BLM THRESHOLDS AND DAMAGE LIMITS FOR COLLIMATORS

A. Mereghetti*, R. Bruce, E.B. Holzer, M. Kalliokoski, S. Redaelli, B. Salvachua Ferrando
CERN, Geneva, Switzerland

Abstract

LHC operation at 6.5 TeV required updating the collimator BLM thresholds adopted in Run 1. At startup in 2015, the BLM thresholds at collimators were computed by scaling linearly the values in 2012 to 6.5 TeV, following the dependence on beam energy deployed during Run 1. This approach enabled a smooth commissioning during the intensity ramp up period. During the year, thresholds have been further optimized to allow for 200 kW primary betatron losses, to accomodate luminosities beyond 10^{33} cm^{-2} s^{-1} and to avoid unnecessary dumps triggered by UFO events around the experimental insertions. The changes deployed in 2015 are presented. On-going studies to improve the understanding of collimator losses, based on beam measurements as well as on detailed simulations are discussed, along with a proposal of the 2016 BLM threshold strategy.

INTRODUCTION

Collimators are amongst the most robust components of the LHC against beam losses. They have been designed [1] to deal with the vast majority of possible sources of beam losses, either normal, i.e. due to beam dynamics or operational variations of the machine, or abnormal, i.e. due to failures or irregular behaviour of accelerator components. In particular, primary (TCP) and secondary (TCSG) collimators should stand accidental, direct beam impacts in case of:

- injection failures, catching a full SPS batch, i.e. $288\times1.15\times10^{11}$ protons at 450 GeV. Resistence to this loss scenario was also verified testing a secondary collimator with beam in the TT40 SPS transfer line in 2004 [2];
- asynchronous beam dumps, with the impact of up to 8 nominal LHC bunches at 7 TeV. Resistence to this loss scenario has been verified with simulations in pessimistic conditions.

These failure scenarios are pertinent to these collimator families since they have the smallest normalised apertures; hence, their jaws are the closest to the beam. In case of regular losses, the collimation system is expected to handle temporary minima of beam lifetime, caused by e.g. instabilities. At top energy, these minima can be as small as 0.2 h for a maximum duration of 10 s, which corresponds to 500 kW beam losses. In 2012, 1 MW beam losses at 4 TeV have been induced with a rising profile over a comparable time scale [3] without damaging the LHC collimation system. The maximum losses that the system can handle in steady state is 100 kW [1].

Even though collimators are characterised by a high resistance to damage, Beam Loss Monitor (BLM) thresholds at collimators are needed to protect them in case of losses beyond design values. In fact:

1. collimators are very high precision devices. Their functionality can be jeopardised even in absence of apparent jaw material damage;
2. "operational thresholds" can be set at collimators, to identify the onset of large losses and thus detect earlier undesired loss conditions;
3. some LHC collimators have metallic jaws, less robust than the jaws of the rest of the collimators, and can thus be damaged more easily.

It should be noted that the beam is dumped within 3–4 turns after the trigger from the BLM system. Hence, fast failures as those discussed previously cannot be covered, and do not enter in the process of setting up BLM thresholds.

For LHC Run I, BLM thresholds at collimators were calculated based on [4]:

1. allowed number of protons impacting the carbon jaws of primary collimators. Values are set first for these collimators, since they are the aperture bottleneck of the machine during regular operation and they are hit first for most sources of operational beam losses (beam instabilities, closed orbit errors, wrong beam manipulations, etc...). The Run I experience showed that this design characteristic of the LHC multi-stage cleaning is well respected during the standard LHC operation. Therefore, detecting losses at TCP collimators is an efficient way to identify early the onset of beam losses;
2. "material" factors, i.e. scaling factors used to derive limits on the number of protons impacting on collimators other than the primary ones. These factors take into account the response of the jaw material to energy deposition and thermo-mechanical stresses, and the presence of nearby sensitive equipment[1];
3. the BLM response to the loss of a beam proton. This is estimated via dedicated FLUKA simulations of average energy deposition in the active region of gas in the BLM per proton impacting on a collimator jaw.

Reference threshold values were computed for the machine configuration at top energy, since this is the most challenging one. For all other beam energies, thresholds were obtained

* alessio.mereghetti@cern.ch

[1] It should be noted that a material factor is assigned also to TCSG collimators, even if they are made of carbon as the TCP collimators, since these are subject to intense secondary particle showers.

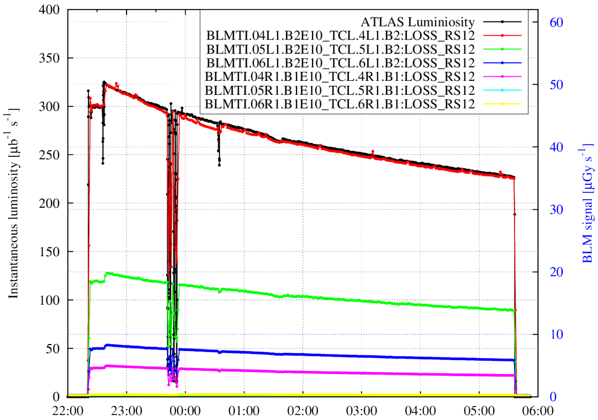

Figure 1: Time evolution of instantaneous luminosity in IR1 and BLM signals for RS12 at nearby TCL collimators during fill 3974.

by linearly scaling those at flat top. Collimators with the same jaw material and similar functions are grouped in families with specific threshold values. Throughout Run I, BLM thresholds at collimators were further adjusted to operational needs. This included also the optimisation based on measured BLM patterns in presence of controlled losses (see later).

In the following, a review of the updates of BLM thresholds at collimators implemented in 2015 is given. The assumptions made for the startup of Run II are briefly recalled, followed by all the updates that became necessary during the LHC operation. All the updates have been documented in specific EDMS documens (LHC-BLM-ECRs), referenced to for each update. Finally, proposals for updates in 2016 are given.

UPDATES TO BLM THRESHOLDS IN 2015

For the LHC Run II startup in 2015, it has been agreed [5] to initially deploy the BLM thresholds as at the end of Run I, but updating them to 6.5 TeV. These thresholds were optimised in 2012 for operation at 4 TeV, since they were based on beam loss measurements, and they have been scaled linearly by energy to obtain values at 6.5 TeV, following the dependence on beam energy presently implemented. The operation-optimised thresholds are based on qualification loss maps performed with beam at flat top energy in 2012, and thus are based on measured loss distributions at collimators. Since the Run II operation started with collimator settings in millimeters as in 2012, loss distributions around the ring were also expected to be similar. Consequently, the beam-based BLM thresholds from 2012 were considered as the best possible guess for 2015, until detailed loss maps at 6.5 TeV would have been available.

Collision Debris (IR1/5/8)

BLM thresholds at tertiary collimators (TCTs) and at debris absorbers (TCLs) in the interaction regions had to be updated in July, due to a high contribution from collision

Table 1: Target instantaneous luminosities considered for increasing BLM thresholds at TCT and TCL collimators based on the relevant contribution of collision debris to BLM signals.

IP	**Luminosity** [cm^{-2} s^{-1}]
IP1 & IP5	10^{34}
IP2	$9{\times}10^{30}$
IP8	$6{\times}10^{32}$

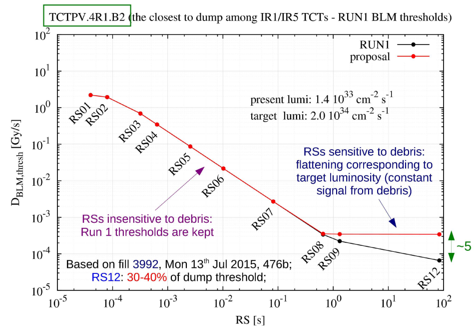

Figure 2: BLM thresholds at the TCTPV.4R1.B2 at flat top energy before and after the update due to collision debris. To be noted, the flattening out of thresholds for RSs above ~0.5 s, sign of the constant contribution from debris.

debris to BLM signals. These collimators are installed in the long straight sections (LSSs) where the two LHC beams are collided; their jaws are metallic, for enhanced absorption capabilities. Secondary particles from proton-proton collisions get scattered on accelerator components or guided through the accelerator lattice structure until they reach the BLM of the collimators concerned, thus contributing to the signal. Since this is a continuous effect during collisions, the longest integration times ("running sums", RSs) of BLM signals are concerned once collisions are established. Figure 1 shows an example of time evolution of the instantaneous luminosity in insertion region 1 (IR1), where the ATLAS detector is installed, and the BLM signals for the longest RS (i.e. RS12, corresponding to an integration time of ~80 s) at nearby TCL collimators. As it can be seen, there is a clear correlation between the time evolution of the BLM signals and the ATLAS luminosity.

BLM thresholds at these collimators had to be increased, in order not to prematurely dump beams while proceeding with the intensity ramp up, limiting the performance reach of the LHC. Hence, new thresholds have been implemented, based on BLM readouts with instantaneous luminosities available in machine, extrapolating BLM signals to target values of luminosity and setting these as new thresholds. Target luminosity values are listed in Tab. 1. A factor 2 of margin on the provided values has been taken. Given the characteristics of debris losses on BLM signals, new BLM thresholds have been implemented as a flat-top correction, i.e. at 6.5 TeV, and flattening out values for long RSs

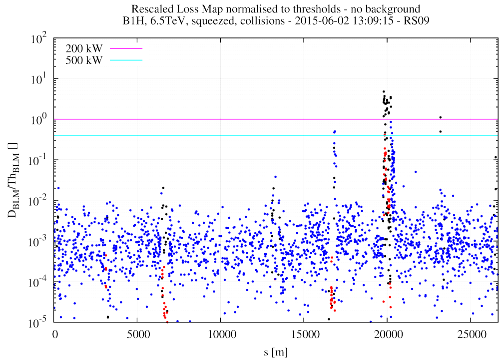

Figure 3: Example of operational scaling of BLM thresholds based on B1H qualification loss maps.

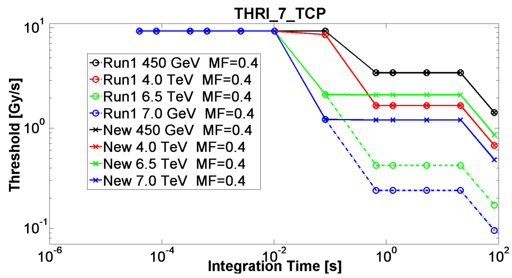

Figure 4: Change in threhsolds of the BLM family at TCP collimators. To be noted that the changes are made only at flat top energies, i.e. above 6.5 TeV included, and they involve only long RSs, i.e. for ~1 s and above.

(i.e. above 0.5 s). Figure 2 shows an example of updated applied thresholds. All the changes are reported in a dedicated technical document [6].

Operational Scaling (IR7)

BLM thresholds at IR7 collimators have been adjusted according to qualification loss maps. These are patterns of losses recorded by the BLM system when beams are separately blown up on each plane in a controlled way. In order for a given configuration of the collimation system to be qualified, the loss pattern must reflect the functional hierarchy of the collimator families. In general, the beam excitation lasts for some seconds, and the BLM signals used for generating the loss maps are those from RS09, i.e. with 1.3 s integration time.

When using qualification loss maps, the new thresholds at each BLM are obtained extrapolating the signal recorded during the loss map (generated by the achieved beam power loss) to the target power loss considered as limit, by means of a linear scaling. An example is shown in Fig. 3. The highest scaled signal found in each family of BLMs at collimators is set as new threshold for the whole family.

Assets of this approach are:

- to set the lowest thresholds compatible with operational loss patterns;
- to avoid useless dumps, i.e. in presence of losses that the collimation system could actually stand;
- to protect the collimation system, avoiding exceeding design limits;
- to deal with dependence of BLM signals on collimator settings, jaw materials and cross-talk from collimators close-by in a factual way.

Such a threshold update was done during Run I in 2012 [7, 8] with beam at 4 TeV, updating all the RS with an integration time of ~1 s and above in all energy levels where thresholds are defined. The same approach was adopted in 2015, to update the BLM operational thresholds to the new beam energy. Contrary to the past, it has been decided [9] to scale thresholds only at flat top. Figure 4 shows the changes implemented in the BLM threshold family of TCP collimators.

As in 2012, thresholds are initially set so that 200 kW peak losses over 1–10 s are allowed instead of 500 kW, thus limiting at 40 % the capabilities of the system, as a staged approached towards the design limits; this is achieved setting the monitor factor (MF) of the concerned BLMs at 0.4 instead of 1. In this way, steady state losses are also limited to 40 kW instead of 100 kW. The BLMs at a few other elements are involved in this scaling, due to their proximity to the collimation system (e.g. MQYs in IR6, and MQTLs/MQWAs/MQs in IR7). All the changes are reported in a dedicated technical document [10].

UFOs (IR1/5/8)

Throughout 2015, two beam dumps were triggered by BLMs at TCT collimators following a UFO (Unidentified Falling Object [11]) event:

- fill 4423, dumped on 26th Sep 2015, 12:31 (local Geneva time) by RS06/RS07 of the BLM at the TCTPH.4L1.B1 collimator, which measured signals 110 % above thresholds (see upper frame in Fig. 5);
- fill 4426, dumped on 27th Sep 2015, 00:17 (local Geneva time) by RS03 thorugh RS07 of the BLM at the TCTPH.4R5.B2 collimator, which measured signals well within a factor 2 above thresholds (see lower frame in Fig. 5).

The UFO events took place in upstream magnets; the present interpretation is that, due to the geometry of accelerator components in that location, secondary particle showers reaching the TCT BLMs are intense enough to trigger a beam dump.

Given the available profiles of BLM signals (see Fig. 5), it has been decided to apply a flat top correction, increasing by a factor 2 the thresholds at RS03 through RS07 of BLMs at the TCT collimators in IR1 and IR5 (see Fig. 6, upper frame). The BLMs at TCT collimators in IR2 (see Fig. 6, middle frame) had thresholds already equal or above the values required by this correction. BLMs at two TCT collimators in IR8 are in the same family as the one of BLMs at TCT collimators in IR1/IR5; hence, they automatically inherit the required correction, even though they have a MF double the

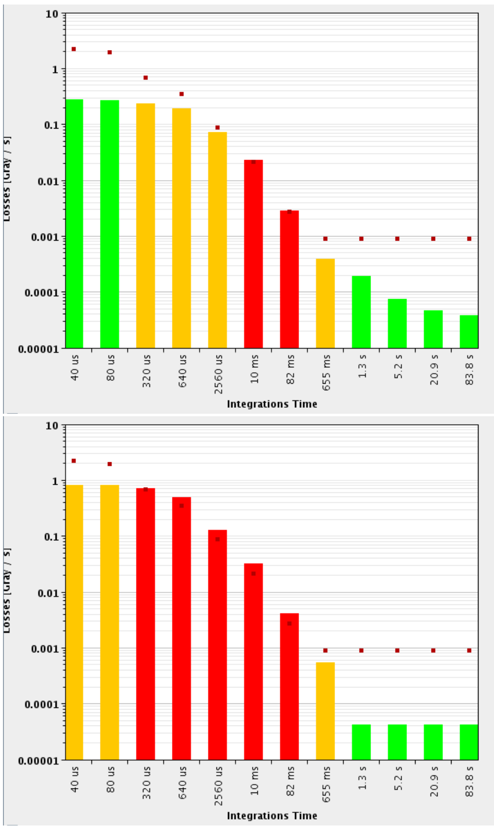

Figure 5: BLM signals and thresholds at the TCTs which triggered the dump of fill 4423 (upper frame) and fill 4426 (lower frame), following a UFO event.

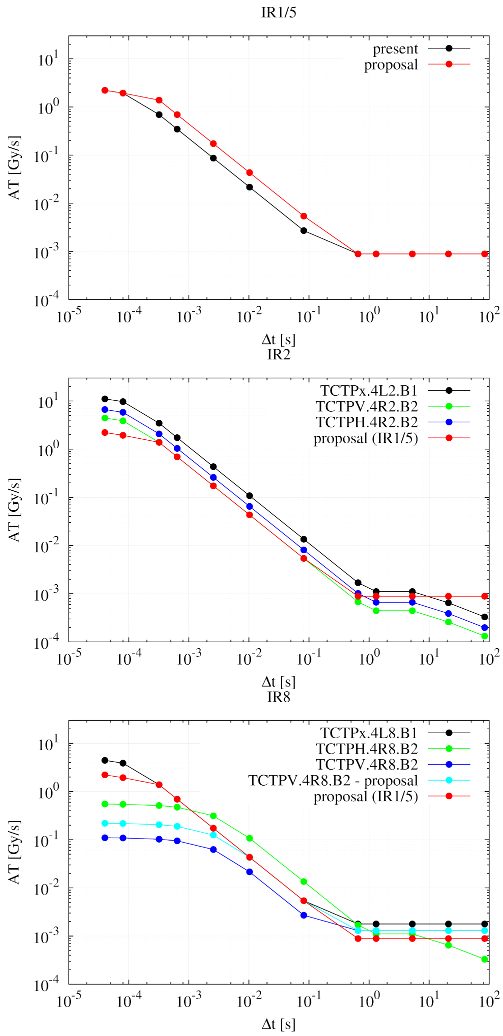

Figure 6: BLM thresholds at flat top at TCT collimators before and after the proposed correction for UFO events: TCTs in IR1, IR5 and left of IR8 (upper frame); IR2 TCTs (middle frame); IR8 TCTs (lower frame).

one of IR1/IR5 TCTs, leading to threshold values already satisfying the requirements from UFO events. One BLM with applied RC filters needed to be corrected (see Fig. 6, lower frame). In this case, RS01 and RS02 were involved in the correction either. All the changes are reported in a dedicated technical document [12].

Other Updates

Other minor changes have been made to BLM thresholds at collimators. These are changes in MF of BLMs at specific collimators in the interaction regions:

- the MF at the IR5 TCL6 collimators have been doubled from 0.1 to 0.2. This update was triggered by a change in the configuration of the debris absorbers in IR5, with TCL5 being opened from 15 σ to 35 σ and TCL6 being closed from 35 σ to 20 σ, following a request from the TOTEM experiment for their proton data taking. The reduction of jaw gap at the TCL6 provoked an increase in the BLM signal due to collision debris, which would have regularly triggered beam dumps before completing the intensity ramp up;
- the MF at the TCTPH.4L2.B1 has been doubled from 0.5 to 1 during the Pb^{82+} ion run. The BLM at this collimator detected very high losses during regular operation, which would have regularly triggered beam dumps before completing the intensity ramp up.

PLANS FOR 2016 OPERATION

During the 2015 Year End Technical Stop (YETS), BLM thresholds at collimators will be reviewed, profiting from the availability of new results from thermo-mechanical analyses [13]. These affect mainly the curve of the limiting number of protons allowed to impact primary collimators for short time scales, during which regimes of energy deposition have been recently studied in detail. Figure 7 shows the comparison between the original curve for 7 TeV protons implemented in Run I (and used also during 2015) and the proposal for the rest of Run II. As it can be seen, limits in the time domain between 10^{-4} s and 10^{-2} s have been lowered by a factor 4; in fact, energy deposition events in this time domain induce dynamic stresses in the jaw that can be up to a factor 3 higher than the static ones. The very last point of

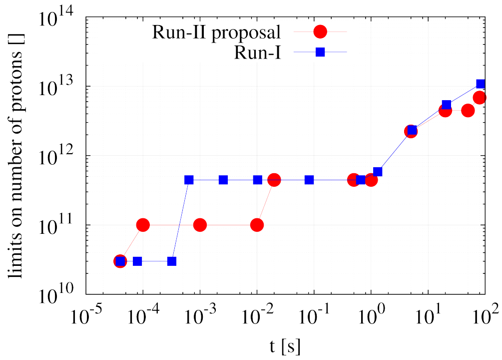

Figure 7: Limits on the number of 7 TeV protons impacting on TCP collimators as a function of BLM integration time.

Table 2: Material factors [13] for computing BLM thresholds at collimators different from the primary ones. TCP thresholds must be divided by the given factors in order to compute new thresholds. For example, tungsten jaw thresholds are 2500 lower than those of primary jaws made of CFC. Values for Run I (as used) and Run II (as proposed) are given.

Collimator	**Run I**	**Run II**
TCSG	10	10
Cu jaw	200	1500
W jaw	2000	2500

the curve, i.e. for ~40 μs is not changed, as this refers to an extremely fast loss scenario, and the limit number of impacting protons is set such that the onset of the loss is detected early enough. Changes are also envisaged for long RSs, to better take into account the 100 kW steady state regime. It should be noted that these changes based on simulation results are complementary to operation-optimised thresholds based on measurements, since measurements performed so far allow to sensibly explore a time domain in the order of seconds and not those covered by the shortest and longest RSs.

The aformentioned numerical analyses lead also to update the "material factors". The comparison between current and updated values is shown in Tab. 2 [13]. New values have been proposed on the basis of a figure of merit for the involved materials, which combines material properties dominating the mechanisms of energy deposition and the thermo-mechanical response.

An extensive simulation campaign will be started to evaluate more accurately the BLM response to the loss of a beam proton when a collimator jaw is accidentally moved towards the circulating beam, correlating the BLM signal to the peak energy deposition in the hit jaw. The aim is to better quantify the margin to the damage level of collimator jaws, especially the metallic ones, in view of possible further operational optimisation of thresholds. With respect to all previous studies, this is focussed on an accidental scenario and not on regular cleaning. Metallic collimators will be the main class of collimators investigated, since these are the most delicate ones. The new simulation campaign will also aim at a better description of the dependence of BLM thresholds at collimators on beam energy. Given recent advancements in the development of tracking tools with ion species [15], this analysis could be repeated also for ion beams.

This review won't take into account:

- limits in the number of protons impacting a TCT jaw in case of an asynchronous beam dump, since this is an accident scenario extremely peculiar, to which the BLM system is not capable of reacting in due time;
- more robust materials for TCT collimators. These are being studied in the framework of the High Luminosity LHC, with very little chances to be installed in machine during Run II;
- the use of the 5$^{\text{th}}$ axis of metallic collimators in IR1/IR5, since this opens the possibility to avoid the exchange of a damaged collimator with a spare one; moreover, it does not apply to metallic collimators in IR2 and IR8, and does not mitigate or prevent onset of damage;
- a better phase advance between dump kickers and TCT collimators, under discussion for the 2016 LHC optics [14]. This option offers better protection of the TCT jaws against proton hits during an asynchronous dump, and does not mitigate or prevent onset of damage from regular cleaning losses.

Results from the quench tests can be of help in tuning the BLM thresholds in the dispersion suppressors (DSs) of IR7. In fact, it was seen with beam that:

- no quench of IR7 DS cold magnets took place with proton beam losses up to ~600 kW [16];
- a quench of a cold magnet in the IR7 DS took place with ion beam losses of ~15 kW [17].

The BLM signals thus induced in the IR7 DSs can be compared to the values presently used and used to set new thresholds based on these outcomes with beam. It should be kept in mind that the present models used for setting thresholds in this region lead to thresholds which may conflict with signals from regular cleaning losses, in case these get close to the figure of 500 kW over 1-10 s.

CONCLUSIONS

Even though the collimation system is amongst the most robust components of the LHC, it needs to be protected by BLMs, to avoid jeopardising its operation. Consequently, collimators are equipped with BLMs able to trigger a beam dump in case losses become too high, hence preventing high heat loads in the jaws and deformation, and consequently possible loss of performance or even damage.

An overview of the BLM thresholds at collimators deployed in 2015 and their updates has been given. Updates include changes in BLM threshold values at many collimator families in several locations in the LHC ring for different reasons, the main ones being: at TCT and TCL collimators in the experimental regions, due to the large contribution from collision debris to the BLM signal; at all collimator families in the IR7 region, with changes based on qualification loss maps to optimise their performance; at TCT collimators in the experimental regions, to avoid useless dumps triggered by UFO events taking place near collimators.

A review of BLM thresholds at collimators is foreseen during YETS. The review is based on available updates in the curve of the limit number of protons impacting jaws of primary collimators and in the material factors, to scale these limits to non-TCP collimators. In the same framework, an extensive simulation campaign will be started, aimed at addressing in more details the relation between energy deposition in the collimator jaws and the respective BLM signal.

ACKNOWLEDGMENT

The authors would like to thank B. Auchmann, R. Schmidt, D. Wollmann and M. Zerlauth for continuous and stimulating discussions.

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