THE BEAM LOSS MONITORING SYSTEM AFTER LHC LONG SHUTDOWN 2 AT CERN

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Abstract

Most of the LHC systems at CERN were updated during the Long Shutdown 2, from December 2018 to July 2022, to prepare the accelerator for High-Luminosity. The Beam Loss Monitoring system is a key part of the LHC's instrumentation for machine protection and beam optimisation by producing continuous and reliable measurements of beam losses along the accelerator. The BLM system update during LS2 aims at providing better gateware portability to future evolutions, improving significantly the data rate in the back-end processing and the software efficiency, and adding remote command capability for the tunnel electronics. This paper first recalls the Run 1 and Run 2 BLM system achievements, then reviews the main changes brought during LS2, before focusing on the commissioning phase of Run 3 and future expectations.

INTRODUCTION

The Large Hadron Collider (LHC) provided proton-proton collisions at a top energy of 8 TeV in Run 1 (11-2009 to 02-2013) and at 13 TeV during Run 2 (04-2015 to 11-2018). To achieve higher luminosity, the accelerator, as well as its injectors and experiments, underwent a first phase of upgrades during the Long Shutdown 2 (LS2), among which the improvement of cryogenic power, magnet diode, dump absorbers, and collimators. The LHC Run 3 started in July 2022 with a 13.6 TeV top energy and is expected to last 3 or 4 years, before LS3 brings a second phase of upgrades to allow 5x to 7x higher luminosity, as described in the High-Luminosity LHC (HL-LHC) preliminary design report [1].

The Beam Loss Monitoring (BLM) system is used for advanced beam diagnostics to tune beam parameters by characterising loss patterns and locations. It is also a key part of machine protection. The system architecture, presented on Fig. 1, has been proposed in 2007 [2] to meet the LHC specifications [3]. The technical choices resulted in a highly reliable system, to protect the machine against excessive losses. Only a small deposition of the order of 100 mJ/cm^3 out of the 320 MJ beam energy stored in the rings risks to provoke a magnet quench. To ensure safe operation, the beam shall be extracted in less than 3 LHC turns when excessive losses are detected.

The LHC BLM system consists of about 4000 detectors, covering all the critical loss locations around the ring, injection and extraction lines, cold superconducting magnets, collimators, etc. Those Ionisation Chambers (IC) are cylindrical tubes filled with N$_2$ and hosting electrodes polarized at 1.5 kV. Those electrodes collect the charges generated by the passage of secondary particles created by protons lost from the LHC beams [4]. The electrical current generated is acquired by Current to Frequency Converters (CFC) located in the tunnel. Measurements are digitised and optically transmitted every 40 µs to the surface. The back-end electronics located in 2 racks per LHC Interaction Point (IP) provides one Gy/s value per channel on 12 different time windows, ranging from 40 µs to 83.9 s. If one of theses values exceeds a predefined threshold a beam dump is requested.

BLM PERFORMANCE IN RUN 1 & 2

During the first two LHC runs, the BLM system protected the machine and contributed to the tuning of the beam parameters [5]. This section reviews the system performance during this period and the modifications implemented based on experience and simulation models.

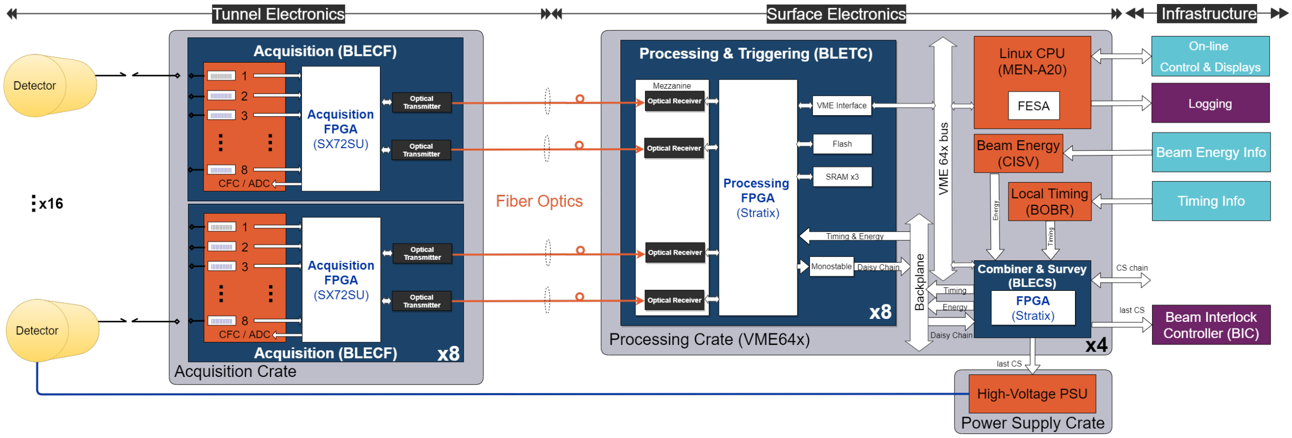

Figure 1: Schematic overview of the BLM system architecture in LHC.

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Beam Diagnostics

The BLM system displays and stores data at 1 Hz. In addition, short buffers with 40 µs resolution can save data on dedicated timing event triggers, such as a beam abort request [6]. In both Runs, the BLM system played a key role in the LHC parameter optimisation. The validation of the accelerator settings was done via loss maps at every stage of the cycle with low intensity ($3{\cdot}10^{10}$ protons): injection, start and end of the energy ramp, and for different beta-star and roman pots configurations [7, 8].

The loss values are published in Gy/s, converted from the electric charge measured by ICs with the factor $7.41{\cdot}10^{-4}$ Gy/mA. To obtain an absolute loss value (number of protons from the beam), the system is calibrated using the beam current variations given by the Beam Current Transformers (BCT), when losses are initiated by primary collimators. During Run 2, the calibration process was enhanced by combining the loss measurements of several BLMs initiated at the same location and loss patterns observed on different planes (horizontal, vertical and longitudinal). In addition, the beam lifetime based on BLMs is a parameter operationally implemented and monitored since Run 2. It is obtained by combining BCTs values with the sum of the signals of 4 specific BLM detectors giving similar losses in horizontal and vertical planes [9].

The Run 1 was affected by unexpected millisecond scale losses caused by dust particles, so-called Unidentified Falling Objects (UFOs). They generated 35 protective beam dumps. But as the beam energy doubled in Run 2, 816 monitors were relocated and their thresholds updated [10] to limit beam dumps caused by UFO (139 dumps during Run 2).

Detectors & Electronics

The high sensitivity of the ICs is suitable for machine protection, but limits the flexibility of the BLM system as a beam diagnostic tool. Little Ionisation Chambers (LIC) are shorter ICs, shown on Fig. 2, which connect to the same electronics and remain below saturation for high losses. With a reduced sensitive volume, they are 30x less sensitive than ICs. Secondary Emission Monitors (SEM) further extend the detection dynamic range, by a factor of $7{\cdot}10^{5}$, using a 3-plate electrodes and 10^{-9} mbar internal pressure [11].

From Run 1, 300 SEMs were used for monitoring only. In Run 2, 108 were replaced with LICs, about 50 additional ICs were added for machine protection, and around 300 defective ICs were opened and repaired, diodes were added to distribution boxes to block high-voltage (HV) return, and 6 new cables were installed per IP to separate the different types of detector, and arcs from straight sections.

Around 670 acquisition cards (BLECF) have been placed along the LHC ring below each quadrupole magnet or concentrated in alcoves. They tolerate up to 500 Gy Total Ionizing Dose (TID) in 20 year lifespan. The input dynamic ranging from 10 pA to 1 mA is covered by using a CFC combined with an ADC to obtain such a resolution [12]. To achieve a Safety Integrity Level 3 (SIL), i.e. 10^{-7} to 10^{-8} failure/h, different test modes, status information, protection circuits, and a redundant data transmission are implemented, as well as firmware triplication to protect against Single Event Upsets (SEU). Finally, at the end of Run 1, several RC filters were added to some detectors to avoid saturation on short losses close to injection. The downside effect is a longer time response and delay on dump request [13]. In Run 2, an option to mask the abort request from a few monitors during the injection process was added but never used operationally.


Figure 2: IC and LIC pair installed on a LHC dipole magnet.

In terms of back-end electronics, 27 crates that house 348 processing boards (BLETC) are distributed among the 8 LHC IPs [14]. During Technical Stops (TS) and LS1, CPUs were upgraded to MEN-A20 (was PowerPC), more electronics were deployed in the injection regions and water-cooled sealed racks were installed to limit optical receiver faults and false dumps. During LS1, the buffers for extraction post-operation check (XPOC) were separated per beam, and 100 Hz refreshed data was provided to help collimator setup.

Machine Protection

As LHC machine protection requires SIL3, achieving high dependability was addressed since Run 1. But increasing reliability often leads to more complex systems which, as a downside, reduces its availability [15]. Compromises were made to meet requirements while generating a minimum of false dumps due to electronics glitches. For example, opting for redundant optical links divides by 2 the failure probability, but doubles the amount of preventive maintenance, components and diagnostics.

The Combiner and Survey module (BLECS) terminates the BLM beam permit daisy-chain. If an error is detected in the electronics or a loss threshold is breached, it immediately requests a beam dump to the Beam Interlock System (BIS). In addition, the BLECS monitors the HV, distributes the beam energy value to BLETCs for the threshold selection, and sends commands to the tunnel electronics. It performs a 20 mn long self-check [16], in particular to test every monitor connection before each LHC refill.

Between the 2 Runs, refined FLUKA simulations led to adjustment of most of the BLM thresholds. In Run 1, thresholds were updated via interactive C++ scripts, then uploaded to the LHC Software Architecture (LSA). To avoid possible human errors, since the number of thresholds is more than $1.2{\cdot}10^{5}$ (12 running-sums and 32 energy levels per monitor), a dedicated tool was designed [17]. A clear predefined threshold management process is occasionally used to update values, agreed by the operation and machine protection teams to match new LHC configurations [18].

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OVERVIEW OF THE MODIFICATIONS DURING LS2

The LHC BLM system underwent major upgrades in LS2 (2018-2022) to improve its performance, reliability, and availability. This section gives more details on these changes.

New Hardware

During LS2, 30% of the detectors were re-installed to allow the opening of the magnet interconnections. Ten detectors were added to the new collimators, or moved, e.g. in the absorder (TDIS), the dispersion suppressor (TCLD), or the beam dump regions. The tunnel electronics has also been consolidated: 15 acquisition cards (2%) have been exchanged for repair, barcodes were added to track assets, and WorldFIP (Factory Instrumentation Protocol) fieldbus receivers have been deployed in all racks to provide reliable remote reset capability and reduce the duration and number of interventions. On the back-end side, 44 processing cards (13%) have been exchanged, and an optical receiver mezzanine less sensitive to temperature and low-power was designed and produced. In addition, a firmware overhaul led to a simpler, modular, and high-performance implementation: in terms of data transfer rate, clock and reset trees, optical link stability, sanity checks time, and also reusability. The generic RTL code will facilitate migration to a new platform in the future. This redesign was extensively verified in simulation through state-of-the-art verification methodology and 4 levels of test-benches to reach full code coverage. On the software side, the CPU OS was migrated to 64b CentOS 7 (was SL6), and consequently the real-time software (FESA) and drivers were ported to this new version. Eventually, the whole BLM application suite was redelivered to correct minor bugs and add more checks.

Reliability & Availability

From the beginning of the BLM system design, many efforts have been made to predict reliability using Failure Mode Effects and Criticality Analysis (FMECA) and Fault Trees. During the first two LHC Runs, to reach even higher results, several weak hardware parts were redesigned to reduce their failure rate, such as the back-end mezzanine for optical reception. Preventive maintenance has been carried out through comprehensive diagnostics that automatically generate early warnings, and through fault monitoring since 2012 [19]. Finally the system dependability analysis was periodically updated [20] to help define the future upgrade and maintenance strategy. As a result, the availability and reliability of the BLM should improve significantly in the next Run, and the number of interventions should decrease consequently. In the extract of the CERN Accelerator Fault Tracker (AFT) presented in Fig. 3, the beginning of Run 3 seems to show a sensible decrease in BLM blocking faults compared to the first Runs. Those faults are only the ones preventing LHC operation, and not the faults shadowed by redundancy for instance. It is difficult to extrapolate from the BLM availability the impact on the LHC luminosity. Although correlated, they do not scale proportionally, as this depends on the fault time in the LHC operational scenario [21].

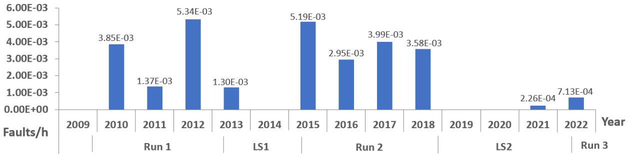

Figure 3: Number of BLM blocking faults per hour of LHC operation (extracted from CERN AFT).

Run 3 Commissioning after LS2

The commissioning of the system for Run 3 followed four consecutive steps at the end of LS2:

1. The Individual System Test (IST), where each channel connection is verified and calibrated by experts.
2. The Dry-Run, in collaboration with LHC operators to validate the connection to the control infrastructure.
3. The Beam Test, with a low-intensity pilot beam, where each location is tested and the connections to the Beam Dump System are verified.
4. The commissioning for Physics, where the beam intensity and energy are increased gradually, and each step is validated by the LHC machine protection committee.

An important parameter of the BLM system performance is the latency, i.e. the time between the passage of particles through the detector and the dump request. A specific test was performed in 2022 during commissioning: for each LHC beam and IP, an arbitrary collimator was closed to generate local losses, and a pilot bunch was injected. The result is presented in Table 1: the LHC BLM system latency was always less 3 LHC turns (267 µs = 3 × 89 µs).

Table 1: BLM Latencies† During Run 3 Commissioning

LHC Interaction Point	Beam 1	Beam 2
IP1 (ATLAS)	46 µs	44 µs
IP2 (ALICE + B1 inj.)	43 µs	41 µs
IP3 (Momentum Cleaning)	61 µs	~ 114 µs††
IP4 (RF) †††	-	-
IP5 (CMS)	30 µs	53 µs
IP6 (B1 & B2 Dump)	35 µs	32 µs
IP7 (Betatron Cleaning)	64 µs	88 µs
IP8 (LHCb + B2 inj.)	56 µs	~ 177 µs††

† Injection kick top to dump request, time of flight corrected.
†† Stretched because of RC filter installed on the detector.
††† No collimator at IP4.

FUTURE CHANGES EXPECTED DURING LS3 & LS4

Despite the consolidation and upgrades in LS2, after more than 14 years of operation, the BLM hardware is ageing, while the number of spare parts is decreasing. Electronics will require replacement within the decade.

New Processing Electronics in LS3

During LS3, the BLM processing electronics will be renewed. As most Beam Instrumentation (BI) systems, the back-end unit is installed in a radiation-free area which allows the use of a standard module [22]. This new board, called VFC-HD, is a high pin count FMC carrier used as a VME-based unit for data concentration and processing. It provides all the common features used in the BI group, as summarised in Fig. 4.

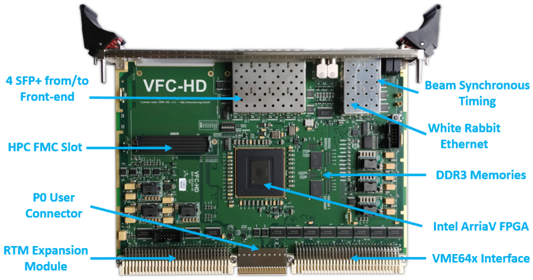

Figure 4: Overview of the VFC-HD features.

For the BLM system, the 4 standard SFP+ transceivers will replace the currently used mezzanine card, and the more recent FPGA will provide additional processing resources to improve efficiency and flexibility, and strengthen critical parts by using redundancy for example. In addition, to maintain a high level of reliability after installation of the VFC-HD modules, extensive testing was carried out after manufacture: destructive, functional, burn-in, validation, and run-in. This testing methodology [23] was implemented on a sophisticated test bench [24] to verify the 1150 assets produced.

New Acquisition Electronics in LS4

A new acquisition electronics is under development to replace the BLM acquisition crate in the SPS in LS3. The plan is to design an architecture that could also be deployed in the LHC in LS4. Another constraint is the need to keep backward compatibility with the current LHC chassis.

The main objectives of this redesign are:

- to reduce the time resolution to 5 μs (was 40 μs)
- to increase radiation tolerance to 1 kGy (was 500 Gy)
- to ensure safety: guarantee SIL3 while protecting against direct HV contacts and improving groundings.
- to improve reliability and availability: less repair time and complexity, more commands and diagnostics.

As illustrated in Fig. 5, this 3U acquisition crate is composed of a special backplane that hosts 8 signal inputs from the detectors, an input power unit with a 230 V_{AC} transformer, a power supply module generating local voltages, a crate controller with a nanoFIP fieldbus connection, and the modernised CFC board (BLECF2) with its 2 optical links to the surface.

BLM ASIC

A new front-end ASIC (Application Specific Integrated Circuit) under development at CERN is depicted in Fig. 6.

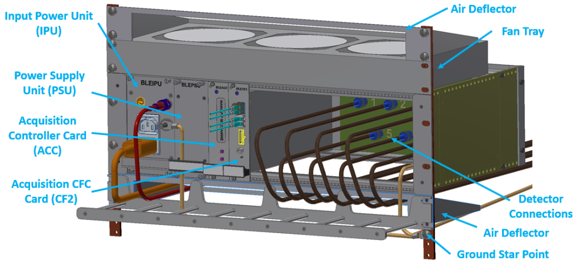

Figure 5: 3D view of the future acquisition crate.

This chip will allow the BLM acquisition system to withstand radiation doses up to 500 kGy (was 500 Gy) resulting from the upcoming HL-LHC upgrade. This will help place electronics closer to the beam and minimise the noise picked up by cables. The chip consists of two independent ADC channels readout by redundant blocks interfaced directly to LPGBT (Low Power GigaBit Transceiver) [25]. Using a CFC combined with a Wilkinson ADC, the ASIC provides a fast 10 μs readout (was 40 μs), which can detect losses and request a beam dump in less than 1 LHC turn.

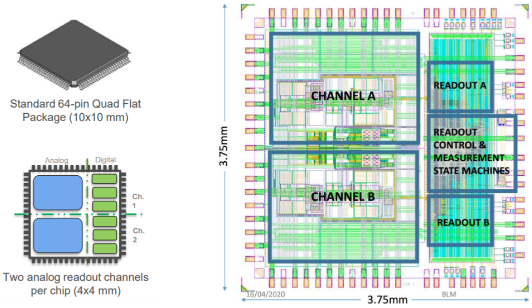

Figure 6: Overview of the BLMASIC chip architecture.

Since BLM protection relies on a reliable detection of a wide range of currents, a strict characterisation and validation of this ASIC is required, including irradiation tests [26]. The test campaigns on prototypes showed that in all cases (SEU, TID, temperature) the device can perform loss measurements down to 1 pA, with an error below 1% in the range [35 μA ; 1 mA].

CONCLUSION

During LS2, the LHC BLM system was significantly updated to solve the issues discovered during Run 1 and 2. The hardware changes are expected to increase reliability and reduce the number of interventions. The firmware and software upgrades aimed at providing more processing time margins, and increasing portability for future hardware replacement. After nearly a year of beam testing and Run 3 operation, the system seems to perform better. Availability and reliability have improved, the number and duration of interventions have dropped, and false dumps have disappeared. Although it is too early and not easy to quantify, this good performance gives hope that the impact of BLM faults on the overall luminosity of the LHC will decrease.

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