COMMISSIONING AND OPERATIONAL SCENARIOS OF THE LHC BEAM LOSS MONITOR SYSTEM

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Abstract

One of the most critical elements for the protection of CERN's Large Hadron Collider (LHC) is its beam loss monitoring (BLM) system. It must prevent quenches in the super conducting magnets and damage of machine components due to beam losses. The contribution will discuss the commissioning procedures of the BLM system and envisaged operational scenarios. About 4000 monitors will be installed around the ring. When the loss rate exceeds a predefined threshold value, a beam abort is requested. Magnet quench and damage levels vary as a function of beam energy and loss duration. Consequently, the beam abort threshold values vary accordingly. By measuring the loss pattern, the BLM system helps to identify the loss mechanism. Furthermore, it will be an important tool for commissioning, machine setup and studies. Special monitors will be used for the setup and control of the collimators.

INTRODUCTION

The start-up of the LHC is scheduled for 2007. An unprecedented amount of energy will be stored in its circulating beams. The loss of even a very small fraction of this beam may induce a quench in the superconducting magnets or cause physical damage to machine components. A fast (one turn) loss of $3 \cdot 10^{-9}$ times the nominal beam intensity can quench a dipole magnet. A fast loss of $3 \cdot 10^{-6}$ times nominal beam intensity can damage a magnet. The stored energy in the LHC beam is a factor of 200 (or more) higher than in existing hadron machines with superconducting magnets (HERA, TEVATRON, RHIC), while the quench levels of the LHC magnets are a factor of about 5 to 20 lower than the quench levels of these machines. In addition to about 130 collimators and absorbers (see [1]) in the phase 1 of LHC, there are about 320 other movable objects which could possibly intercept the beam.

The detection of the lost beam particles allows protecting the equipment by generating a beam abort trigger when the losses exceed certain thresholds. In addition to the quench prevention and damage protection, the loss detection allows the observation of local aperture restrictions, orbit distortions, beam oscillations, particle diffusion, etc. Since a repair of a superconducting magnet would cause a down time of several weeks or months, the protection against damage has highest priority.

Figure 1 gives a classification of the beam losses according to their duration. It shows which protection system is applicable for the different loss durations. The BLM system is the main active system to prevent magnet damage from all the possible multi-turn losses. It is critical for short and intense particle losses, while at medium and longer loss durations it is assisted by the quench protection system and the cryogenic system. (Supplementary systems for redundancy for fast losses are under discussion.) Quench prevention is only ensured by the BLM system.

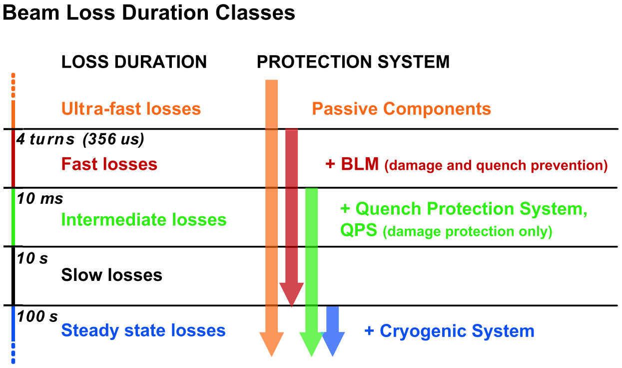

Figure 1: Classification of beam losses according to their duration and the applicable active protection systems for the different loss classes.

The challenges of the BLM system are the required reliability, availability, dynamic range, precision, range of beam loss integration times and reaction time. The tolerable failure rate is 10^{-7} per hour per channel. Assuming 100 dangerous losses per year that would amount to a loss of 10^{-3} magnets per year due to failures in the BLM system. This is achieved by choosing reliable and radiation tolerant components, by redundancy and voting (when a single component is not reliable enough) and by constantly monitoring the availability and possible drift of readout channels. To guaranty the operational efficiency, the system must cause less than two false beam aborts per month. The dynamic range of the particle fluencies to be measured is 10^8 (10^{13} at certain locations, assured by installing two monitor types with different sensitivity at the same location - see below). The functional specification of the BLM system [2] includes a factor of 2 absolute precision on the prediction of the quench levels - to be achieved by calibration and dynamically changing threshold values. In addition, a wide range of integration times (89 μs to 84 s) and a fast (one turn) trigger generation for the beam abort signal are required. For a more detailed description of the BLM system see [3].

Detectors

Signal speed and robustness against aging were the main design criteria for the detectors. The standard monitors are N_2 filled ionization chambers with parallel aluminum electrode plates separated by 0.5 cm. The detectors are about 50 cm long with a diameter of 9 cm and a sensitive volume of 1.5 liter. The collection time of the electrons and ions is of the order of 300 ns and 80 μs respectively. At locations with very high (potential) loss rates (about 300) the ionization chambers will be complemented by secondary emission monitors. They are based on the same design, but hold only three electrodes. The electrodes are made of titanium. The chamber is about 10 cm long, the pressure inside has to stay below 10^{-7} bar. The sensitivity is about a factor of $3 \cdot 10^4$ smaller than in the ionization chamber. Both chambers are operated at 1.5 kV. The dynamic range of the detectors is higher than 10^9. It is limited by leakage currents through the insulator ceramics at the lower end and by saturation due to space charge at the upper end.

Acquisition System

The electrical signals of the detectors are digitized with a current to frequency converter and these pulses are counted over a period of 40 μs. The counter value is transmitted every 40 μs to the surface analysis electronics using a high speed optical link (with a cyclic redundancy check). The signal treatment and transmission chain is doubled after the current to frequency conversion to meet the required failure rate probability of 10^{-7} to 10^{-8} per hour. The surface electronics calculates the integrated loss values and compares them to a table of loss duration and beam energy depended threshold values. Warning information is transmitted by a software protocol. The beam abort signals are transmitted to the beam dump kicker magnets using the LHC beam interlock system (LBIS). The beam energy information is received over a dedicated fiber link. Details to the readout system can be found in [5] and [4]. The signal for the beam abort is issued if any integration time window of any monitor is above threshold (trigger on single monitor). The BLM system will drive an online event display and write extensive online logging (at a rate of 1 Hz) and postmortem data (up to 1000 turns plus history 10 minutes) to a database for offline analysis.

OPERATIONAL SCENARIOS

Families of BLMs

There are four different families of beam loss monitors. They are listed in Table 1. The highest number of monitors, BLMA, will be installed around the quadrupole magnets all around the ring (six per quadrupole). They constitute local aperture minima, and therefore likely loss locations. The second family, BLMS, will be installed at global aperture limits other than the collimators (i.e. final focus magnets of the experimental insertions at 7 TeV) and other critical loss locations (e.g. losses due to beam injection or extraction errors). One set of detectors, BLMC, will be installed after each collimator. They will be used to set the position of the collimator jaws and to continuously monitor their performance. In addition, there will be a set of movable BLMs to cover unexpected loss locations. For beam studies there is the possibility to ignore a beam abort signal from the maskable monitors, if the stored energy in the beam does not reach damage potential. The BLMS and BLMC are not maskable. All non-maskable monitors have to be available to allow beam injection into the LHC. The fourth family, BLMB, will only be installed after the commissioning of the LHC, to be used for dedicated beam studies on a bunch scale.

Arc and Straight Section Monitors - BLMA and BLMS

Their highest priority is the damage protection of the magnets. Quenches of the superconducting magnets are avoided by setting the threshold values to 30% or less of the magnet quench levels. The BLMS protect and monitor critical aperture limits and critical loss positions, e.g. the dispersion suppressors after collimation, the insertion triplets, loss locations specific for ion operation. At locations with potentially high losses the dynamic range is extended to 10^{13}, e.g. at the location for the set-up and surveillance of beam injection and extraction. The monitors will also serve for machine setup and studies and for the diagnostics of the loss mechanism by recording the time development and spacial pattern of losses. Aperture limitations, pressure bumps (at BLM locations or elsewhere with movable BLMs), beam blow-up, etc. can be diagnosed. The collimation scheme (or the collimator settings) can be validated by comparison to the predicted (or previously measured) typical loss pattern around the ring for the ideal collimator setting. A wrong collimator settings, e.g. when a secondary collimator becomes primary, can also be diagnosed by its loss pattern.

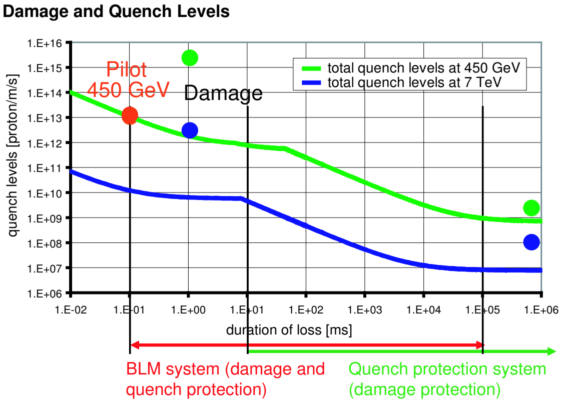

Figure 2: Quench levels of the LHC bending magnets as function of loss duration at 450 GeV and at 7 TeV (dark green and dark blue). The damage levels for short and long duration losses and the pilot bunch intensity are shown as well.

Quench and Damage Levels The calculated magnet damage and quench levels as a function of beam energy and

Table 1: Families and locations of beam loss monitors

Type	Locations	Main Purpose	Mask-able	Dynamic Range	Time Resolution	Number of Monitors
BLMA	All along the rings (6 per quadrupole)	Protection of superconducting magnets	yes	10^8	2.5 ms	$\sim$ 3000
BLMS	Critical aperture limits or critical positions	Machine protection and diagnostics of losses	no	10^8 or 10^{13}	1 turn (89 μs)	$\sim$ 400
BLMC	Collimation sections	Set-up the collimators and monitor their performance	no	10^{13}	1 turn (89 μs)	$\sim$ 150
BLMB	Primary collimators	Beam studies	yes	10^8	1 bunch	$\sim$ 10
Movable	Any location possible ($\sim$ 1300 channels)	Studies, cover unforeseen loss locations	as needed	as needed	as needed	up to $\sim$ 170

loss duration [9] are shown in Figure 2. The ratio of damage to quench level is large for fast losses (320 at 450 GeV and 1000 at 7 TeV). Hence, the abort of the beam at quench level ensures safety against magnet damage. New estimates are needed for the damage levels at slow losses. The current estimates give a ratio of only 5 at 450 GeV and 25 at 7 TeV. In this region, the quench protection system independently protects against magnet damage. The LHC pilot bunch is on the quench limit at 450 GeV and 50 times higher than the damage limit at 7 TeV, assuming that the losses are distributed over 5 m. To achieve an approximation error of less than 25%, each monitor has a threshold table with 12 time windows and 32 energy steps (dynamically changing threshold values). Figure 3 gives a schematic time sequence of a beam abort for a fast beam loss. A minimum time interval of 3 to 4 turns from reaching the abort threshold to reaching the damage level is required for a safe abort.

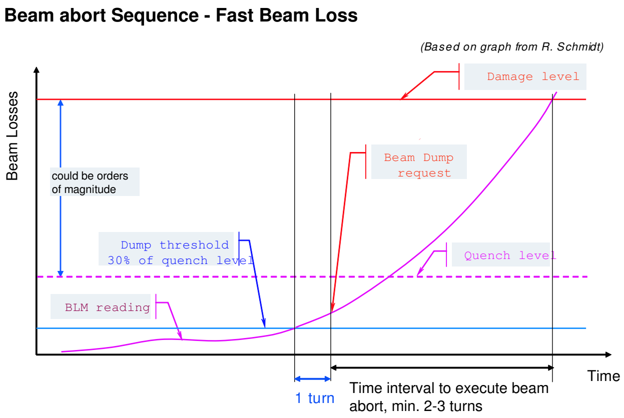

Figure 3: Schematic time sequence of a beam abort for a fast beam loss.

Collimation Region Monitors - BLMC

The chambers (ionization chambers and SEM for extended dynamic range) are installed right after the collimator, in the particle showers. The BLM reading is a good measure of the heat load on the collimator. For damage protection, the maximum BLM threshold values are 30% of the collimator damage levels. Different collimator and absorber types are made from different materials, hence they have different damage and beam abort thresholds. The setup of the collimators relies on the reading of the associated BLM. At start-up, a manual procedure is foreseen, but an automatic set-up procedure with BLM feedback could be possible in the future. The collimator performance is continuously monitored by surveying the absolute and relative changes in the loss pattern. With operational experience, it should be possible to define the acceptable variations. An automatic beam abort in case of unacceptable variations, and/or an automatic feedback loop for collimator positioning could be envisaged in the future.

Fast Beam Loss - Ideal Sequence

In case of a fast beam loss (emittance growth, orbit change, etc.) ideally the first loss location is in the collimation region. A fraction of the beam starts hitting the primary collimator and the scattered beam particles and secondary particle showers from the primary collimator hit the secondary and tertiary collimators and the absorber. The signal in the collimator BLMs increases. Secondary shower particles and scattered beam particles escape the collimation regions and hit the downstream parts of the LHC. The threshold values in the BLMC are set to avoid damage in the collimators, so they are orders of magnitude higher than in the in the BLMA and BLMS. It is probably not possible to avoid quenches in the downstream magnets with the help of the collimator BLMs as they can probably not be correlated well enough. This is the task of the BLMA and BLMS. Which monitors will first request the beam abort will depend on the operational parameters (cleaning efficiency, orbit, tune, beta-beating, etc.).

Other Loss Scenarios

There are other loss scenarios which do not follow the ideal sequence of events described above. A movable object other than the primary collimator can touch the beam (there are $\sim$ 450 in the LHC); the beam orbit can move into the aperture outside the collimation regions; a secondary or tertiary collimator could become the primary collimator; etc. Some of these scenarios can cause very fast losses. Table 2 lists the loss scenarios, which have been considered so far, which can reach damage level within less than 10 turns after the beam abort signal.

Table 2: Other fast loss scenarios

Failing Equipment	**Protection System**
Injection and extraction kicker	Passive absorbers, too fast for BLM.
Aperture kickers	Passive absorbers, too fast for BLM.
Some warm magnets (D1 and few others)	Fast magnet current change monitor (DESY and CERN development), BLM can prevent damage.
General power failure	Also covered by the concerned fast magnet current monitor.

COMMISSIONING

System Tests

The testing procedures are described in [4]. They have been defined in order to achieve the required reliability and availability of the system. The functionality of all components will be tested before installation. Thereafter, there are three different inspection frequencies: tests after installation and during yearly maintenance, test before (each) fill and tests which take place with beam, in parallel to the data taking. Figure 4 lists the most important tests and their frequency.

The availability of all electronics channels is constantly monitored and radiation dose induced drifts in the electronic channels are corrected for (up to a maximum level, which corresponds to 10% of the lowest beam abort threshold value). The availability of all detectors, the acquisitions chain and the generation and communication of the beam abort signal is verified for each channel before each injection into the LHC. The composition of the chamber gas is the only component in the BLM system which is not remotely monitored. The properties of the chamber gas are sufficiently close to the ones of air at ambient pressure (i.e. inside a detector which has developed a leak) not to compromise the precision of the BLM system, but sufficiently different to detect a leak during the scheduled annual test of all the chambers with a radioactive source.

Environmental tests have taken place during the design of the tunnel electronics. All components are radiation certified to 500 Gray, corresponding to 20 years of LHC operation. No single event effect was observed during these tests. The temperature was tested from 15 to 50 degrees Celsius.

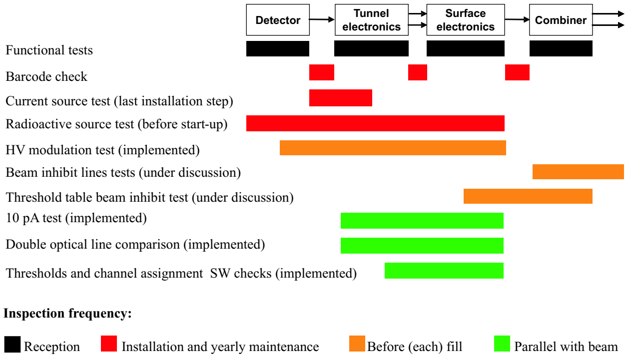

Figure 4: Overview of the most important BLM testing procedures from [4]. The colored bars show what part of the system is tested and at what frequency.

Threshold Calibrations

The BLM interlock limits can be set for each of the about 4000 chambers individually. With 12 integration time intervals and 32 energy ranges, there are $1.5 \cdot 10^6$ threshold values in total. In addition to the beam energy and the loss duration they also depend on the machine component to be protected, the exact loss location and the detector position. The determination of these values is based on simulations. A number of simulations have to be combined for these calibrations. Whenever possible, crosschecks of the simulations by measurements are performed before the start-up of the LHC. These complex simulations and measurements are the effort of many people over the last 8 years. A factor of 5 and a factor of 2 are the specified initial and final absolute precisions on the prediction of the quench levels respectively. The relative precision for quench prevention is requested to stay below 25%.

The aim of the calibration is to relate the BLM signal to the number of locally lost beam particles, to the deposited energy in the machine components and ultimately to the quench and damage levels. The distribution of the loss locations along the LHC is simulated by particle tracking with a detailed aperture model [6]. The lost beam particles initiate hadronic showers. Proton induced showers through cold magnets in the LHC arc and dispersion suppressor [7] and through the collimators [8] have been simulated. These simulations yield the heat load on the magnets (or the collimators) and the particle fluence at the location of the beam loss monitors. Magnet quench levels as a function of beam energy and loss duration have been calculated [9], simulated and measured. The signal response of the ionization chamber to the mixed radiation field in the tail of the hadronic shower has been simulated and measured in various beams at CERN. The corresponding simulations for lead ion beams are being performed as well [10].

The tuning of the BLM interlock levels will begin with the first beam, using the beam loss and magnet quench data of the logging and post mortem database respectively. Dedicated beam tests will be required if the “parasitic” tuning speed of the BLM system cannot keep pace with the increasing demand on precision, as the beam intensity and energy increase during LHC commissioning. Apart from damage protection, the threshold levels also have to be precise enough not to compromise the operation efficiency by false dumps or magnet quenches.

Updating the Threshold Tables

The threshold tables can be downloaded on the charge-to-frequency converter card remotely via the VME interface. This possibility will be used in the lab. Before installation it will be disabled by a hardware switch. During LHC commissioning and operation the threshold tables can only be changed locally (i.e. in the surface buildings which house the electronics cards) via a dedicated interface.

Conceptually, two different approaches will have to be used when changing the threshold tables. An empirical procedure needs to be defined to apply fast changes according to the needs of the LHC operation and within certain safety limits. After an analysis of loss data, more fundamental changes can be applied. They can then also affect the energy and loss duration dependence of the threshold values. For the generation, the failsafe management and the archiving of the threshold tables software tools will have to be specified and developed. I.e. it should be possible to group monitors according to magnet type for a faster changing of the threshold tables.

SUMMARY

The LHC tolerates less fractional beam loss than any existing hadron machine because it features higher stored beam energy in combination with superconducting magnets which withstand less energy deposition. The BLM system is the main system for damage protection for losses from 4 turns to 10 ms and the only system for quench prevention. Open questions concern the rise time of possible fast loss scenarios.

The hardware commissioning steps are precisely defined. The beam abort thresholds in the LHC system change dynamically not only with the beam energy but also with the duration of the loss. A high accuracy in the quench level determination (requiring extensive simulation studies) became necessary for machine protection and for operational efficiency. Simulations and measurements still need to be performed to define all the initial threshold values. The management and changing of threshold tables still needs to be specified. A procedure for safe and yet fast changes of the threshold tables - especially for the commissioning phase - still has to be defined.

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