently of the intensity reaching the cathode. Drive Laser transport and launch systems have several active beam steering stabilization devices. Position of the sample of the laser beam is monitored by a CCD camera, which provides the feedback signal to the mirror position controllers. When the laser beam shifts, the mirrors, driven by the feedback signal, will return the beam to the proper position.
Table 1. Component specifications for each loop. Loop information in gray text (and italics) is a special diagnostic mode which is not used during nominal LCLS operations. Device names are taken from both the current optics listing and the SLC control system and will be enhanced with LCLS control system names at a later date.

<table>
<thead>
<tr>
<th>#</th>
<th>Loop Description</th>
<th>Sensors</th>
<th>Actuators</th>
<th>Control Precision</th>
<th>Loop Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DL1 Energy</td>
<td>BPM9-15</td>
<td>L0 (20-8) klys. ampl.</td>
<td>0.01%</td>
<td>120 Hz</td>
</tr>
<tr>
<td>2</td>
<td>or Spectr. Energy</td>
<td>BPM9-12, BPM9-2, BPM9-4</td>
<td>L0 (20-8) klys. ampl.</td>
<td>0.01%</td>
<td>120 Hz</td>
</tr>
<tr>
<td>3</td>
<td>BC1 Energy &amp; Bunch Length</td>
<td>BPMS11, BPM15, BPM21201, BL11</td>
<td>L2 (21-1) klys. ampl. &amp; phase</td>
<td>0.01%, 5%</td>
<td>120 Hz</td>
</tr>
<tr>
<td>4</td>
<td>BC2 Energy &amp; Bunch Length</td>
<td>BPMS21, BPM24401, BPM24601, BL21</td>
<td>L2 (24-5, 6) klys. ampl. &amp; phase</td>
<td>0.01%, 5%</td>
<td>120 Hz</td>
</tr>
<tr>
<td>5</td>
<td>DL2 Energy</td>
<td>BPMDL1, BPMDL3**</td>
<td>L3 all (29-30) klys. (sec. 29-30 phases)</td>
<td>0.003%</td>
<td>120 Hz</td>
</tr>
<tr>
<td>6</td>
<td>or BSY Energy</td>
<td>BPMS FB31 57, 302, 702</td>
<td>FB31 PHAS 271, 281 (sec. 27-28 phases)</td>
<td>0.02%</td>
<td>120 Hz</td>
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<tr>
<td>7</td>
<td>Injector Launch</td>
<td>BPM9-15</td>
<td>XC04, XC07, YC04, YC07</td>
<td>10%*</td>
<td>10 Hz</td>
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<tr>
<td>8</td>
<td>L2-linac Launch</td>
<td>BPM21901-BPM23501</td>
<td>XC21402, XC21802, YC21503, YC21900</td>
<td>10%*</td>
<td>10 Hz</td>
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<td>9</td>
<td>L3-linac Launch</td>
<td>BPM25701-BPM27901</td>
<td>XC25202, XC25602, YC24900, YC25503</td>
<td>10%*</td>
<td>10 Hz</td>
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<tr>
<td>10</td>
<td>LTU Launch</td>
<td>BPMEM1-4, BPM31-36</td>
<td>XCQT32, XCDL4, YCQT2, YCQT42</td>
<td>5%*</td>
<td>120 Hz</td>
</tr>
<tr>
<td>11</td>
<td>Undulator Launch</td>
<td>1st n BPMs in und. (n = 10-30)</td>
<td>XCMU1, XCMU4, YCMU2, YCMU3</td>
<td>10%*</td>
<td>0.1-0.01 Hz</td>
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<tr>
<td>12</td>
<td>Bunch Charge</td>
<td>IM01 toroid</td>
<td>drive laser power</td>
<td>0.5%</td>
<td>10-120 Hz</td>
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<tr>
<td>13</td>
<td>Drive Laser Pointing</td>
<td>CCD camera</td>
<td>mirrors</td>
<td>1%*</td>
<td>10-120 Hz</td>
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<tr>
<td>14</td>
<td>Inj. Transverse Deflector</td>
<td>BPM9 or BPM10</td>
<td>TCAV0 RF phase</td>
<td>&lt;1 deg</td>
<td>120 Hz</td>
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<tr>
<td>15</td>
<td>L3 Transverse Deflector</td>
<td>BPM25701 or BPM25701</td>
<td>TCAV3 RF phase</td>
<td>0.1 deg</td>
<td>120 Hz</td>
</tr>
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* This value reflects the percentage of rms beam size (in position & angle, \( x \) & \( y \)).

** This feedback loop needs to continue running when the abort kicker is firing, which stops the beam after BPMDL1 but before BPMDL3. In this case, the energy must be calculated based on BPMDL1 only (or including other nearby BPMs if necessary).
Stability and Resolution Requirements

1. Beam energy:
   a. DL1 – The 263 mm dispersion at BPM13 produces a relative energy resolution at 135 MeV of $\delta < 8 \times 10^{-5}$ with a 20-µm resolution BPM.
   b. BC1 – The 231 mm dispersion should produce a relative energy resolution of $\delta \approx 9 \times 10^{-5}$ with a 20-µm resolution BPM.
   c. BC2 – The 363 mm dispersion should produce a relative energy resolution of $\delta \approx 8 \times 10^{-5}$ with a 30-µm resolution BPM.
   d. LTU – The 125 mm dispersion produces a relative energy resolution of $\delta \approx 3 \times 10^{-5}$ with two 5-µm resolution BPMs.

2. Bunch length:
   The actual CSR relative bunch lengths monitors have not been tested yet, but results from Ref. [3] suggest a relative bunch length resolution of a few percent.

3. Beam orbit:
   A BPM single-shot resolution equivalent of 10-20 microns rms or better is sufficient to keep the beam stable at ~10% of the rms beam size in the injector and linac. In the LTU, with its 5-µm BPM resolution, the feedback system will resolve down to 5% of beam size.

4. Bunch charge:
   The relative charge stability requirement for the LCLS is 2% rms. A toroid just after the RF gun should be capable of measuring the relative charge variations at substantially less than this level (e.g., 0.5% rms).

Steering Corrector Magnet Response Time

The 12 correctors in loops #7, 8, 9 are wrapped around the copper accelerating structure in the linac and magnetic field changes cannot penetrate the beam-pipe at rates much above 10 Hz. The 4 LTU correctors in loop #10 can be mounted on special ceramic sections of beam-pipe to allow for operation at the maximum possible rate of 120 Hz. The weakest corrector in the LTU loop (XCDL4) requires a 0.0013-kG-m integrated field in order to kick the beam by one rms beam size (position and angle combined into amplitude). If we assume a corrector with 0.06-kG-m maximum integrated field at a 6-A current, as in the linac, then a sudden, worst-case trajectory change of 2-times the rms beam size (70 microns in the undulator) will require $2 \times (0.0013 \text{ kG-m}) \times (6 \text{ A})/(0.06 \text{ kG-m}) \approx 260$ mA change within one pulse (8 msec). Given beam-pipe field penetration and system delay, the maximum rate for these 4 correctors should be substantially faster than this, such as a net change of ~260 mA within 2 msec in order to achieve 80-90% of the intended field (i.e., ~2 time constants). The other 3 correctors in this 120-Hz loop will be even less demanding (i.e., <100 mA within 2 msec).
Cascade Requirements

A downstream feedback loop should be decoupled from similar class upstream feedback loops in such a way that the two loops do not simultaneously try to correct the same error. This requires a high speed control link between the feedback processors and an adaptive algorithm to calculate the propagation of the error along the beam line from one loop location to the next. It is not yet clear whether single cascade is adequate or if multi-cascade is necessary for the transverse loops. However, multi-cascade will be used for the longitudinal feedback. In single cascade mode a feedback loop only receives information from a loop immediately upstream from it and passes this information only to the next feedback loop immediately downstream of it. A multi-cascade mode is where each loop broadcasts the information to all loops downstream. This behavior should be modeled in a particle tracking code such as LIAR which can model the nonlinear response to an upstream trajectory perturbation, taking into account collective effects from wakefields in the linac. Wakefield effects, however, are not expected to be a major limitation in the LCLS feedback loops, as compared to SLC experience with 7-times higher charge and 3-times longer linac.

Control System Requirements

The control system needs to accommodate feedback devices that can be remotely located from each other and operating in different crates with different processors. The overall goal of the feedback system is to provide controlled correction at the full rate of 120 Hz for the machine, especially at undulator entrance. This implies that the devices such as BPMS and other signals read through gated ADC’s need single-pulse readback with beam pulse identification to allow all signals to be coherently buffered. Similarly, the feedback actuator devices like magnet correctors and RF phase shifters and attenuators need to be commanded to respond on a single pulse basis at 120 Hz.

We also specify that the 120-Hz rate be achieved in the controls with zero pulse latency. In other words, it is not acceptable to have the controls pipeline the data so that it was acted upon at 120 Hz and delayed by one or more pulses in a queue. Of the 8.3 ms duration available between beam pulses for feedback, we expect that the time budgeted to the control system is less than 1 ms.
References


