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THE LCLS-II BEAM LOSS MONITOR READOUT SYSTEM*

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Abstract

The Linac Coherent Light Source II (LCLS-II) is a new addition to the SLAC accelerator complex. It is a 4 GeV, 120 kW superconducting Linac operating in continuous RF mode at 1.3 GHz with a beam repetition rate of up to 1 MHz. The prior generation of protection system beam loss monitors, whose operation is based on ion collection principles, are not suitable for operation in LCLS-II due to their slow recovery times. A new group of detectors have been identified and evaluated. These fall into three categories: Cherenkov detectors using optical fibers and photomultiplier pickups for distributed losses. Point detectors based on diamond pickups, and YAG:ce screens with photodiode pickups for burn through detection. These new detector elements require new readout and signal processing electronics to be developed. In addition, because these detectors are part of the SLAC Beam Containment System (BCS), a certified safety system, a self-check mechanism is required to continuously verify the health of the detector and readout. This paper describes the design, operation and performance of the readout electronics.

INTRODUCTION

The new LCLS-II superconducting x-ray FEL at SLAC has undergone commissioning and achieved first light in fall of 2023. Driven by a new 1.3GHz superconducting Linac, this new facility provides up to 4 GeV electron beam at rates up to 1MHz to the soft x-ray (SXR) or hard x-ray (HXR) undulators, which generate x-ray beams at energies of 0.3…1.3 keV and 4.5…11 keV, respectively. LCLS-II runs in parallel with LCLS-I, commissioned in 2009, a normal-conducting copper Linac which provides electron beam at energies up to 14 GeV at a repetition rate of 120 Hz to the HXR and SXR undulators. LCLS-I utilizes the existing final one third of the original SLAC 3 km Linac. LCLS-II requires a new Beam Containment System.

SYSTEM DESIGN

Beam Containment System (BCS) Design

The LCLS-II BCS is a new design [1], in contrast to the LCLS-I BCS, which was an upgrade to the original Stanford Linear Collider (SLC) era system. The increased energy and repetition rate of LCLS-II presents new complex and serious beam induced hazards that must be protected against. The primary function of the BCS is to limit beam power and losses to prevent excessive radiation in occupied areas of the accelerator complex. The accelerator BCS is distributed across the accelerator complex, with a separate system on the photon side [2].

The LCLS-II accelerator BCS is split into two paths: fast and slow (> 500 ms) shutoffs as shown in Fig. 1. The slow side is implemented with a safety-rated PLC system. The fast side is implemented in custom-designed electronics [3].

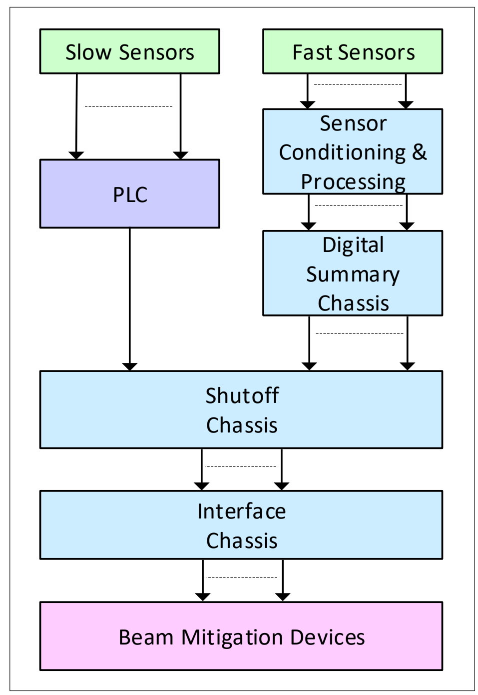

Figure 1: LCLS-II BCS Block Diagram

The system consists of two redundant chains, A and B, arranged in a tree-like topology. Each chain accepts sensor inputs (e.g. loss monitor detector signals), processes the sensor signals and outputs permits to beam generation and mitigation devices. The chains each have their own independent sensor and processing electronics. The processed sensor signals are turned into digital go/no-go signals. These are summed at various points in the machine complex by the Digital Summary Chassis (DSC), whose function is similar to an AND gate. The ANDed DSC signals are then forwarded to one of two Shut Off Chassis (SOC), which are geographically located at two key accelerator points and are interlocked together. Beam mitigation devices include an acousto-optic modulator (AOM) at the injector laser, an RF switch to interrupt the RF reference to the Low-Level RF system, injector photocathode laser shutters and the copper Linac cross interlock. BCS system mitigation response is required within 200 us after beam loss.

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Beam Loss Monitor Design

The existing LCLS-I (and pre-LCLS era) beam loss monitors consisted of Protection Ion Chambers (PICs), a gas-based detector consisting of multiple, interleaved metal plates. And Long Ion (LION) devices, which were simply air-core heliax cables. Studies were undertaken [4] to understand and characterize the behaviour of these legacy devices at the increased beam rates of LCLS-II. The studies revealed that these legacy devices were inadequate for LCLS-II type beam losses due to the fact that their ion collection times may allow the accumulated ion space charge to null the electric field inside the detector, blinding them to any increases in loss. It was clear that faster detection devices were required. Detectors capable of sensing beam loss at higher rates were identified and evaluated [5, 6]. For beam loss, two new detectors were selected and another for burn-through detection.

Fiber Detectors To cover broad areas of the 4 km accelerator complex, radiation hardened quartz core optical fiber were selected, which emit Cherenkov light in response to a loss shower passing through it. The PMT selected was a red-sensitive Hamamatsu H7422P-40 (later upgraded to a H16722P-40 due to reliability issues) with integrated high voltage supply and a thermoelectric cooler. The PMT is integrated into a 4u, 19-inch rackmount chassis with the system electronics and power supplies. This is called the Long Beam Loss Monitor (LBLM). The loss detection fiber is divided into segments with a maximum length of 200 m. The length was chosen based on signal attenuation and transit time requirements. The other end of the fiber is mated to an LED, which generates a continuous 0.8 Hz sinewave self-check signal. LBLM chassis are daisy-chained together with the LED output of one chassis feeding the PMT input of the next downstream unit, via the detection fiber.

Diamond Detectors The other loss detector required, replacing the protection ion chambers, is located near beam containment devices (e.g. collimators) to detect more localized beam loss. This is called the Point Beam Loss Monitor (PBLM). A mono crystal diamond substrate solid state detector was chosen from Cividec [7]. In this type of detector, a loss shower creates electron-hole pairs, which take only a few nanoseconds to propagate to reach the electrodes avoiding pileup, even at the 1 MHz beam rate. Self-checking is implemented by modulating the detector -250 V bias power supply with a 5 Vp-p sinewave. The readout electronics are packaged in a small SIM modules [8], along with the detector high voltage bias supply.

Photodiode Detectors The third type of sensor is required for detection of catastrophic failure (burn-through) of BCS beam absorbers [9]. In this detector a YAG:Ce screen is positioned in the direct path of FEL x-ray beam, downstream of the absorber. Should the beam burn through the absorber, the screen will fluoresce generating a transient burst of light. This light signal is detected via a photodiode, located in a light-proof box. Self-check of the signal chain is via an LED modulated with a 0.8 Hz sinewave. The sensor head (photodiode + LED) is cabled to the readout electronics, which are also packaged is a SIM module.

System Electronics

In order to maximize utility and minimize design effort, a common electronics design was developed that was capable of processing signals from all three types of detectors while interfacing with each type's support electronics. The readout electronics [10] consist of a RC integrator circuit (for the LBLM and PBLM) at the front end, whose time constant is fixed at 500us. The front end provides two signal outputs: a low- (LF) and high-frequency (HF) output. The HF output is essentially AC-coupled and passed to a buffer for input to an external digitizer for diagnostics. The LF output is passed into an amplifier circuit. The BTM photodiode directly feeds a transimpedance amplifier, without the integrator front end. The output of the amplifier is applied to a comparator whose threshold is set by front panel controls. The comparator output is ANDed with other on-board health and housekeeping monitor signals, along with the self-check status. If any status signal faults, this condition is propagated to the SOC and the beam permit is removed. The electronics are designed to respond within 10us. The protection path consists of discrete analog and digital circuity for simplicity and fast response. An on-board DSP microcontroller (MCU), (TI TMS320F28377S) is used for implementation of the self-check generation and receive processing, monitoring of on-board controls and status, and general housekeeping. This device provides a stream of serial data containing status, measurements of self-check, high voltage, threshold settings, etc. that is read into the LCLS-II control system. The self-check signal is tapped off of the LF path after the amplifier and applied to a 0.8 Hz two-pole analog bandpass filter. The filtered signal is converted into a differential signal which is digitized by the MCU's internal ADC, which samples at 10 Hz.

Self-Check Signal Processing

The MCU is responsible for generation and receive processing of the 0.8 Hz sinewave self-check signal, which is generated using Direct Digital Synthesis (DDS) techniques. This drives an on-chip DAC, sampled at 1 kHz. The received self-check signal is recovered using lock-in amplifier techniques [11], implemented in the digital domain via digital signal processing. The ADC output is mixed to baseband by multiplying each sample with the cosine and sine self-check DDS output to form quadrature I/Q signals. The I/Q signals are processed independently, but in parallel, by a cascaded chain of three filters: a 28-tap low-pass FIR (F_{3dB} = 0.25 Hz), a smoothed moving median (192 samples) and a single-pole, low-pass IIR (F_{3dB} = 777e-6 Hz).

The output of the signal processing chain is a number measuring the amplitude of the loss fiber input self-check signal, indicating the functional integrity and health of overall BCS beam loss detector and electronics chain. This number is applied to a software window comparator in the MCU, whose thresholds are programmable. If the measured value strays outside of the threshold window, the

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MCU asserts a hardware signal indicating a fault, leading to the removal of the beam permit. The amplitude and phase at each filter stage are also reported to the control system.

System Firmware

The MCU firmware code is written in C and assembly, and makes use of several TI-supplied libraires and functional blocks, along with custom routines. The code is implemented as a series of nested Interrupt Service Routines (ISRs), which are triggered by programmable timers in the CPU. There are three main ISRs: the self-check ADC sample trigger, which runs at 10 Hz, and contains the self-check signal processing routines. The 1 kHz DAC sample timer ISR also runs DDS, and the housekeeping routine, which runs at 1 Hz. This last routine performs the status checking, the self-check result comparison and manages the streaming of data to the control system. The 1 kHz ISR has the highest priority.

System Software

At the control system level, the BCS BLM system software is part of the larger EPICS software suite. At the very top level, there is a master screen used by the accelerator operators for display of BCS fault status over the entire accelerator. From this main screen, multiple sub-screens provide access to each BCS subsystem including the loss monitors. Each loss monitor has its own dedicated GUI, which provides status on faults as well as measurement data of high voltage, board temperature and self-check signal amplitude and phase. Select BLM data is saved in the EPICS channel archiver, which is sampled every 6 minutes; archived data is saved for long-term reference.

OPERATIONAL EXPERIENCE

Commissioning of the system began in fall of 2022 [12] and has been running continuously since then. The loss monitors have provided protection for beam containment, machine protection and diagnostics. During this time, we have experienced several problems [13]. Most recently, additional issues have surfaced.

Analog Switch Failures The LBLM electronics contain a built-in test circuit which applies a pulsed test charge directly to the PMT input. The pulse is generated by a one-shot triggered by either a front panel switch, or an external PLC input. The one-shot pulse is used to set a (normally open) analog switch into the test position, where it applies a small fixed voltage to the PMT input node. This is used to emulate a beam loss signal, providing a check for the electronics. Over time, it was discovered that the analog switches have been failing, in a mode showing a moderate to low impedance short between the output and one of the switch's +/-15 V power rails, causing a DC level to appear on the PMT input node, leading to a BCS fault. Subsequent investigation revealed that the switches tend to become leaky prior to complete failure, and in some cases the failure was catastrophic (melted IC package). The failure mechanism has been conjectured to be a large loss signal, producing a significant amount of charge at the PMT output: 1 pC with the PMT risetime of 1ns can produce a 50 V pulse at its output (with a 50 ohm termination). This voltage is enough to forward-bias the analog switch's ESD protection diodes. These diodes are designed to handle transient electrostatic discharges, but most likely cannot withstand lower amplitude periodic overvoltages without breaking down. The solution is to add external protection diodes and current-limiting resistors to the switch output. Another switch device has also been selected which contains built-in latchup protection for added robustness. A new LBLM main board is being designed with this fix.

Self-Check/Loss Signal Bleed Trough The self-check signal is a very low amplitude 0.8Hz sinewave. The system has experienced false-positive self-check signal over/under limit faults correlated to periods of beam loss (which have not been large enough to exceed the loss threshold). Though the self-check mechanism has four stages of filtering (one analog bandpass, two digital low pass, one digital median) the loss signal still appeared to bleed through. An analytical model of the signal processing chain was constructed using Matlab and simulated beam signals were injected into it. The model revealed that when a loss signal (a sequence of pulses) has constant amplitude, the original filtering scheme works quite well. When the loss amplitudes are randomized (gaussian randomization), the signal does indeed bleed through the filter chain, causing the final amplitude to vary beyond the set threshold window. This is more pronounced at 1Hz. We experimented with different digital filter configurations, settling on two cascaded stages of single-pole IIR filtering; with time constants of 204.8 and 409.6 seconds, respectively. In addition, the self-check frequency is changed to 0.796 Hz (10/13) and sample rates of the DSP chain and DAC DDS are increased to 80 and 1280 Hz, respectively for better immunity.

The change is purely firmware and simply requires field reprogramming of the MCU. This change is being implemented and will be tested on a small set of LBLM units with real beam loss prior to full release. The real beam loss may follow a different random distribution, requiring changes to our filter algorithm.

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