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ELECTRONICS FOR LCLS-II BEAM CONTAINMENT SYSTEM LOSS MONITORS*

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Abstract

LCLS-II is a new FEL facility which is under construction at SLAC National Accelerator Laboratory. Its super-conducting electron linac is able to produce up to 1.2 MW of beam power. In the event of electron beam loss, radiation can exceed allowed levels outside the thin shielding originally built for the lower power LCLS linac. Beam Containment System (BCS) loss monitors are employed to detect the beam loss and shut off the beam within 200 µs, limiting the radiation dose in occupied areas and minimizing damage to equipment associated with personal safety. Single-crystal (sCVD) diamond particle detectors are used as Point Beam Loss Monitors (PBLM) to detect losses locally. Long Beam Loss Monitors (LBLMs) measure losses throughout the beam path, from electron gun to beam dump, using optical fibers up to 200 m long. A PMT at the downstream end of each fiber detects light produced by Cherenkov radiation along the length of the fiber. A unified electronics design integrates the charge from the PMT or diamond detector, compares the loss with a predefined threshold and generates a fault if the limit is breached. Continuous self-checking is implemented for both types of sensors.

INTRODUCTION

Loss detection sensors previously used for LCLS are based on gas ionization chambers that have undesirable qualities at loss rates possible for LCLS-II [1]. Also a gas system deployed over the full accelerator complex would be unreliable and expensive. Therefore, new types of sensors were selected. These new sensors, and a more stringent shutoff time requirement, demanded a new system architecture and electronic design.

When a loss shower crosses the radiation-hard fused-silica optical fiber of an LBLM, Cherenkov light is emitted. A portion of the light is captured and transmitted through the fiber to the PMT installed at the downstream end of each fiber to measure the light [2].

In a PBLM, electron-hole pairs are generated within the diamond by ionising radiation. The pairs are collected with an HV bias applied to the faces of the sCVD sensor [2]. Negative biasing on the diamond sets an output signal polarity matching that of the PMT, and selecting proper charge integration parameters gives similar voltage levels. Therefore, a unified electronic front end was designed for these two sensors. This resulted in significant savings in engineering and design verification effort.

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SYSTEM REQUIREMENTS

Requirements for functional safety are found in SLAC Radiation Safety Systems Technical Basis Document [3] and supplemented by functional and technical developed by LCLS-II project:

- The design shall be as fail-safe as possible.
- Built in automated test features are required that verify the interlock path of the electronics.
- A continuous non-invasive self-checking of the device should be implemented.
- System elements shall be under configuration control including labelling and locking sensors, electronics and connections where possible.
- Combined offsets, noise voltage and self-checking amplitude should be less than 10% of the lowest threshold expected. Input offset, bias and noise current shall be below 100 pA.
- Because loss detectors are very small current sources, the input impedance of the electronics is high; guard drives or similar elements are required in the design.
- The input integration time constant is 500 ms.
- Input protection from excess signals is required along with buffering of all external interfaces against any reverse signals.
- Electronics shall respond to a threshold breach within 10 µs. As discussed in [4], the beam shutoff time required for the entire system is 200 µs.
- The accelerator gallery is not temperature controlled and the racks are not cooled. The design shall withstand temperatures within the rack of 0 to 50°C and high humidity.

FUNCTIONAL DESIGN

The charge from the diamond sensor or PMT is integrated on the passive circuit shown in Figure 1. It is comprised of integration capacitor C_1 and discharging resistor R_1. R_2 is used for high frequency component termination. C_1 uses a film capacitor with an insulation resistance >10 GΩ and a 1-kV DC voltage rating. The capacitance is selected based on the expected charge and varies with the sensor type and location. For the PBLM, the capacitance of the long signal cable is taken into account in the calculation of the total integrating capacitance. R_1 is selected to keep the time constant of the capacitor discharge close to 500 ms. For the PBLM, R_1 is split into three series resistors of 4.99 MΩ each. Additionally, this area of PC board is made free of solder mask and potted with dielectric compound for greater stability and lower leakage.

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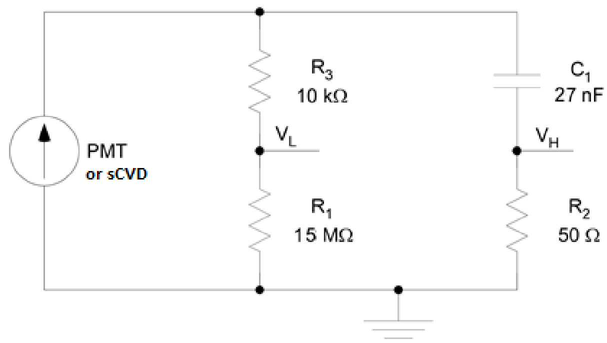

Figure 1: Input splitter and integrator circuit. Values shown for PBLM version of the electronics.

High and low frequency components are then processed separately as shown in Figure 2. The high-pass component V_H is connected to the diagnostic output through a fast isolation amplifier with GBWP of 350 MHz. The low-pass component V_L passes through a buffer amplifier with an optional gain and is compared with the nominal BCS threshold level set with thumbwheel switches on the front panel of the unit. The gain is set with DIP switches on the board and ranges from 2 to 50. The threshold levels are calculated for various loss scenarios and are different for most of the sensors. The value of the threshold is continuously monitored by a PLC through a 4-20 mA signal. If the value read doesn't match the expected level, the PLC initiates a BCS supervisory fault that shuts off the electron beam.

The comparator output is summed with other board faults including the self-checking fault (discussed later in this paper), input overvoltage and supply-voltage monitors. The summed fault is latched and passed to the fast BCS beam shut-off path and to the PLC. Positive logic is used for faults and permit distribution: high voltage levels and closed contacts indicate permitting conditions. The latched fault can be reset locally from the front panel or remotely through the PLC. Overvoltage monitor protects PMT against excessive light in case of accidental fiber damage or powering the chassis with the fiber disconnected at either end.

The integrated signal is also passed to a digitizer that is part of the Machine Protection System (MPS). MPS has a threshold level which is order magnitude lower than the BCS threshold level and is designed to react by lowering the beam rate or power class before the BCS trip occurs.

Input Amplifier Selection

The input buffer amplifier for V_L needs to have a low input bias current, to keep all charge from the sensor on the capacitor, and a low input offset voltage, to avoid affecting the signal on the comparator. Additionally, a low temperature drift is required to keep this offset low across the temperature range of 0 to 50°C. We selected the LMP7721 for its input bias current in the femtoampere range, its maximum initial offset voltage of 180 µV, and its offset drift of 4 µV/°C. A combined offset below 100 µV was measured on the first articles built. The buffered input signal is applied to the outside boundary of the analog front end, providing a guard drive to additionally decrease the leakage on this part of the board.

Self-checking

Continuous verification of the PBLM is implemented by modulating the HV bias voltage and detecting the modulation in the sensor's response. A 5 V peak-to-peak modulation of the sensor's −250-V bias is sufficient for stable detection.

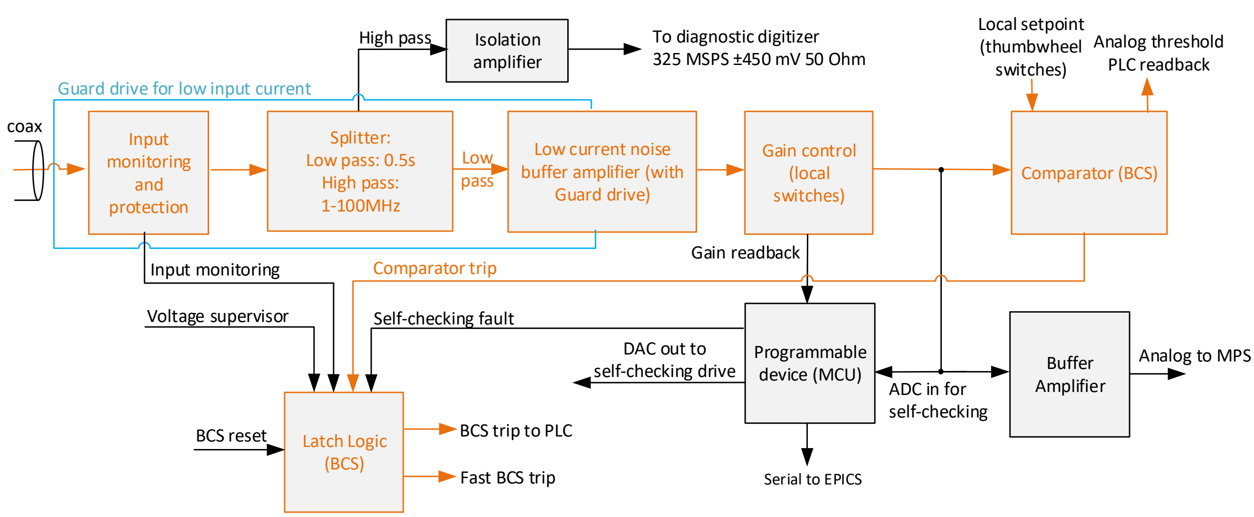

Figure 2: BLM electronics functional block diagram. The direct interlock path is highlighted.

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For the LBLM, an LED at upstream end of the fiber is driven with a small modulation. Demodulating the signal from the PMT at downstream end indicates any problems with the fiber (such as radiation-induced attenuation), the PMT, or the analog front end continuity. Modulating the LED current was found to be more tolerant to temperature variations than voltage modulation.

A modulation frequency of 0.8 Hz is used for both subsystems, since this avoids any subharmonic of the beam rate (which may have an effect on the demodulated amplitude), and since this low frequency passes through the *RC* integration filter. For the PBLM, the same microcontroller modulates the drive signal and detects the modulation; thus the phase of self-checking tone is known and constant. For the LBLM, the modulation and detection are far apart, at the two ends of the optical fiber. The modulation and demodulation frequencies are matched by counting 75 cycles of the 60-Hz AC power line in firmware (60/75 = 0.8).

Test Fixture

An on-board analog switch opens momentarily and injects charge into the input integration circuit when triggered with the front panel pushbutton or remotely through the PLC. The switch has 85 dB isolation, and so the test circuit affects the input signal only when activated. The test pulse width is adjusted with a potentiometer on the board and is set sufficiently high to generate the comparator trip but low enough not to trip input the over-range monitor. This ability to instigate the test charge, in addition to continuous self-checking, gives a very high diagnostic coverage of the system and mitigates most of failures identified in the Failure Modes and Effects Analysis (FMEA).

Programmable Logic Firmware

In the PBLM and LBLM electronics, the use of a programmable device is limited to housekeeping and diagnostics. It is not in the direct interlock path that trips the machine upon beam loss. Therefore it is not subject to the highest levels of rigor required in SLAC's graded approach for programmable logic in safety systems. To minimise failure modes, it runs a very specific code application for the processor, and it is not field reprogrammable.

The firmware is implemented in C and assembly, and runs on TI's 32-bit TMS320F28377S microcontroller with 1 MB of on-chip flash memory at 100 MHz. It implements the lock-in amplifier to detect the "heartbeat" modulation down to an amplitude of 100 µV, which is about 15 times lower than the lowest threshold expected in the system. Another verification step that firmware performs is comparing the control voltage and the scaled readback of the HV bias for the PBLM and the PMT gain setting for the LBLM. If the readback doesn't match the parameter setting within 5%, a self-checking fault is activated.

Besides verification, the firmware latches all status registers at the time of a BCS fault and sends them along with live status as periodic ASCII strings through a unidirectional serial interface. An EPICS asyn driver is used to parse the serial stream. The microcontroller is "air gapped" such that there can be no writing or changing parameters through this interface.

External Interfaces

As a backbone for the entire system, a Siemens S7-1500 safety PLC interfaces to the BLM electronics. As mentioned earlier in this paper, the PLC monitors the threshold level, receives latched and live BCS fault status, is able to reset the fault and is able instigate a test charge. In addition, the PLC is able to select one of two operational thresholds. The second threshold is used in the LBLM implementation to automatically switch between two loss limits depending on personnel access state. This ability to switch between two thresholds is also used for automated testing of threshold readback. In this test, the PLC selects a different threshold and verifies that the 4-20 mA readback has changed accordingly.

A live fault is not expected to remain for longer than the beam shut-off time, as all hazards are mitigated as soon as beam production is inhibited at the gun. A continuing live fault in an LBLM is a possible indication of high dark current coming from cryomodule field emission [4]. If a live fault stays longer than two seconds, BCS escalates the fault to the Personnel Protection System (PPS).

PBLM IMPLEMENTATION

The diamonds detectors are delivered from the vendor, Cividec, housed in an aluminium box with double RF shielding. The boxes are then mounted in 3D-printed covers installed on a backplate to avoid tampering and electrically isolate the box, thereby grounding the device only through the electronics. Signal and bias cables connect sensor to the electronics in the accelerator gallery, and have lengths between 31 m and 168 m. There are 33 PBLM detectors in LCLS-II BCS. Additional PBLMs are used in MPS.

Cable and Connector Selection

Sensor sensitivity of about 1.5 nC/mGy gives input currents in order of 1 nA. The requirement for a high input impedance implies careful cable selection for the sensor output. Several cable types were evaluated including LMR-100, LMR-200, Triaxial Belden 9222, some MIL-specification cables and RG223. Tests were made for low losses, high noise immunity (good shielding) and low leakage through the cable dielectric (high insulation resistance). Triaxial cable was tested with the guard drive connected to the inner braid to further reduce leakage in cable. Later this was found unnecessary and in fact increased the leakage at the transition from the triaxial cable to the coaxial output of the sensor.

During the tests, we observed a peculiar feature of some cables: the cable retained charge even with a long discharge through 50 Ohm terminations at either end. A long-lasting DC current of as much as 1 nA was measured with nothing attached to the other end of the cable, using a sensitive picoammeter with a 10-fA resolution. The charge

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was presumably stored after factory cable testing. The material of the shielding foil stackup and its bonding to the dielectric are suspected as the root cause. Unbonded foil can also generate static charge in vibration that can affect the sensor reading. SF-223 from Times Microwave did not exhibit this effect and discharged promptly after being biased with 500 VDC during our measurement of the insulation resistance.

Reynolds Type C, a widely used cable across multiple systems at LCLS-II, was selected for the HV bias.

Connectors at sensor side will be custom made SMA and LEMO NIM/CAMAC 00 series, for signal and bias respectively. The insulators will use PEEK rather than the standard PTFE, for high radiation tolerance.

Instrumentation Base and Grounding

The PBLM electronics module is comprised of the unified BLM main board, a 1 W HV power supply CN05N-5 with a control input, and a thumbwheel switch assembly used to set the threshold level. A double-wide Stanford Research Systems (SRS) Small Instrumentation Module (SIM) was selected as a hardware base for this design, and SRS SIM900 is used as mainframe.

Use of a low power HV power supply made it possible to leave PBLM sensor floating in the accelerator housing, in order to prevent any ground loops and ground level differences that can affect the input signal and cause nuisance trips, which had been observed with the legacy ionization chambers. The shields of the signal and bias cables are shorted through the sensor housing, but effects of this current loop are reduced by adding series resistance to the ground connection of the bias cable at module end.

LBLM IMPLEMENTATION

No long cables are needed for the LBLM, since each fiber end continues from the tunnel to a chassis in the rack. The fiber runs through one of two 6-mm polyethylene tubes in a flexible “duct”. The duct protects the fiber and allows it to be blown through either tube using a “jetting” tool actuated with compressed gas. If necessary, a fiber can be replaced without accessing the tunnel.

The LBLM electronics fit in a 3U rack chassis. The chassis combines a Hamamatsu H7422P-40 PMT, M13413 PMT control board, unified BLM main board, external cooler with controller and two sets of thumbwheel switches for setting the trip threshold level and the PMT gain. There are 49 fiber runs spanning almost 4 km along the electron beam path from the gun to the dump.

Environmental Tests

The selected PMT module includes an integrated Peltier cooler that keeps the temperature of the tube at 0°C for lower dark current. The unit operates in a maximum ambient temperature of 35°C, which is below the expected maximum inside a rack in the accelerator gallery. We added an external thermoelectric cooler that directly couples heat from the PMT housing and provides an additional temperature difference of up to 15°C. To avoid any issues with moisture while cooling, the external cooler is configured to operate when the temperature of the PMT housing reaches 30°C, which is above dew point expected in the gallery.

The chassis was tested in an environmental oven with a maximum temperature of 50°C and a relative humidity up to 100%. No condensation was observed on PMT window or the housing, the detected self-checking amplitude remained stable, and the input voltage offset (from PMT dark current and electronics) was within specification.

Configuration Control

The LBLM chassis are in locked racks where possible. A protection bracket was designed for a chassis installed in a rack shared with other systems. The U-shaped bracket built of clear Plexiglas protects the front panel controls, and a mating slotted pattern on the back secures all rear panel connections. The rear side of the bracket has latches for padlock that has to be removed to access chassis connections and controls.

SUMMARY

Cherenkov-fibers and sCVD single-crystal diamond detectors are the new types of beam loss monitors that set new challenges in electronics design and sensor deployment. Common aspects of these sensors motivated designing a unified set of electronics. The system is self-checking and has embedded testing features.

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