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Functional Specification

ON THE MEASUREMENT OF THE BEAM LOSSES IN THE LHC RINGS

Abstract

This functional specification is dedicated to the beam loss monitoring system (BLM) of the LHC main rings. Its use, both for machine protection and for machine operations and studies is considered. Taking into account the uses and the available information on quench and damage limits, the functional requirements are deduced.

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History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
0.1-draft	11-04-2002	All	Initial Spec for Discussion
0.2-draft	25-07-2002	All	Serious revision of quantitative information by JBJ + Integration of all comments of BISpec meeting Improvements and additions after presentation to the BI Technical Board.
1.0	14-08-2002		EDMS number attributed – Submitted to Approval
1.1	24-03-2003		Clarifications and adjustments following H. Schmickler comments and BISpeC meeting of 12-02-2003. Relax some requirements following meeting with B. Dehning and F. Ferioli. In agreement with R. Schmidt, submit the provisional machine protection policy relevant to the BLM's to the MPWG. Changes are highlighted in red and with a vertical bar on the left side. This will be eventually removed on the released version.
		Section 5	Section submitted for approval to the MPWG
		Section 6.4	The integration time for the BLMB's need not be fast
		Section 6.7	Relax the dynamic range of the BLMB's for nominal use and extend it as an option.
		Section 9.4	• The higher limit of the dynamic range for all collimators is increased from 2 to 3 quench threshold. This gives an overall safety factor of 7.5 between nominal beam dump threshold and saturation. This may be useful if the magnets are more robust than anticipated. • The lowest limit for long integration times is increased by a factor of 2 by reducing the safety limit (extrapolation from pilot to intermediate energy) • For the BLMS, the higher limit is reduced to the dump threshold measured at 2.5 ms, even if the loss time constant is faster. The aim is to gain a factor of 10 on the dynamic range by allowing premature dumps in cases estimated to be rare. • For the BLMC, the lower limit for long integration times is increased by a factor of 10. This assumes that extrapolation is done for nominal collimation efficiency.
		Section 9.5	The tolerance on the absolute calibration of the BLM's is increased from 2 to 5 for estimates based on simulations. This is still compatible with the damage limit with a safety margin of at least 2. The final goal remains to calibrate with beam to a factor of 2.

History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
2.0	14.10.2003	Section 5	Addition for sliding dump levels
		Section 6.3 (new)	Diagnostics in case of bad injection
		Section 6.4	Addition for collimators settings
		Section 9.4	Data recording and storage
		Section 9.2	Table 9 modified (some counters doubled)
		Section 9.4	Addition for collimators settings
		Section 9.4.2	Addition for fast rates at injection
		Section 9.4.3	Addition for collimators settings Table 11 modified Figure 3 modified

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1. SCOPE

This document covers the beam loss monitoring system of the LHC main rings. The injection beam transfer lines [1] and the dump lines [2] are covered in separate documents.

2. INTRODUCTION & GOALS

At LHC top energy, the stored beam energy is as large as 0.35 GJ. The local loss of a very small fraction of the beam may induce a quench of the super-conducting magnets or even a physical damage to machine components. Beam losses at a much lower level are indicative of local aperture restrictions, orbit distortion, beam oscillations, particle diffusion towards larger amplitude, etc… From experience, the measurement of beam losses in hadron colliders provides the most sensitive observable of the beam behaviour. It may be used to optimise the machine tuning, prevent the occurrence of hazardous situations or dump the beam depending on the time scale of the loss processes and the protection strategy.

A conceptual design of the BLM system was presented in [3].

To proceed with a more accurate definition of the needs and of the BLM system, answers to the following questions are required: what are the loss scenarios? Where is the beam lost and how? What is the strategy for machine protection and what is expected from the BLM's? At this time, the precise strategy of machine protection based on the BLM's is not yet defined. A tentative strategy is therefore developed and discussed in the sections preceding the specification of the requirements. An important issue in this strategy is the calibration of the measured losses versus the heat deposited in the super-conducting magnets. The Machine Protection Working Group now endorses this provisional strategy.

3. BEAM LOSS SCENARIOS

The beam loss scenarios considered in this specification are summarized in Table 1. The list does not aim at being exhaustive but rather at identifying the extreme scenarios necessary to specify the beam loss monitors. The scenarios are classified according to the loss time constants. The expected azimuths of the losses are provided. The quantitative information required to specify the dynamic range and time response of the BLM's is provided later in this document (chapter 7).

Table 1: Beam loss scenarios

	Machine status	*Source of Losses*	*Location of Losses*	*Case #*
Steady losses	Nominal losses	Beam halo at collimators	collimators	1
		Tertiary beam halo & Beam-gas	All along	2
		Collision products	Q13.L -> IP -> Q13.R	3
	Partial obstructions	He and air leaks, partial obstruction of a beam channel	Local ± 10 m	6
Slow transient losses	Beam manipulations & measurements	Local orbit bumps, β-beat	Local ± 10 m	4
		Global corrections (tunes,…)	IR3 + IR7	5
		Beam scans with targets (wire, screens,…)	Local ± 10 m	4
Fast transient losses	Obstructions	Complete obstruction of a beam channel	Local + 10 m	7
	Accidental kicks (failures)	Injection errors	TDI, coll. at Q6 downstream of TDI,IR3/IR7	8
		Fastest PC trips (5 turns)	IR3 & IR7	9
		Asynchronous dump kick	Masks in IR6, IR3, IR7	10
	Magnet quench	Drifting beam/machine parameters	Collimators, any local aperture limit	11

4. PROTONS VERSUS IONS

Ion beam parameters can be found in [4]. Considering lead beams, the bunch intensity is N_{Pb} = 6.8 10^{7} ions. The equivalent energy carried by one bunch translated in equivalent number of protons is Z=82 times larger, i.e., n_{equ} = 5.6 10^{9} protons. With 608 stored bunches, the total stored energy is equivalent to 3.4 10^{12} protons. These two quantities are very close to respectively a pilot bunch and a proton beam of intermediate intensity (5 10^{9} and 2.2 10^{12}). It can be concluded that no particular properties need be added to the present specification with respect to ion beams.

5. USE OF THE BLM'S FOR MACHINE PROTECTION

The strategy for machine protection impacts on the BLM design in two ways, its time response, i.e. the choice of the sensor technology, and the reliability.

The Beam Instrumentation Specification WG has defined a provisional machine protection scenario as far as the BLM's are concerned. This scenario is now endorsed and is being developed by the Machine Protection Working Group.

Protection of the machine from beam losses has two aspects:

- protection against beam losses that could lead to damage of equipment,
- protection against beam losses that could lead to a quench of a magnet.

Since a repair of superconducting magnets would take several weeks, the protection against damage has highest priority and damages should be strictly avoided.

In case of a quench, the quench protection system would prevent equipment damage. However, the beam would be lost and re-establishing operation would take several hours. Therefore the number of quenches should be minimized.

The protection of the machine relies on several systems:

- collimation system,
- quench protection system,
- beam loss monitor system,
- beam dump system,
- machine interlock system.

We consider the likely case of a fast beam loss due to a quench of a super-conducting magnet. In case of such an event, the quench protection systems detect the quench and prevent the damage of the magnet. Whenever a quench in a magnet is detected, the beams are dumped via the machine interlock system. However, the time required might be too long to ensure an early enough beam dump. Since the change of the magnetic field in the quenched magnet induces in general an orbit distortion, the beam halo is likely to touch the collimators. The beam loss monitors at the collimators would detect such losses and trigger the beam dump via the beam interlock system. If the magnet quenches due to increased beam loss, beam loss monitors close to the magnet that quenches would detect the losses first and trigger the beam dump.

The assumed collimation efficiency is very large (Table 6) and [5]. Even in unfavourable conditions, the loss rate at the collimators will be several orders of magnitude larger than on the aperture limits in the ring. However the rates at the collimators will depend on their precise transverse settings. Experience shows that the optimisation of the collimator settings is delicate and requires frequent adjustments. Situations where the loss rates at the collimators become less significant must therefore be anticipated. These observations lead to distinguish three families of BLM’s for machine protection and operation. A fourth family is necessary for refined beam observation. They are listed in Table 2 with their essential characteristics:

Table 2: Functional families of BLM's

Type	*Area of use*	*Criticality*	*Time resolution*
BLMC	Collimation sections	yes	1 turn
BLMS	Critical aperture limits or critical positions	yes	1 turn
BLMA	All along the rings	no	2.5 msec
BLMB	Primary collimators	no	1 turn bunch-by-bunch

By criticality, we mean that the system must be 100% operational to allow beam injection and that the beam is dumped if it fails. In general hardware interlocks that cannot be removed enforce this strategy. It is an obvious requirement for the BLMC’s placed at the collimators to enter in this category. The other critical locations in the rings are the points of tightest aperture, e.g. the low-β triplets after squeeze. In certain conditions (Table 1), significant losses could be expected. It is most likely that these places, monitored by the BLMS’s, require the same level of protection as the collimators. Even-though the final protection strategy is still to be defined, the BLMS’s should be designed as critical components.

The BLMA’s cover situations for which the occurrence of a fast loss has not been identified. Slow losses can often be prevented by good operation practice (software interlocks on potentially dangerous beam manipulations) and are less dangerous for the machine components. The BLMA's are therefore not critical in the sense that the machine can be operated even if a small fraction of the BLMA's is unavailable. They are however very important as the only means to localize beam losses, as it may be deduced from the anticipated uses (section 6).

The BLM's monitoring warm sections or warm elements of the machine protect them against damage. It is not defined yet whether they require the turn-by-turn resolution of the BLMS's but should be considered as critical elements.

Table 3:

3a) Hierarchy of beam lifetimes, loss levels and protection strategy, in the regime of **steady losses**. Loss levels are relative to the quench level at the same energy. At 7 TeV, the values relative to the 450 GeV quench level are equally provided between brackets. The lifetime calculation assumes the intermediate collimation efficiency η=3000.

	Loss level					*Protection strategy*
	450 GeV		7 TeV			
	τ	level	τ	level		
Damage to components		5		25	(0.25)	
Quench level	< 1mn	1	1 hr	1	(0.01)	
Beam dump threshold for quench prevention	2 mn	.3	2.5 hr	.4	(4×10^{-3})	Dump the beam
Warning	6 mn	.1	4 hr	.25	(2.5×10^{-3})	Stop interruptible actions
Nominal losses	1 hr	.01	30 hr	.03	($.3\times10^{-3}$)	

3b) Hierarchy of loss levels and protection strategy, in the regime of **transient losses**. Values are relative to the quench level at the same beam energy and, within brackets at 7 TeV relative to the quench level at 450 GeV. The data are given for a transient loss time of 1 ms, or 10 beam turns.

	Loss level			*Protection strategy*
	450 GeV	7 TeV		
Damage to components	320	1000	(3)	
Quench level	1	1	(3×10^{-3})	
Beam dump threshold for quench prevention	0.3	0.3	(1×10^{-4})	Dump the beam
Warning	0.1	0.1	(3×10^{-5})	Stop interruptible actions

In all cases, the BLM's of any type should dump the beam(s) if the loss rate exceeds a threshold to be defined in the section on observables. This assumes an absolute calibration discussed in section 9.5. Provisionally, thresholds relative to the estimated quench level are fixed in Table 3. At injection, the warning level is fixed a factor ten above expected nominal losses and a factor ten below the quench limit. A top energy, the ratio quench/nominal is only thirty and therefore another scaling must be chosen. The warning level is closer to the quench limit, because it is believed that the beams are more stable (absence of or much smaller effects related to persistent currents). Table 3 and Table 7 in Section 7.3.3 contain data only at injection and top energy. They must be interpolated at intermediate energies, in order to provide sliding levels, in particular for the dump threshold. A first and safe approximation is a linear interpolation. The exact interpolation law is under study.

The coverage of the situations identified in Table 1 is summarized in Table 4.

Table 4: Coverage of the loss scenarios by the BLM's

Case	1	2	3	4	5	6	7	8	9	10	11
BLMC	⊗	⊗			⊗				⊗	⊗	⊗
BLMS	×	×	⊗		×				×	×	×
BLMA		□		⊗	□	⊗	⊗	□	□	□	□

The hierarchy of symbols (⊗: first line, ×: second line, □: third line) reflects the potential of the BLM's for protection.

6. USE OF THE BLM'S FOR MACHINE OPERATION AND STUDIES

The characteristics of the BLM system should be adapted as well to its `civilian' use as an aid in machine operations. Experience in the ISR, the $Sp\bar{p}S$ and LEP shows that it is an essential beam diagnostics tool. The requirement to prevent quenches in LHC makes it even more important. The typical uses identified are listed below.

6.1 HELP IN COMMISSIONING

The beam loss monitors will be very important in case of generally poor or not well known conditions, as it is typical at commissioning times. In such a situation, one may have to deal with the combination of reduced collimation efficiency and locally enhanced losses from poor orbit, vacuum bumps and aperture restrictions. A complete coverage with loss monitors will be particularly important in such situations. Amongst other services, the BLM system may help disentangling the geometrical and dynamic aperture limits which are about equal.

6.2 MEASUREMENT OF THE TRANSIENT AZIMUTHAL LOSSES

Due to the large non-linear field components, obtaining circulating beams in LHC will require a systematic threading based on beam position measurements. The threading algorithm is very sensitive to wrong position readings. This is likely to occur when beam losses disturb the beam position monitors. It is therefore necessary that the BLM technology allows for the collection of useful information on the first turn(s) with the pilot bunch intensity to help threading.

Another application is the search of obstructions in the rings. The cryostats in LHC are either continuous or rather long. The signature of an obstruction must be very clear before deciding to cut the cryostat. The BLM's distributed in the ring will be the instrument relied upon for such searches. But studies showed that a single BLM's has a response fading down quickly with increasing distance to the loss point [6, 7, 8]. To limit the total number of monitors, it is foreseen to install a small set near every quadrupoles, see Table 9. Therefore a set of movable BLM's should be anticipated to measure the losses along a half-cell in case of obstruction or leak. The distance between the detectors shall be approximately 3m. An autonomous data acquisition system might be transported locally together with the set of detectors, in order to avoid costly additional fixed cabling. The sum signal of the BPM's will certainly be very useful to crosscheck the BLM data.

6.3 DIAGNOSTICS IN CASE OF BAD INJECTION

Injection failure of different nature may induce the loss of a large fraction of a full batch at several locations. In the clean case of an injection kicker failure, most of the batch will impact the TDI. But a transfer line or a MSI failure may produce a very different loss map. The strategy of protection of the ring will limit the loss points to a few, but at these locations it is important to measure which fraction of the batch was lost. The range of sensitivity of the BLM counter installed nearby these locations must be linear up to the maximum of a full batch lost. The concerned locations are listed in Table 9. Their sensitivity is discussed in Section 9.4.2.

6.4 SETTING OF COLLIMATORS AND OTHER MOVABLE TARGETS

6.4.1 COARSE SETTING

There are over 130 movable targets that need to be set and controlled dynamically, taking into account the closed orbit and beam size. To avoid a waste of physics time, an automated setting of the collimators and targets in `coarse' position is needed. For that purpose, a functionality of `beam finder' is required, whereby the BLM's close to a movable target can be used to stop the motion when the losses exceed the warning level defined in Table 3.

Operations time can be saved if the losses from beam 1 and beam 2 are disentangled at these positions, allowing a simultaneous setting up of ring1 and ring2.

6.4.2 COMMISSIONING

Two scenarios are considered:

- Operation with intermediate intensity beams below the damage limit of the collimators. 3 10^{13} p and 5 10^{11} p are safe at 450 GeV and 7 TeV. Assuming lifetime targets of 1 hour at 450 GeV and 10 hours at 7 TeV, the corresponding loss rates would be 8 10^{8} p/s and 1.5 10^{6} p/s, assuming a minimal collimation efficiency of $1/\eta=1000$. The resolution requested for an integration time of 1 to 10 seconds are 10^{8} p/s at 450 GeV and 1.5 10^{5} p/s at 7 TeV.
- To allow for safe and comfortable commissioning conditions of the collimators, it is advisable to consider that the transient losses induced by the motion of a jaw shall not damage the ring, and possibly produce no quench. We consider a working scenario where the motion of a jaw by 1 mm shall last not less than 1s, in order to ensure the interruption of the action in case of excessive losses. We further consider that during commissioning (or later re- commissioning after optics or hardware changes) the collimation efficiency may be reduced to its minimum, i.e. $\eta=1$ [1/m]. Using the damage and quench limits of Table 7, and a margin factor of ten to get visible signals, the minimum sensitivity of the BLMC must be 10^8 p/s and 10^6 p/s at 450 GeV and 7 TeV respectively

  These two scenarios point to very similar requirements on the monitor resolution.

6.4.3 TUNING WITH NOMINAL BEAMS

The expected loss rates are 10^{11} p/s at 450 GeV and 3 10^{9} p/s at 7 TeV at the BLMC positions (Table 7) for a nominal collimation and 10 times less for an minimal collimation compatible with nominal beams ($1/\eta=1000$). For fine tuning, the beam loss monitors should be able to detect 10% of the steady losses, i.e. 10^{9} p/s at 450 GeV and 3 10^{7} p/s at 7 TeV over an integration time of the order of one second.

For commissioning and tuning, discrimination of the losses at the various collimator jaws would be highly to speed-up operation.

6.5 PROBING THE MACHINE WITH LOWER INTENSITY BEAMS

The aim in using pilot bunches is to probe the machine while suppressing (injection) or minimizing (higher energies) the probability of quench. This allows to correct safely the machine parameters (orbits, tunes…). After these corrections, the machine is deemed to be in a state where it can accept the nominal intensity. Scaling the losses observed with the pilot to the nominal beam intensity should allow a better quantitative judgement on the machine state. The consensus is that space charge effects will change the situation too much to allow a meaningful scaling over such a large range.

One can imagine several possible scenarios where the scaling of the losses should be meaningful (Table 5). We have considered here the possibility of a single nominal bunch, the intermediate beam intensity defined in [9] and the early day’s parameters [10]. It should be noted that a long integration time (up to about 1 mn) is acceptable for this purpose.

Table 5: Various scenarios, for extrapolation. The first scenario defines the largest dynamic range covering all possibilities. The other scenarios correspond to typical uses.

Scenario	Intensity range	Number of bunches	Total range
Pilot → Ultimate	$\boldsymbol{5\times10^{9}\rightarrow 1.7\times10^{11}}$	***1 → 2808***	***95000***
Pilot → Intermediate	$5\times10^{9}\rightarrow 3\times10^{10}$	1 → 72	430
Intermediate → Nominal	$3\times10^{10}\rightarrow 1.1\times10^{11}$	72 → 2808	145
Pilot → 1 nominal bunch	$5\times10^{9}\rightarrow 1.1\times10^{11}$	1	22
1 nominal bunch → Intermediate	$1.1\times10^{11}\rightarrow 3\times10^{10}$	1 → 72	20
Intermediate → Early-day’s	$3\times10^{10}\rightarrow 2.75\times10^{10}$	72 → 2520	32
Early-day’s → Nominal	$2.75\times10^{10}\rightarrow 1.1\times10^{11}$	2520 → 2808	4.5

6.6 OPERATIONS SAFEGUARD

Any beam manipulation in LHC is prone to produce a quench, as the aperture is small and the collimation system required to stay highly efficient, i.e. only weakly perturbed.

The BLM system is therefore expected to produce warnings whenever the loss level exceeds the warning level defined in Table 3 and suitable events that can be used to automatically interrupt an on-going action. The strategy proposed is as follows: any action, whether started by the operator or automatically should be done by default under the surveillance of a “BLM controller”. In case the beam losses exceed the warning level, all processes that invoked the controller are stopped. To improve the performance of the machine, it might nevertheless be possible to inhibit the action of the “BLM controller” in a few well understood situations.

For this functionality, it is very useful that the losses from beam 1 and beam 2 are disentangled all around the machine.

6.7 MONITORING OF THE AZIMUTHAL STEADY LOSSES

A continuous display of the losses along the azimuth of each of the two rings provides a global view of the machine in operation. It allows safely attempting empirical tunings well known to improve performance.

A discrimination of the signals of beam1 and beam2 is liable to speed up operation and simplify diagnosis of problems.

6.8 MONITORING OF THE BUNCH-BY-BUNCH STEADY LOSSES

A few BLM's (BLMB's) positioned in each ring where the rates are highest (at the primary collimators in each plane) should provide information on the losses for *each bucket* (40 MHz) in each beam. Given the very large number of bunches and of beam parameters necessary to define a beam, this measurement is perhaps the only one which can be routinely used during normal operation at the bunch level. The potential of this measurement is twofold:

- detection of beam size changes along the batches; the sensitivity should be of the order of 10% of the nominal steady state losses; the integration time is not constrained and can span over seconds.
- detection of ghost bunches and of the debunched fraction of the beam in the dump gap; the dynamic range is then pushed towards the very low losses, between 1 per mil and a few percent of the nominal steady losses [31]. Preventive actions could be carried out if the integration time can be limited to 0.1s. This mode is optional, as a longitudinal profile monitor is foreseen to measure directly the number of protons at 40 MHz. The detection of small losses, if it sticks out from the background, would be a useful redundancy.

6.9 BEAM AND MACHINE STUDIES

The potential of BLM's for beam studies is large in principle, probably more for qualitative understanding. The Fourier analysis of the losses has been a powerful tool to detect beam perturbations [11]. A sliding data storage over several seconds, with possibilities of data archiving must be foreseen. The measurement of the induced activity (without beams) has shown to be a useful tool for the detection of hot spots and hence aperture restrictions (SPS). A high sampling rate (one turn for every bunch) must be granted for the BLMB and possibly for the BLMC which are located near the primary collimators. A lower sampling rate, to be adjusted to memory capabilities, is acceptable for the other BLM's.

6.10 POST-MORTEM ANALYSIS

In case of a beam dump, the BLM system should help answering the following questions:

- is the beam dumping clean or were there unexpected losses around the machine?
- what is the cause of the dump action: beam losses triggering the BLM or internal magnet quench protection interlocks? Other machine interlocks without prior beam losses?

7. BEAM LOSSES: DYNAMIC RANGE AND TIME CONSTANTS

7.1 DEFINITION OF THE OBSERVABLE

A *beam loss* is defined by the number of *primary protons* lost on the vacuum chamber per unit length of ring for transient losses and per unit length of ring and unit time for steady losses. It can be defined equivalently by the associated local energy or local power deposition, produced by ionisation ultimately converted to heat.

A direct in-situ measurement of the losses at the surface of the vacuum chamber appears technically difficult if feasible at all. It would further be biased by secondary particles from showers developing upstream of the detectors with a large dependence on the local geometry of massive objects (the effective length of the shower is approximately 1 meter long at 7 TeV [12]). The calibration of the monitor would therefore be made very difficult, if not impossible for an adequate reliability.

The preferred observable is the energy of the showers produced by the interaction of the primary protons with the surrounding materials (vacuum chamber, overall cold mass) and deposited in the volume of a small detector located at some distance from the vacuum chamber. It integrates the effect of local losses over a distance of a few meters and is directly related to the power deposition in the coil, which can initiate the quench process. The location of the monitor, both longitudinal and transverse can be chosen to adjust the longitudinal domain of integration. Simulated data exist [e.g. 13] which allow relating the energy deposition in a small volume of matter to the equivalent number of primary protons lost in its neighbourhood.

The beam losses and quench limits will therefore be expressed in terms of equivalent primary beam proton losses at the surface of the beam chamber.

7.2 ASSUMED COLLIMATION EFFICIENCIES

The losses detected at the collimators are enhanced by the collimation efficiency $1/\eta$ as compared to the losses at the surface of the vacuum chamber along the ring. The quantity η is the inefficiency of the collimation defined as the overall tertiary halo rate leaving the collimation insertion above a given normalised betatron amplitude divided by the halo impacting the primary collimators (integrated inefficiency, estimated to about 10^{-3} in the case of nominal collimation). This quantity is further divided by the effective longitudinal length of dilution of this tertiary halo along the ring. This quantity is estimated to an average value of more than 10 m, but will ultimately depend on the detailed local misalignment of the elements. Here, this amplitude is the normalised geometrical aperture of the ring, which is A=10 r.m.s beam sizes both at injection and top energy. In the following, we use the η values given for different scenarios, but always for A=10. The data are taken from [5].

Table 6: Collimation efficiency $1/\eta$ in various scenarios

Scenario	$1/\eta$ [m]	
	450 GeV	7 TeV
Nominal collimation $1/\eta_N$	10^4	10^4
Imperfect collimation $1/\eta_I$	3×10^3	
Minimal collimation near the aperture (9σ) $1/\eta_M$	10^3	

7.3 STEADY LOSSES

7.3.1 SOURCES

The sources of steady beam losses under nominal conditions are

- the beam halo particles diffusing to larger amplitudes,
- the beam-gas interactions,
- the beam collision products at very small angles.

Several other sources arise from either a non-perfect tuning of the machine or from defects:

- local restrictions of the effective aperture due to large closed orbit excursions, misalignments of the chamber, solid obstacles.
- halo by imperfections such as power converter ripple,
- enhancement of beam-gas interactions by helium or air leaks.

7.3.2 AZIMUTHAL DISTRIBUTION

In steady beam conditions with collimation, the collimators set the aperture limitation of the ring in the cleaning insertions. Most of the beam losses associated to beam halo are therefore located in these areas. A tertiary halo, weaker by four orders of magnitude (see above) will be lost at aperture limitations in the ring [14],[5]. Beam-gas interactions will be another source of distributed losses. Another kind of losses is associated to beam collisions in experimental insertions. Their level is directly proportional to the luminosity. The loss pattern extends from the collision point to quadrupole 13 at the end of the dispersion suppressor [15, 16].

In case of local losses, most of the secondary particles emitted towards the aperture impact on the vacuum chamber not far (<10m) downstream from the aperture limitation, because of their very large momentum offset. Only a small fraction of nearly on-momentum particles can travel at larger distances.

A pilot bunch may be used during commissioning or study sessions without collimation. In this mode of operation, beam losses occur erratically all around the ring. It would be advisable to set a few collimators to just shadow the arc (~9 r.m.s beam sizes). In this way, there is a fair probability for the BLMC system to detect losses first.

7.3.3 LOSS RATES

Steady loss rates are given in Table 7. The nominal beam lifetimes considered are 1 hr at injection and 30 hr in collision [17, 18]. In the latter case, the worst possible lifetime will be fixed by the quench limit and the achieved efficiency of collimation, for which a nominal value $\eta_N = 10^{-4}\,m^{-1}$ is used here [5]. The ratio of BLMC and BLMA data is η. The quench limits are taken from [12]. The damage limits are estimated by calculating which local power deposition in the beam screen or the cold bore induces a temperature map corresponding to the ultimate tensile strength, using stainless steel data. The quench levels quoted at the BLMC's are the quench limit of cold elements multiplied by η_N. In the real case, protons will be lost only once, and at one or a few locations where the aperture is limited. Therefore in particular in the absence of collimation (at injection energy and with pilot bunches), only a few monitors will detect the quoted values, all the other ones will detect nothing.

Table 7: Steady primary proton loss rates. The collimators are short devices, therefore the BLMC will detect a signal proportional to the total rate impacting the jaws (p/s). Along the ring, the losses will be diluted over many meters and the BLMA will be detect a signal mostly proportional to the longitudinal density of losses (p/m/s). The starred values (*) correspond to the quench limit in the arcs multiplied by the collimation efficiency, i.e. the largest acceptable primary steady losses.

	450 GeV		7 TeV	
	BLMA's & BLMS's	BLMC's	BLMA's & BLMS's	BLMC's
	p/m/s	p/s	p/m/s	p/s
Pilot bunch with collimation	2×10^{3}	2×10^{7}	20	2×10^{5}
Pilot bunch without collimation	2×10^{7}	2×10^{7}	-	-
Nominal beam lifetime	10^{7}	10^{11}	$<3\times10^{5}$	$<3\times10^{9}$
Quench level	10^{9}	$10^{13\,(*)}$	8×10^{6}	$8\times10^{10\,(*)}$
Damage level	5×10^{9}	$\sim10^{13}$	2×10^{8}	$\sim10^{12}$

7.4 TRANSIENT LOSSES

Transient losses are expected to provide much higher instantaneous rates as compared to steady losses. The quantity of interest becomes the number of protons lost in a given time rather than the rate. The number of protons necessary to provoke the quench of a super-conducting magnet varies by three orders of magnitude depending on the time scale of the loss process (Figure 1). In the following, we make a compendium of typical transient losses and of their time scales (Table 8). To evaluate each situation from the loss map, we assume that the targets and collimators needed to protect the machine are in place. Failure to meet this requirement would cause the loss maps to differ substantially. Destructive level of losses would be reached at some locations in the ring in most of the cases. How to avoid such situations is a subject for the Machine Protection System [18]. Any impact on the BLM system will be included in updates of this specification.

Table 8: Time scales for transient losses

Case	*Time scale*
Injection errors	1 turn
Fast growth of amplitude	10 turns
Beam manipulations	2.5 ms to seconds
Longitudinal ramp losses	0.1 – 10 seconds

7.4.1 INJECTION ERRORS IN IR2 AND IR8

During the injection process, rare but heavy losses will be associated to either bad beam conditions at the end of the transfer line or to injection kicker fault [20]. Most of the beam losses will be absorbed in several protection devices (collimators in the transfer lines, TDI 70m downstream of the kicker between the D1 and the D2 magnet, two collimators located on each side of Q6 on the downstream side of the injection area). It is expected that the detection of these losses will be used to trigger the dump of the remainder of the beam. Apart in the D1 magnet located next to the TDI which might quench in some particular cases of kicker faults and in the collimation insertions (IR3 and IR7), the amount of losses should be kept small in the rest of the ring.

7.4.2 ASYNCHRONOUS KICK BY THE DUMP KICKERS IN IR6

Two kinds of accidents might be expected with the dump kickers, namely asynchronous kicker action and kicker not responding to a dump request. The probability of the latter accident is estimated to be once in several hundred years [21]. A similar situation would arise from a dump signal not being properly issued or transmitted. The situation where the beam is not dumped is not relevant to the BLM design and not further considered here.

Asynchronous kicker action might have two causes. A dump action might be triggered outside the abort gap of the beam or a kicker module might fire spontaneously. In both cases, the fraction of the stored beam, which is synchronous with the rise time of the kicker system, will be swept transversely and populate betatron amplitudes well beyond the aperture of the ring. Local fixed and movable absorbers will catch all protons with amplitude larger than 9 r.m.s. beam sizes. No substantial losses should therefore be visible in the arcs [22]. In IR3 and IR7 the collimators are at a nominal position below 9 r.m.s. beam sizes. They will thus catch some bunches which escape the protections in IR6 during their first turn after the kicker fault. Once loaded, the kicker modules have a slow decay time. Therefore at their next passage, the protons which still circulate in the ring will be dumped. The losses will therefore be located in IR6, IR3 and IR7. It must be noted that in case of dump errors, the BLM system cannot be used actively and will serve mostly to the post mortem analysis.

7.4.3 FAST GROWTH OF THE BEAM AMPLITUDE

The fastest amplitude growth is expected when the power converter of the warm D1 magnets trips [23]. The worst case occurs at 7 TeV with a maximum drift of 1σ in 4 turns. It is possible that the primary collimators scrape a Gaussian beam down to 4σ while being comfortably away from the quench limit. The time scale is therefore about 10 turns. This rise of amplitude is sufficiently slow to first induce losses only on the collimators in IR3 and IR7. Losses nearby the faulty magnet are not expected. A dump action will be initiated soon enough to avoid either a quench or destructive effects. Beam losses will therefore be concentrated in IR3 and IR7. In the rest of the ring, the rates will increase approximately in proportion to the increase in IR3 and IR7.

7.4.4 BEAM MANIPULATIONS AND MEASUREMENTS

With few exceptions, the beam manipulations or measurements are made on time scales of 10 ms to several seconds. This corresponds to an intermediate situation between fast and steady losses (Figure 1) with respect to the quench limit. Two cases of beam manipulations must be distinguished with regards to their potential impact on beam losses, namely changes of local and global beam parameters.

A closed orbit bump is a clear case of a local change. Whenever the bump reaches a high enough amplitude, a local aperture limitation will build-up. It will be accompanied by local beam losses. The source of the local losses is the tertiary beam halo emitted by the secondary collimators. No substantial distant beam losses are expected (see also Section 7.3.2).

A change of tune is a clear case of a global change. A sweep across resonances produce amplitude growth. If the process is slow enough (amplitude growth per turn much smaller than 1 r.m.s beam size), the losses will be confined to the collimation insertions. Associated beating of the β-functions may cause local losses in case of pathologic local reductions of the aperture. The time scales related to quench prevention are evaluated in [24] and amount to 0.4 s at 450 GeV and 2.5 ms at 7 TeV. In this note, assumptions have to be made on the halo drift speed. We consider that an integration time of up to 10ms is consistent with the assumption uncertainties and can be considered if it helps the implementation. A limitation of the dI/dt of the orbit correctors in case of large bumps would as well alleviate the problem of fast losses.

8. ASSUMED QUENCH AND DAMAGE THRESHOLDS

8.1 QUENCH LIMIT

8.1.1 LIMIT TO THE LOCAL HEAT DEPOSITION

The quench process induced by heat deposition is discussed in details in [12][5] and summarised in [8] out of which Figure 1 is taken. The quench limit is strongly dependent on the duration of the beam loss process. In Figure 1 the rate of local protons losses corresponding to the quench limit is given as a function of the duration of the loss. The asymptotic flat segment of the curves corresponds to the limit for steady losses; it is related to local heat flow capacity in the coil of the magnet. At small time-scale, the heat reserve of both the metal and the helium allow for larger transient loss rates. The curves present a kink that is related to different time-scale for the diffusion in the metal and the helium. Smoother curves would be obtained with a more refined model of heat transfer.

In practice, the allowed energy deposition in a given time (in practice, in a finite set of sliding time windows) is the parameter of relevance. It is simply the integral of the loss rate at the quench limit over the observation time.

8.1.2 LIMIT TO THE HEAT DEPOSITION PER CELL

The overall heat load per cell induced by beam losses is limited to about 50 W. This is a lower limit, granted according to a pessimistic evaluation of other dissipative factors. This corresponds to 7×10^8 protons/cell/s at 450 GeV and to 4.5×10^7 protons/cell/s at 7 TeV. Considering the asymptotic flat segment of the curves (8×10^8 protons/m/s at 450 GeV and 8×10^6 protons/m/s at 7 TeV), the distance over which the loss rate can be near the quench limit are 1 m at 450 GeV and 6 m at 7TeV. Those values are pessimistic especially at 450 GeV, where the overall heat load is lower than at 7 TeV (the cryogenic system is dimensioned for 7 TeV, where the critical temperature of the cable is small). We therefore do not modify the asymptotic segment of the curves. One should nevertheless keep in mind that in practice, the steady quench level may have to be adjusted to somewhat smaller levels at particular locations. The global/local limit is relatively more severe at 450 GeV; the local values given in Section 8.1.1 and in Fig. 1 are proportional to the local density of energy deposition, a value which is not linearly proportional to the primary proton momentum. At lower energy, less energy is deposited and in addition, the shower is more diluted transversely. The ratio of the maximum local densities is ~70, while the ratio of energies is 15.

8.2 DAMAGE LIMIT

The damage limits are estimated by considering the stress beyond the elastic induced by temperature excursions. In the case of steady losses, the thermal conduction in the absence (local evaporation) of helium is used. In the case of fast losses the specific heat is used. The worst case is considered (coil or beam screen). A basic discussion can be found in [25].

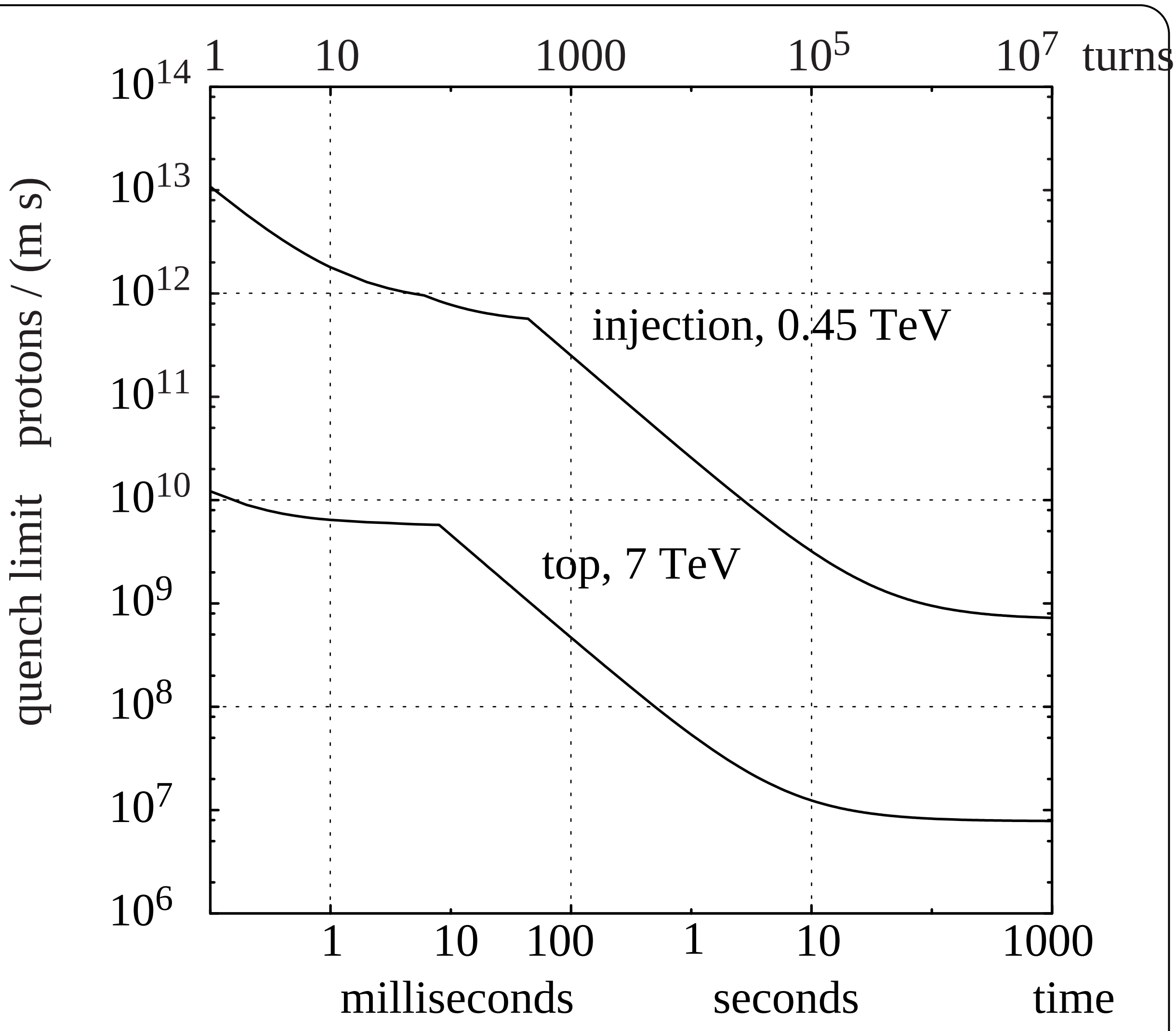

Figure 1: Rate *q* of losses per unit longitudinal length to quench a magnet versus the duration of the loss Δt. The corresponding total number of protons lost is $\Delta N = q \Delta t$.

9. FUNCTIONAL REQUIREMENTS FOR THE BLM SYSTEM

In the following we define the requirements arising from the uses and figures quoted. It should be made clear that the calculations of beam losses are bound to have large uncertainties. As a consequence, if the technology allows exceeding the specifications at no significant cost increase, it should be taken advantage of.

9.1 LOGICAL STRUCTURE OF THE BLM SYSTEM

The four functional families of BLM’s are defined in section 5 and Table 2.

9.2 LAYOUT & NUMBER OF LOCATIONS TO BE MONITORED

The beam losses shall be monitored at all potential aperture restrictions. The list is given in Table 9. Some uncertainties remain near experiments. Their request are not yet known (discussions starting July 2002) and the case of TOTEM is still pending at the LHCC level.

Table 9: Location and number of monitors. See also 6.2 about a movable system to detect local leaks or obstructions. BLMS locations marked with a (*) require an extended range monitor, see Sections 6.9 and 9.4.2.

	Location		*Number*	*Comments*
BLMC	IR3	1 primary, 6 secondaries	7 x 2	At about 0.2 meter downstream of each collimator
	IR7	4 primaries, 16 secondaries	20 x 2	
BLMS	IR3	Cryobox DFBA	2 x 2	Monitoring of the losses on the cryogenic feed-box
	IR7	Cryobox DFBA	2 x 2	
	IR2,IR8	Septum MSI*, Target TDI*, TCDD*, 2 collimators*,D1*	6 x 2	Monitoring and protection against injection errors
	IR1, IR5	Absorbers: 2 TAS*	4	Monitoring of the losses at the TAS
	IR1,IR2, IR5, IR8	Triplets (2 per triplet) + BPM.Q1	16x2x2 8 x 2	Maximum of beam size Exit of IP
	IR1, IR5	2 TAN absorbers, 4 experimental collimators	12 x 4	Monitoring at the targets around the experiments
	IR6	Septum MSD*, TCDQ*, TCDS*, DFBA	4 x 2	Monitoring of the ejection to the dump channel
	DIS	MB adjacent to Q8 (* in IR2R and IR8R), between Q7/Q8 + last MB before Q11 (* in IR2R and IR8R), all DS's	8 x 4 x2	Aperture limit in dispersion suppressors (momentum)
BLMA	LHC	At every quadrupoles	368 x 2	At the local maximum of the beam size
	movable		1	Movable goniometer covering a half-cell to be used in case of suspected aperture restriction
BLMB	IR7	At one primary collimator per plane	2 x 2	Monitoring of the losses at 40 MHz

9.3 GEOMETRICAL ACCEPTANCE OF THE MONITORS

The geometrical acceptance of the monitor is the machine length over which the monitor can measure the beam losses within the tolerances discussed in section 9.5.

Simulations show that the distance between the loss impact and a loss monitor is a very sensitive parameter: the signal of the shower decreases by orders of magnitude over a few meters [26].

The β-beating may shift the loss point in the focusing quadrupoles away from its expected position. A β-beating of 80% is necessary to shift the loss impact from the beginning to the end of a cell quadrupole. The maximum allowed β-beating is fixed to 20% [27, 28] for operation but a good margin must be foreseen for commissioning. An aperture restriction may arise as well from a misalignment or a deformation of an object (e.g. of RF contacts) not located at the maximum β. The BLM active length of detection should thus be centered on the quadrupole and should extend on each side up to the interconnection with the adjacent magnets, i.e. ± 3m.

9.4 DYNAMIC RANGE, RESOLUTION AND RESPONSE TIME

The time resolution of the different BLM families was used to define them and is given in Table 2. The dynamic range is the domain of variation of the beam losses inside which the calibration goal provided in section 9.5.2 must be reached. The criteria used to define the dynamic range are based on the expected uses, the estimated loss levels and the strategy of machine protection discussed in the former chapters. There are two basic criteria and one modification common to all BLM families:

- The high end of the dynamic range shall be three times the quench level. This takes into account the uncertainty on the evaluation of the quench level (factor of two). It further leaves a safety margin by a factor of 9 (7.5) between the Dump Threshold defined in Table 3 and the high end of the BLM dynamic range at 450 GeV (7 TeV). This safety margin would be useful if the magnets happen to be more robust than anticipated.
- The low end shall be 5% of the quench level.
- For long integration times, the low end of the dynamic range is significantly reduced at 450 GeV to allow for extrapolation of the losses as foreseen in section 6.5. The extrapolation from the pilot beam to the intermediate intensity beam requires a factor of 430 (Table 5). The working margin of 20 between sensitivity and quench level can be reduced to 10 to decrease the demand on the instantaneous BLM sensitivity. If this high sensitivity would still not be reachable, the assumed operation scenario would need to be modified by inserting a second intermediate intensity level when setting up LHC.
- The setting of the collimators requires high sensitivity in the 1s time range, as explained in Section 6.3. This is reflected in Figure 3 and Table 11 at injection for t>1s (point D of the curve and above). These conditions are stronger than the ones discussed in the above item. The data at 7TeV will de facto offer a similarly extended range, see Section 9.4.3.

Given the specificity of each type of BLM, we provide graphical and tabulated specifications for each of them.

9.4.1 BLMA

The BLMA's with a minimum integration time of 2.5 ms cannot be used to provide a signal for the beam dump after one turn in case of very fast losses. Therefore the high end of the dynamic range corresponds to beam losses three times above the quench level, assuming a duration of the loss of 2.5 ms (point A in Fig.2). The dynamic range is specified on Figure 2 and Table 10.

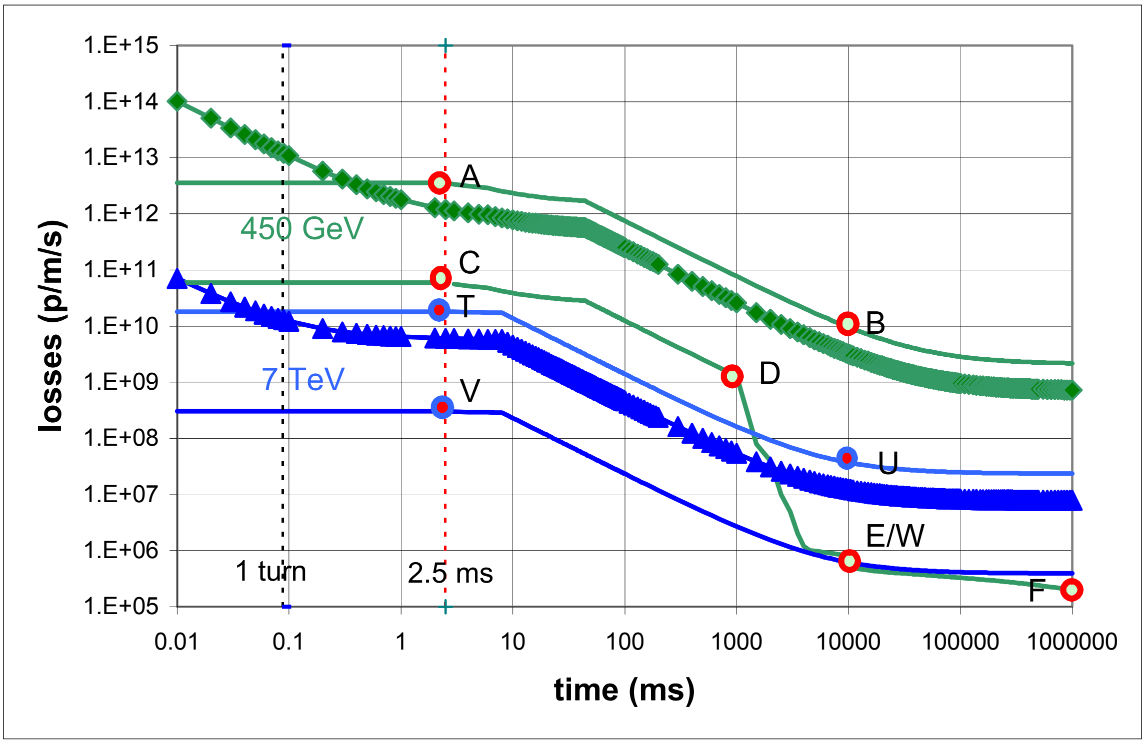

Figure 2: Dynamic range for the BLMA's and BLMS's. The loss rates marked by letters appear in Table 10, with their corresponding numerical values.

Table 10: Dynamic range for the BLMA's and BLMS's in p/m/s

	2.5 ms (BLMA) 0.1ms (BLMS)		1 s		10s		100s	
	MIN	*MAX*	*MIN*	*MAX*	*MIN*	*MAX*	*MIN*	*MAX*
450 GeV	6×10^{10} (C)	3.6×10^{12} (A)	1.3×10^{9} (D)		8×10^{5} (E)	9.6×10^{9} (B)	2×10^{5} (F)	
7 TeV	3×10^{8} (V)	1.8×10^{10} (T)			6.25×10^{5} (W)	3.7×10^{7} (U)		

9.4.2 BLMS

Except for their faster time response (1 turn vs. 0.25ms), the BLMS's share the requirements of the BLMA, given on Figure 2 and Table 10. To reduce the dynamic range, the high limit of the range experienced for 1 turn at 450 GeV is reduced to the rate expected at 2.5 ms. This reduction will lead to premature beam dumps in some cases, but their anticipated low probability makes it acceptable.

In case of the loss of a full batch at injection (See section 6.9), it must be considered that the full intensity may be lost at one location in one turn. The required upper limit of sensitivity must be equal to 3.2x10^13 p/turn/m. The high-end range of sensitivity of the regular BLMS is 3.6x10^12 p/s/m, or 3.3x10^8 p/turn/m (See Table 10 and Fig. 2). This counter will thus be saturated by five orders of magnitude. Doubling the BLMS counter with either a BLMC side by side or another BLMS are possible solutions offering the desired extension of the dynamic range. Most of these extended-range BLMS's will be located near injection absorbers or protection, one exception being the dispersion suppressors which are located downstream of the injection points in IR2 and IR8. They are marked with a * in Table 9.

9.4.3 BLMC

The BLMCs have a resolution of one turn. Their dynamic range must take into account the loss enhancement due to the collimation efficiency (with one exception, see the second part of this Section). The low end assumes in general the minimal collimation efficiency while the high end of the dynamics assumes the nominal efficiency (efficiencies are given in Table 6). For the purpose of extrapolating the losses, we should assume that the collimators are properly set and provide the nominal efficiency. This gain allows restoring the margin factor of 20 between sensitivity and quenching level. The requirements are given in Figure 3 and Table 11. For 450 GeV operation and integration for one turn, the high end corresponds to point A on Fig.3, and the low end to point C. For 7 TeV operation, the high end corresponds to point T, and the low end to point V. If necessary, the size of the counter must be adapted to this dynamic range, or alternatively two detectors of different sizes may be installed near every collimator.

Due to the loss enhancement, the damage limit of the collimator itself is anticipated to lie a little above the high end of the dynamic range for the best possible materials.

In order to allow for safe setting of the collimators, see Section 6.3, the dynamic range must be quite large at large time scale (>1s). This is reflected in Table 11 and Fig. 3 by the drop of the curve beyond the point D at 450GeV, according to the value fixed in Section 6.3. The resulting dynamic range of 10^7 is most likely excessive for a single counter but still required after thorough analysis of the need. A natural possibility is to associate a BLMA counter for the low rates and a specific counter for the high rates. If this solution is retained, the sharing of the dynamic ranges must be adjusted at best for injection conditions. The range of the two BLMC counters must overlap to ensure that at least one loss signal is present at all times. If the overlapping range is one order of magnitude, then the dynamic range of every family must be 10^4.

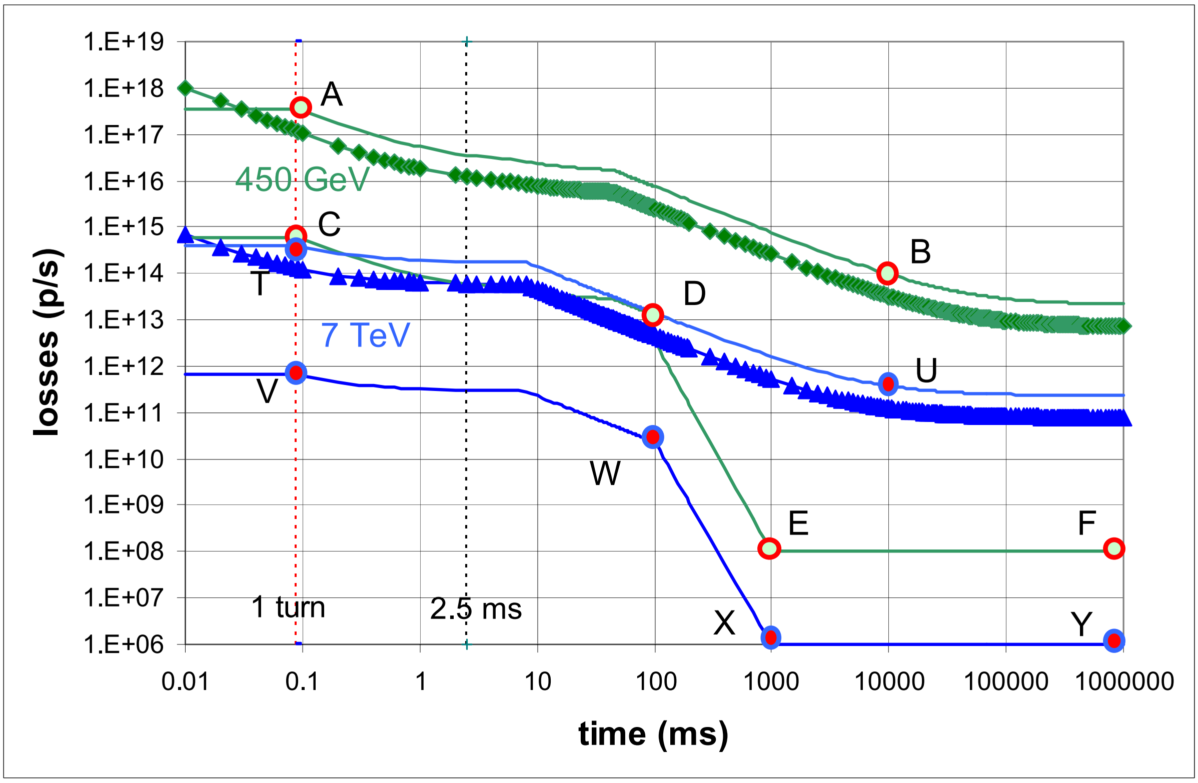

Figure 3: Dynamic range for the BLMC's. The loss rates marked by letters appear in Table 11, with their corresponding numerical values. See Section 9.4.3 for a discussion. Green curves : 450 GeV, blue curves : 7 TeV.

Table 11 : Dynamic range for the BLMC's in p/s.

	0.1 ms		0.1 s		1s		10s		100s	
	MIN	*MAX*	*MIN*	*MAX*	*MIN*	*MAX*	MIN	MAX	*MIN*	*MAX*
450 GeV	6×10^{14} (C)	3.6×10^{17} (A)	1.3x10^{13} (D)		10^{8} (E)			9.6×10^{13} (B)	10^{8} (F)	
7 TeV	6.5×10^{11} (V)	3.9×10^{14} (T)	2.3x10^{10} (W)		10^{6} (X)			3.7×10^{11} (U)	10^{6} (Y)	

9.4.4 BLMB

The nominal functionality of the BLMB's is to monitor the possible bunch-to-bunch variations. As an option, this very sensitive instrument can be used to verify than only the allowed buckets are filled with particles. To become useful, the sensitivity must then be much better than 1 proton per bunch per turn. It is likely that this requirement call for a separate instrument. This option seems a valuable redundancy with respect to the nominal detection by the longitudinal profile monitor. It shall not be considered as an alternative to the latter one.

Table 12: Criteria and resulting dynamic range

	Lower limit	*Upper limit*
BLMB	10% of the nominal steady losses at the collimators: 3.5×10^6 p/s per bunch (450 GeV)/ 1×10^5 p/s per bunch (7 TeV)	Warning level: 3.5×10^8 p/s per bunch (450 GeV)/ 7×10^6 p/s per bunch (7 TeV)
BLMB option	0.025% of the nominal steady losses at the collimators: 9×10^3 p/s per bunch (450 GeV)/ 2.5×10^2 p/s per bunch(7 TeV)	2% of the nominal steady losses at the collimators: 7×10^5 p/s per bunch(450 GeV)/ 2×10^4 p/s per bunch (7 TeV)

9.5 PRECISION AND CALIBRATION

As already said in Section 7.1, a BLM measures a quantity which is proportional to the incident flux of energy on either the vacuum chamber or a collimator. We distinguish between three kinds of uncertainties:

- The detector accuracy properly speaking. This relates the amplitude of an output signal to the flux of ionising particles impacting on the detector.
- The fluence per incoming proton or geometrical calibration which relates the incident flux of energy on either the vacuum chamber or a collimator to the flux of ionising particles which impact on the detector.
- The topology of the loss: the distance between the loss azimuth and the detector is a sensitive parameter. The shape of the loss may as well vary.

9.5.1 ABSOLUTE PRECISION OR CALIBRATION OF THE LOSS SCALE

The uncertainties on the two latter parameters set the error on the absolute scale of the losses. It is partly systematic (correctness of the model used to track the shower) and partly random (uncertainty on the azimuth of the loss impact within the monitor acceptance, variation of the geometry depending on the collimator position).

A prior knowledge of the absolute calibration will significantly minimize the learning process in operating LHC beams by better preventing quenches and unnecessary beam dumps. The uncertainty on the absolute loss scale must indeed be included in the safety factor used for alarm and dump actions. Given the difference between the quench and damage levels by a factor of 5 at 450 GeV (Table 3), the ultimate goal shall be to calibrate the loss scale to within ± 50%. This tolerance includes the sensitivity of the loss monitor to the exact azimuth of the loss within its geometrical acceptance. The levels defined in Table 3 are consistent with this specification.

To reach this goal, the following prescriptions should be followed:

- Minimize the types of monitors and geometries,
- Calculate the geometrical calibration by simulation; calculates its variations in the case of the collimator sections,
- Foresee a check of the prediction of the calibration on the SPS,
- Foresee a programme of calibration with beam in the LHC, including one short straight-section over-equipped with BLM’s for a coverage of the

losses as complete as possible. It would be preferable to equip a SSS in Sector 7 (IP7 to IP8) opening the possibility of a test during the sector test.
- Given the large sensitivity of the monitors to their exact position (section 9.3), the monitors should be mounted in a way that prevents accidental displacements.

The minimum difference between the level at which the beam shall be dumped and the damage level is a factor of 15 (Table 3). At start-up time, one should aim at a calibration within a factor of 5 to safely initiate the learning process. More precise calibration coefficients will probably only be obtained by combined calibration with beam and simulations.

9.5.2 RESOLUTION AND RELATIVE PRECISION OF THE MONITORS

After the above-mentioned uncertainty on the absolute loss scale has been reduced by experimental observations, the other components of the precision of the monitor shall be consistent with the planned BLM functionalities:

- Quench prevention: the uncertainty of the monitor signal smaller than the separation of the typical loss levels shown in Table 3. This requires a relative accuracy better than ± 25%.
- Extrapolation of the losses over a relevant beam intensity range. In order to allow scaling the losses over the required minimum intensity range, the resolution of the monitors shall be better than their sensitivity (see section 9.4).

Table 12: Precision of the detectors

Absolute precision (calibration)	< factor 2 (initial < factor 5)
Relative precision for quench prevention	< ± 25%
Resolution for extrapolation	< quench level at 7 TeV/50

9.6 SIGNAL SEPARATION

9.6.1 BEAM 1/BEAM 2 DISCRIMINATION

There is a definite advantage if the losses from the two beams can be disentangled, at least at the BLMC's. If this would not be possible, the collimators of the two rings would have to be operated one after the other and the search for aperture limitations carried out with a single beam. The price to pay in integrated luminosity might not be negligible. The BLM system should thus preferably be able to distinguish between the two rings or designed to be upgradable to this capability.

9.6.2 COLLIMATOR TO COLLIMATOR DISCRIMINATION

Given the large number of collimators, an important requirement is to be able to discriminate the losses for each collimator jaw. Simulations [29] show clearly that the shower process does not allow distinguishing directly the primary flux impacting a downstream collimator from the secondary one issued from other collimators. From the protection point of view, a conservative dump threshold may alleviate this deficiency. For operation however, a general uncertainty on which out of several collimators produces a high rate is not acceptable. Means must be found for disentangling in real time the signals for this non-critical but most important use. A nominal map of losses must be simulated and later compared to the nominal real map. Then departure from the nominal maps shall be analysed by software control code, to allow for easy diagnostics during operation. This item goes beyond the goal of this specification.

9.7 DATA AND DATA HANDLING

9.7.1 DATA PROCESSING FOR QUENCH PREVENTION

The strategy for machine protection and quench prevention is presently based on the BLM system (see section 5). At each turn, there will be several thousands of data to record, process and transmit to the interlock system and display. The processing involves a proper analysis of the loss pattern in time (transient losses) and a proper account of the energy of the beam. This complexity must be minimized by all means to maximize the reliability of the BLM system as a whole.

Given the tolerance acceptable for quench prevention (Table 12), it is proposed to convert the quench threshold versus loss time curve of Figure 1 into a stepwise function with a minimum of steps fulfilling the tolerance. In this way, the number of sliding integration windows can be reduced drastically.

9.7.2 DATA FOR THE CONTROL ROOM AND THE LOGGING SYSTEM

The loss rates should be normalized with respect to the quench level, i.e. the calibration should be energy and integration time-dependent. Abnormal, higher local rates can thereby be spotted easily [30].

The display should be updated frequently, typically every second. In case of very small losses (steady state losses), a moving average can be used to allow for a longer integration time.

In addition, it may be useful to provide coincidence signals from several close-by quadrupoles.

It will also be useful to store the beam loss data to allow for more sophisticated off-line studies like frequency analysis and the possibility of long term summation for comparison with data on integrated radiation doses all around the machine.

9.7.3 EXPERIMENTAL BEAM LOSS MONITORS

BLM’s will be installed in the LHC experiments by the experimenters. It would be most useful that their data are transmitted to the control room at similar rates and possibly the same format for display, logging and cross checks.

9.8 POST-MORTEM ANALYSIS

The signals of all monitors should be buffered for the last 100 - 1000 turns, such that they can be read out and analysed after a beam-dump. In addition, the average rates of all monitors should be easily available for time scales of a few seconds and 10 minutes before a beam-dump.

9.9 RELIABILITY AND RADIATION RESISTANCE

The BLM system being connected to the machine interlock system, detailed requirements on the reliability and MTBF are expected from the WG on machine Protection. We only provide a rough guideline. Assuming about 100 critical BLM's and an overall fault rate of less than one per month, the MTBF of the BLM's should reach at least 10 years to contribute to a negligible way to the machine down-time.

The machine should not operate with more than 5% missing BLMA's.

Expected radiation levels in the collimation insertion can be found in [12].

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