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Beam Loss Monitoring for LHC Machine Protection

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Abstract

The energy stored in the nominal LHC beams is two times 362 MJ, 100 times the energy of the Tevatron. As little as 1 mJ/cm^3 deposited energy quenches a magnet at 7 TeV and 1 J/cm^3 causes magnet damage. The beam dumps are the only places to safely dispose of this beam. One of the key systems for machine protection is the beam loss monitoring (BLM) system. About 3600 ionization chambers are installed at likely or critical loss locations around the LHC ring. The losses are integrated in 12 time intervals ranging from 40 μs to 84 s and compared to threshold values defined in 32 energy ranges. A beam abort is requested when potentially dangerous losses are detected or when any of the numerous internal system validation tests fails. In addition, loss data are used for machine set-up and operational verifications. The collimation system for example uses the loss data for set-up and regular performance verification. Commissioning and operational experience of the BLM are presented: The machine protection functionality of the BLM system has been fully reliable; the LHC availability has not been compromised by false beam aborts.

Keywords: beam loss, beam instrumentation, machine protection, quench protection, damage protection

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1. Machine Protection for Proton Beam Operation

The LHC holds the world record for hadron collider luminosity: 4.67×10^{32} cm^{-2}s^{-1} on 21 April. By mid August 2011 the integrated luminosity delivered to all four experiments had already reached 5.5 fb^{-1}, and the peak luminosity delivered to ATLAS and CMS had reached 2.2×10^{33} cm^{-2}s^{-1}. Table 1 compares the parameters of the LHC as of mid August 2011 with the nominal design values. The LHC is running at half its nominal energy and twice its nominal bunch spacing. The bunch intensity is 17% above nominal and the normalized transverse emittances are a factor of 1.9 smaller than nominal. Due to the lower energy and bigger beta function at the collision points of ATLAS and CMS, the transverse beam sizes at collision are about a factor of 1.7 bigger than at nominal conditions. The peak luminosity at the Altas and CMS experiments as of August 2011 was a factor of 4.5 below nominal. ALICE and LHCb luminosities on the other hand are not limited by LHC performance, but by the experiments' desiderata. The LHC aims at

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further reducing the collision beta function for ATLAS and CMS to 1.0 m at the beginning of September 2011.

Table 1. LHC parameters at collision as of mid August 2011 compared to the nominal design values.

	August 2011	**Nominal**
Energy per beam	3.5 TeV	7 TeV
Bunch spacing	50 ns	25 ns
Bunches per beam	1380	2808
Bunch intensity	1.35×10^{11} p	1.15×10^{11} p
Intensity per beam	1.86×10^{14} p	3.2×10^{14} p
Transverse normalized emittance	$\sim 2\,\mu$m rad	$3.75\,\mu$m rad
β^* (ATLAS and CMS)	1.5 m	0.55 m
Peak luminosity (ATLAS and CMS)	2.2×10^{33} cm^{-2}s^{-1}	1.0×10^{34} cm^{-2}s^{-1}
Energy per beam	105 MJ	362 MJ

The energy stored in one LHC beam has already surpassed 100 MJ in July 2011. One nominal LHC beam at 7 TeV will hold 362 MJ and 10 GJ will be contained in the magnets. A tiny fraction of this energy can cause serious material damage. The estimated quench and damage limits at 7 TeV are 1 mJ/cm^3 and 1 J/cm^3 respectively. Even the destruction of the complete LHC is possible in case of a catastrophic failure of the protection system. The damage of one magnet would amount to a downtime of months and cost about one million USD. Quenching of a magnet can cause up to several hours of downtime. Two incidents in the past highlight the destruction potential: In June 2008 [1] an incident in the SPS at 400 GeV with a beam of 2 MJ slit open the vacuum chamber over a length of 10 cm. In October 2004 [2] a 450 GeV full LHC injection batch of 3.4×10^{13} protons in 288 bunches (2.5 MJ) caused a 25 cm long cut in the vacuum chamber. Beam intensities below the ‘set-up beam limit’, which has been derived from material damage studies [3], are considered safe for the machine: 5×10^{11} protons at injection energy (450 GeV) and 3.15×10^{10} protons at 3.5 TeV.

The LHC machine protection system (see Figure 1) comprises several 10’000 channels from about 250 input connections. They feed the beam interlock system (BIS), which transmits the beam dump request. About 3600 out of 4000 BLM channels are configured to demand a beam abort if a loss above the predefined threshold value is detected. 21% of the machine protection aborts above injection energy from 2010 till mid August 2011 came from the BLM system. Table 2 gives the number of aborts by system.

Table 2. Protection aborts from 2010 till mid August 2011 for energies above injection energy per system.

Magnet System (incl. Cryogenics)	134	Experiments Interlock	16
Beam Loss Monitors	96	False Beam Dump by MP System	16
Software Interlock System	45	Quench Protection System	14
Orbit Excursion Extr. Region	36	Beam Dumping System	14
Collimator Interlock	31	Beam Interlock System	14
Fast Magnet Current Change Monitors	25	Access System	2
RF Interlock	16	Aperture Kicker	1

2. BLM System

The main aim of the BLM system [4] is to prevent damage of machine components and magnet quenches due to beam losses. The second crucial aspect of the system is beam loss surveillance which helps to

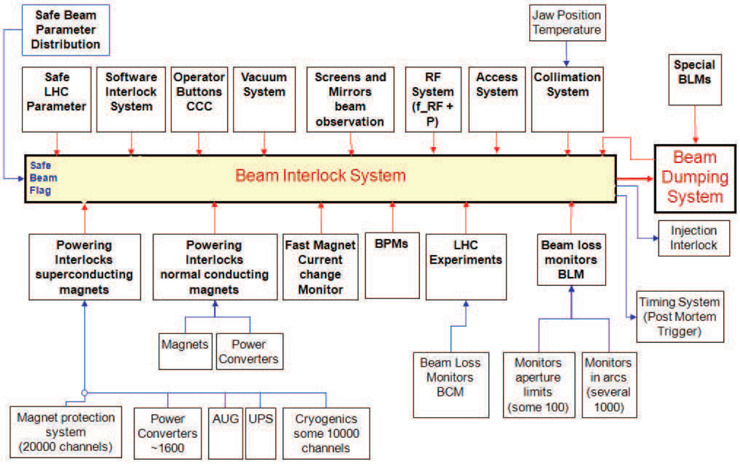


Fig. 1. Overview of the machine protection system. Each input channel individually can request a beam abort via the beam interlock system.

diagnose the cause of the losses. About 3600 parallel plate Ionization Chambers (IC) filled with nitrogen gas at 1.1 bar are installed at likely or critical loss locations, most of them around the quadrupole magnets. 97% of these monitors are connected to the BIS. A few ICs are for observational purposes only: ICs in the dump lines, monitors installed for future upgrade elements, and redundant monitors with RC-delay filter. 300 Secondary Emission Monitors (SEM) with a 70'000 times smaller sensitivity are used for observation only. In the LHC arcs, the front-end electronics are installed below the quadrupole magnets. They are tested to be radiation-tolerant up to 500 Gy. In the straight sections, due to the higher radiation, the front-end electronics are housed in side tunnels, leading to analogue signal transmission cables of up to 800 m. As these long cables were shown to be sensitive to electromagnetic interference (EMI), new front-end electronics with a radiation tolerance of up to 10 kGy are currently being developed. They will be placed close to the monitors in the straight sections. The tunnel electronics holds a Current-to-Frequency-Converter (CFC) and a parallel ADC, which is used to increase the low end of the dynamic range, as well as an FPGA for signal counting and multiplexing. The signal is transmitted optically to the surface, where the comparison with the threshold values and the connection to the BIS is made. The digital part of the readout chain is doubled to satisfy the required design dependability.

The loss signals are integrated during 12 different time intervals, ranging from 40 μs (about half the duration of one turn) to 84 s. In addition, the abort thresholds depend on the beam energy; they are defined in 32 energy intervals. Hence, each monitor has 12×32 beam abort thresholds associated. Determining and manipulating these threshold values is critical to the safety of the LHC; tools and procedures are described in [5]. With few exceptions, the thresholds are set according to a local protection strategy. They are determined based on measurements and extensive simulations of the impact distribution of lost beam particles, of the development of hadronic showers through the magnets / machine elements, of the energy deposition in the magnets, of the critical energy deposition for quench and damage, of the radiation field at the monitor location, and of the monitor response. Thresholds for collimators and protective masks are set according to operational scenarios; hence their thresholds are typically much lower than the associated damage level. At the start-up of the LHC, thresholds were typically set conservatively. As the beam intensity and the luminosity were increasing, it was also necessary to increase the thresholds.

Each monitor aborts the beam if any one of 12 loss integrals is above the threshold, or if one of its internal tests fails. The system test validation procedures [6, 7] have been defined to achieve the required dependability of the system. The functionality of all components was tested before installation. Thereafter, there are three different inspection frequencies: tests after installation and during yearly maintenance, tests before each fill and tests which take place continuously including the time of beam operation. Figure 2 lists

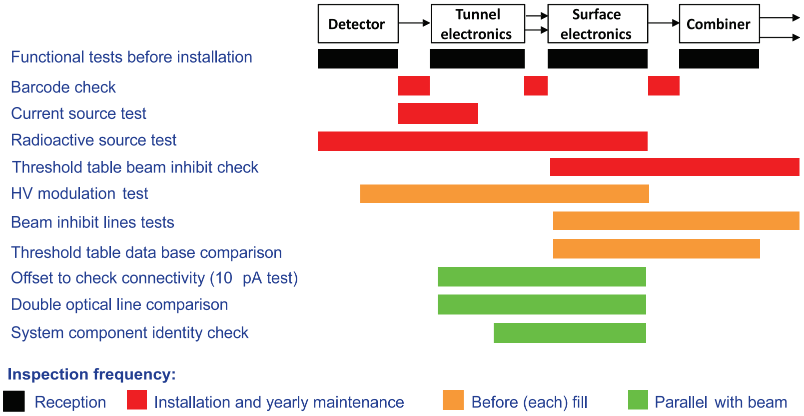


Fig. 2. Overview of the most important BLM testing procedures. The colored bars indicate which part of the system is tested at which frequency. The barcode check for example is used to test all cable connections from the detector till the combiner card during installation and after maintenance. Some procedures test only certain parts or functionalities of the electronics, indicated by the length of the colored bar. The current source test e.g. is verifying the cable connection between the detector and the tunnel electronics and the analogue part of the tunnel electronics. The digital transmission part of the tunnel electronics is not covered by this test, but for example by the radioactive source test.

the most important tests and their frequencies. Additional machine protection tests [8], mostly verifications of the above system tests, have been executed during the commissioning phase. Before start-up and before a new release the firmware is tested extensively for all operational aspects. Every time an issue is detected, a dedicated test covering the issue is added to the firmware test procedure. This ensures that there are no regressions when a new firmware version is introduced.

The ‘vertical slice’ test is executed on a test system located at the LHC point IP2: The complete hardware chain from the ionization chamber to the beam interlock output is verified. A specific part of the test uses a front-end emulator of the analogue part of the electronics. It allows for exhaustive threshold triggering tests, optical link reception and status tests, and verification of the response to predefined input signal patterns (linearity tests, etc.).

Performance tests with beam include beam aborts with defined injection losses on a closed collimator and measurements of the reaction time of the BLM from injection to breaking of the beam permit loop by the BLM. The validation tests between fills are enforced by the BLM system to be executed at least once every 24 hours, otherwise the next injection into the LHC is inhibited. The tests are executed and analyzed in BLM surface electronics FPGAs (combiner cards) and take about 7 minutes to execute. Three tests are executed on each monitor: A comparison of system parameters including thresholds between data base and surface electronics, an internal (VME crate) beam permit line test, and a connectivity check by modulation of the chamber high voltage.

During start-up and commissioning of the LHC, the machine protection functionalities of the BLM system had been switched on in stages. This way, they provided the required protection level depending on the damage potential of the beam, without compromising the machine availability. The input to BIS from individual monitors was switched from masked to unmasked in stages. The abort request from a ‘masked’ monitor is ignored when the ‘set-up beam’ flag is true. Most of the channels had been unmasked by the end of 2009. Similarly, the system validation tests became active in stages, with almost all of them active before the 2010 re-start.

3. Dependability - Reliability, Availability and Safety

There is no evidence of a single beam loss event having been missed by the BLMs. No avoidable quench, nor any component damage occurred. All beam induced quenches were either intentional (quench tests) or occurred with injected beam, which cannot be avoided by BLMs. The number of false beam aborts due to hardware failures are as expected and within requirements. Mostly, the onset of a system degradation was detected by regular off-line checks before malfunctioning, and components could be replaced in the shadow of other interventions. Noise events never caused beam aborts. No big deviation has been detected between the protection thresholds and the magnet quench levels. Key elements leading to this outstanding performance of the BLM system have been:

1. A Safety Integrity level (SIL) approach to the system design using a downtime cost evaluation as input
2. Extensive system tests at all stages of system design, construction and operation
3. Internal and external review procedures during the system design and the commissioning phase

Several design choices were lead by the dependability [6] analysis. It was assumed that 100 dangerous beam losses per year would occur, which can only be detected by one BLM. 96 actual emergency dumps for energies above injection energy in 1.5 years show that this number was quite realistic. But we consistently observe higher protection redundancy, with several local monitors and monitors at aperture limits observing the dangerous losses. Table 3 summarizes the requirements and predictions for damage risk and the number of false beam dumps and compares them to 2010 and 2011 experiences.

Table 3. Damage risk and false dumps for one year required and predicted by simulation compared to observations in 2010 and 2011 (January - June).

per year	**Requirement**	**Simulation**	**2010** (above 450 GeV)	**2011** (beam with damage potential)
Damage risk	$< 10^{-3}$	5×10^{-4}	–	–
False dumps	< 20	10 - 17	3 (7 - 14 per year of standard operation)	3

Nevertheless, several system changes had become necessary after the 2010 start-up. Hardware as well as firmware and threshold changes are highly safety-critical operations, which require approval and change procedures and dedicated extensive systems test, e.g. the ‘vertical slice test’ for firmware changes.

1. The upper end of the dynamic range for short losses was extended for certain ICs by a factor of 10 or a factor of 180 by adding an RC-delay filter. This became necessary because at 23 Gy/s the current from an IC reaches the upper end of the electronics measurement range while the SEMs are plagued by spurious signals due to ionization in air at connections and EMI issues mostly due to their long cables.
2. At certain locations the particle showers from upstream loss locations (non-local losses) had to be added to the local protection thresholds. This concerns the collimation regions and the injection energy thresholds in the injection regions. On a small sub-set of these locations protection of the element is not ensured any more by the locally installed BLM, but by other monitors in the vicinity (non-local protection).
3. Thresholds of all cold magnets had been tuned for the 2011 start-up based on 2010 experience (see below).
4. Three updates of the FPGA firmware of the processing module (surface electronics for threshold comparison etc.) were performed during the early commissioning phase of 2010, and one more before the 2011 start-up. The changes included: the activation of the beam abort request in the case of an internal system test discovering a failure; the implementation of recommendations from the external audits; the addition of new status information such as the RC-delay filter values of each channel, as the installation of RC-delay filters had not been envisaged before 2010. During the LHC operation period, modifications of this critical firmware are to be avoided for dependability considerations. Nevertheless, one firmware update per year was required during the running periods of 2010 and 2011. Both of them were declared absolutely necessary, as their aim was to solve intermittent problems with the data recording of the post-mortem circular buffer, and to change the functionality of the beam injection and extraction buffers to compensate for limitations of the network infrastructure.
5. One important limitation concerning the system safety was detected in 2011 when a cable powering a set of detectors was cut on the surface during a period without beam. This event was detected by

the internal monitoring, but the system had not been specified to immediately revoke the beam permit in such an event. The beam permit loop was only opened during the regular system check before the subsequent beam injection, correctly inhibiting injection into the LHC. This safety hole was closed by adding a software interlock on the high voltage status flags of the BLM system. In the winter break, hardware and firmware updates will replace the software interlock, as for reliability purposes all interlocks of the BLM system have to be performed by hardware.

Figure 3 presents an arc quadrupole (MQ) monitor as example of the threshold adaptations of the cold magnets at the 2011 start-up. The changes were based on measurements of quench tests at injection and with circulating beams, on accidental quenches of dipole magnets at injection, on tests with wire scanner induced losses and on ‘UFO’ losses (see below). In black are the 2011 applied thresholds, with the dots denoting the 12 integration time windows. The blue line shows the 2010 applied thresholds. Green dots are measurements of ‘UFO’ losses at MQs which did not quench the magnets, and red dots are measurements during quench tests, when the magnet actually quenched. The applied thresholds are intended to be a factor three below the magnet quench level. For integration times up to several ms, the thresholds were increased by a factor of 3-5, and for integration times above 0.08 s the thresholds were reduced by a factor of 3.

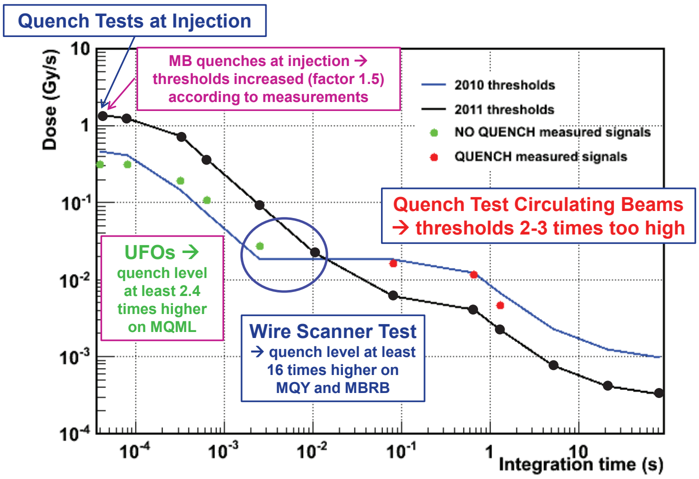


Fig. 3. Threshold changes for cold magnets at the 2011 start-up and the measurements on which they were based, shown for the example of a monitor in the arc. In black are the 2011 applied thresholds, with the dots denoting the 12 integration time windows. The blue line shows the 2010 thresholds. Measurements of different cold magnet types have been combined to define the threshold update. MB are main arc dipole magnet. MQML, MQY and MBRB are magnets located in the insertion regions.

4. Beam Loss Surveillance

Beam loss measurements play a crucial part in understanding and tuning the machine performance [9]. Every second logging data records one value for each of the 12 integration intervals for offline analysis. For integration times below one second, the maximum during the previous second is stored, for the longer integration intervals the last value is saved. This way short losses are also adequately recorded and their duration can be reconstructed to $\approx$ 20-30% using the logging data. This data set is also used for online display. Furthermore, various data buffers are read out on request. These event-triggered buffers are used for post-mortem, collimation movement (to be implemented), injection and extraction validation, and for special studies like the study of ‘UFO’ losses. See Table 4 for details.

4.1. Fast ms-time-scale Losses

Fast, localized losses, typically on the ms time scale, surpassing the BLM or the LHC experiment thresholds have lead to 35 beam aborts, 17 in 2010 and 18 in 2011 [10]. 13 of these losses occurred around the injection kickers (MKI), 6 aborts were requested by one of the experiments (alone or together with the BLM

Table 4. Buffer data of the LHC BLM system. The readout is triggered by timing events.

BLM Buffer	**Modes**	**Integration Time**	**Buffer Length**
Post Mortem		40 μs	80 ms online, 1.72 s offline
Collimation Buffer		2.6 ms	80 ms
Extraction Validation		40 μs	80 ms
Capture Data	Injection Quality Check (8 crates)	40 μs	20 ms
	Study Buffer (e.g. ‘UFO’ study)	80 μs	Dynamic, currently up to 350 ms

system) and only one beam abort happened at injection energy. These losses are believed to be caused by macro particles intercepting the beam, hence they have been dubbed UFOs for Unidentified Falling Objects. These losses occur all around the LHC, even at locations which are otherwise free of losses, for example in the arcs. Each UFO is detected by several local monitors and by the BLMs at global aperture restrictions. Most of the events are far below the abort thresholds, and the number of UFOs decreases inversely proportional with the magnitude of the loss signal. Stepwise increases of the BLM abort thresholds in the relevant integration times during 2010 and at the start-up of 2011 reduced the number of beam dumps. The events also became less frequent. From 10 UFOs per hour above detection levels at the beginning of 2011 they decreased to 3-4 per hour towards the end of the year. However, when the energy of the LHC increases, the magnet quench levels will decrease and at the same time the particle showers from the UFOs will deposit more energy in the magnets. This could possibly be a problem for the machine availability.

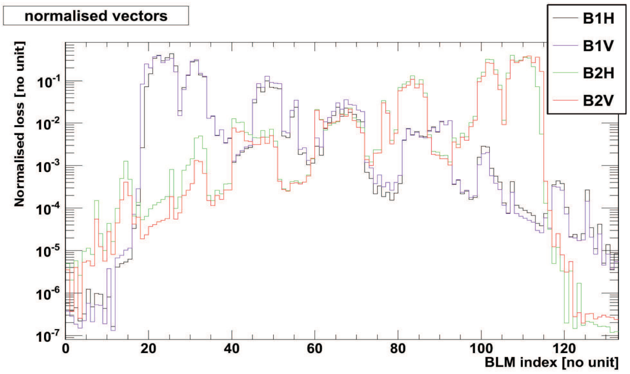
4.2. Losses at the Collimators

The collimation insertions are designed to concentrate the losses: betatron losses at LHC point 7 and longitudinal losses at point 3. The BLMs installed directly at the collimators are essential for collimation set-up and cleaning performance verification. Dedicated beams are used for these purposes. Collimation cleaning verification measurements (so called loss maps) are performed regularly, every 4 weeks, by blowing up a beam of 1 or 2 bunches in either the horizontal, vertical or longitudinal direction. The analysis of the resulting three ‘loss maps’ per beam yields the cleaning performance.

To identify the dominant loss type, a program was developed which decomposes the loss pattern into the standard loss scenarios of the loss maps [11] using singular value decomposition (SVD) or the Gram-Schmidt (GS) process. Figure 4 (top) shows the loss pattern (loss vector) at the betatron collimators for horizontal and vertical losses of beam 1 and beam 2. Losses of beam 1 and beam 2 have a very different pattern, but vertical and horizontal losses can only be distinguished at a few collimators. Before decomposition, the standard loss scenario vectors as well as the unknown loss vectors are normalized to their Euclidean norm. Figure 4 (bottom) gives SVD decomposition result of 2 hours of physics beam in collision ‘stable beams’. The factors of the decomposition are calculated every second. During the first six minutes of this stable beams period beam 1 horizontal losses dominate. Afterwards, the losses are mainly beam 2 horizontal. Vertical losses play a minor role at the beginning, but at the end of this two hours they are comparable in size to the horizontal losses. The error is the norm of the difference between the unknown normalized loss vector and the reconstructed vector. The reconstructed vector is the sum over the four loss scenarios of the factor of the decomposition multiplied by the standard loss vector of each scenario. The error represents the fact that the four loss scenarios used in this decomposition cannot fully reconstruct the measured loss.

5. Summary

This paper describes how the LHC BLM system is used to prevent damage of machine components and magnet quenches, to diagnose the cause of beam losses, and to tune the machine performance. Most



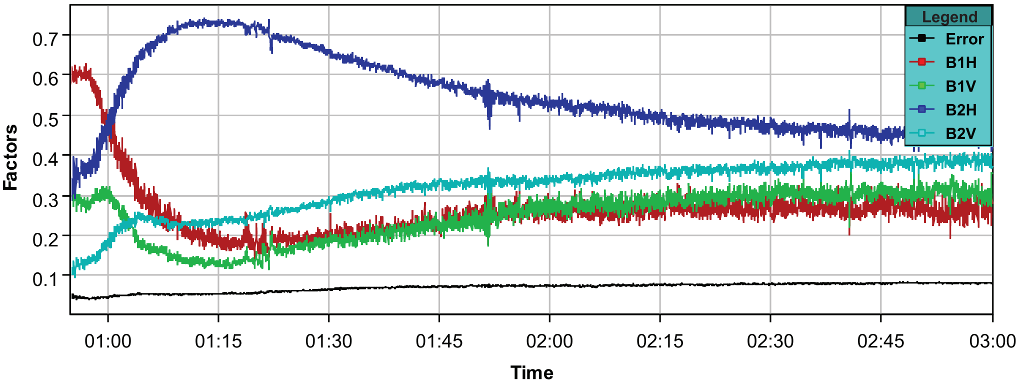


Fig. 4. Top: Standard loss scenarios for horizontal and vertical losses for both beams as determined by the measurements of the loss maps. All BLMs in the betatron collimation region are shown with a consecutive index. The four vectors (B1H, B1V, B2H, and B2V) containing the BLM signals are normalized with respect to their Euclidean norm. Bottom: SVD decomposition results for 2 hours of physics beam. Plotted are the factors of the decomposition of the measured signals of the BLMs in the betatron collimation region into the standard loss scenarios shown on the top. Before decomposition, also theses loss vectors are normalized with respect to their Euclidean norm.

notable are the analysis of the so-called Unidentified Falling Objects (UFOs) and the monitoring of the collimator beam cleaning performance. Multi-stage test procedures assure the required dependability and performance of the BLM system. The BLMs have not missed a single beam loss event and there has been no avoidable quench. All performance parameters fulfill or exceed the requirements. Furthermore, several system changes which have become necessary since the 2010 start-up have been described.

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