CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
LHC-

CERN Div./Group or Supplier/Contractor Document No.
-

EDMS Document No.
-

Date: 2001-10-26

Functional Specification

MEASUREMENT OF THE BEAM LOSSES IN THE LHC RINGS

Abstract

Temporary abstract. This document is advanced draft of the functional specification of the beam loss monitoring system, issued in view of the BI review workshop on "LHC Beam Instrumentation" to be held the 19th & 20th of November 2001. The authors ask for the indulgence of the reader for incomplete material and not well polished style.

Prepared by :	***Checked by :***	
Bernard JEANNERET **Bernard.Jeanneret@cern.ch** **And** **Helmut Burkhardt**		

History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*

Table of Contents

1. SCOPE

In LHC, large stored beam energies imply to protect the machine elements from destruction initiated by beam losses. At even lower level of losses, super-conducting magnets must be protected from quench, to ensure smooth operational conditions. The Beam Loss Monitoring system must detect beam losses at an adequate level of sensitivity, with adequate time and space resolution. This note describes the effects of beam losses and their related observables, in view of specifying an efficient beam loss detection system. In advance of further justifications and in order to simplify some discussions, the basic structure of the beam loss monitoring system (abbreviated 'BLM' system below) is already given here. It is shown below that with most modes of operation, a collimation system will be into operation and catch most of the beam losses. Special protections are needed in injection and dump areas, where fast loss monitoring is needed. The system will be therefore be split into

- Distributed arc monitoring, covering most of the ring and with slow time resolution, called BLMA.
- Local monitoring near every collimator with faster time resolution, called BLMC
- Local monitoring near injection and dump elements, called BLMS. The time resolution must be equal or smaller than the one of BLMC's. With aperture limitations located near experimental areas at top energy, such monitors must also be installed in these areas.

2. DESCRIPTION OF THE OBSERVABLES

2.1 DEFINITION OF THE OBSERVABLES

Beam loss monitors must measure a quantity which is proportional to the number of protons lost locally per unit length of ring, or equivalently a local quantity of energy (transient losses) or power (steady losses) deposition. A direct measure of the number of stored protons lost in one location is technically difficult. It would need to install counters at the inner surface of the vacuum chamber. This measurement would also be strongly biased by a massive surrounding, inside which protons interact and develop a hadronic shower, which is made of several thousand particles at LHC beam energies. Indicatively, a charged particle looses dE/dx~1 Gev/m along its path by ionisation. During the shower process, most of the energy of the parent beam proton is dissipated by ionisation. In the case of a proton of energy E=7000 GeV, the integrated path length of all the tracks of the shower is thus L=E/(dE/dx)=7000 m. Whenever developed in a massive object, the effective length of the shower is approximately 1~meter long [lr44]. This indicates that the ionisation energy of the track of impacting beam protons as measured in a small detector cannot be isolated from the overall shower energy of other protons lost slightly upstream of the detector. It is therefore advisable to rather measure the energy deposited by the showering process in an adequate volume. This has several advantages. First of all, the density of energy (or power) deposition is directly related to the quench process, which can be induced by an increase of temperature. Then, in some cases, the distant trail of showers induce a substantial energy deposition, which is not related to a local loss of primary protons. An example is given by the neutral particles produced by beam gas interactions all along a straight section, which impact the vacuum chamber over a short distance near the end of the first dipole of the adjacent dispersion suppressor. For practical reasons (lack of space, cryogenic areas, maintenance, radiation level…)

the measurements must be made outside the cryostat in the arcs, and outside the collimator tanks in the collimation insertions. The residual trail of the hadronic showers provide sufficiently large signals and the process can be simulated precisely. Many simulated data exist already, which allow to relate the energy deposition in a small volume of matter to the equivalent number of protons lost in its neighbourhood. While other reference quantities might be used, the quantification of beam losses and quench limits in terms of equivalent primary beam proton losses will be used here. This is a simple and unambiguous quantity.

2.2 PROPERTIES OF THE OBSERVABLES

2.2.1 AZIMUTHAL DISTRIBUTION OF STEADY LOSSES

2.2.1.1 STEADY LOSSES WITH COLLIMATION

In steady beam conditions with collimation, the aperture limitation of the ring is set by collimators 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 below) will be lost at local aperture limitations in the ring [lr156],[cham00].

Beam-gas interactions will be another source of distributed losses. They shall be nearly constant along the azimuth, the nominal rate being 2.6e4 protons/m/s. A substantial local increase of rate will be associated to helium leaks in the cold sections of the ring, to air leaks elsewhere and to solid obstacles accidentally present in the vacuum chamber. The losses are initiated by the interaction of the beam protons with the nuclei of the material which is present on their path. Most of the secondary particles emitted at the interaction point impact the vacuum chamber not far downstream (<10m).

Another source of local losses will be associated to large amplitude local closed orbit excursions, which might be associated to vacuum chamber or displacement. In such a case, the beam protons interact with the nuclei of the vacuum chamber.

The two cases can be distinguished by the BLMA system. Beam-gas (or beam obstacle) interaction rates will not change if the closed orbit is modified locally, while beam-vacuum-chamber interactions will change.

Another kind of losses is associated to beam collisions in experimental insertions. Their level is directly proportional to the luminosity and they are present at every location between the collision point and quadrupole 13 at the end of the dispersion suppressor [refs].

2.2.1.2 STEADY LOSSES WITHOUT COLLIMATION

It is not foreseen to use steady stored beam properly speaking without collimation into operation. Pilot beams of sufficiently low intensity might nevertheless be used during commissioning or study sessions, especially at injection energy. These beams might be kept stored over a quite large numbers of turns. In this mode of operation, beam losses occur erratically all around the ring and will be detected mostly by the BLMA system, especially in case of closed orbit changes. In this mode of operation, it would be advisable to set a few collimators (a pair of them separated by ninety degrees in each plane) at a depth which defines an aperture limitation slightly smaller than the aperture of the arcs, in case of fast losses to which the BLMA system might be blind. Beam losses would thus be detected also by part of the BLMC system.

2.2.2 AZIMUTHAL DISTRIBUTION AND TIME CONSTANTS IN ACCIDENTAL LOSSES

In all cases of accidental losses discussed here, we consider that the active protections of the ring are operational at all times. But we must state that most of these protections are not defined precisely at the date of issuing this document. At least, the collimators will be fully operational for production runs. Reduced collimation schemes might be envisaged for machine studies, but with adequately lower beam sizes. Otherwise, the loss maps would differ substantially, and destructive level of losses would be reached at some locations in the ring in most of the cases.

2.2.2.1 INJECTION 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 [lr291]. Most of the beam losses will be absorbed by several protection devices (collimators in the transfer lines, TDI 70m downstream of the kicker between the D1 and the D2 magnet, two collimators located in front of Q6 on the downstream side of the injection area) . Intense losses will be observed at these locations which must be used to initiate immediate dump actions. 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 shall kept small in the rest of the ring.

2.2.2.2 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 action.

2.2.2.2.1 ASYNCHRONOUS KICKER ACTION

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 sweeped transversely and populate betatron amplitudes well beyond the aperture of the ring. Local fixed and movable absorbers will catch all protons with an amplitude larger than 9 r.m.s. beam sizes. No substantial losses should therefore be visible in the arcs [mokhov]. In IR3 and IR7 the collimators are at a nominal position below 9 r.m.s. beam sizes. They will thus catch some of the 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 of low amplitude which still circulate will be dumped correctly. The losses will therefore be located in IR6, IR3 and IR7.

2.2.2.2.2 KICKER NOT RESPONDING

In this case, heavy hardware consequence are possible, especially in case of emergency dump request. The most probable locations for heavy losses are the collimation insertions IR3 and IR7, but even tertiary losses might be quite intense and affect any area of the ring. Fortunately, this event is expected to occur not more than once every few centuries.

2.2.2.3 AMPLITUDE GROWTH IN A FEW TURNS

Amplitude growth in a few turns will occur whenever the power supply of a warm magnet will experience a power drop. A drop of power of the warm D1 dipole magnets in IR1 and IR5 is the worst case. It would induce a growing transverse oscillation of 2mm in 5 beam turns [oliver]. This rise of amplitude is sufficiently slow to first induce losses only on the collimators in IR3 and IR7. Losses shall even not occur in the nearby the faulty magnet. A dump action will be initiated soon enough to avoid either a quench or a destructive effects. Beam losses will therefore be observed only in IR3 and IR7.

2.2.2.4 BEAM MANIPULATIONS

Two cases of beam manipulations must be distinguished with regards to their potential impact on beam losses, namely local and global changes of the beam parameters, even if in practice most cases will be intermediate ones.

2.2.2.4.1 LOCAL CHANGES

A closed orbit bump is a clear case of local change. Whenever the amplitude of the bump reaches a high enough amplitude, a local aperture limitation will build-up. It will be accompanied by local beam losses. If the collimation system is in operation, the source of the local losses is the tertiary halo of the emitted by the secondary collimators. No substantial distant beam losses will occur.

2.2.2.4.2 GLOBAL CHANGES

A change of tune is a clear case of global change.

2.2.2.4.2.1 ASSOCIATED LOCAL LOSSES

One effect associated to a change of tune is related to the change of the betatron functions in some or all parts of the ring. Thus aperture limitations might appear at locations where, because of local misalignment or local maxima of the betatron functions, the aperture was quite small prior to the change. In practice, the locations of the associated losses cannot be predicted in that case.

2.2.2.4.2.2 DISTANT LOSSES

Another effect causing losses is dymamic. In non-linear beam conditions, the tune of individual particles is quite widely spread. A tune change can move part of the beam halo onto resonances, a process which can induce amplitude growth and therefore losses. 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, where the aperture limitation of the ring is deliberately set.

2.2.2.5 TIME CONSIDERATIONS

To the exception of the injection and dump kickers, none of the elements of the ring can induce a dangerous rate of losses in less than 1 beam turn. There is a single dump section around the ring, installed in IR6. A dump action must be synchronised with the dump hole in the stored beam structure and trigger signals must travel around the ring up to IR6. A dump action is thus effectively delayed by approximately two beam turns. The time resolution of the BLMC's, which must detect these fast losses shall therefore be of approximately one beam turn for best efficiency. A better resolution would be useless for quench prevention and machine integrity.

As for injection and dump kickers, passive protections must be used (TDI, local collimators, TCDS, …), but they cannot catch all of the bad beams in all cases. It is therefore mandatory to initiate a dump action as soon as possible. The time resolution of some BLMS might then be usefully slightly smaller than one turn, a value to be fixed once the timing strategy of the dump trigger will be known.

Needed time resolutions are further discussed in Section 3.2.1.

2.3 CALIBRATION OF THE OBSERVABLES

As already said in Section 2, a BLM measures a quantity which is proportional to the incident flux of energy on either the vacuum chamber or a collimator. It is therefore important to distinguish two kinds of calibration. There is the calibration of the counter properly speaking, which relates the amplitude of an output signal to the flux of ionising particles impacting on the counter. Quench levels are known to a precision of +-50%. Therefore this calibration factor need not be known to better than +-10% (tolerance), essentially to avoid operational complications in case of replacement of a counter. Then, another factor, which depends on the geometry and on the local magnetic field map, relates the incident flux of energy on either the vacuum chamber or a collimator to the flux of ionising particles which impact on the counter. This factor will be different for BLMA's and BLMC's and is called geometrical calibration below. Furthermore, in the arcs, even if the BLMA's are located at identical positions, their response to beam losses will depend on the location of the loss point. Simulations clearly showed that with growing distance between the loss point and a small counter, the signal decreases by orders of magnitude over a few meters. The losses are expected to be concentrated near quadrupoles, where the aperture reaches a local minimum. It is therefore advisable to measure the losses over an adequate length around the quadrupoles, in order to get an adequately homogeneous response along the expected section where the losses are likely to be concentrated. This is discussed

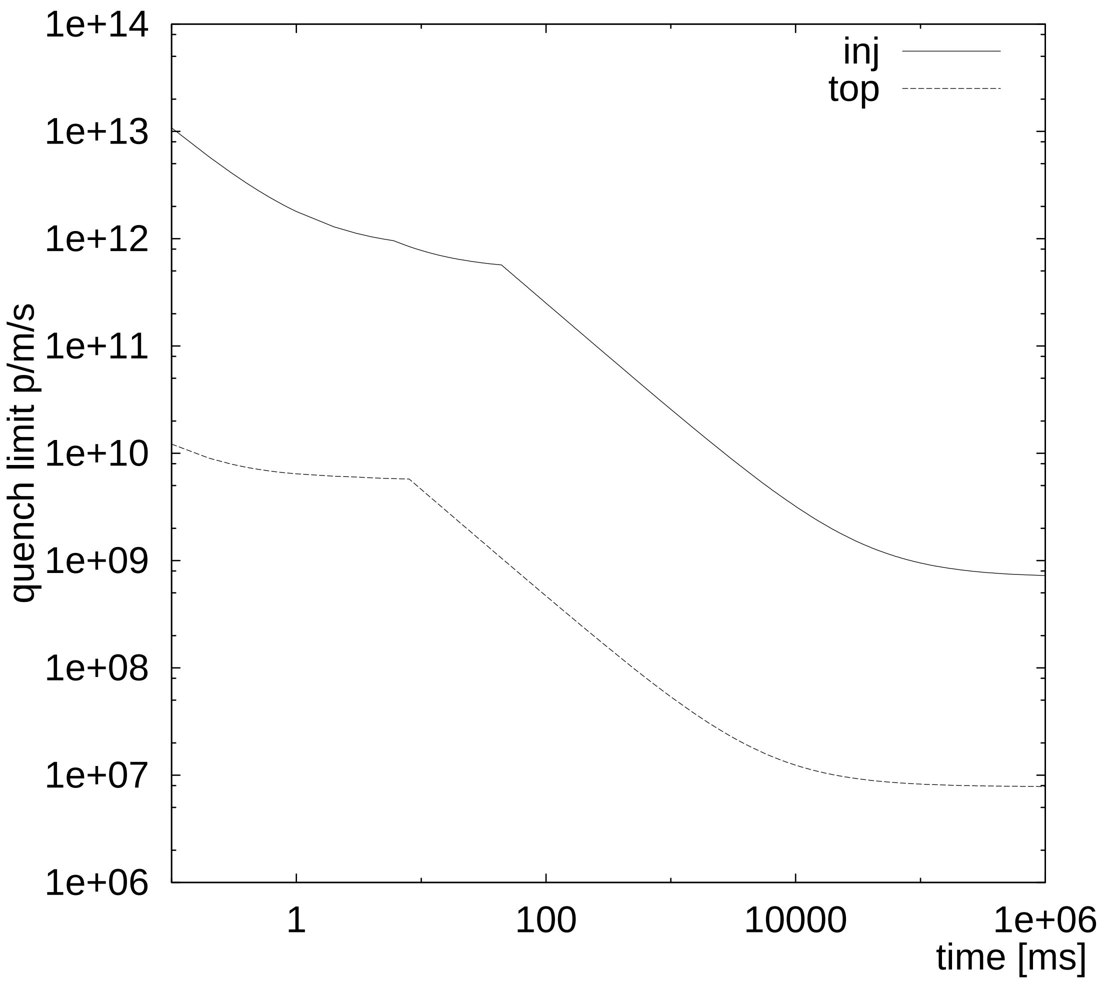

Figure 1 : Rate q of losses to quench a magnet as a function of the duration of the loss Δt and per unit longitudinal length. The corresponding limit total number of protons lost during time Δt is $\Delta N = q\Delta t$, see text.

in Section [BLMA]. Simulations must allow to know how precisely the geometrical calibration can be determined. The residual uncertainty must be included in the safety factor used for alarm and dump cation levels. As for BLMC's, the loss points are well located, but the local geometry is not identical in all cases. Therefore, simulation work is needed to determine a geometrical calibration factor for every collimator. In all cases, the geometrical calibration factor depends on the primary beam energy, and must therefore be determined at least at injection and collision energies. A preliminary simulation was done already and is discussed in Section 4.2.1. Prior to LHC operation, where additional calibration work can be made with pilot bunches, the geometrical calibration must be made in an external beam, where the experimental conditions can be precisely controlled, thus allowing a precise comparison with simulations.

2.4 QUENCH LIMITS

The quench process induced by heat deposition is discussed in details in [lr44],[cham00] and summarised in [ara01], out of which Fig. is taken. No further detailed discussion is made here. The quench limit is strongly dependent on the duration of the beam loss process and thus does not allow the use of simple relations. In Fig. the rate n_q of local protons losses corresponding to the quench limit is given as a function of the duration Δt of the loss process. The corresponding integrated rate is $\Delta N = n\_q \, \Delta t$ (exemple: at injection energy with $\Delta t = 0.1$ s, N_q = 2.5 10^11 p/m/s and ΔN = 2.5 10^10 p/s). The asymptotic flat segment of the curves corresponds to the limit for steady losses, which is related to 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 which is related to different time-scale for the diffusion in the metal and and the helium. Smoother curves would be obtained with a more refined model of heat transfer.

2.5 DESTRUCTION LIMIT

(define destruction levels)

3. USE

At LHC top energy, the stored beam energy is 0.35GJ while the electromagnetic energy stored in the super-conducting magnets is 10.4GJ [ybook]. The local loss of a small fraction of the beam induces a quench of the super-conducting magnets. This is discussed quantitatively below. The loss of a larger fraction of the beam induces physical damage to, or even destruction of, machine elements. The most serious incident can be the melting of parts of ring elements. This is independent of the quench phenomenon. Another effect is related to quench. Whenever a quench occurs, the super-conducting cable becomes locally resistive. In the absence of adequate design and specific protections, all of the electromagnetic energy which is stored in the electric circuit to which the quench area belongs might be dissipated locally, in which case a physical destruction is inevitable. It must be noted that a quench can be induced by processes which are internal to a magnet and are thus not related to beam losses. Therefore, the magnets are designed with a BUILT-IN QUENCH PROTECTION system, i.e. a system which in case of quench, distributes and evacuates safely the electro-magnetic energy. This system must be fail-safe. This subject is not discussed in this document. This document specifies a beam loss monitoring system which must in order of importance do the following tasks.

	Dump trigger	Warning
Avoid destructions initiated by beam losses	Yes	-
Avoid quenches initiated by beam losses.This task is named below 'QUENCH PREVENTION'	Yes	-
Provide guidance for safe and good operation of the LHC machine	No	Yes
Detect aperture limitations or obstacles along the beam path	No	Yes
Allow for collimator setting	No	Yes
Allow beam studies related to beam lifetime and beam dynamics	?	?

It must be noted that the level of transient beam losses that induces a quench (later loosely named 'quench limit') is smaller by several orders of magnitude than the limit of destruction. Therefore, provided that the detection of losses covers adequately the entire ring, i.e. not only the cold sections, the quench prevention ensures de facto the physical integrity of the ring. The beam loss monitoring system must therefore be designed in order to avoid beam induced quenches. Below, we use the abbreviation 'BLM system' for 'beam loss monitor(-ing) system' in a generic sense.

3.1 MACHINE INTEGRITY

(define destruction levels)

3.2 QUENCH PREVENTION

In LHC, the expected level of beam losses can, or will, be larger than the quench limits in all modes of operation, one exception being the pilot bunch mode. Therefore a collimation system, installed in IR3 (momentum collimation) and IR7 (betatron cleaning) will be active at all times. On average, the rate of losses in IR3 and IR7, captured by the collimators, will be three orders of magnitude larger than the loss rate integrated along all the cold sections. The BLM system must therefore be adapted to, and take advantage of this fact.

3.2.1 STRATEGY FOR QUENCH PREVENTION

The expected collimation efficiency will be approximately equal or larger to 10^4 m in good conditions if the aperture limitation of the ring is 8 r.m.s beam sizes [cham00]. This value is the product of the absorption by the collimation system by the dilution of the residual tertiary losses along the ring. With an effective hadronic shower length of ~1m, the measurements will be local, i.e. it will be a measure of the local rate of losses. The ratio of the amplitude of the signals which will be detected in the collimation insertions and the arc respectively will thus be of the order 10^4. It is shown below that in some cases, the signal induced in a reasonably sized counter (BLMA) cannot be easily detected in the arcs in a turn by turn basis. It was already said above that it is not useful to detect harmful losses in a time-scale smaller than a beam turn. Therefore, with the aperture limitation deliberately fixed by the collimators, a useful detection of fast losses (time-scale: one turn) need not be done all around the ring. It can be concluded that a time resolution of ~1 turn is needed in the collimation insertions, where large enough signals can be used for dump triggering purpose. It must be further noted that the source of multi-turn losses cannot necessarily be localised by a distributed system of detection which would rather display a map of aperture limitations. The tasks assigned to a distributed system are therefore related to slow time resolution. This includes the detection of aperture limitations and of obstacles in the passage of the beam, like cold helium pressure bumps.

Another task, related to the operation, would be the detection of losses associated to the undue growth of closed transverse orbit bumps, which by essence cannot be detected easily at long distance. Time constants associated to this kind of event are discussed in [timejbj]. To summarise the content of this note, with the fastest speed of growth of a closed dump and some hypothesis about the halo size and density, a quantity of locally lost protons for a given time is compared to the transient quench limit during the same time. The needed time resolution makes these two quantities equal. It is found that at injection energy the time resolution must be 0.4 second while at top energy 0.0025 second (2.5 msecond) is needed, unless boundaries are set in the control software to strictly control the growth of a bump.

3.2.2 DIFFERENT KINDS OF MONITORS

To summarise, fast counters must be installed in the collimation insertions (time resolution: one turn), while a slower distributed system can be installed in the rest of the ring. The counters will be named BLMC and BLMA respectively (with 'C' for 'collimator' and 'A'for 'arc'). A third kind of counter must be installed at particular locations, like injection and dump insertions, large beta locations in experimental areas and also near local dump devices (TAS and TAN in IR1 and IR5). These counters will be named BLMS (with 'S' for 'special') even if they will most likely be identical to the BLMC's. Their time resolution might need to be slightly faster than one turn.

Table 1 Kind of counters and time resolution

Kind of counter	Area of use	Time resolution
BLMC	IR3 and IR7 (collimation)	1 beam turn = 89 musec
BLMS	IR2,8,1,5,6	<1 beam turn
BLMA	Arcs and Dispersion Suppressors	2.5 msec

3.2.3 OPERATIONAL ENVIRONMENT, ALARM AND DUMP ACTION LEVELS

In case of growing beam losses, two kinds of actions will be used. Below a sufficiently small reference level of losses and/or for a slow growth of them, corrective actions can be taken (display of alarm, automatic interruption of the current action on the beam, …). Above a higher reference level of losses, a dump action must be initiated. Alarm and dump action levels are fixed in Section 4 with reference to quench limits, which can vary substantially for different beam conditions (injection and top energy, steady or transient losses,…). In addition, the reference value will much differ between BLMA's and BLMC's. In the arcs, the local quench limit is the direct reference. In the warm collimation insertions, where a quench cannot occur, the efficiency of the collimation system must be used in the definition of the quench limit, which is also related to distant cold magnets. In other words, the level of losses in the collimation insertion multiplied by the inefficiency shall not be larger than the quench limit in the cold sections of the ring. Detailed limits will therefore be given separately for the different kinds of monitors in the sequel. Indicatively, the alarm level must be set respectively to 1/5th and the dump level to ½ of the quench limit. But enough flexibility must be left to change these values. More conservative limits will certainly be used in the early days of operation, until at least quench limits are properly determined. In collimation insertions, where a counter will be installed near every collimator, further studies are needed in order to determine the best strategy of decision (action based on every individual counters or on a composite signal,...)

4. FUNCTIONAL REQUIREMENTS

4.1 BLMA

The system should allow to safely protect the machine from accidental losses, resulting in quench and damage, and at the same time avoid unnecessary beam dumps. This implies a good absolute calibration of the BLMA system in terms of the quench level.

It is proposed to design the system such, that an absolute calibration in terms of the quench level to within a factor of about two should be possible.

A full calibration of all ring BLMA's with the beam appears to be a rather non-trivial task. The design, construction and positioning of the BLMA system should aim for good stability and some a priori knowledge of the calibration from simulation and prototype tests.

4.1.1 TIME RESOLUTION

- Requirement for standard operation: safely detect losses approaching the quench level in 1 ms (100 turns) to be able to stop driving of large (local) orbit bumps [In270].
- Useful for special operation and back-up in case of reduced collimation: detect losses approaching the quench level in a single turn (100 microseconds).

To detect slower losses, it should be foreseen to accumulate loss counts over several seconds. Potential sources of local losses like pressure bumps and leaks will likely affect only one of the two rings of the LHC. It will be useful to distinguish between losses from the two beams. Bunch to bunch resolution is not required.

4.1.2 SENSITIVITY AND DYNAMIC RANGE

Needs in sensitivity and dynamic range have been studied by Monte Carlo techniques [Ara00a,Bos00,Ara00b].

The sensitivity should be such, that losses which could lead to a quench appear clearly above noise.

Typical quench levels are expected to be roughly 10^7 protons at 7\,TeV or 10^9 protons at 450 GeV or two orders of magnitude difference. BLMA's should be positioned preferably such, that observed signals at the quench level will be similar. Still, depending on optics and position, differences up to an order of a magnitude have to be anticipated. The dynamic range should cover at least a factor of thousand.

To the extend that these estimates rely heavily on Monte Carlo simulation, it will be important to perform early measurements to cross-check with simulations, or to foresee an additional safety factor of an order of magnitude in the dynamic range and noise level.

4.1.3 AVAILABLE DATA

Two signals from every quadrupole in the arcs and in addition from most of the quadrupoles in the straight sections. There will be close to 1000 signals to acquire, transmit and display.

The display should update frequently and the rates displayed be normalized, such that abnormal, higher local rates can be spotted easily [Bu00]. Besides quench and damage protection, the system can also be useful to find possible anomalies like major misalignment, major optics errors (from various causes including magnet and power-converter failures) or vacuum bumps. 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.

4.1.4 DATA FLOW

Each signal may be derived by combination (sum or coincidence) of several monitors. These signal can be combined locally to one signal per quadrupole and beam. A single, fast signal per quadrupole should be available for dump/abort.

These fast signals should be sufficiently noise free and reliable, to allow to connect them individually to the dump trigger. In addition, it may be useful to provide coincidence signals from several close by quadrupoles.

To the extend, that the BLMA's are there to protect the machine against abnormal, local problems, it should not be necessary to provide fast coincidence signals from very distant loss monitors.

For monitoring and display, it should be sufficient to average over relatively long time (maybe 1 minute).

4.1.5 POST MORTEM

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

4.1.6 DESIGN CONSTRAINTS

4.1.6.1 INSTALLATION

No particular constraints. All beam loss monitors can be installed outside the cryostat, which should make access and if necessary replacement straightforward.

4.1.6.2 RADIATION

The loss monitors and their attached electronics should be sufficiently radiation hard to have a lifetime of many years.The signals of all monitors should be buffered for the last 100 - 1000 turns, such that they can be read out and analyzed after a beam-dump. In addition, average rates of all monitors should be available for the last seconds before a beam-dump.

4.2 BLMC

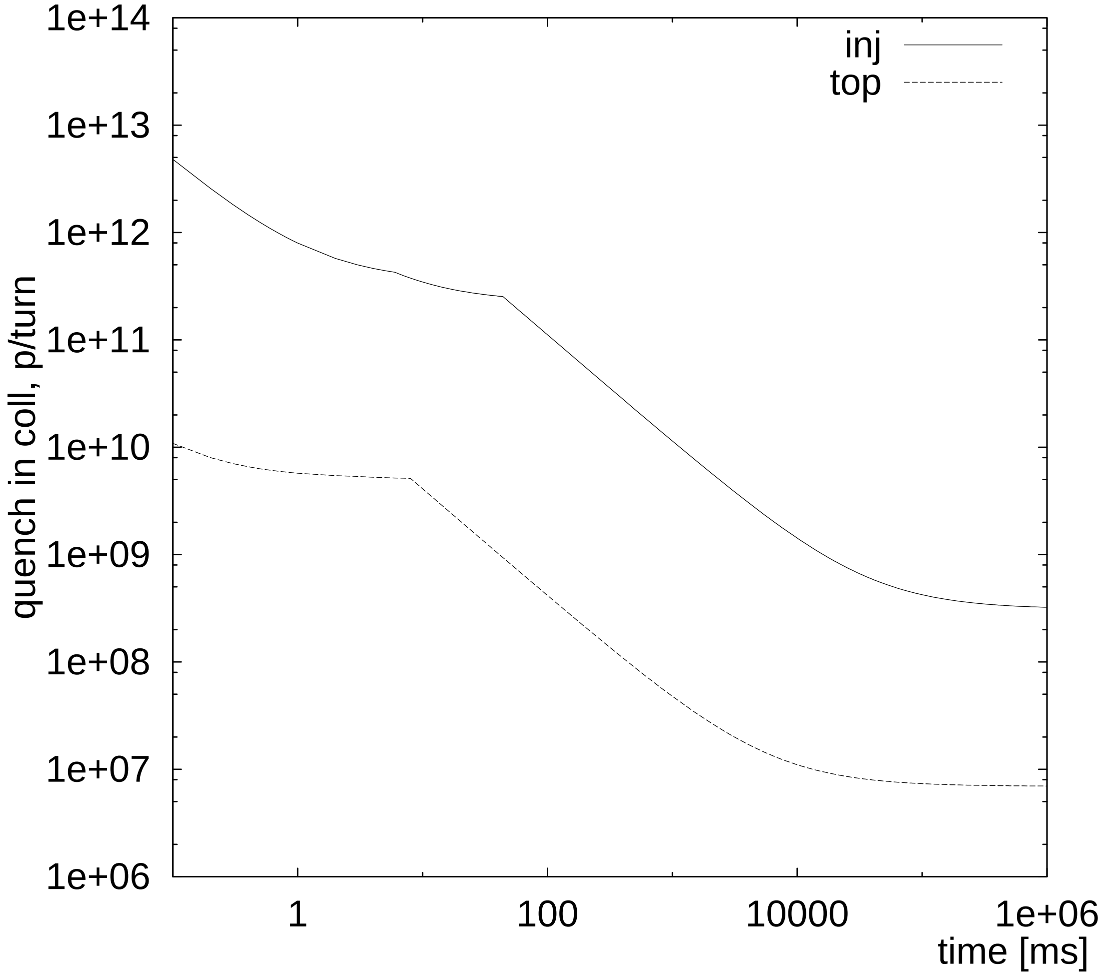

Figure 2: Loss rates *n_coll* in the collimation insertions which correspond to the quench limit in superconducting magnets, as a function of the duration of the loss *t* (in abscissa)

4.2.1 AMPLITUDE OF SIGNAL AND DYNAMIC RANGE

The signal measured by a counter is proportional to the energy deposited by ionisation in the sensitive medium. The coefficient of proportionality depends on the kind of counter (see below). The energy deposition is obtained by shower simulation in the collimators and in the nearby massive elements. The result is expressed by the relation

E = 10^(-3) F dE/(ρdx) n

with E [eV/g] the energy deposited per unit mass of counter and per proton impacting in the collimation insertion, F [hadrons/m^2/proton] the fluence as simulated at the location of a counter and dE/(ρdx) = 1.5 10^5 [eV/(kg/m^2)] the ionisation energy per unit path length in the counter, n the flux of primary losses (or equivalent) [protons/s] while the coefficient 10^-3 is used to convert E form [eV/kg] to [eV/g]. The extreme fluences given in Table 1 are extracted from the maps of fluences of the note [ln121]. Beam loss maps and subsequent shower development in the beam elements were simulated in the entire collimation insertions. Fluences were recorded in a scoring shell made of a thin cylinder surrounding the beam axis and of radius r = 0.8 m. A counter located on the cylinder at the longitudinal coordinate is irradiated by the fluences F(s), neglecting here a weak angular dependence. The minimum and maximum values of F(s) near every collimators in either IR3 or IR7 are given in Table~1. Would these values result in too small signals, locations closer to the beam/collimators can be envisaged. In a preliminary simulation work [igor_private], it is shown that a counter placed next to the vacuum chamber, downstream of the collimator tank and without shielding in between will detect signal which are 20-50 times larger than the values displayed at the scoring shell.

Table 2 Extrema of fluences f per proton in the collimation insertion [h m-2]

	Minimum	Maximum
Injection Energy	0.2	8
Top Energy	1	60

4.2.2 QUENCH LIMIT AND COLLIMATION EFFICIENCY

The quench limit in a magnet is reached in particular when the rate of losses is too large in the collimation insertions, i.e. when the rate of losses multiplied by the inefficiency of the collimation system is larger than the quench limit. This is discussed in [lr256] and [cham00] and the inefficiencies used here, η = 2 10^-4 m^-1 at injection and η = 10^-4 m^-1 at top energy, correspond to a ring normalised aperture of eight r.m.s beam sizes. The critical rate of losses n_coll [proton/turn] in the collimation insertion are given in Fig. 2 and are derived from the quench rates n_q in Fig. 1 with n_coll = T_{beam} n_q/η with T_{beam} = 8.9 10^-5 s the beam revolution frequency.

4.2.3 ENERGY DEPOSITION ON THE SCORING AREA NEAR THE COLLIMATORS

The energy deposition E in [eV/g/turn] in the scoring area near the collimators and for a rate of primary losses in the collimation insertion equal to the quench limit of Fig. 2 is given in Fig. 3. It is obtained with the expression given in Sect. 7.2.1 where the fluences F are taken from [ln121] and given in Table 2 and with n = n_coll taken from Fig. 2. Assuming an ionisation yield of 30 eV, the number of electron/ion pairs produced in an ionisation counter are given in Fig. 4. As already discussed in Section 4.2.1, the quantities displayed in Fig. 3 and 4 can increase by a factor 20/50 if the counter are installed close to the vacuum chamber just downstream of a collimator tank.

4.2.3.1 DYNAMIC RANGE

The sensitivity needed must be smaller than the lowest signal of all the curves given in Fig. 3, i.e. the signal given by the least exposed counter at top energy in the case of steady losses. The nominal loss rate of *n_loss* = 2x10^9 p/s = 2x10^5 p/turn [ybook] is certainly an optimistic value and is 40 times smaller than the quench limit, see Fig.~2. A factor 10 below the minimum of Fig.~3, or *dE_min*=10^9/10=10^8~eV/g/turn is therefore adequate. The effective dynamic range *d* is obtained by dividing the ratio of the maximum of the highest curve in Fig.~3, *dE_max*=10^16~eV/g/turn, or *d*=*dE_max*/*dE_min*=10^8. This is an outstandingly large value. A change of sensitivity range between injection and top energies is certainly required, combined to integration strategies with time, in order to reach this effective range.

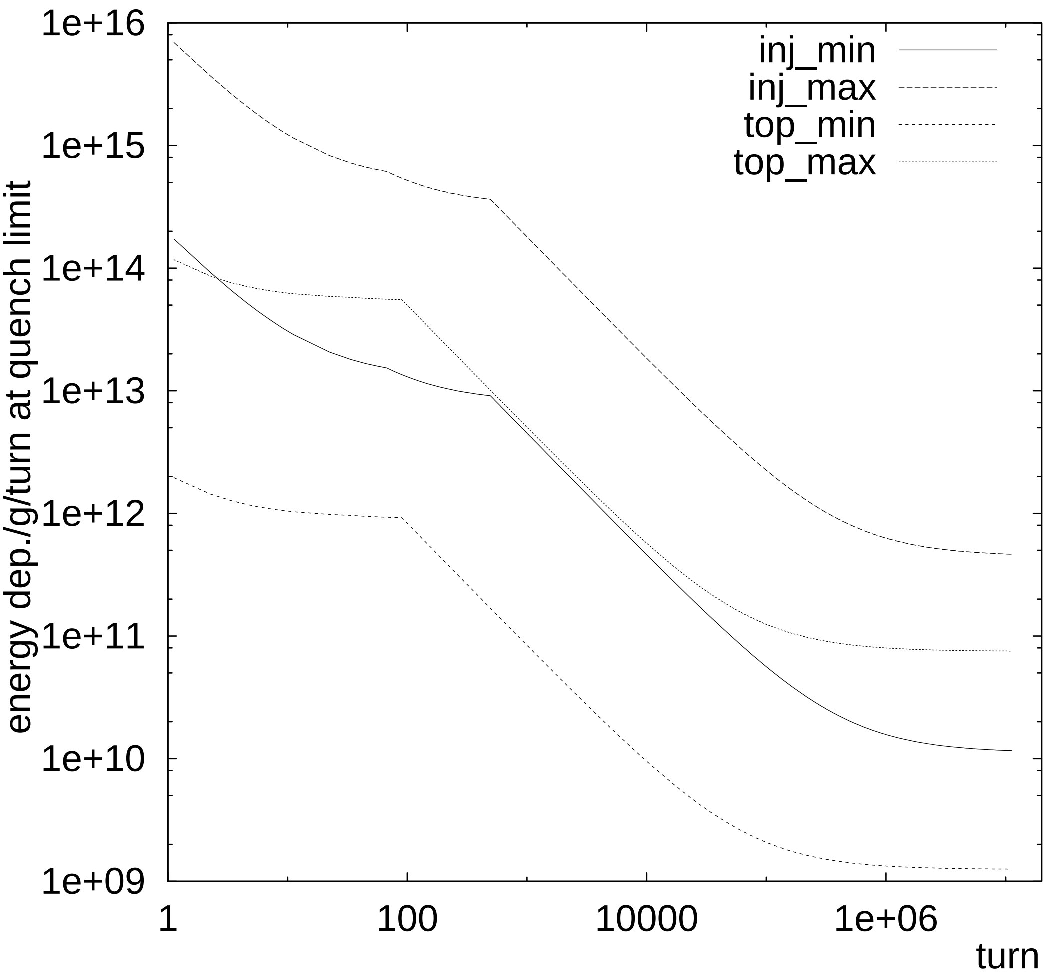

Figure 3. Energy deposition per beam turn for extreme fluences near the collimators and corresponding to the transient quench limit in the magnets. The energy is recorded at the scoring shell and given per unit mass and per beam turn, see text. b).

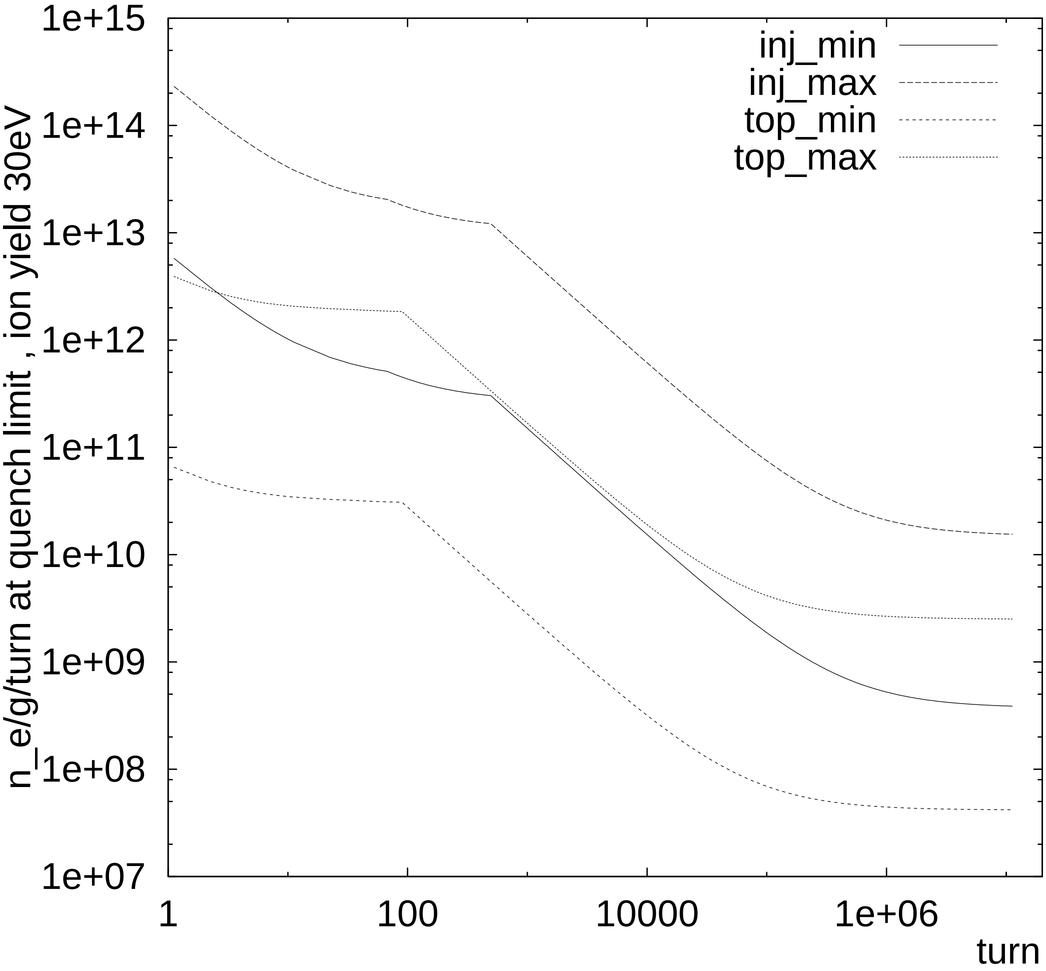

Figure 4. The energy deposition of Fig. 3, converted to a quantity of electrons (ionisation counter) for an electron yield of 30 electron-Volt

4.2.4 BEAM 1/BEAM 2 DISCRIMINATION

4.2.5 COLLIMATOR TO COLLIMATOR DISCRIMINATION

4.2.6 POST-MORTEM ANALYSIS

4.3 BLMS

The BLMS counters will be used in experimental insertions (IR1,2,5,8) and in the dump insertion (IP6). They are essential at injection (IR2 and 8), in order to trigger promptly a dump action in case of failure (MKI) or bad beams at the end of the transfer line. At top energy, the aperture limitation of the ring is located in the triplet of quadrupoles of the final focus, on each side of the experiments. With potentially destructive beam losses, a short time of reaction to trigger a dump action is mandatory. As already said, the BLMS counters might be identical to BLMC. The range of sensitivity is similar, but still needs to be further worked-out. The number and location of counters in given in Table 1.

Table 3 : Location and quantity of BLMS and BLMC counters

BLMC	IR3: prim,6 sec,dfba	16 (two beams)
BLMC	IR7: 4 prim,16 sec,dfba	42 (two beams)
BLMS	IR2,IR8: msi,tdi,tcdd, 2 coll, 2exp	14
BLMS	IR1,IR5: 2 tas,2tan,4 coll,2 exp	16
BLMS	IR6: 2msd,2tcdq,2dfba	6

5. REFERENCES

[ara00] A. Arauzo and C. Bovet, Beam loss detection system in the arcs of the LHC, CERN-SL-2000-052-BI.

[Ara00b] A. Arauzo and B. Dehning, Configuration of the beam loss monitors for the LHC arcs, LHC Project Note 238.

[Bos00] J. Bosser et al, LHC beam instrumentation: Conceptual design report, CERN-LHC-PROJECT-REPORT-370.

[Bur01] H. Burkhardt, How to use beam loss monitors at the LHC, in Proc. of the Chamonix XI workshop and CERN SL/2001-003 (DI),2001.

[cham00] J.B. Jeanneret, Handling the protons beams much above the quench limit, Proc. of the X-Chamonix Workshop, CERN-SL 2000-007 DI, P Le Roux, J.Poole and M. Truchet Eds, February 2000.

[cham01] J.B. Jeanneret, Collimation schemes and Injection protecton Devices in LHC, to appear in Proc. of the XI-Chamonix Workshop, CERN-SL 2000-XXX DI.

[ln270]] J.B. Jeanneret, A proposal for the time resolution of the Arc Beam Loss Monitors (BLMA), LHC Project Note 270, October 2001.

[ln121] Cascade simulations for the betatron cleaning insertion, I.~Azhgirey, I.~Baishev, N.~Catalan~Lasheras and J.B.~Jeanneret, LHC Project Note 121, 1997.

[lr44]Quench levels and transient beam losses in LHC magnets, J.B.~Jeanneret, D.~Leroy, L.~Oberli and T.~Trenkler, LHC Project Report 44, July 1996.

[lr156] Proton collimation in TeV colliders, N.~Catalan~Lasheras, G.~Ferioli, J.B.~Jeanneret, R.~Jung, D.I.~Kaltchev and T.~Trenkler, Proceedings of the Symp. 'Near Beam Physics', Fermilab, 1997, edited by D. Carrigan and N. Mokhov, p. 117 and CERN LHC Project Report 156, 1998.

[ybook] The Large Hadron Collider, Chapter 4, CERN/AC/95-05(LHC), 1995.