

## Beam Loss Monitoring System for the LHC

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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 the superconducting magnets from quenching and protect the machine components from damages, as a result of critical beam losses. By measuring the loss pattern, the BLM system helps to identify the loss mechanism. Special monitors will be used for the setup and control of the collimators. The specification for the BLM system includes a very high reliability (tolerable failure rate of  $10^{-7}$  per hour) and a high dynamic range of  $10^8$  ( $10^{13}$  at certain locations) of the particle fluencies to be measured. In addition, a wide range of integration times (40  $\mu$ s to 84 s) and a fast (one turn) trigger generation for the dump signal are required. This paper describes the complete design of the BLM system, including the monitor types (ionization chambers and secondary emission monitors), the design of the analogue and digital readout electronics as well as the data links and the trigger decision logic.

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# Beam Loss Monitoring System for the LHC

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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 the superconducting magnets from quenching and protect the machine components from damages, as a result of critical beam losses. By measuring the loss pattern, the BLM system helps to identify the loss mechanism. Special monitors will be used for the setup and control of the collimators. The specification for the BLM system includes a very high reliability (tolerable failure rate of  $10^{-7}$  per hour) and a high dynamic range of  $10^8$  ( $10^{13}$  at certain locations) of the particle fluencies to be measured. In addition, a wide range of integration times (40  $\mu$ s to 84 s) and a fast (one turn) trigger generation for the dump signal are required. This paper describes the complete design of the BLM system, including the monitor types (ionization chambers and secondary emission monitors), the design of the analogue and digital readout electronics as well as the data links and the trigger decision logic.

**Index Terms**— beam loss, beam instrumentation, machine protection, quench protection, damage protection.

## I. 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  $3 \cdot 10^{-9}$  and a constant loss of  $3 \cdot 10^{-12}$  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. The detection of the lost beam particles allows protecting the equipment by generating a beam dump trigger when the losses exceed certain thresholds. These thresholds depend on the momentum of the stored beam, the duration of the beam loss and on the location of the beam loss monitor. In addition to the quench prevention and damage protection, the loss detection allows the observation of local aperture restrictions, orbit distortions, beam oscillations and 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.

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## II. SPECIFICATIONS AND REQUIREMENTS

The functional specifications of the BLM system are defined in [1].

### A. Families of BLMs

There are four different families of beam loss monitors. They are listed in Table I. 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. All these monitors use the same particle detectors (see Section III-A) and the same readout electronics (described in Section III-B). The extended dynamic range of  $10^{13}$  is realized by installing two detectors with different sensitivity next to each other. The minimum acquisition time of this electronics is 40  $\mu$ s, covering both required time resolutions. 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 not be described in this paper. It will only be installed after the commissioning of the LHC, to be used for dedicated beam studies on a bunch scale.

### B. Quench Levels and Observation Range

The dynamic range of the system is given by the calculated damage and quench levels (see Figure 1) and the expected usage from pilot beam intensity to ultimate beam intensity. The dynamic range for the arc monitors (BLMA) is  $10^8$ . At a certain number of the BLMS locations higher loss rates could occur due to machine component failures. The collimation sections (BLMC) will have the highest continuous loss rates. Therefore, the dynamic range at these monitor locations is extended to  $10^{13}$ . The observation time range is defined by the fastest possible use of the trigger signal by the beam dump (on the

TABLE I  
FAMILIES AND LOCATIONS OF BEAM LOSS MONITORS

Type	Locations	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 $\mu$ s)	$\sim 400$
BLMC	Collimation sections	Set-up the collimators and monitor their performance	no	$10^{13}$	1 turn (89 $\mu$ s)	$\sim 150$
BLMB	Primary collimators	Beam studies	yes	$10^8$	1 bunch	$\sim 10$

side of short integration intervals) and the response time of the helium temperature measurement system (on the long side). The required time resolution for the arc monitors is 2.5 ms and for all other monitors 89  $\mu$ s (1 turn). With this 1 turn resolution it will be possible to allow beam extraction with a maximal delay of three turns. The longest integration time is 84 s.

### C. Failure Rate and Availability

The measurement system failure rate and the availability requirements have been evaluated using the Safety Integrity Level (SIL) approach [2]. A downtime cost evaluation is used as input for the SIL approach. The beam loss monitor system 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. The required probability of not detecting a dangerous beam loss, and therefore losing a magnet, is  $10^{-3}$  per year, which corresponds to SIL3. The unavailability of the BLM system has been calculated (using the program Reliability Workbench V10.0, ISOGRAPH) to be  $5 \cdot 10^{-6}$  per channel. Assuming 100 dangerous losses per year this satisfies the SIL3 requirement. The required probability of generating a false dump is calculated to be  $10^{-6}$  to  $10^{-7}$  per hour (SIL 2) per channel, corresponding to 20 false dumps per year. The simulation of the BLM system yields 10 to 17 false beam aborts per year, again satisfying the SIL2 requirement. A detailed record of the reliability calculations for the BLM system and for the whole LHC can be found in [3], [4] and [5] respectively.

## III. ARCHITECTURE OF THE BLM SYSTEM

### A. Detectors

Signal speed and robustness against aging were the main design criteria for the detectors. Because of the high dynamic range two types of detectors will be used. The standard monitors are ionization chambers with parallel aluminum electrode plates separated by 0.5 cm, as shown in Figure 2. 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  $\mu$ s respectively. The

chambers are filled with  $N_2$  at 100 mbar overpressure. The composition of the chamber gas is the only component in the BLM system which is not remotely monitored (see Section III-B). 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.



Fig. 2. Photograph of the inside of an ionization chamber. The stack of aluminum electrodes with the insulator ceramics at both ends can be seen.

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 signal (middle) electrode is made out of titanium, as its secondary emission coefficient shows better stability as the integrated dose increases [6]. The chamber is 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 and are equipped with a low pass filter at the high voltage input. 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.

The estimated radiation dose on the detectors during 20 years of LHC operation is  $2 \cdot 10^8$  Gray in the collimation sections and  $2 \cdot 10^4$  Gray at the other locations. To avoid radiation aging (electronegative gases, organic compounds) a strict cleaning procedure for the chambers is followed (including glow discharge cleaning for the collimation section detectors). Impurity levels due to thermal and radiation induced desorption are estimated to stay in the ppm range. No organic material is

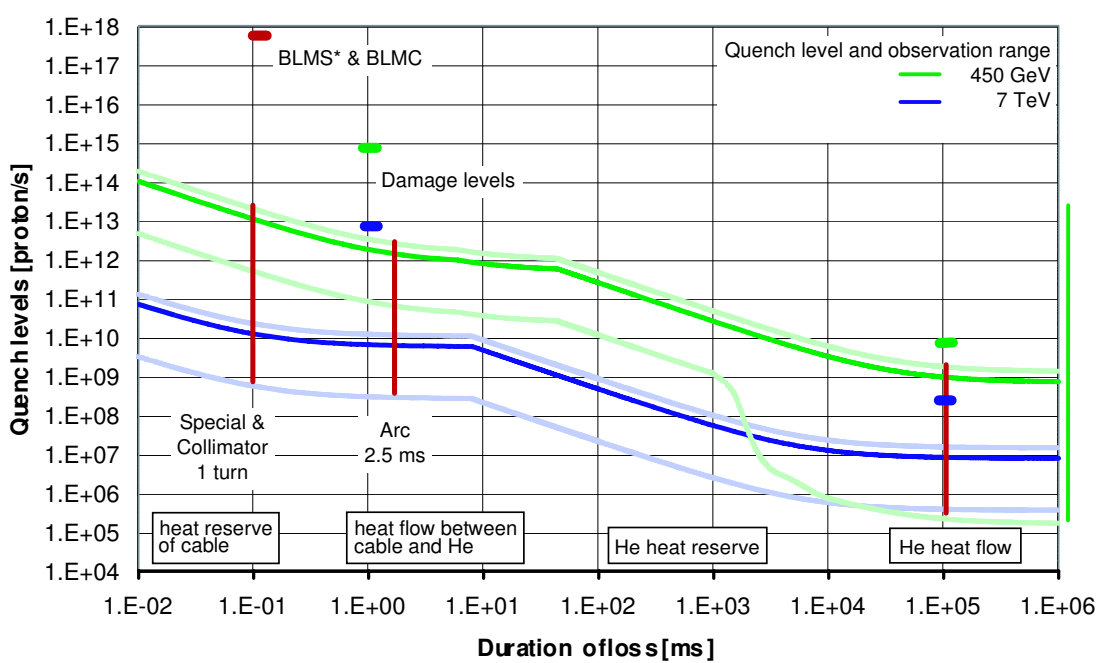


Fig. 1. Quench levels of the LHC bending magnets as function of loss duration at 450 GeV and at 7 TeV (dark green and dark blue). The required observation range for both energies is indicated in light green and light blue color. The damage levels for short and long duration losses are indicated as well.

present, neither in the production process (pumping, baking and filling) of the detectors, nor in the detectors themselves.

The positioning of the detectors was determined by simulation studies (see Section IV-A). In the arcs, three monitors per beam will be installed around each quadrupole located in the horizontal plane defined by the beam vacuum tubes (see Figure 3). At this position the secondary particle fluence is highest and the best separation of the losses from the two beams is reached. Their longitudinal positions are about 1 m downstream of the most likely loss locations.

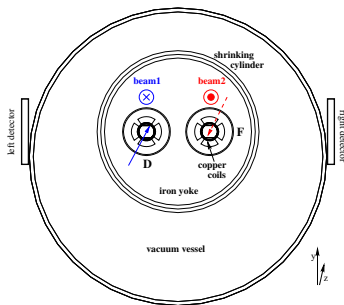


Fig. 3. Cross section of a quadrupole cryostat with the two beams. The location of the BLMs is indicated on the outside of the cryostats.

### B. 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  $40 \mu\text{s}$  (see Figure 4). The counter value is transmitted every  $40 \mu\text{s}$  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 [7] and [4].

The analog electronics is located below the quadrupole magnets in the arc. For all detectors of the dispersion suppressor and the long straight sections the electronics is located in side tunnels to the LHC. All components of the tunnel electronics are radiation certified to 500 Gray. The dose expected at the electronics locations is about 20 Gray per year. The analog signal transmission cables have a length of a few meters in the LHC arcs and up to 500 m in the long straight sections. This part of the transmission is subject to the injection of electromagnetic crosstalk and noise.

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 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 averages of up to 10 minutes) to a database for offline analysis.

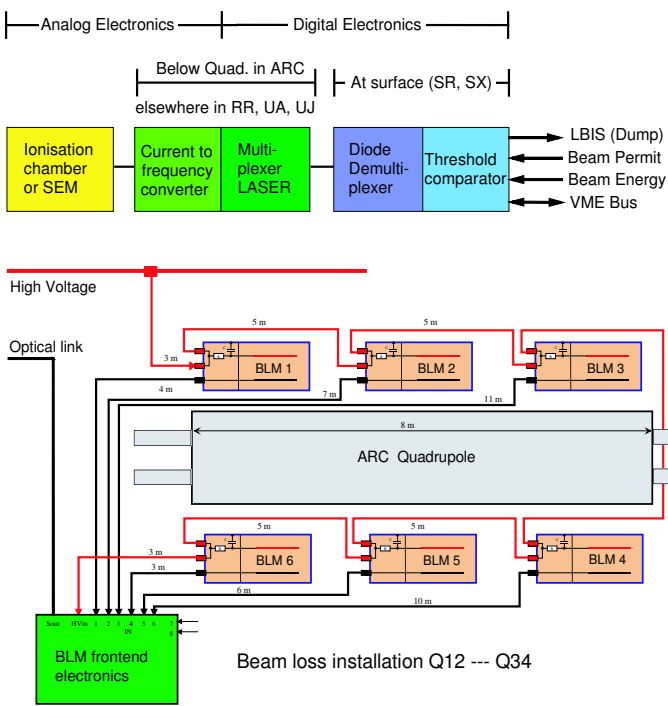


Fig. 4. Schematic view of the signal transmission chain and the BLM installation around one arc quadrupole.

#### IV. THRESHOLD CALIBRATIONS

The BLM interlock limits can be set for each of the about 4000 chambers individually. In the arcs they will be set to 30% of the magnet quench levels. They vary with integration time (12 integration time intervals between  $89 \mu\text{s}$  and  $84 \text{s}$ ) and the energy of the beam (32 energy ranges). The determination of the thresholds 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. 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%.

##### A. Simulations

The aim of the simulation 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 [8], see e.g. Figure 5.

The lost beam particles initiate hadronic showers. Proton induced showers through cold magnets in the LHC arc and dispersion suppressor [9] and through the collimators [10] 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, see e.g. Figure 6.

Magnet quench levels as a function of beam energy and loss duration have been calculated [11] and will also be

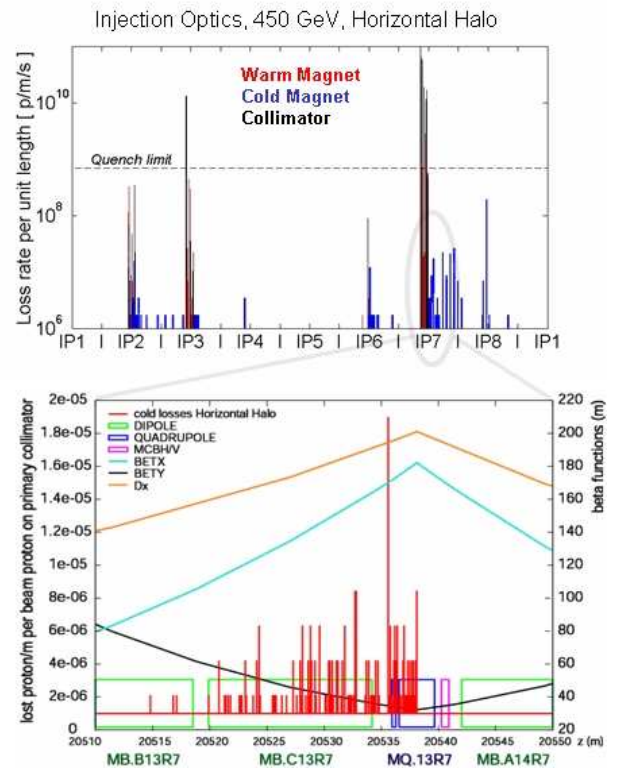


Fig. 5. Simulated proton loss locations along the LHC at injection energy for beam 1. The lost protons are given in bins of 10 cm. In the upper picture losses in warm magnets are marked in red, losses in the collimators in black and losses in cold magnets in blue. The lower picture shows the loss pattern around one arc quadrupole of beam halo particles escaping the betatron cleaning insertion in IP7. In blue color the quadrupole magnet and in green color the neighboring dipole magnets are shown. The beam beta functions are given as well. The dispersion function indicated is not to scale. The loss pattern (horizontal losses in this region) is explained by the beam optics functions. The strong peak at the entrance of the quadrupole magnet is due to the enlarged vacuum chamber at the bellows between the magnets. (Data courtesy of R.W. Assmann, G. Robert-Demolaize and S. Redaelli.)

simulated [12]. The signal response of the ionization chamber to the mixed radiation field in the tail of the hadronic shower has been simulated [13] and measured in various beams at CERN. The corresponding simulations for lead ion beams are being performed as well [14].

##### B. Measurements

The uncertainties in the threshold level determination are dominated by our knowledge of the longitudinal loss distribution and of the magnet quench levels. Hence, the future investigations will concentrate on these points. Quench level measurements on LHC magnets for different time constants (without beam) are planned [12]. A beam loss measurement program at HERA/DESY has started in 2004. It aims to crosscheck the simulation of hadronic showers through superconducting magnets and of the chamber response to the mixed radiation field in the tail of the hadronic shower.

In the LHC itself a sector test with beam could take place in 2006. It would allow to crosscheck the threshold simulations

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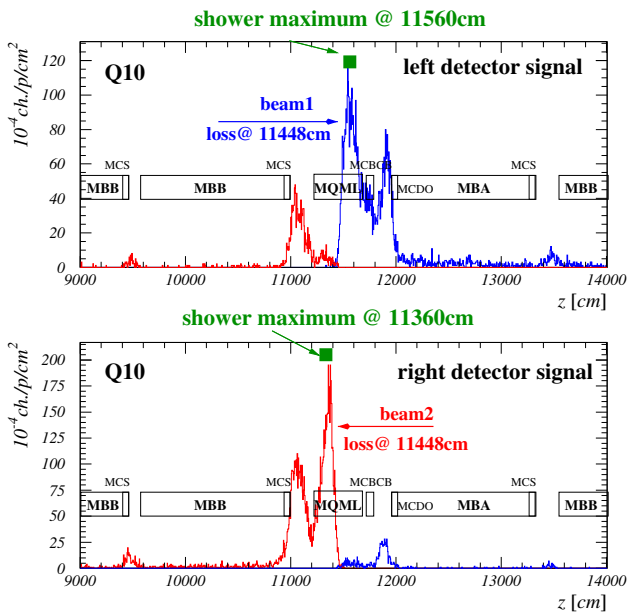


Fig. 6. Simulated longitudinal particle shower distribution at the outside of the cryostat in the horizontal plane of the beam pipes. Proton impact positions are in the center of the quadrupole. The maximum signal occurs one meter after the proton impact position.

for instant losses at 450 GeV. 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.

## V. CONCLUSION

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. This lead to challenging requirements on the beam loss monitoring system and to several novel features in respect to existing systems. They include a large dynamic range and a high reliability. To satisfy the reliability requirements radiation tolerant electronics and a failsafe system design is employed (reliable components, redundancy and voting for less reliable components and a constant monitoring of the availability of the channels). 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 on the one hand and for operational efficiency (to avoid false dumps) on the other hand.