THE BEAM LOSS MONITORING SYSTEM AFTER LHC INJECTORS UPGRADE AT CERN

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Abstract

The LHC Injector Upgrade (LIU) project aims to increase the available brightness of the beams and improve the efficiency of the whole accelerator chain. The Beam Loss Monitoring (BLM) system is a key element of CERN's accelerator instrumentation for beam optimisation and machine protection by producing continuous and reliable beam loss measurements while ensuring safe operation. The new BLM system for the LHC injectors aimed to provide faster measurements with a higher dynamic range, to install more detectors along the beamlines, and to give the operator more flexible use. A review will be given on the versatility provided by the system to cover requirements from various accelerators and their transfer lines, focusing on the measurements and the operational scenarios.

INTRODUCTION

CERN Accelerator Complex

The High-Luminosity LHC (HL-LHC) upgrade requires the injector chain to produce beams with higher brightness. The LHC Injector Upgrade (LIU) project aims to meet the beam performance in terms of reproducibility, availability, and efficiency [1]. This project consisted of building a new H- linac (i.e. Linac4) and renovating the accelerator chain: The Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS), with all their transfer lines.

The upgrade of the Beam Loss Monitoring (BLM) system in the injectors (i.e. BLMINJ) is an integral part of the LIU program and serves two main purposes: first, to automatically protect the accelerator equipment from damage if it detects excessive losses, and second, to allow operators to observe in real-time losses and adjust machine parameters accordingly. The system development and installation took six years in total and included 322 detectors integrated along the beamlines between the Linac4 source and the SPS injection. This paper first describes the new BLMINJ system recently deployed, before focusing on the commissioning phase and the performance achieved.

BLMINJ SYSTEM ARCHITECTURE

In 2012, an architecture that met the BLMINJ specifications has been proposed [2]. The technical choices resulted in a generic, configurable and high-performance system, in addition to the reliability and availability expectations. The following sections describe the final design, the specification evolution, and the deployment solutions.

The BLMINJ system consists of detectors placed in strategic locations at the tunnel installation and Beam Loss Electronics (BLE) for acquisition & processing located on the surface buildings in a single rack per location, as shown in Fig. 1.

Detectors and Cabling

The BLM detectors are mounted outside the vacuum chamber and measure the secondary shower caused by stray particles interacting with the vacuum chamber walls or magnets. Sensitivity and detection efficiency depend on the size, technology, and positioning of the detector. The BLMINJ system accepts various types of loss monitors as input, all of which were characterised in detail in 2018 [3].

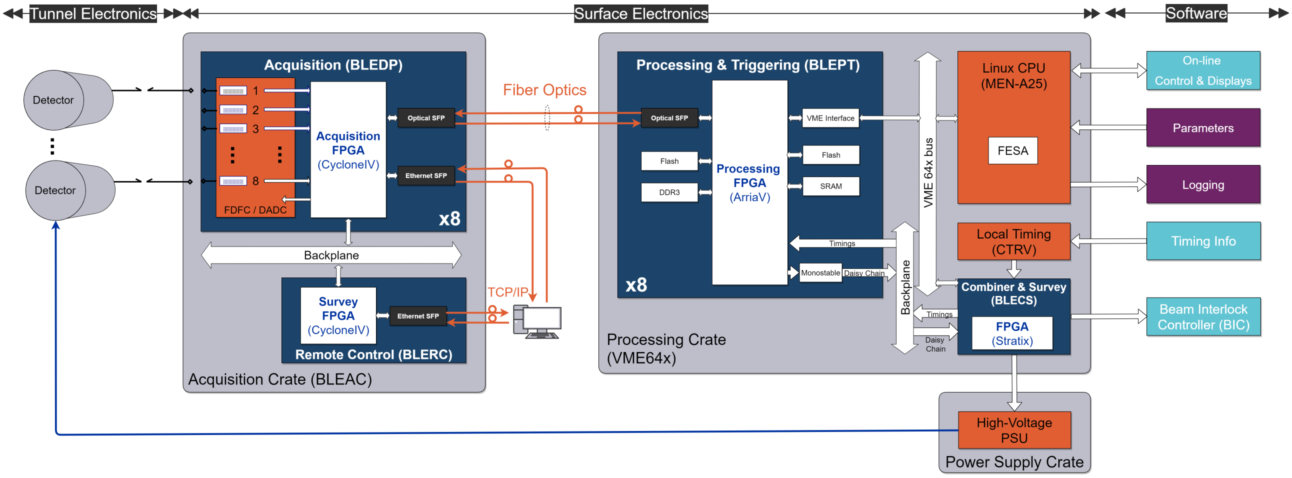

Figure 1: Schematic overview of the BLMINJ system architecture.

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Two detector types, shown in Fig. 2, have been deployed:

- The Ionization Chamber (IC) - 50 cm long, 1.5 litres, nitrogen-filled - is already used in the LHC. It is optimised to give an ion collection time of 85 µs and is polarised at 1.5 kV.
- The Flat Ionization Chamber (FIC) is similar to the IC, but with a different geometry for space-constrained locations in the PSB.

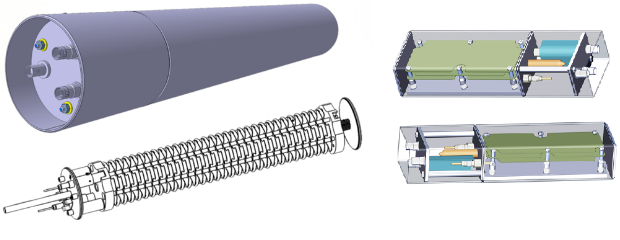

Figure 2: View of an IC (left) and an FIC (right).

A separate high-voltage cable connects the power supply to each detector for additional reliability and testability. Thus, periodic connectivity checks can accurately identify any faulty detectors. This test is currently manual and will be automated in the future.

The implemented cabling schema, shown in Fig. 3, offers the necessary noise immunity by comprising custom coaxial cables and triaxial connectors developed with industry partners.

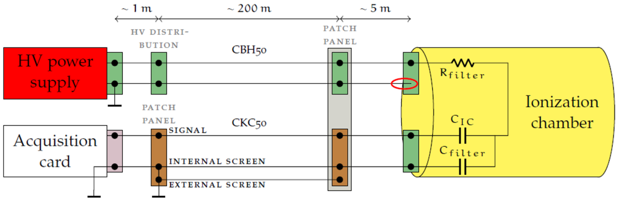

Figure 3: Schematic diagram of the cabling installation.

For the long transfer lines spanning more than one km, a different cabling architecture was deployed to reduce the number of cables in congested areas such as the PS Switchyard (SWY), where the Linac4, PSB, and PS transfer lines cross. A double-shielded multi-wire cable of nine differential pairs and a distribution box chain for nine channels, as shown in Fig. 4, allowed to reduce the installation cost in the long transfer lines while minimizing the number of cables needed.

Acquisition Electronics

The Acquisition Crate (BLEAC) has a custom-designed backplane that can accept up to 64 detector connections. The crate supports up to 8 acquisition modules, one remote-control module (BLERC) [4], and the main panel for system monitoring. The crate also allows to remotely inject a current individually to each channel via an external input or from an internal source via relay contacts. The design foresees the functionality of an automatic calibration sequence, which is planned as a future upgrade.

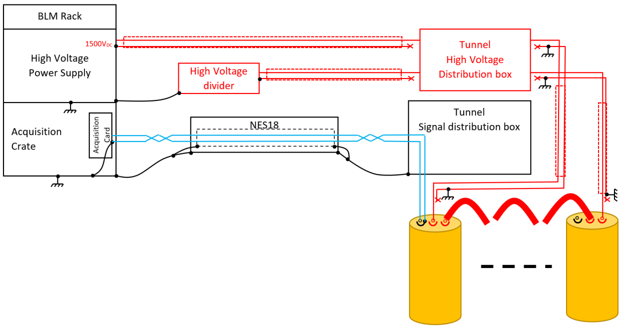

Figure 4: Multi-wire cabling architecture.

The dual polarity acquisition (BLEDP) board acquires, digitises, and transmits the input current from eight BLM detectors in parallel while offering a high level of reliability. The PCB of the board can connect detectors with positive or negative current polarities and ensures the input insulation for low SNR. Its power supply design prevents fault propagation through circuit breakers and current limiters.

Two measurement techniques cover the $2 \cdot 10^{10}$ input range by overlapping [5]:

- The first technique, called the *Fully Differential Frequency Converter* (FDFC), covers the low range from 10 pA to 10 mA. It uses a two-branch differential integrator and comparators to toggle the active branch via a switch. The on-board FPGA keeps count of the toggle pulses, whose frequency is proportional to the input current, and reads the fractional part with an ADC every 2 µs.
- The second technique, called the *Direct ADC* (DADC), covers the high range from 100 µA to 200 mA. Another switch routes the input to the ground, while the FPGA reads the voltage drop across a 3-Ohm resistor via the same ADC.

The FPGA manages the automatic switching between modes and the combination of signals [6]. Figure 5 shows the simplified block diagram of the digitisation circuitry. It generates a 20-bit sample for every 2 µs time period, which represents the beam loss accumulated during this period. A supervision module ensures that the acquisitions are performed correctly, to increase reliability. It allows several hardware parameters of the board, such as temperature, current consumption, and voltage levels, to be periodically monitored and sent to the processing board along with any errors and warnings detected.

Processing Electronics

The Versa Module Europa (VME) crate hosts several modules: a central processing unit (MEN-A25), up to eight Processing & Triggering boards (BLEPT), a timing receiver and a Combiner & Survey module (BLECS). The crate backplane is custom-built for the P0 connector to provide two daisy-chain links between the processing modules, general-purpose I/Os, broadcast lines to distribute timing events, and extra supply voltage outputs.

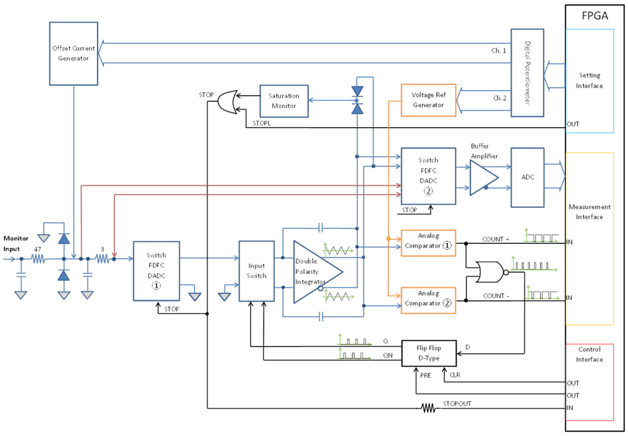

Figure 5: Mixed acquisition circuit.

The BLEPT module uses a new signal processing platform (VFC-HD), which underwent thorough testing and validation [7]. This board also contains an FPGA device that receives the data produced by the BLEDP, calculates different running sums, stores raw data in buffers, and publishes the results and status to the CPU.

The BLEPT keeps track of the user's cycle and the beam presence by using timing triggers and delivers accurate loss measurements to operators, such as the loss integration over beam presence, the evolution of losses along the cycle, one on-demand capture buffer with a resolution of 2 µs, or a global dose value for dosimetry. It can block the beam permit daisy-chain at any time if the measured losses breach a given threshold. This fully redundant hardware interlock function protects the machine by responding within a few µs and is designed to be failsafe.

The Combiner and Survey module (BLECS) is located at the last location of the beam permit daisy chain. If an error is detected in the electronics, the BLECS requests immediately a beam interlock to the Beam Interlock System [8]. In addition, it monitors the various power supplies and distributes timing signals, such as beam cycle or presence events, to each of the processing modules in the crate, as well as initiates the detector connectivity check.

Finally, the FPGA firmware for each of the three module types of the BLMINJ system is common for all machines, which eases debugging and maintenance, with the overhead of additional software configuration parameters. The BLM experts or operators perform and maintain the entire configuration through the CERN operational settings database. This firmware was extensively verified to increase the system reliability by testing individual submodules, including corner cases, random endurance scenarios, covering 100% of the source code, and using the Open Source VHDL Verification Methodology (OSVVM).

Software and Database

Each Front-End Computer (FEC) runs a local server instance, built using the Front-End Software Architecture (FESA) framework, that reads and publishes all the system parameters and diagnostics every 1.2 seconds. Additional functionality provided by the server is used by the operators to limit the radiation levels in the machine by blocking injections on the next cycle using a set of dedicated software thresholds and bad shot counters. This software-generated interlock source is latched until acknowledged and is unique per beam user and channel.

Users can analyse in real-time the data generated by the FESA class through expert applications or fixed displays in the control room. For instance, the PSB BLM vistar shown in Fig. 6 gives the total loss during the beam presence. Operators can also rearrange measurements by assigning detectors to virtual devices and obtain custom plots or scales.

At the PS ring, the system makes use of a concentrator to aggregate data from the two FECs monitoring this location and computes the global sum of losses to trigger a common interlock line.

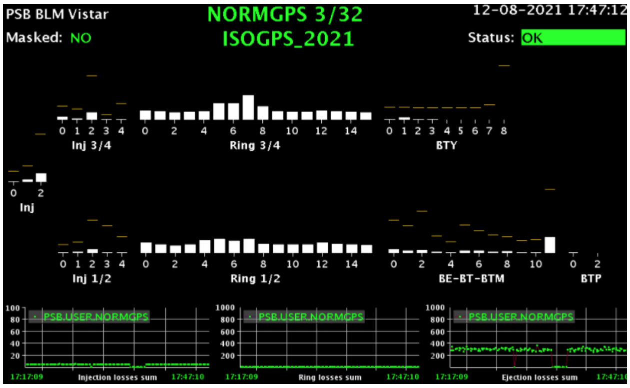

Figure 6: PSB BLM vistar and injection data.

BLMINJ SYSTEM COMMISSIONING

Deployment

The initial request from the CERN LIU management was to install the BLMINJ in Linac4 as a priority to validate this new machine. The BLMs for PSB, PS and their transfer lines have been installed during the long shutdown (LS2). A staged deployment mitigated the risks:

- A prototype with 64 channels was installed in the PSB in 2015.
- In 2016, 15 channels were deployed in Linac4 to start up the new accelerator.
- During the 2016 End-Of-The-Year Technical Stop, the system was fully installed in the PSB and PS rings, representing 164 channels.
- In 2018, 9 channels were added to the Linac4 transfer line to PSB.
- Finally, during LS2, all the remaining detectors were installed, especially in the transfer lines. The legacy BLM system – with 168 channels and 3 racks in PSB and PS – was decommissioned. The processing electronics of the new BLMINJ system were updated together with the firmware and software layers.

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By the end of LS2 in early 2021, 322 channels had been deployed and 14 racks installed for a total of 51 pairs of acquisition and processing boards.

On the firmware and software deployment, an overhaul of three FPGAs was performed between the prototype and the final installation, enabling the migration to the new VFC-HD processing module. In addition, the use of common libraries eases maintenance and traceability, reduces development and debugging time, and makes the system more flexible and reliable.

Commissioning after LIU

The commissioning of the system followed three stages: Individual System Tests (IST), dry-runs, and beam tests.

The IST are time-consuming checks that verify the hardware lines from the detector to the electronics: checking each channel connection by modulating the power supply as shown in Fig. 7, and calibrating the acquisition (offset current, analogue threshold) to ensure that all channels have the same offset level, regardless of location and cable lengths.

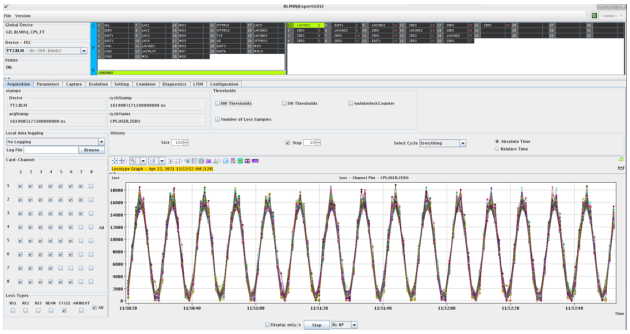

Figure 7: Modulation test of the detectors belonging to one sub-system visualised by the expert application.

BLM experts and operators performed the dry-run to validate the connection of the system to the controls infrastructure. The first test at this stage consisted in an overall high voltage modulation to ensure that all channels were publishing the acquired data to the operational applications. Then, beam interlocks were intentionally triggered to validate the entire chain from the BLECS to the Beam Interlock System (BIS). The correctness of the data logged in the measurement database was verified and the information shown on the fixed display values in the control room and the different expert applications were compared.

Finally, intentional losses were generated at each detector location to trigger the corresponding interlock and measure the value of the loss. This allowed to detect any remaining channel swap. In the long term, the total dose will be correlated with the dosimetry system installed in the tunnel and compared to previous years of operations.

This three-step commissioning was carried out rapidly during LS2 on each accelerator of the injector complex. First was the Linac4 in 2019, then the PSB and PS in 2020, and finally the SPS injection in early 2021. The focus is now on defining fine threshold values to better protect the machine while increasing beam availability for users.

System Performance

The acquisition resolution of the radiation loss depends on the predefined measurement period: when the time resolution is set to 2 µs, the smallest measurable dose is $1.19 \cdot 10^{-9}$ Gy. The measurement periods depend on the system requirements: 600 µs, 1 ms, and 1.2 s are used in the Injectors and correspond respectively to resolutions of $3.98 \cdot 10^{-12}$ Gy, $2.39 \cdot 10^{-12}$ Gy, and $1.99 \cdot 10^{-15}$ Gy.

RF cavity X-rays affect two detectors in the LINAC4-C section. The disturbance is deterministic; hence the BLM threshold was increased by the same offset.

Noise peaks generating saturation are observed at the PS Switchyard despite precautions against electromagnetic interference. The magnetic field of the nearby injection kicker magnet power cables couples to the BLM signal cables. A second source of disturbance, asynchronous to the beam, comes from the non-coaxial DC power cables of the magnets. An additional grounded metal braid can shield BLM signals from the electric field, but the distance between the cables must be increased to avoid magnetic coupling.

Dosimetry is checked on all machines in the CERN accelerator complex. The Radiation Monitoring and Calculation Working Group regularly cross-checks the deposited energy and the ambient radiation levels measured by BLMs against the simulation results from FLUKA, as well as the radiation monitor records and TIDs from fibre-optic dosimeters. The first outcome is very promising and shows a good correlation. Further measurements in the long term will confirm these results during the next run.

CONCLUSION

The commissioning of the Injectors went remarkably well, from the first beam in Linac4 up to the injection in the SPS. The new BLMINJ system played a key role in this success. All the electronics and most detectors worked from day one so that the protection and monitoring functions were always assured. Since the summer of 2021, the BLM phase has moved from commissioning to optimisation. For example, the effort is put to reduce EM interference in the SWY and transfer lines, refine the synchronisation triggers, and adjust the thresholds. In the future, more functionalities are expected to be added to further improve the flexibility and reliability of the system, with a target of 10^{-7} failures per hour. For instance, continuous functional supervision of the detector connection will be integrated [9]. A redundant optical link will be also added between the acquisition and the processing crates to remove this single point of failure. An Ethernet link will still be available when a suitable SFP module is plugged in, so that the BLEDP can be used in standalone mode, but the main Ethernet interface will be moved to the BLEPT where more SFP connections are available.

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