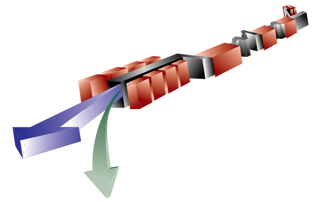
11 Controls



TECHNICAL SYNOPSIS

The LCLS incorporates several new systems into the existing SLAC accelerator complex. The parts of the existing accelerator complex used for LCLS will also serve non-LCLS functions. The control system architecture for the LCLS will be the same as that used currently for running the SLAC accelerator complex. This architecture consists of the original custom CAMAC-based VMS system developed at SLAC and subsequently extended by incorporating EPICS-based systems into the control system. The new systems required only by the LCLS will be EPICS-based. These systems include: (1) The LCLS Injector systems, such as, the gun, the gun laser, the injector linac and the DL1 beamline. (2) The undulator segments, the associated steering magnets, the mechanical movers and the undulator diagnostics. (3) The x-ray beamline components. The electronics for modifications to the LCLS accelerator, such as the bunch compressors and DL2 beamline, will use CAMAC for cost reasons and for ease or sharing these systems with the rest of the SLAC experimental program.

The control requirements for the LCLS are straightforward and similar to the existing FFTB controls. The x-ray beamline controls have two major objectives. One objective is to provide control of the x-ray optical elements. The second objective is to provide sufficient data collection capability to allow for thorough testing of different components.

Most of the LCLS x-ray experiments will require synchronization of the experimental station's equipment with the electron beam. The electron beam, in turn, is phased to the 476 MHz of the SLAC master clock. Temporal jitter between the RF and the beam is specified to less than 0.5 ps. A timing system is designed to assure that the synchronization between experiment lasers and the FEL x-ray (External Pulse Class of experiments) have jitter better than 0.5 ps for time delays of +/-1 ns and better than 1 ns for time delays of +/-10 ms. Some experiments will require significantly better timing that 0.5 ps jitter and the techniques to achieve this will be developed as part of the LCLS R&D plan.

At SLAC the Beam Containment Systems (BCS), Machine Protection Systems (MPS) and Personnel Protection Systems (PPS) are included in the control system and are described in this chapter.

11.1 Control System

The LCLS operation will be controlled by two systems: (1) the accelerator systems that are shared with the rest of the SLAC accelerator program (i.e. L1, BC1, L2, BC2, L3 and beam switchyard) will be controlled using the existing accelerator control system; (2) The new systems that are exclusively LCLS (i.e. the injector, the undulator and the x-ray optics) will use EPICS-based controls that will be linked to the SLAC accelerator control system (much like the system used to control the PEP-II RF). The LCLS will be controlled from the SLAC Main Control Center (MCC). Touch-panel consoles located in the MCC provide the human interface to the machine hardware. For commissioning and maintenance purposes, additional control terminals will be built into the electronics racks in the LCLS support buildings.

The present SLAC linac is controlled and monitored using the SCP (SLC Control Program), which is a twenty-year-old VMS-based, monolithic user interface. It has a centralized architecture with limited peer-to-peer capabilities. The hardware and software overview of this system is shown in **Figure 11.1**.

EPICS, more recently developed by LANL and ANL is also in use at SLAC and numerous laboratories in the USA and around the world. EPICS uses Client/Server techniques to provide communication between various computers. Most servers, called Input/Output Controllers (IOCs), perform real-world I/O and local control tasks, and make information about their state available to clients using the Channel Access (CA) network protocol. CA has been designed for the kind of high bandwidth, soft real-time network applications for which EPICS is used. EPICS hardware architecture is distributed. Each IOC or OPI (OPerator Interface) can communicate with all the others. The hardware and software schematics of a generic EPICS based system are shown in **Figure 11.2**. Some experience using EPICS based controls already exists at SLAC (e.g. the PEP-II RF system controls). Although SLAC does not at present possess EPICS drivers for all the standard devices at SLAC, there is a large user base from which software is available. In addition, the LCLS collaborators at the APS have extensive experience with EPICS.

Since part of the SLAC Linac will be used as the LCLS accelerator, the control system currently running the SLAC facility will be used to operate the LCLS systems in the existing linac enclosure. Systems, such as the L1, L2, L3 linacs and the bunch compressors will be integrated into and controlled and monitored using the existing control system. Control of the systems hardware and the acquisition of data from the sensors and diagnostic instrumentation for the electron beam in the Undulator Hall will be done by a refurbished existing CAMAC-based system that will provide for an update of the existing SLAC control structure. More details of the LCLS accelerator controls are given in **Section 11.3**.

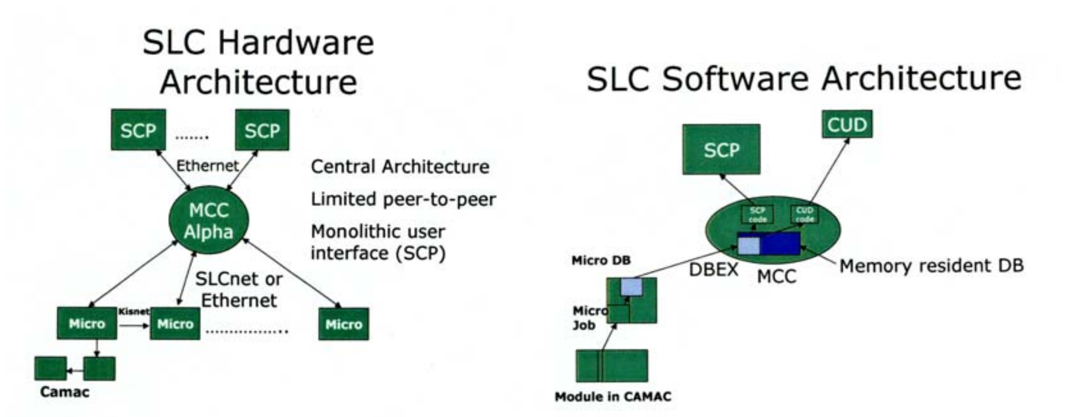


Figure 11.1 SCP Control System Hardware and Software Scematic

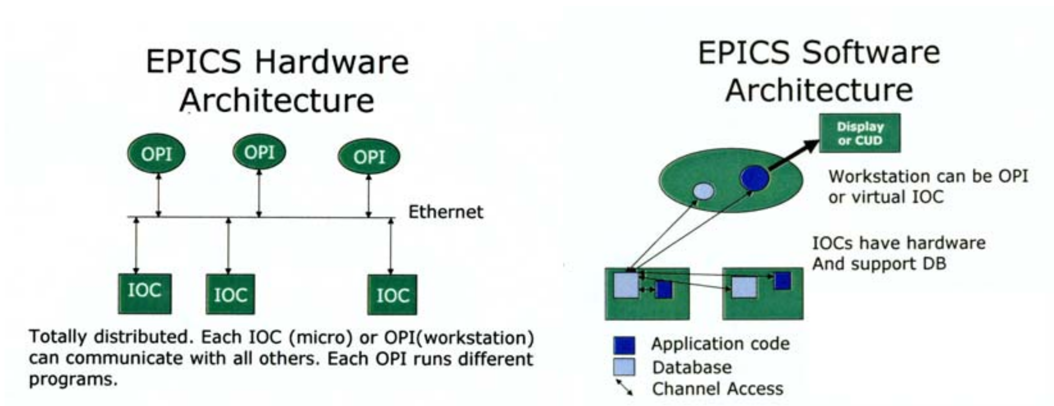


Figure 11.2 Generic EPICS Hardware and Software Schematics

The new systems needed specifically for LCLS will be controlled using an EPICS-based system. Three new control consoles running EPICS, are envisioned for the new systems, one for the Injector area and one each for the Near and Far Halls. With the judicious placement of the Operator Interfaces (OPIs), local control for initial testing and commissioning of the injector, undulator and x-ray beam transport and diagnostics will be facilitated. In normal operation, the LCLS will be controlled from the Main Control Center (MCC). **Figure 11.3** shows the integration of the EPICs systems into the overall SLAC control system. This is very similar to the existing integration for PEP-II.

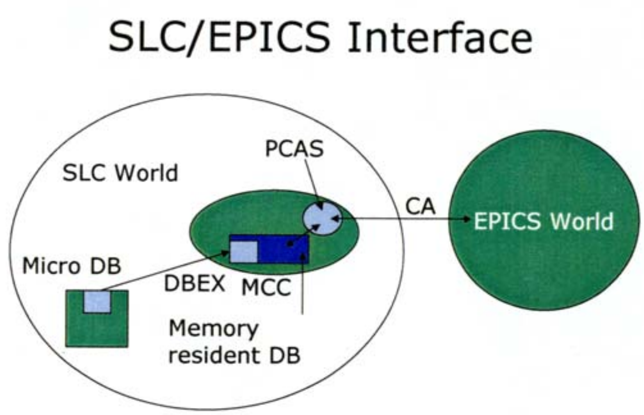


Figure 11.3 Integration of the EPICS subsystems into the SLC control system

Control of the hardware and acquisition of data from the sensors and diagnostics instrumentation will be done by refurbished existing CAMAC and/or new VME-based systems. The workstations will be linked to a new CAMAC or VME Crate Controller module. The workstations will also be linked to the SLAC network via Ethernet. This link will allow communications with the SLC computer and with other control consoles.

The LCLS is a demanding accelerator system to tune and run. It will require extensive use of feedback systems. Most of these feedbacks will be similar to existing systems at SLAC and others will require new algorithms and software. The controls hardware will be designed with these feedbacks in mind.

11.2 Injector Controls

The LCLS injector provides a 150 MeV electron beam that is injected into the existing SLAC linac at the beginning of sector 21. The injector is a new device housed in the off-axis injector enclosure near sector 20. Its main components are an RF gun and associated laser, a short accelerator (L0) and a beam transport line (DL1). The laser for the RF Gun is similar to the system currently used for the polarized electron gun on the linac. Similar controls will be required for the LCLS laser. A table of the control points for the injector is included in appendix B.

11.3 Accelerator Controls

The main components of the LCLS accelerator are three pieces of existing linac (L1, L2 and L3) and a reconfigured beam transport line (DL2) in the Undulator Hall. The LCLS requires new systems for manipulating and transporting the required electron beam. These consist of two new bunch compressors (BC1 and BC2), two transverse S-band RF cavities, an

X-band RF structure and a superconducting wiggler. There will be additional standard diagnostic equipment most of which will be copied from existing designs. However, the BPM hardware has to be re-designed to meet the LCLS specifications. Sophisticated feedback techniques will be required to successfully tune and operate the LCLS. These will require design and software effort. A table of the control points for the accelerator is included in appendix B.

11.4 Undulator Control

The LCLS undulator has thirty-three segments and has a total length of 121 meters.. The separations between segments will each accommodate a permanent magnet quadrupole, a Beam Position Monitor (BPM), x and y corrector magnets, beam intercepting electron and photon position monitors, and vacuum ports. The undulator segments will be supported on piers. Movers will be mounted atop the piers to align each end of an undulator segment. Movers will align the quadrupole magnets in x and y. In addition, there will be movers at each end of the undulator segments to adjust the vertical gap. The electron beam position monitors will be mounted to piers at each gap, so that the electrical center of the BPM remains stable.

11.4.1 Movers

The movers are needed for the initial alignment process of each undulator segment and quadrupole as well as for their mechanical repositioning during the beam-based alignment procedure. The movers are designed to correct long term drifts in position using this procedure. The undulator segments will be mounted on five-cam movers (x, y, roll, pitch, and yaw), and each motion will be driven by a stepper motor. The mover design is similar to the movers used in the FFTB and the SLC final focus, which have a positional accuracy of ± 5 μm and an incremental positioning precision of ~0.5 μm under loads of several tons for all 5 degrees of freedom.

The motion controls and the movers of the quadrupoles need to operate over a limited range of ±0.5 mm, with a position resolution of 1 μm. The quadrupoles will be mounted on x-y slides with no remote control of roll.

11.4.2 Undulator Diagnostics

The 48 BPMs will be attached to local piers. The BPMs need to operate with high stability, low drift, low impedance, and high resolution (1 μm or better). The beam trajectories measured by the electron BPM signals will be processed on-line, and then fed back to the quadrupole magnet movers, in the form of the number of steps and direction of motion.

A pop-in will be installed between each pair of undulator segments. This will allow observation of the optical transition radiation (OTR) from the electron beam and scatter radiation from the x-ray beam. Beam loss monitors based on the PEP-II design will be installed at each gap between undulator segments.

A table of the control points for the undulator is included in appendix B.

11.5 X-Ray Beam Line Electronics and Controls

For instrumentation and control purposes, the LCLS x-ray optics system can be divided into two parts: (1) the x-ray transport line, (2) the x-ray beam line(s).

The x-ray transport line carries the x-ray beam from the undulator to the x-ray beam line. The x-ray transport line will be installed inside the FFTB tunnel and will include the following diagnostic equipment: differential pumping sections to isolate the high vacuum systems, horizontal and vertical adjustable collimators (slits), a gas attenuation cell, and calorimeters.

The x-ray beam line carries the x-ray beam from the transport line and directs it to the experimental halls for LCLS commissioning and beamline testing. The x-ray beam line will be installed in shielded enclosures and will include diagnostic equipment such as mirror systems, monochromators, differential pumping sections, horizontal and vertical adjustable collimators, and other instrumentation.

11.5.1 Control System Objectives

The x-ray optics controls have two major objectives. One objective is to provide control of the x-ray optical elements. The x-ray optics include the take-off mirror(s), the crystal monochromator, collimators, a gas attenuation cell, and filters. The second objective is to allow experimental data collection for testing and commissioning of optical elements needed for LCLS experiments and of timing techniques needed for the different types of possible experiments using the LCLS x-ray beam. In addition, the control system should allow for functional upgrade to support the LCLS experimental program as it is defined and approved.

11.5.2 Control System Layout

The x-ray control system will control the operation of the various motion controllers and actuators in the x-ray transport line and x-ray beam line(s). The optics and experiment control system will be installed in the LCLS Experimental Halls. An EPICS console in each hall (to allow for future expansion of control and data acquisition capabilities), will allow local control of the x-ray optics and the data acquisition from the diagnostics that will be tested using the x-ray beam. The EPICS console will allow local operation of various equipment such as the mirror and crystal monochromator movers, optical tables, adjustable slits, the gas attenuation cell, sample positioners, calorimeters, and detectors.

11.5.3 Motion Controls

The x-ray transport line and x-ray beam line(s) include systems such as adjustable collimators, mirror optics, crystal optics, and adjustable slits. To operate these systems requires position control and position readback. The design goals, such as positioning accuracy, position encoder linearity and resolution, and processing electronics resolution, differ from mover to mover.

The mechanical position will be measured directly with linear variable differential transformers (LVDTs). LVDTs were chosen for their resolution (essentially determined by the number of bits in the read-out ADC and the LVDT range of travel), their linearity (<0.15%), and their ease of use.

The x-ray optics and experiment control computer will calculate the number of steps and directions that each motor needs to take. Stepper Motor Control (SMC) commands will be sent out to the drivers in the form of the number of steps and direction to move. Currently, the movers controls design is based on a CAMAC system and SLAC SLC-type motor drivers. The final design may use a VME based system and commercially available stepper motor drivers.

11.5.4 Feedback Systems

The x-ray beamline control system requires the ability to set up feedback systems. An example of a needed feedback system is the requirement to stabilize the photon beam. Experiments that require irradiation of a fixed sample point (e.g., diffraction from an individual microstructure) require the stable positioning of the beam to within 10% of its diameter. Factors contributing to positional beam jitter or drift at the sample plane might include the following: (1) power supply and other component fluctuations in the gun-to-undulator system, (2) phase shifts in linac klystron low-level rf, (3) vibration or positional drift in the linac and undulator structures, (4) vibration or positional drift of the x-ray optics system components. For factors contributing to beam motion that have sufficiently long time constants, detection of jitter or drift and their stabilization may be accomplished with suitable detectors providing feedback to any of the upstream LCLS system elements that govern beam position and direction.

Detection of positional and directional jitter or drift will be accomplished with non-destructive photon beam position monitors. The output signal of the monitor will be fed back to positional/angular controllers in the mirror or crystal tanks.

11.5.5 Timing System

Most LCLS x-ray experiments require synchronization of the experimental stations' equipment with the electron beam. The electron beam, in turn, is phased to the 476 MHz of the new LCLS master clock originating from Sector 20. Temporal jitter between the RF and the beam is specified to less than 0.5 ps rms. A timing signal will be sent from the electron gun laser in sector 20 to the experimental hall using a fiber.

A table of the control points for the x-ray transport and diagnostics is included in appendix B.

11.6 Radiation Safety and Protection Systems

The components for the LCLS, except for the injector, x-ray beam line and the experimental stations, are either already in operation or will be built and installed in the SLAC Linac and the FFTB tunnel. The Linac and FFTB tunnel already have active control systems and radiation protection systems. Radiation safety and protection systems include the Personnel Protection System (PPS), the Beam Containment System (BCS) and the Beam Shut-Off Ion Chamber (BSOIC) system.

11.6.1 Radiation Safety Systems - Control System

The radiation safety systems control systems will communicate with the general control system, yet contain the following features:

(1) a dedicated hard wire or optical fiber communication backbone;

(2) redundant or independent units of safety logic, using a combination of relays, PLCs, or other electronic printed circuit boards (PCBs) that are single purpose and independent of all other control systems;

(3) typically a local control interface with the capability of status and control by the general control system; and

(4) subsystems that contain redundancy and multiplicity for a multiple beam shut-off paths with a fail-safe design. The LCLS radiation safety systems control system will take advantage of the latest technology as well as the existing technology for safety instrumentation and control.

The design of these systems must be approved by the SLAC Radiation Safety prior to implementation. The implementation of these systems will be reviewed at an Accelerator Readiness Review prior to beam operation.

11.6.2 Radiation Safety and Protection Systems Description

The radiation safety and protection systems are designed to create barriers, both physical and electronic between personnel and radiation hazards. For example, personnel working inside the Undulator area will be protected from radiation that could be generated by other beams in the accelerator tunnel and Beam Switch Yard, and personnel working outside the accelerator enclosure will be protected from potential radiation generated during the LCLS operation. The radiation safety and protection systems in place include the following: (1) Shielding, (2) Personnel Protection System (PPS), (3) Beam Containment System (BCS) and (4) Beam Shut-off Ion Chamber (BSOIC).

The shielding consists of earth, concrete or other equivalent material designed to attenuate the undesirable radiation. The control system will monitor the movable shielding of the LCLS through the use of interlocks.

The PPS is an access control system that turns off electrical and beam-related hazards prior to personnel entering the local accelerator housing area.

The Injector PPS has a local access mode to allow entry into the injector vault when the linac is operating. The Injector PPS will ensure that the laser, microwave, and electrical hazards are off prior to personnel entry.

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The Undulator Hall PPS, as already exists in the current FFTB tunnel, is designed to protect personnel from radiation and electrical hazards. The function of the system is to prevent access into the tunnel where there is the potential for beam and/or electrical hazards. It is also designed to prevent the radiation dose or dose rate from exceeding the radiation design criteria inside the tunnel when access is permitted, or outside the tunnel during the LCLS operation.

The Undulator Hall PPS is composed of beam stoppers, an entry module, a search/reset system, and emergency buttons. The system is controlled from the SLAC Main Control Center (MCC). It allows beam stoppers to be opened only after the tunnel has been searched and secured and is in the No Access state. Access to the tunnel is permitted by the PPS only if all the beam stoppers are closed.

The Undulator Hall radiation safety is ensured by a beam dump, beam stoppers, a Burn Through Monitor (BTM) installed up stream of the muon shielding; and several Beam Shut-Off Ion Chambers (BSOICs) installed down stream of the muon shielding at the upstream end of the hall. This system prevents the beam from striking the muon shield and shuts the beam off if radiation levels inside the tunnel exceed the allowed limit. An additional BTM is installed behind the electron beam dump, and several BSOICs are installed outside the tunnel to monitor the radiation levels outside the Undulator Hall shielding. The BTMs are interlocked through the PPS.

The Experimental Hall PPS will consist of a shielded hutch. The PPS can accommodate additional hutches. Each hutch will be designed to contain all radiation so that the dose rates outside the hutch are acceptable when photons from the FEL are inside the hutch. Control for the hutches will be local to the hutch. The Hutch Protection System (HPS) will be modeled after the latest SSRL hutch design. The key parts of the HPS are the access door, photon stoppers, and hutch security search/reset logic. The HPS allows either personnel access or beam operation in the hutch. The HPS contains the logic circuits that govern the sequence of access operations based on the status of the stoppers. It allows releasing or retaining the hutch door keys, acknowledges completion of a hutch search, and enabling the experimental hutch to be placed on-line (beam operation) or off-line (personnel access). The LCLS HPS will control the operation of photon stoppers for each experimental hutch. The system will allow the photon stoppers to be opened (go on-line) only if the hutch has been searched and secured, and the hutch door key is captured in the HPS panel. Access to the hutch is permitted only if all photon stoppers are closed. Photon Stoppers with burn-through monitors will be installed inside the FFTB tunnel, and redundant hutch stoppers will be installed to protect each hutch. The stoppers located in the FFTB tunnel, upstream of Experimental Hall #1, are designed to protect personnel from radiation generated by the FEL. The Experimental Halls photon stoppers are designed to protect personnel in each hall and hutch from scattered radiation. The initial design is for one main hutch in each experimental Hall.

The Beam Containment System (BCS) prevents the accelerated beams from diverging from the desired channel, and from exceeding levels of energy and intensity that may cause excessive radiation in potentially occupied area.

The Injector BCS will consist of a few Protection Ion Chambers (PICs) for protecting personnel in the Injector from main Linac beam losses.

The Undulator (FFTB) BCS already in place consists of the following:

(1) devices which limit the incoming average beam power to 2.4 kW (3 current monitors);

(2) devices which limit normal beam loss so that the radiation level outside the tunnel shielding is less than 1 mrem/hr (current monitors and long ion chambers);

(3) protection collimators which ensure that errant beams do not escape containment; and

(4) ion chambers and water flow switches which protect collimators, stoppers and dumps.

The BSOIC system consists of radiation monitors in areas that could be occupied that insert beam stoppers when raised radiation levels are sensed. The Injector and Experimental Halls will have some new BSOICs installed and connected through the PPS and interlocked with area stoppers. The general and PPS control systems monitor and display the BSOIC analog level. The control system can reset a BSOIC trip, after elevated radiation levels are sensed by the BSOIC and the PPS inserts the area stoppers.

11.7 Machine Protection System

A Machine Protection System (MPS) is designed to protect the LCLS components from damage by the beam. The three primary functions of the MPS are to protect: (1) the integrity of the vacuum system; (2) the proper cooling of the water-cooled components; and (3) the LCLS components from damage resulting from errant steering of the electron beam.

1. The MPS will control and monitor the operation of vacuum components such as differential pumping sections, ion gauges, ion pumps, and isolation valves.

2. The MPS will monitor temperature sensors and water flow switches that insure that the magnets, collimators, stoppers, x-ray mirror, and monochromator crystals are sufficiently cooled.

3. Ionization chambers and long ion chambers capable of detecting average radiation are currently installed in the FFTB tunnel. If the average rate of beam loss is found to be sufficient to threaten machine components, the beam repetition rate is automatically reduced. In addition, a pulse-to-pulse comparator system measures the beam current. The operation of the pulse-to-pulse comparator is based on measuring the beam current in two locations. The signal from a toroid at the beam's final destination (beam dump) is compared with that from a toroid at the beginning of the area being protected. If the comparison on a pulse-to-pulse basis shows a beam loss greater than some specified amount the beam is automatically turned off.

The LCLS MPS will consist of two separate systems. One system will protect the LCLS components from accidents with the electron beam and the second system will protect the components of the undulator, the transport line, the x-ray beam line, and the experimental stations from accidents with the x-ray beam. The two control systems will be interfaced to provide vacuum and thermal interlocks to protect the LCLS accelerator and the x-ray beam line from the following: (1) accidental exposure to atmospheric pressure; and (2) accidental interruption of the Low Conductivity Water (LCW) to water-cooled components. Status signals such as vacuum and LCW faults as well as permits to open or close isolation valves will be shared by both systems.

The existing FFTB MPS control panels are installed in the support building next to the enclosure. These controls will be modified to protect the LCLS components in the tunnel. The FFTB and LCLS requirements are very similar. The undulator-to-experimental stations MPS control panels will be installed in the Experimental Hall. This system will include a Programmable Logic Controller (PLC) and control panels. The architecture of this system is similar to the existing systems in SSRL.