Commissioning the Beam-Loss Monitoring System of the LCLS Superconducting Linac

Alan S. Fisher, Namrata Balakrishnan, Garth Brown, Edward Chin, William G. Cobau, John E. Dusatko, Bryce T. Jacobson, Sung Kwon, Jeremy Mock, Jino Park, Jeremy Pigula, Evan Rodriguez, Jacob Rudolph, Daniel Sanchez, Leonid Sapozhnikov and James J. Welch

SLAC NATIONAL ACCELERATOR LABORATORY

SLAC National Accelerator Laboratory
Menlo Park, California, USA

U.S. DEPARTMENT OF ENERGY
Office of Science

Abstract

A 4-GeV superconducting linac has been added to the LCLS x-ray FEL facility at SLAC. Its 120-kW, 1-MHz beam requires new beam-loss monitors (BLMs) for radiation protection, machine protection, and diagnostics. Long radiation-hard optical fibres span the full 4 km from the electron gun of the SC linac to the final beam dump. Diamond detectors at anticipated loss points and other points of concern provide local protection. Detector signals are continuously integrated with a 500-ms time constant and compared to a loss threshold. If crossed, the beam is halted within 0.1 ms. Commissioning began in March 2022 with the 100-MeV injector and with RF processing of the cryomodules. At IBIC 2022 last September, we presented commissioning results from the injector BLMs. In October, the beam accelerated through the full linac, passed through the bypass transport line above the LCLS copper linac, and stopped at an intermediate dump. In August it continued through the soft x-ray undulator and achieved first lasing. Here we present BLM commissioning at energies up to 4 GeV and rates up to 100 kHz. We discuss measurements and software using the fast diagnostic-waveform output to localize beam losses and to detect wire-scanner signals.

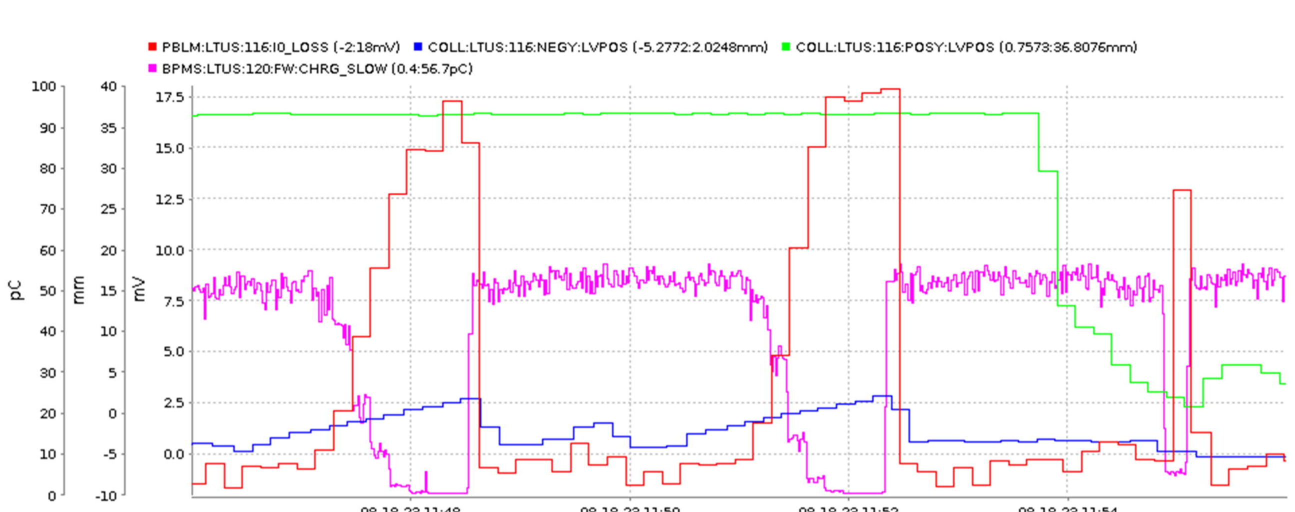
Point Beam-Loss Monitors (PBLMs)

Cividec B1HV Diamond Detector

- Beam-loss shower creates electron-hole pairs.
- Charge is collected by 250-V bias between electrodes on the two faces.
- 4-mm-square diamond chip, 0.5-mm thick
- Single-crystal diamond is necessary.
  - Polycrystalline diamond has charge traps at crystal boundaries.
  - Traps are slow to fill and slow to empty. Signal does not decay to zero when beam loss stops.

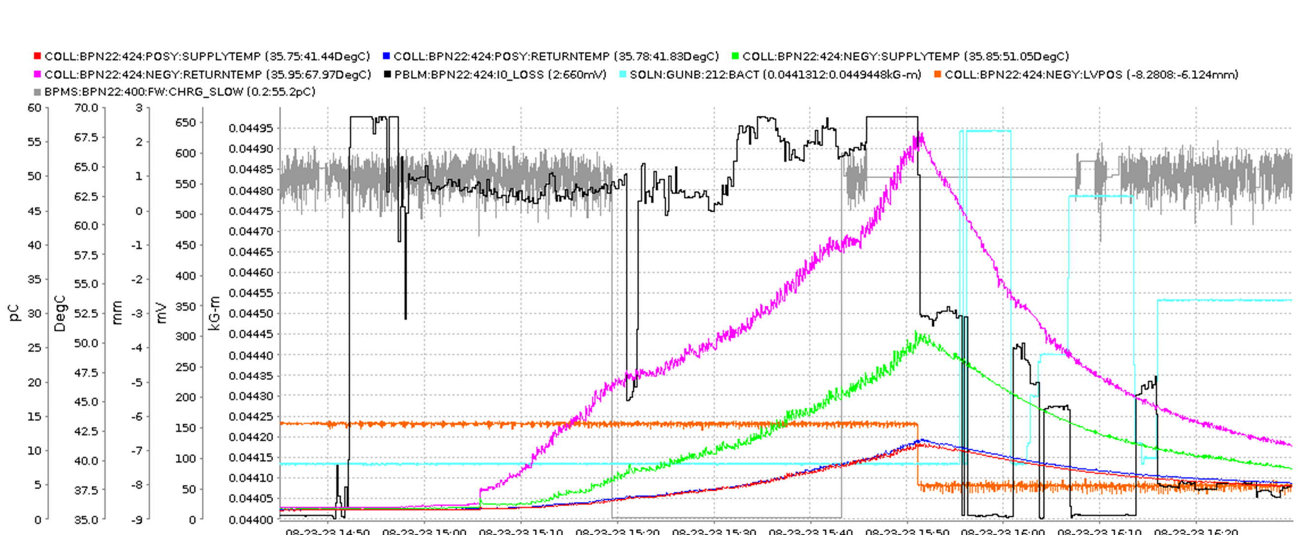
PBLM Electronics

- For protection from losses at any beam rate (1 Hz to 1 MHz, or variable), a filter with $RC = 500$ ms integrates the charge arriving from the detector.
  - The board includes an adjustable gain, from 1 to 74.
- Two applications:
  - Beam Containment System (BCS)
    - Ensures that beam stays on desired path and does not pose a risk to people or to safety systems
    - Simple analogue comparison of integrated signal to a threshold, done on the board
  - Machine Protection System (MPS)
    - Prevents activation and damage to beamline components
    - Integrated signal is buffered and sent to a digitiser
    - Fast comparison with a threshold in firmware
    - Aware of beam paths and of timing



Photocurrent Beam on Collimator Jaws

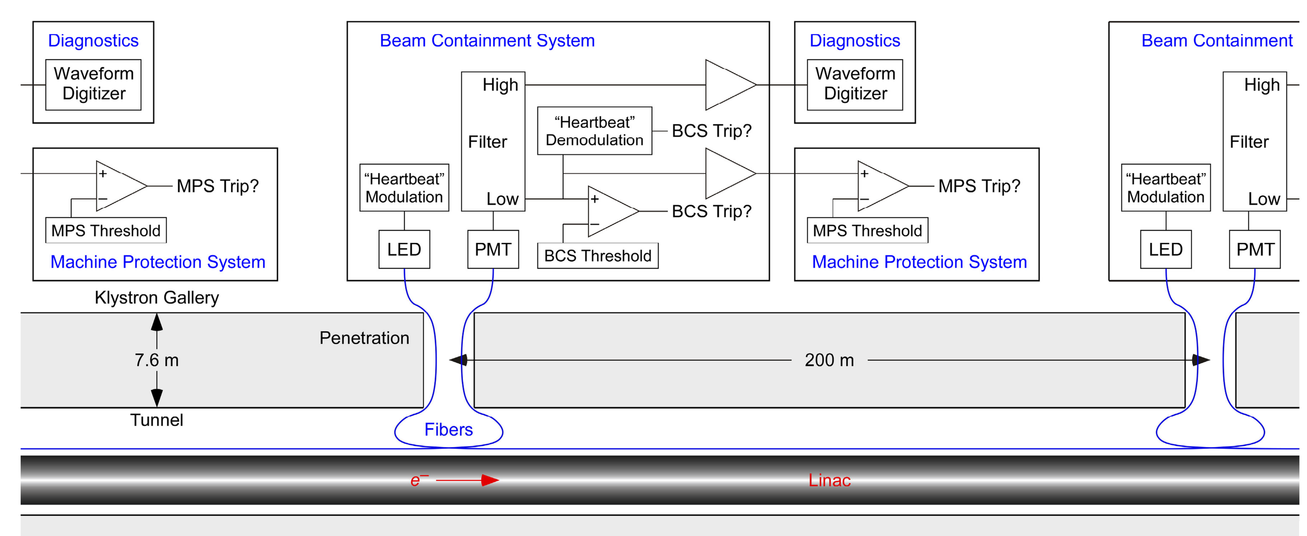
- The $+y$ jaw (green) of a vertical collimator in the Linac-to-Undulator (LTU) transport line was open.
- The $-y$ jaw (blue) was scanned across the beam.
- The charge (magenta) at the next beam-position monitor (BPM) downstream gradually dropped.
- The PBLM signal (red) went up as the charge reaching the BPM fell.

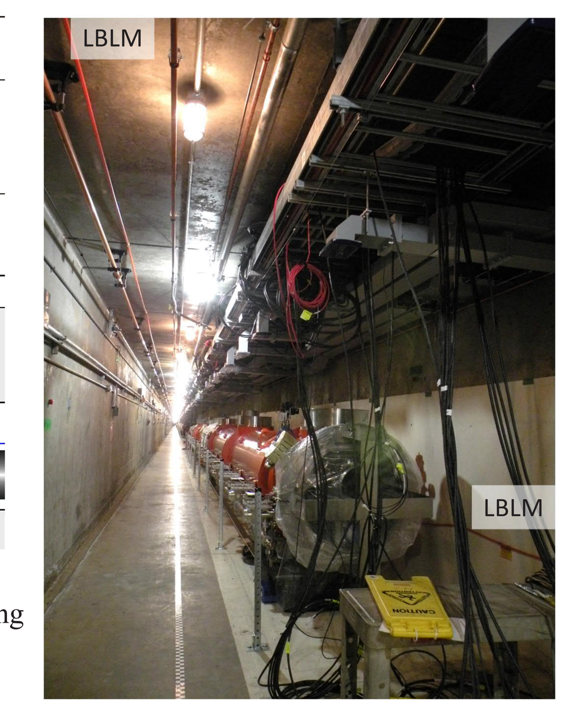


Dark Current Heating Jaws of a Collimator

- The collimator 2.2 km from the gun had a gap of 14 mm.
- The PBLM signal (black) suddenly jumped up to the saturation level of the digitizer.
- Jaw temperatures started to rise.
  - Both supply (red, green) and return (blue, pink) water got hot, suggesting a low cooling-water flow.
- The photocurrent charge (grey) at BPM tripped off. Temperatures continued rising.
  - Dark current from the gun was heating primarily the hotter jaw, $-y$.
- The $-y$ jaw was opened by 1.8 mm.
  - The PBLM signal dropped, and the temperatures started to decrease.
- The gun solenoid was raised, reducing the dark current.
  - The PBLM signal dropped nearly to zero.

Long Beam-Loss Monitors (LBLMs)



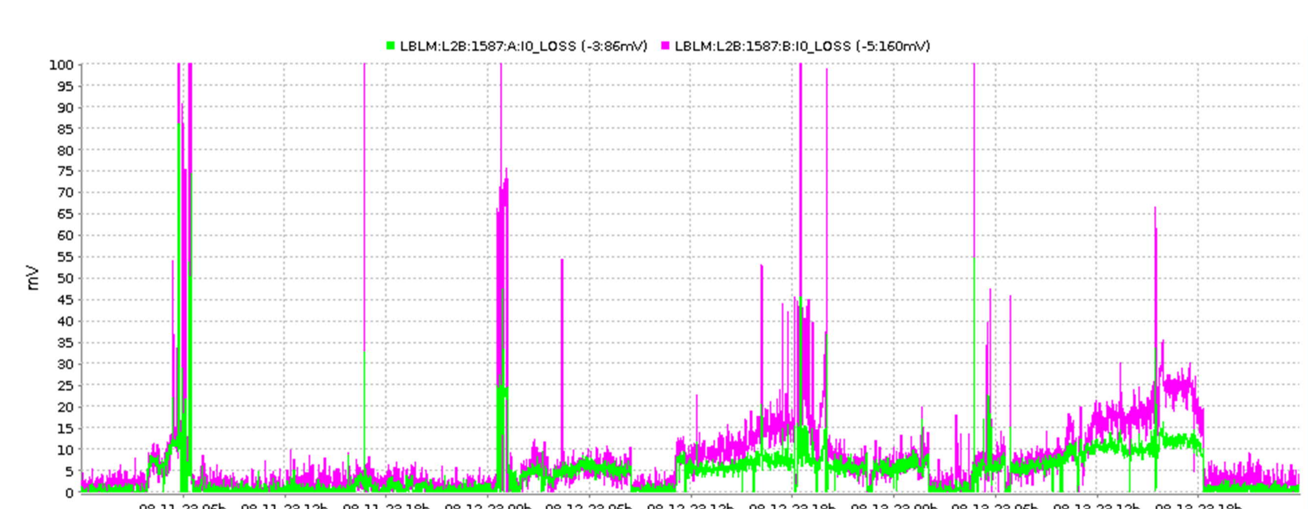


Both fibres are visible during cryomodule installation.

LBLM System

- Installation
  - Fibre lengths span up to 200 m along the tunnel, starting and ending at a chassis in a rack.
  - Cherenkov light is detected by a PMT at the downstream end of a fibre.
  - The PMT signal (like the PBLM signal) is integrated over 500 ms.
  - In some regions (*e.g.*, along the linac), we use two fibres to improve protection by redundancy and by providing two views.
    - See the A and B fibres in the plot below.
- Applications
  - BCS and MPS: These protection systems use the "slow" integrated signal from the LBLMs (and the PBLMs).
  - Beam diagnostics: The raw PMT waveform—the "fast" signal"—has two diagnostic uses.
    - Finding loss locations by arrival time at the PMT
      - At right, beam hits a screen and saturates the waveform digitiser.
    - Numerical integration of the loss peaks from the passage of a wire scanner
- Self-check
  - An LED at the upstream end emits weak light modulated at 0.8 Hz
  - Detected by a lock-in amplifier circuit implemented in a DSP, for a continuous self-check
    - BCS trips if the self-check is too small or too large.

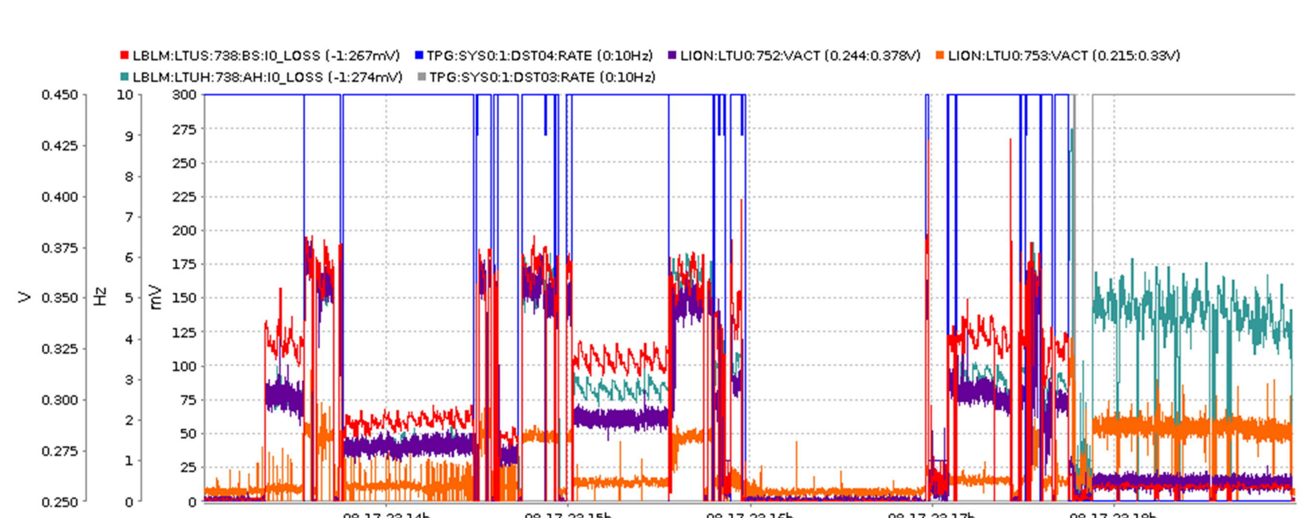
Fast waveform showing the beam hitting a screen, saturating the digitiser.



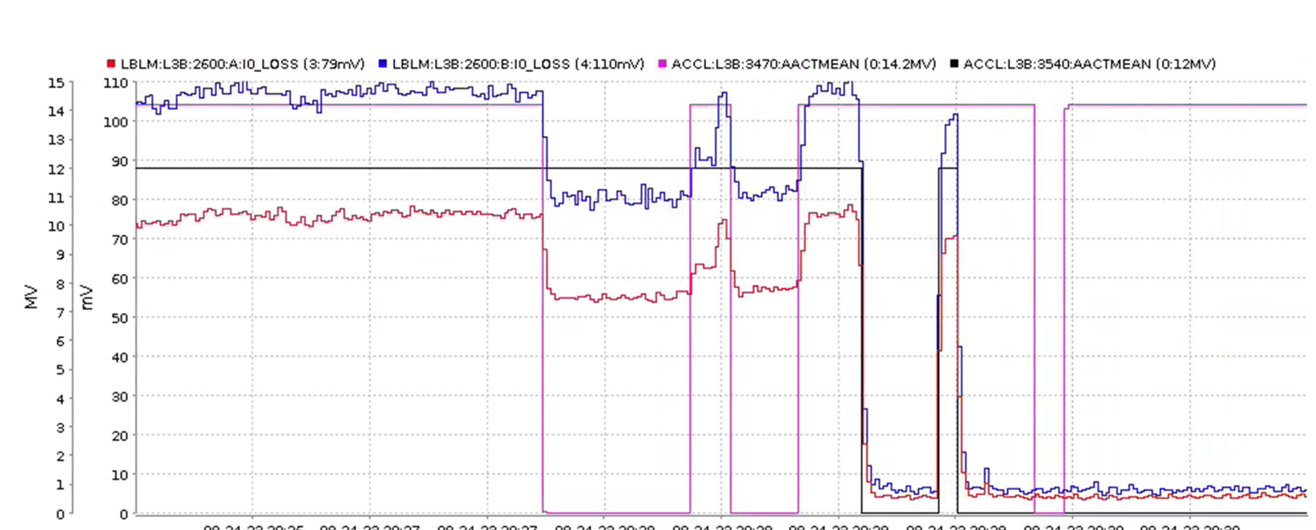
Comparing the responses of A and B fibres in linac region L2B

LBLMs versus LIONs

- SLAC has long used gas-filled coaxial cables to protect regions (LIONs, long ionisation chambers).
- Ions clear too slowly to be suitable for high-power, high-rate losses.
  - Ion space-charge can blind the detector.
- LIONs (for the LCLS normal-conducting linac) and LBLMs both cover portions of the LTU (linac-to-undulator transport hall), providing an opportunity for comparison at 10 Hz.



LBLM and LION signals in the LTU as 10-Hz beam was switched from the soft x-ray (SXR, north side) beamline to the hard x-ray (HXR, south) line. Blue: Rate to SXR. Grey: Rate to HXR. Red: LBLM on SXR side. Green: LBLM on HXR side. Purple: LION on SXR side. Orange: LION on HXR side. Both LBLMs and LIONs responded to the switch and gave similar signals, but the LIONs appear noisier.



LBLM signals from cryomodule field emission. Two fibres span the downstream half of L3B, on the wall (red) and ceiling (blue). Both signals suddenly jumped up, and MPS tripped the photocurrent. The gun dark current was low. Cryomodules along this region were cycled off and on, one at a time. Cryomodule 34 cavity 7 (CM34-7, magenta) lowered losses, but turning off CM35-4 (black) drove them nearly to zero.

Cryomodule Field Emission

- Sudden jump in both A and B fibre signals along second half of linac L3B
- No photocurrent, low gun dark current
- Cryomodule cavities were cycled off and on, one by one, to find the source.
- The loss stopped when cryomodule 35, cavity 4, was off.
  - Likely location of emitter
- CM34-7 and neighbours each reduced loss signal (with CM35-4 on).
  - Charge from 35-4 accelerated upstream from source and hit wall in 34-7 and neighbours.
  - Direction of acceleration depends on emission location and phase.