# COLLIMATOR BLM THRESHOLD STRATEGY

S. Redaelli, A. Bertarelli, R. Bruce, F. Carra, A. Mereghetti, B. Salvachua
CERN, Geneva, Switzerland

## *Abstract*

The collimators of the Large Hadron Collider (LHC) are among the most robust components of the accelerator as they are designed to intercept and withstand without damage beam losses that could otherwise damage more sensitive equipment. Small fractions of the 7 TeV LHC beams, which have a design stored energy of 362 MJ, are sufficient to quench the superconducting magnets and even induce permanent damage to accelerator components that are not adequately protected. On the other hand, the overall collimation performance relies on achieving precise positioning of the collimator jaws that are set close to the circulating beams with a mechanical accuracy of $\sim$40 $\mu$m. This is required to control the transverse hierarchy of devices distributed around the 27 km-long LHC ring. Even small permanent deformations of the jaws, e.g. induced by beam loads, could jeopardise an optimum collimation performance. Thus, in any machine configuration beam loads on collimators must not exceed the values that the system has been designed for.

The strategy for defining the dump thresholds of the beam loss monitors (BLMs) that protect collimators is reviewed. Since collimators intercept most primary beam losses, their BLMs are ideal candidates to detect early on the onset of abnormal beam losses. These BLMs are therefore also used to dump the beam in case of undesired high losses that are not necessarily putting in danger of damaging accelerator components. The strategy to set these "operation-optimised" BLM collimator thresholds is also addressed.

## INTRODUCTION

At the CERN Large Hadron Collider (LHC) [1] at the European Organization for Nuclear Research (CERN), a multi-stage collimation system is used to reduce the risk of quenches of superconducting magnets from unavoidable beam losses with beams of unprecedented stored energies up to 360 MJ. This is achieved by placing collimator "jaws" close to the circulating beams at amplitudes ordered in a well defined hierarchy. The LHC multi-stage collimation also provides the machine with passive protection as collimator jaws shield the machine aperture and intercept primary beam losses. At the LHC, the collimation hierarchy ensures that the warm and cold apertures are shielded by not less than four levels of collimator families, including the LHC protection devices.

Operational experience from the LHC Run I at beam energies up to 4 TeV showed that the multi-stage collimation system successfully protected the machine aperture in all conditions. The LHC relies on carbon-based collimators for the primary and secondary stages of the hierarchy for maximum robustness, and materials with larger Z (tungsten alloys and copper) for shower absorbers and local protection. The latter are more fragile against beam losses but also the carbon collimators must be protected because the positioning of their jaws close to the beam requires a very accurate mechanical system. For example, flatness errors above 40 $\mu$m could cause breakage of the hierarchy at the Insertion Region (IR) 7, which hosts the betatron cleaning system. Losses at collimators are monitored by dedicated beam loss monitors (BLMs) installed at each collimator. Collimator BLMs are essential to collimator protection, as they are meant to trigger a beam dump in case of losses that could cause permanent damage to the jaws. Moreover, collimator BLMs are also used for the collimator beam-based alignment and for checking that the hierarchy of the collimators is respected. A photograph with the tunnel layout of an LHC collimator, with the dedicated BLM visible as the yellow cylinder immediately downstream, is shown in Fig. 1.

The observation that most losses in standard LHC operation occur at collimators makes the monitoring of such losses a powerful tool to detect early on the occurrence of undesired beam losses before they lead to damage of equipment or quenches, or before the beam quality is deteriorated to unacceptable levels. In 2012, Run I BLM thresholds were reviewed and set to "operation-optimised" values [2, 3], aimed at dumping the beam when losses intercepted by the primary collimators of the betatron cleaning insertion (IR7) reached the level of 200 kW, i.e. 2.5 times less than the design level of 500 kW, as discussed in detail later.

In preparation for the operation in 2015 at 6.5 TeV, the strategy for collimator BLM thresholds has been reviewed with the main goals of ensuring adequate protection of the LHC and of the collimators at larger beam energies, and a safe and efficient operation. In this paper, the different LHC collimator families are introduced, and a proposal of thresholds for the Run II operation is presented and compared to the strategy applied in Run I, focussing on collimator protection thresholds and the consequent limits in terms of number of protons impacting the collimator jaws. In addition, while the full review of BLM thresholds for Run II will be implemented at a later stage, the operational thresholds established for the initial operation in 2015, still based on Run I thresholds scaled according to measured loss dis-

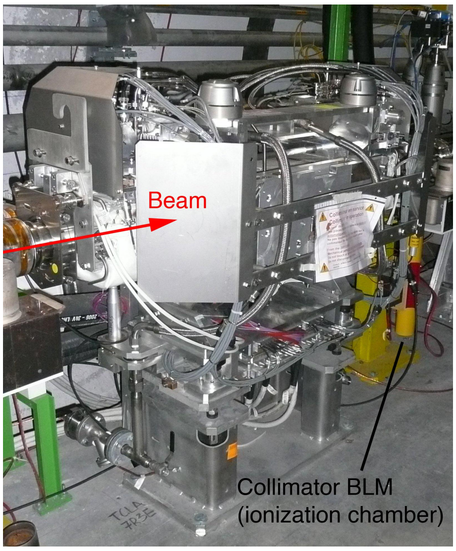

Figure 1: LHC collimator installed in the tunnel. The BLM used to measure losses immediately downstream of the collimator is the yellow cylinder indicated by the black arrow.

tributions at the collimators, are also discussed. Conclusions are drawn and possible further improvements are finally outlined.

## COLLIMATION LAYOUTS AND COLLIMATOR FAMILIES

The collimation system is described in detail in [1]. Collimators are present in all LHC IRs except in IR4 where the radio-frequency (RF) system is located. The collimator active jaws are made of different materials: carbon fibre-composites (CFC), graphite (Gr), copper and tungsten heavy alloys. The design of each collimator family has been derived from a common base design, adapting it according to the specific functionality of the family. Presently, eight designs can be identified, different from each other for jaw material and length. They are listed in Table 1. It should be noted that a new design type has been added for operation in 2015, characterised by the addition of beam position monitors (BPMs) embedded in the collimator jaw [4, 5].

In IR3 (momentum cleaning) and IR7 (betatron cleaning) a three-stage hierarchy relies on primary (TCP) and secondary (TCSG) collimators and on shower absorbers (TCLAs). These insertions are designed to catch the primary beam losses from transverse and off-momentum losses. In front of each experiment, tertiary collimators (TCTP) protect the inner triplets from incoming-beam losses and optimise the detector background. In the high-luminosity IR1 and IR5, physics debris collimators (TCLs) are used to protect matching sections and downstream arcs from collision products. IR2 and IR8 also house injection protection devices (TCLIA and TCLIB). In IR6, secondary collimators with embedded BPMs (TCSPs) are used. Other movable collimators not under the responsibility of the collimation project are the injection (TDI) and dump (TCDQ) protection blocks.

Table 1: Collimator types and main characteristics. The types highlighted in blue are equipped with button BPMs. It should be noted that TDI and TCDQ are listed for the sake of completeness, but they are not treated in the present work as they are not under the responsibility of the LHC collimation project. Contrary to all the other devices, the jaws of these last two types of collimators consist of segments of different absorbing materials (hBN stands for hexagonal Boron Nitride).

| **Name** | **Design type** | **Length** [m] | **Mat.** | **IP** | **Num.** |
|---|---|---|---|---|---|
| TCP | TCP | 0.6 | CFC | 3/7 | 8 |
| TCSG | TCSG | 1 | CFC | 3/7 | 30 |
| TCSP | TCSP | 1 | CFC | 6 | 2 |
| TCLA | TCLA | 1 | W | 3/7 | 18 |
| TCL6 | TCLA | 1 | W | 1/5 | 4 |
| TCL4/5 | TCLP | 1 | Cu | 1/5 | 8 |
| TCTP | TCTP | 1 | W | 1/5/ 2/8 | 16 |
| TCLIA | TCLIA | 1 | Gr | 2/8 | 2 |
| TCLIB | TCSG | 1 | Gr | 2/8 | 2 |
| TDI | TDI | 4.2 | hBN, Al,Cu | 2/8 | 2 |
| TCDQ | TCDQ | 9.5 | Gr,Al | 2/8 | 2 |

It is proposed to group the collimator families in BLM threshold families, listed in Table 2. This allows reducing further the number of families compared to Table 1 by grouping collimators in sets of equivalent robustness levels. It is assumed that:

1. the design with the in-jaw BPMs has the same robustness as the design with the same materials but without BPMs; consequently, threshold families can be set to the same values at start-up, i.e. TCSG_THR and TCSP_THR, even though TCSPs are more sensitive than TCSGs since they are tapered with Glidcop, and TCLA_THR and TCTP_THR;
2. Gr and CFC have the same robustness for the scope of BLM thresholds for circulating beams[1];
3. the two-in-one TCLIA design has the same robustness of the single-beam collimators TCLIB and TCSG.

## COLLIMATION PROTECTION THRESHOLDS

BLMs are installed in the vicinity of sensitive LHC equipment [6]; they issue a beam dump request in case the

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[1] The injection protection collimators are moved out of the beam, close to full-out positions, before the start of the ramp. So, during standard operation they do not risk of being hit by high energy beams.

Table 2: Proposed collimator BLM threshold families. Devices of Table 1 are grouped in sets with equivalent damage limits. The TDI and the TCDQ collimators are not present as they are not under the responsibility of the LHC collimation project.

| **Name** | **Device list** | **Properties** | **Num.** |
|---|---|---|---|
| TCP_THR | TCP IR3/7 | CFC/0.6 m | 8 |
| TCSG_THR | TCSG IR3/7,<br>TCLIA/B IR2/8 | CFC/1 m | 34 |
| TCSP_THR | TCSP IR6 | CFC/1 m/BPM | 2 |
| TCLA_THR | TCLA IR3/7,<br>TCL6 IR1/5 | W/1m | 22 |
| TCTP_THR | TCTP IR1/2/5/8 | W/1m/BPM | 16 |
| TCL-Cu_THR | TCL4/5 IR1/5 | Cu/1m | 8 |

readout exceeds a pre-defined threshold. Each BLM is assigned a set of threshold values, which are functions of the beam energy and are defined for twelve integration times (called “Running Sums”, RSs), in order to protect the machine over a wide range of loss mechanisms. The collimator BLMs are also connected to the dump system and can trigger beam aborts for all twelve RSs. Thresholds must be set to prevent losses above the damage limits of collimators and of surrounding accelerator equipment.

The choice of proper BLM thresholds at LHC collimators is based on the allowed number of protons impacting the jaw and the signal induced in the BLM per impacting proton. Values are set for the primary collimators, as they are the aperture bottleneck of the machine during regular operation and they are hit as 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 multistage cleaning is well respected during the standard LHC operation.

The thresholds for the other collimators are derived by means of scaling factors, which take into account jaw material and presence of nearby sensitive equipment. The scenario of the machine operating at top energy is the reference one; for all other energies, thresholds are obtained by linearly scaling those at flat top.

The number of protons allowed to impact a primary collimator is based on the design loss rates of protons, reported in Table 3 [1]. As it can be seen, primary collimators should withstand continuous beam losses for 100 kW (steady-state) and tolerate drops of the beam lifetime to 0.2 h (corresponding to ~500 kW of primary beam losses, at 7 TeV), for at most 10 s, at top energy. The latter represents the most demanding scenario, and exceeding this value might induce permanent deformation of the collimators most exposed in IR7, i.e. the secondary ones immediately downstream of the TCPs that intercept the largest fractions of the showers out-scattered from the primary. Note that the 100 kW scenario can be dealt with by the system without permanent damage for long times. Exceeding this value might induce dynamics deformations of the jaw that might ultimately result in an extremely poor cleaning performance and even in quenches. Consequently, exceeding the 100 kW steady loss scenarios should also be avoided[2]. Nevertheless, the possibility of handling higher steady state losses should be further studied, in case it is required by the LHC operation. It should be kept in mind that if primary beam losses largely exceed 100 kW, the jaw temperature significantly increases, with consequent high outgassing, potentially overcoming vacuum specifications.

Table 3: Maximum allowed loss rates, as specified in the LHC design report [1], over 10 s and for continuous (cont.) losses.

| **Mode** | $T$ [s] | $\tau$ [h] | $R_{\text{loss}}$ [p/s] | $P_{\text{loss}}$ [kW] |
|---|---|---|---|---|
| Injection | cont. | 1.0 | $0.8 \times 10^{11}$ | 6 |
|  | 10 | 0.1 | $8.6 \times 10^{11}$ | 63 |
| Ramp | ≈1 | 0.006 | $1.6 \times 10^{13}$ | 1200 |
| Top energy | cont. | 1.0 | $0.8 \times 10^{11}$ | 97 |
|  | 10 | 0.2 | $4.3 \times 10^{11}$ | 487 |

Amongst the nominal design loss rates (see Table 3), the peak loss rate is at the start of the ramp, when the beam lifetime was expected [1] to drop down to 20 s in the first seconds of the ramp and up to ~5% of the total beam intensity was expected to be uncaptured beam. During Run I, beam lifetimes at the start of the ramp were dropping down to a few hours [7], with consequent much lower loss rates at this moment during the LHC cycle.

## CALCULATION OF PROTON IMPACT LIMIT FOR TCP

Figure 2 shows the BLM thresholds for TCP collimators expressed in number of 7 TeV protons allowed as a function of integration time of losses. Two curves are compared, i.e. the one used to set BLM threshold for Run I and the one proposed for Run II. For both cases, values were calculated by looking at different regimes of the material response to energy deposition, but while for the former only the two regimes identified by the design loss rates (reported in Table 3) were taken into account, for the latter more refined energy deposition and thermo-mechanical analyses were performed, which are here briefly explained.

In the steady-state scenario ($t$ >10 s), the power loss on the collimator is calculated for a beam life time of one hour (see Table 3). This corresponds to about 100 kW distributed on the whole collimation system, after initial im-

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[2] Presently, the machine is being operated with a collimator setting hierarchy more relaxed than the nominal one. Thus, the system is less sensitive to hierarchy problems so larger dynamics deformation than in the design case could be tolerated.

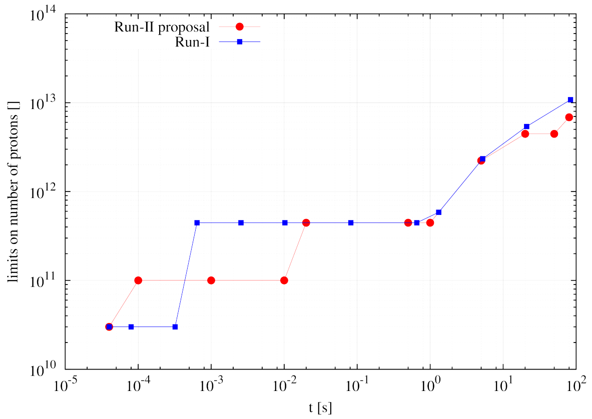

Figure 2: Limits on the number of 7 TeV protons impacting on TCP collimators as a function of BLM integration time.

pact on the TCPs. In the following, we will consider the effects on the downstream TCSGs that are actually more affected than the TCPs themselves.

The temperature increase in different points of a collimator can then be calculated through Fourier's law

$$\dot{Q} = -k\nabla T, \tag{1}$$

where $\dot{Q}$ is the thermal flux, $k$ the thermal conductivity of the material and $T$ the temperature. According to specifications [8] (see also Table 3), the temperature on the collimator should be low enough to satisfy the following requirements:

- Maximum flatness tolerance in operation remains below 100 $\mu$m. This includes manufacturing tolerance (accounting for 40 $\mu$m), self-weight deflection for vertical and skew collimators (accounting for 30 $\mu$m) and thermally-induced deformations (accounting for 30 $\mu$m). As shown in Fig. 3, a TCSG jaw heating which is eccentric with respect to the neutral axis leads to a jaw deflection in the order of 20 $\mu$m in the nominal case.
- Vacuum compatibility: the maximum average temperature of the TCSG jaw should not exceed 50°C to limit major outgassing in IR7.

Another regime is found for time $t \leq 10$ s. In this case, the threshold has been adjusted to take into account an accidental case generating a thermal power 5 times higher than nominal, lost on the collimator for a maximum duration of 10 s. In this case, the system does not reach thermal steady-state conditions, and a transient analysis is necessary to evaluate the temperature increase on the jaw. The requirement in this scenario is to avoid any plastic deformation of the component.

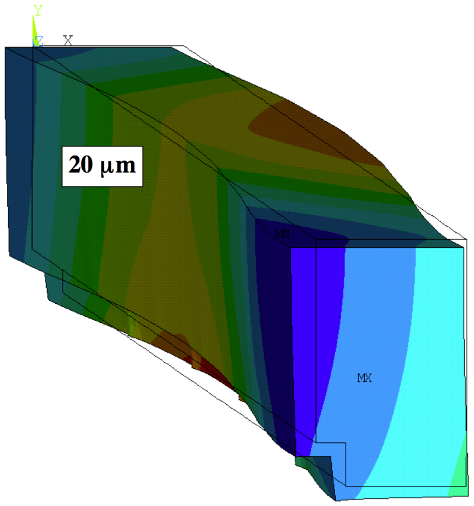

Figure 3: Deformation of the CFC collimator jaw under thermal loads in nominal conditions of loss rate scenario of 100 kW (slow-loss scenario with 1 h beam lifetime).

A third regime can be identified for times between $10^{-2}$ s and 1 s. Here, given the fast energy deposition, the thermal diffusion can be ignored (conservative approach) and the maximum temperature $T_f(x)$ of the component in position $x$ becomes

$$q_V(x) = \int_{T_i}^{T_f(x)} \rho \cdot c_p(T) \cdot \mathrm{d}T, \tag{2}$$

where $q_V$ is the energy per volume, $\rho$ is the density, $c_p$ the specific heat of the jaw material and $T_i$ the initial temperature. In this case, the problem is driven by the energy deposited and not by the power loss. For this reason, Fig. 2 shows a *plateau* in the acceptable number of protons versus time in this regime. The design is done to avoid plastic deformation of the components under this load. It is useful to note that even tighter conditions in terms of collimators losses were successfully tested in 2013 during LHC quench tests at 4 TeV [9].

Finally, in the fourth regime (i.e. for $t < 10^{-4}$ s), the energy is deposited so rapidly in the jaw that dynamic stresses are induced on the component. The maximum amplitude of dynamic stresses can be up to three times higher than the static stress [10]. The BLM threshold has been modified accordingly.

The last point of the proposed curve for Run II shown in Fig. 2, i.e. at $t = 40$ $\mu$s, considers the same loss scenario as that of the last three points in the Run I curve, i.e. a sudden drift of the closed orbit due to a magnet failure and the consequent direct impact of protons onto the jaw of a TCP [11]. The BLM threshold is set to trigger the dump early enough during the onset of the loss.

It should be noted that the curve proposed for Run II and shown in Fig. 2 is different from the one deployed during Run I not only for regimes in time lower than 1 s, but also for steady state.

As discussed above, the thresholds are first calculated for TCP collimators, taking into account the collimation hierarchy and the distribution of losses at the most exposed devices downstream of the TCP. For example, a factor 10 reduction of allowed proton losses was applied during Run I for the calculation of TCSG thresholds. Even if their robustness is comparable to that of the TCP, this factor was applied since elements further downstream might be exposed to high losses, in particular if a collimator downstream of the cleaning insertion is hit [12].

In order to scale the threshold values to different collimator families, the robustness of other jaw materials is compared to that of CFC through figures of merit. In particular, an index, called Thermo-mechanical Robustness Index (TRI), is proposed to assess the material robustness against particle beam impacts [13]. Larger TRI values indicate a better resistance to fast energy depositions. This factor is defined as

$$\mathrm{TRI} = \frac{R_M c_p X_g}{\bar{E}(1-\nu)\bar{\alpha} C_R \rho^n} \cdot \left( \frac{T_m c_p X_g}{C_R \rho^n} - 1 \right)^m , \qquad (3)$$

where $R_M$ is the ultimate strength, $X_g$ the geometric radiation length, $T_m$ the melting temperature, $m$ is a coefficient related to the material loss of strength with temperature increase. These terms at the numerator characterise the material robustness. The properties at the denominator are detrimental for the material resistance: $E$ is the Young's modulus, $\nu$ is Poisson's coefficient, $\alpha$ the coefficient of thermal expansion, $C_R$ an arbitrary scaling factor and $n$ a coefficient expressing the influence of density on the energy distribution generated by the impact. Values with bar $(\bar{E}, \bar{\alpha})$ indicate the average along 3 dimensions, for anisotropic materials or composites. The TRI values for relevant LHC collimator materials, which drove the choice of thresholds material factors introduced in the previous section, are reported in Table 4. Table 5 lists the material factors deployed to set Run I BLM thresholds at non-TCP collimators, and those proposed for Run II, which come from Table 4 rounding in a conservative way.

Table 4: TRI factor as computed from Eq. (3) for the present collimator materials.

| **Material** | **TRI factor** |
|---|---|
| CFC | 1200 |
| Inermet (W heavy alloy) | 0.5 |
| Cu-OFE (annealed) | 0.9 |

Table 5: Material factors for setting BLM thresholds at non-TCP collimators. The Table reports values for both Run I (as used) and Run II (as proposed).

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

## PROPOSAL OF COLLIMATOR THRESHOLDS FOR RUN II AT 6.5 TeV

For the LHC Run II, which started with commissioning with beam in April 2015, it has been agreed [14] to initially deploy the BLM thresholds as at the end of Run I, keeping the existing BLM threshold collimator families, in order not to lose memory of the changes required by past LHC operation. This implies that the energy scaling at the end of Run I, characterised by operation-optimised values at 4 TeV (see Introduction), is adopted. This decision is based on the fact that, using the same collimator settings (in mm) as the 2012 ones, the beam-based BLM thresholds from 2012 are representative of the 2015 case. Moreover, the intensity ramp up at the beginning of the LHC Run II after a long shutdown leaves time to learn before reaching very high stored beam energies. It is planned to deploy the new thresholds as presented here during one of the LHC technical stops. As already mentioned, the applied BLM thresholds at collimators have been set based on qualification Loss Maps (LMs), hence adapting the thresholds to the pattern of losses actually taking place in IR7. This scaling has also the advantage of minimising the number of spurious dumps due to losses below design limits of the collimation system. In the meanwhile, simulations are being carried out to better characterise the relation between energy deposition in the collimator jaw and BLM signal recorded, to be used for the final establishment of BLM thresholds at collimators. It should be noted that the final calculation of BLM thresholds will also include the scaling by LMs.

## BEAM-BASED COLLIMATOR THRESHOLDS

LMs are used to qualify the LHC collimation system. In particular, the betatron cleaning system in IR7 is qualified inducing controlled betatron losses by means of a beam blow up of one beam (B1/2) and plane (horizontal/vertical) at a time. The loss pattern thus generated is recorded and its consistency with the functional hierarchy of the different collimator families is verified. In general, the beam excitation lasts for some seconds, and the BLM signals used for generating the LMs are those from RS09, i.e. with 1.3 s integration time.

When using qualification LMs for setting new BLM thresholds, the signal at each BLM (for a given LM) is scaled by the factor $P_{\mathrm{tgt}}/P_{\mathrm{LM}}$, where $P_{\mathrm{LM}}$ is the beam power loss during the LM and $P_{\mathrm{tgt}}$ is the target beam power loss set as limit. For each BLM family, the highest scaled signal among the four LMs is used as new BLM threshold.

Figure 4 shows an example of such a scaling, in particular the case of exciting the B1 on the horizontal plane. The BLM system was conceived such that the "Applied Thresholds" (ATs) operationally used are obtained as product of a "Master Table" (MT$(E,t)$), listing the BLM thresholds of a given BLM family for each integration time $t$ and beam energy level $E$, and a "Monitor Factor" ($\mathrm{MF}_i$)

$$\mathrm{AT}_i(E,t) = \mathrm{MT}(E,t) \times \mathrm{MF}_i.$$

The $\mathrm{MF}_i$ is unique to each BLM $i$, and ranges between 0 and 1, allowing some flexibility in setting the ATs based on local variations. Given the integration time of RS09 (i.e. 1.3 s) used for the LMs, the 500 kW figure is taken as target beam loss power for scaling the MTs; setting MF=0.4 at all the collimators, an operational limit of 200 kW is set as AT instead of the 500 kW figure, to be then raised following the LHC intensity ramp up, when needed.

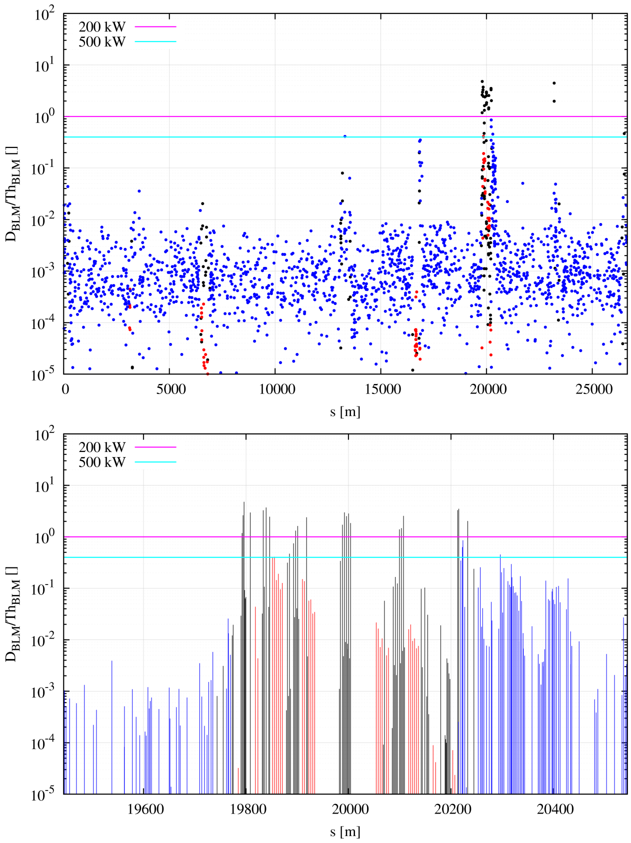

Figure 4: Scaling BLM signals from LMs to target power losses. Upper frame: overview over the whole LHC. Lower frame: zoom on IR7. The case of exciting B1 on the horizontal plane is shown.

It has been decided [15] to scale thresholds only at flat top, i.e. 6.5 TeV, and only those for "long" RS, i.e. with integration times comparable to 1 s, following the same philosophy as the one of the update in 2012 [2, 3], based on operational experience. Figure 5 shows an example of updated AT for the BLM threshold family of TCP collimators. Details about the other existing BLM threshold collimator families and other families involved in the scaling can be found in [16].

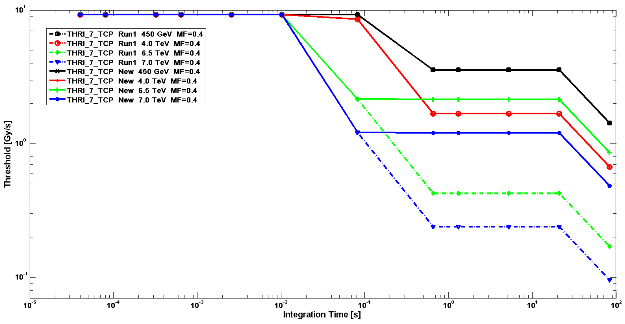

Figure 5: Updated AT [16] for the BLM threshold family of the TCP collimators.

## CONCLUSIONS AND OUTLOOK

In the beginning of the LHC Run II, the BLM threshold settings at the LHC collimators are the same as those at the end of Run I. Thus, the operation-optimised thresholds at 4 TeV and their energy scaling are deployed. This decision is based on the fact that, using the same collimator settings (in mm) as the 2012 ones, the beam-based BLM thresholds from 2012 are representative of the 2015 case and the intensity ramp up at the beginning of the LHC Run II leaves time to learn before reaching very high stored beam energies.

A follow up has been presented in this paper, based on simulation studies, measured loss patterns in machine and operational experience. In particular, a scaling of the present thresholds to loss patterns as measured in the machine has already been applied; on the contrary, a more refined curve of allowed proton losses for different time regimes of energy deposition and more accurate evaluations of material robustness will be implemented soon, in view of a full review of the BLM thresholds at the LHC collimators.

The full review of the BLM thresholds at LHC collimators will also include the estimation of energy deposition and BLM signals at selected collimators when these become primary. These studies are especially focussed on metallic collimators, in particular the copper and the Inermet ones (very little results are available for the former), for which little investigations have been carried out in the past. Moreover, the interest is also on the dependence of the thresholds on the beam energy. At present, this dependence is linear, whereas an hyperbolic behaviour could be expected (excluding the energy dependence of the BLM signal per single proton), allowing for 500 kW primary beam losses throughout the ramp. However, the updated function with beam energy should be of limited importance as it is difficult to have sustained steady losses over 10 s during the ramp. Nevertheless, this aspect needs to be quantified and studied.

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