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BLM SIGNAL THRESHOLDS FOR ION OPERATION DURING THE LHC RUN 3

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Abstract

In 2024, the Large Hadron Collider (LHC) delivered Pb-Pb ion collisions at a beam energy of 6.8 Z TeV with a stored beam energy of more than 20 MJ. In order to clean beam halo particles and avoid quenching the LHC superconducting magnets, the novel crystal collimation method employing 4 mm-long crystals was introduced for ion operation in the LHC Run 3. The LHC Beam Loss Monitoring (BLM) system triggers the beam dump in case the measured losses are above certain predetermined thresholds. Important adjustments were needed in order to optimize these thresholds in accordance with the peculiar loss pattern produced by crystal collimation. This contribution explains the newly observed beam loss patterns during Pb ion operation with crystal collimation in place, as well as the study that was carried out to update the BLM thresholds at the betatron collimation region for Pb ion operation in the LHC Run 3.

INTRODUCTION

Most of the operation of the LHC at CERN is aimed at accelerating and colliding proton beams. However, there are also scheduled periods for ion collisions, normally with Pb, typically of around one month every operational year [1].

The next major upgrade for CERN's flagship collider and its experiments, called High Luminosity LHC (HL-LHC), has the goal of increasing the LHC instantaneous luminosity beyond its design values [2]. For proton beams, HL-LHC operation is expected to begin in 2030, at the start of Run 4.

On the other hand, the HL-LHC upgrades for Pb ion operation were already implemented for Run 3, the present LHC operation period. These upgrades have resulted in more than a factor 6 higher instantaneous luminosity at the ALICE experiment, specialized in heavy-ion collisions [3]. This comes together with a stored beam energy reaching more than 20 MJ [4].

One of the main hardware upgrades concerned the LHC betatron collimation system, that was initially designed primarily for proton operation. This same system had been used for heavy-ion operation despite its cleaning being around 100 times less efficient in this case [5].

During Run 3 Pb ion operation, due to the increased stored beam energy, the particles escaping from the standard betatron collimation system would risk to quench the superconducting magnets located downstream. In order to mitigate this issue, it was decided to introduce a novel collimation method called "crystal collimation" that has been proven to reduce significantly the leakage to the aforementioned magnets down to acceptable levels for operation [6–8].

This new setup includes four crystal collimators, two per beam and plane; horizontal and vertical. If correctly aligned, halo particles are trapped in the potential well between crystalline planes and follow their bending. They hence exit the crystal with an angular kick and are "channelled" onto four different dedicated absorbers, creating completely different loss patterns compared to operation with the standard collimation system. However, if the alignment between the crystal and the beam changes such that the incoming particles are no longer trapped between the planes, the channelling conditions are lost, which increases the leakage to the downstream superconducting magnets.

In addition to the collimation system, the LHC BLM system actively protects the machine elements to avoid high energy deposition from beam losses by triggering the beam extraction when its recorded signals exceed certain predetermined thresholds [9]. For proton operation, the thresholds of the BLM detectors that are placed in the collimation areas are based on the specifications of maximum loss rates at the collimators and the expected loss patterns resulting from regular cleaning.

Run 3 Pb ion operation requires an adjustment of these thresholds not only due to the different loss patterns produced by crystal collimation, but also because the leakage to the downstream superconducting magnets is more critical. In this case, the BLM thresholds at the collimators must constitute an extra layer of protection for the magnets. This means that the allowed beam power loss at the collimators must adapt to the mode of interaction of the halo particles with the crystals at all times, posing a challenge to the management of the BLM signal thresholds.

This contribution describes the main differences between the beam loss patterns recorded at the LHC betatron collimation system in Run 3 for protons and Pb ions. The necessary updates and BLM signal thresholds strategy for Pb ion operation are explained.

LHC COLLIMATION SYSTEM

In order to clean the beam halo particles and prevent them from hitting the vacuum chamber at the superconducting regions, the LHC has a betatron collimation system that intercepts the beam losses with very high efficiency, minimizing the leakage to the superconducting magnets.

Standard Betatron Collimation System

The standard betatron collimation system comprises an arrangement of so-called Target Collimator Primary (TCP) and Target Collimator Secondary (TCS) collimators. Each collimator is composed of two parallel blocks, typically

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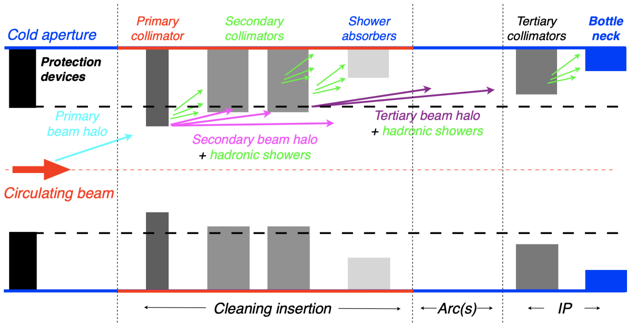

Figure 1: Key elements and arrangement of the LHC standard collimation system, used for proton operation [10].

between 0.6 to 1.2 m long, that are called collimator jaws and that define a variable gap through which the beams circulate [10].

The jaws of the TCPs are set at a transverse aperture below that of the machine bottleneck, intercepting the primary impacts from beam halo particles. The particles that are scattered leave at larger transverse amplitudes and with different energies, conforming the so-called secondary beam halo which is intercepted by the TCSs, set at a larger aperture than the TCPs. Additional absorbers are installed to minimize the hadronic and electromagnetic showers that are produced from the interaction between the halo particles and the collimators. The key elements and arrangement of the LHC multi-stage collimation system are shown in Fig. 1.

Crystal Collimation System

The LHC standard collimation system manages to reduce the leakage to downstream superconducting magnets down to acceptable levels for proton operation, and it is expected to suffice even for HL-LHC. However, it is not the case for Pb ion operation. This is due to ion fragments with different charge-to-mass ratios that are generated and scattered out of the collimators, making the cleaning process more challenging than for protons [5].

A novel collimation system for heavy-ion operation was introduced to mitigate this issue. Its concept relies on planar channelling, a phenomenon where positively charged particles hitting a crystal with specific impact conditions get trapped in the electrostatic potential generated by the adjacent crystalline planes. This causes the particles to follow the "channel" along the full crystal length and experience a net deflection if the crystal is bent. Nuclear interactions with well-aligned crystals are also much reduced compared with a TCP, lowering the probability of ion dissociation and fragmentation.

The illustrative layout for the LHC crystal-based collimation scheme is shown in Fig. 2. In this system a bent silicon crystal, called Target Collimator Primary Crystal (TCPC), acts as a primary collimator for each cleaning plane, horizontal and vertical. It is placed at the edge of the circulating beam and oriented so that the crystalline planes at the TCPC entry face are aligned to the direction of the individual halo particles at that amplitude. Halo particles are then channelled by the TCPC and deflected directly onto a standard TCS which serves as a halo absorber.

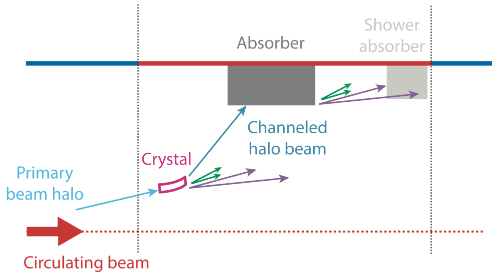

Figure 2: LHC crystal-based collimation layout [10].

During Pb ion operation, the TCPCs are inserted closer to the beam, providing an improved cleaning, while the TCPs are retracted to the level of the TCSs, maintaining protection in case of failures. During proton operation, the TCPCs are retracted to parking position.

In addition to channelling, other physical processes can occur in the TCPC. For larger incoming angles, particles may be reflected by the crystalline plane. This is called volume reflection. Outside the ranges for channelling and volume reflection, the TCPC acts as an amorphous material. Therefore, it is important to keep the channelling conditions to guarantee the correct operation of the setup.

LHC BLM SYSTEM

The LHC BLM system complements the machine protection functionality of the collimation system. It consists of around 3 600 ionisation chambers distributed all along the LHC, downstream the most likely loss locations.

Their signal is acquired every 40 µs by the tunnel electronics. The resulting values are sent to the surface electronics, where 12 longer moving integration windows are produced for each signal. These are called Running Sums (RS), and they range from 40 µs up to approximately 83.8 s. These data are stored at a minimum rate of 1 Hz in units of Gy/s.

BLM Signal Thresholds

Each BLM detector is assigned a set of threshold levels which is a function of various factors, notably the energy of the beam, the duration of the losses and the element that the detector is protecting. If the BLM detector signal is eventually above one of these thresholds during operation, a beam dump is requested.

These values are specified such that machine protection is ensured without affecting the operational efficiency of the LHC, avoiding unnecessary beam dump requests, during which the machine components are not actually at risk.

In practice, BLM detectors protecting the same elements and with similar signal responses are grouped in families with the same Master Thresholds (MT) [11]. Each family implements BLM threshold values for each RS and each energy level, making it a total of 384 different values per family.

However, the final BLM thresholds for a particular detector can still be tuned with a so-called Monitor Factor (MF), that can vary between 0 and 1. The Applied Thresholds (AT) are then built as the multiplication of the MT and the MF.

For BLM detectors placed at superconducting elements, the main goal is to prevent quenches. For BLMs protecting elements at room temperature, like the collimators, the main goal is to prevent damage due to energy deposition from beam losses and to maintain the losses below the collimation system specifications. In all cases, a safety margin is left for the chosen MT. The BLM threshold at a collimator can then be expressed as:

$$\mathrm{BLM}_{\mathrm{threshold}}(E,t) = \mathrm{BLM}_{\mathrm{resp}}(E,t) \times \mathrm{DL}(E,t), \qquad (1)$$

where DL is the design limit expressed as the maximum number of protons allowed to be lost in the entire collimation system, and $\mathrm{BLM}_{\mathrm{response}}$ is the BLM response to collimation losses, i.e., expected BLM signal per proton lost in the entire collimation system. E and t account for the different energies and loss durations or RS [12].

For Run 3, the MT at the betatron collimators were set to an equivalent power loss of 500 kW for proton operation. For the case of ion operation with crystal collimators, the goal is to provide the necessary machine protection without limiting operation both when crystals are operating in optimal channelling or in amorphous/volume reflection orientation. Due to the higher leakage to the superconducting magnets, the allowed power loss at the betatron collimators must be at least one order of magnitude below. More details are given in following sections.

COLLIMATION LOSS MAPS

In order to understand the BLM threshold changes required at the collimators, the first step is to analyse the crystal collimation loss patterns recorded during the collimation loss maps.

The collimation loss maps are beam tests that are performed to analyse the distribution of beam losses in the LHC when generating betatron losses in a safe and controlled way on a low-intensity beam. The primary purpose of these loss maps is to verify the selection of the collimation settings, making sure that the collimation hierarchy is respected. The data gathered during these tests are also used to determine the cleaning inefficiency of the collimation system and identify loss locations that may not have been foreseen in simulations.

Betatron loss maps are generated by slowly exciting circulating low-intensity bunches using the transverse damper [13]. This device adds white noise to the beam horizontally or vertically in a gated window that can be selected according to the chosen bunch. This is done independently for both beams and planes. The beam is excited until beam losses are observed in the BLM detectors in the superconducting regions downstream the betatron collimation region, or when the bunch is lost completely.

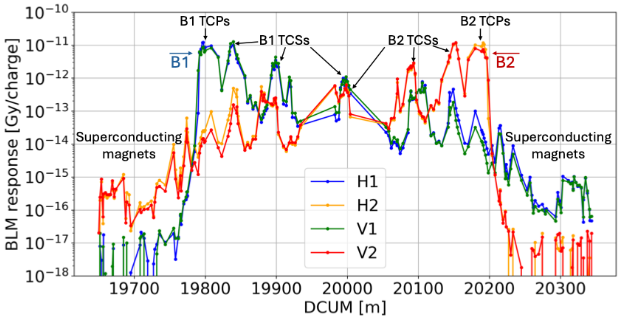

Figure 3: BLM responses at the betatron collimation region measured during betatron loss maps using the standard collimation system with protons at top energy.

The BLM response that is used for the BLM MT at the collimators is based on the collimation loss maps. For that reason, it depends on the collimator settings, as different loss patterns will lead to different BLM responses.

For the calculation of these responses, the BLM signal is integrated for the duration of the loss map, and divided by the total beam intensity lost, as measured by a Beam Current Transformer. Therefore, it is measured in Gy/charge.

Protons with Multi-Turn Collimation System

During a loss map with the standard betatron collimation system, it is expected that the primary impacts will happen on the horizontal or vertical TCP, respectively. A shower of particles is created boosted in the beam direction, generating a signal in the BLM detectors around, with the secondary beam halo impacting on the TCSs.

Figure 3 shows the measured BLM responses at the betatron collimation region during a set of betatron loss maps at top energy with protons, using the standard betatron collimation system. The blue dots indicate the BLM responses recorded during the horizontal loss map with Beam 1 (B1), which circulates clockwise, while the responses recorded during the vertical B1 loss map are indicated in green. On the other hand, the BLM responses recorded during the horizontal and vertical Beam 2 (B2) loss maps are shown in yellow and red, respectively. The x-axis indicates the position of the BLM detector in the LHC, with DCUM (Distance Cumulated) being equal to zero at the centre of the ATLAS detector, and increasing clockwise along the tunnel, reaching 27 km when completing the circumference.

In the figure, B1 is travelling from left to right, while B2 is going from right to left. The positions of the TCPs and TCSs and are indicated, as well as the closest superconducting magnets.

The highest BLM responses, in the order of 10^{-11} Gy/charge, appear at the TCPs and the first TCSs. The responses at the first superconducting magnets downstream reach a maximum of between 10^{-14} and 10^{-13} Gy/charge, more than two orders of magnitude below. The observed beam loss patterns for horizontal and vertical

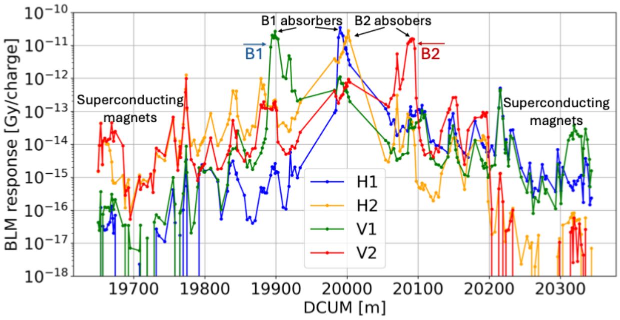

Figure 4: BLM responses at the betatron collimation region measured during betatron loss maps using the crystal collimation system in optimal channelling with Pb ions at top energy.

loss maps are similar for each beam, differing slightly only around the TCPs.

Pb Ions with Crystal Collimation System

In the case of Pb ion loss maps, the horizontal or vertical blow-up is expected to generate more particles to be channelled by the horizontal or vertical TCPC onto its designated absorber, respectively.

Figure 4 shows the measured BLM responses at the betatron collimation region during a set of betatron loss maps at top energy with Pb ions, using the crystal collimation system in optimal channelling. Observe that the highest responses are not recorded at the TCPs, but downstream the TCSs that are acting as absorbers for each one of the TCPCs. In this case, the highest BLM responses recorded are above 10^{-11} Gy/charge. The BLM responses at the superconducting magnets reach a maximum of between 10^{-13} and 10^{-12} Gy/charge, and they are consistently around one order of magnitude higher with respect to the case of protons.

Figure 5 shows the measured BLM responses at the betatron collimation region during a set of betatron loss maps at top energy with Pb ions, using the crystal collimation system in amorphous. Observe that, due to the worse cleaning, the highest responses can occur at the first superconducting magnets (in cell 6) instead of the collimators, reaching more than 10^{-11} Gy/charge. The magnets placed in this location operate at higher temperature than the rest, 4.5 K instead of 1.9 K, making this higher response acceptable. The rest of BLM responses at the superconducting magnets are also consistently around one order of magnitude higher with respect to the operation with TCPCs in optimal channelling.

The responses measured with the TCPCs operating in volume reflection are very similar to the case of amorphous.

BLM THRESHOLD CHANGES AT THE BETATRON COLLIMATION REGION

A beam test was performed in 2015 with Pb ions and the standard betatron collimation system. The aim was to probe the quench limit from collimation losses of the downstream superconducting magnets [14]. During the test, a quench was achieved at a peak beam power loss of 15 kW at the betatron collimation system.

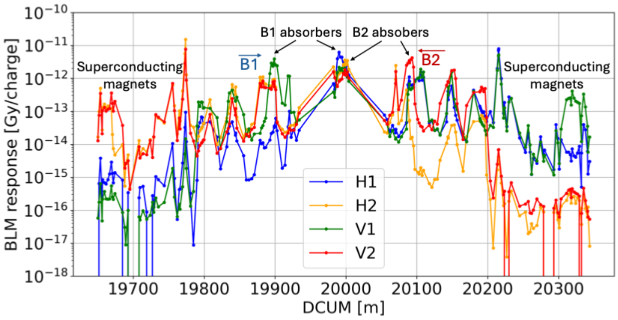

Figure 5: BLM responses at the betatron collimation region measured during betatron loss maps using the crystal collimation system in amorphous with Pb ions at top energy.

Several BLM detectors placed at superconducting magnets reached higher signals during this test than the current proton BLM MT without quenching. For this reason, it was proposed to increase the MT at those BLM detectors for Run 3 Pb ion operation to the measured signals during the test.

A different strategy was followed to adjust the BLM thresholds at the collimators. With the crystals operating in optimal channelling, energy deposition simulation studies predict that a quench could occur following a power loss of between 30 and 50 kW [15]. When operating in volume reflection or amorphous orientation, the quench limit is expected to be around 4 times lower, as the leakage to the superconducting magnets increases.

Following this, it was decided to set the BLM MT at the betatron collimation system for Pb ion operation in Run 3 to limit at a power loss of around 60 kW when the crystals are in optimal channelling, and starting with a MF of 0.6, so that the AT allow up to 36 kW losses during operation [16], thus close to the quench level. This setup was agreed so that there would be margin to increase the AT if needed given that no quench was observed. In case of a quench, the MF would be lowered [17].

For the cases of amorphous and volume reflection, the MT were set to limit at a beam power loss of around 15 kW, with the equivalent AT allowing up to 9 kW losses. This is the first time that the LHC BLM thresholds are set to protect for two different beam power limits in the same collimation region.

In order to apply these changes, the BLM MT in each crystal configuration were calculated using Eq. (1). The resulting values were compared with the BLM thresholds for proton operation, using the following expression:

$$\text{Factor}(E,t) = \frac{\text{BLM MT Pb Ions}(E,t)}{\text{BLM MT Protons}(E,t)}, \tag{2}$$

where BLM Threshold Pb is the intended Pb ion BLM threshold and BLM$_{\text{threshold}}$ is the proton BLM threshold for that detector.

If this factor is above 1 for a BLM detector in any of the TCPC configurations, it is moved to a new BLM fam-

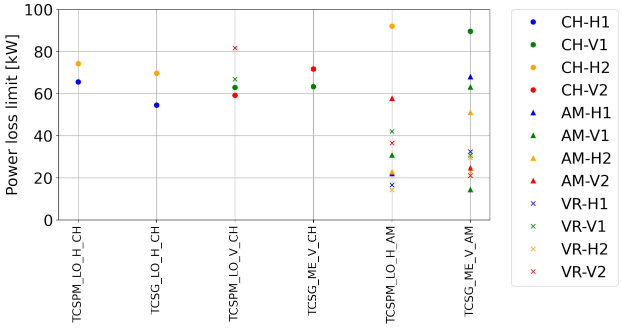

Figure 6: Power loss at which the dedicated Pb ion BLM thresholds families for protection would limit for each one of the analysed loss maps with crystal collimation.

ily together with other BLM detectors that need a similar increase. The thresholds in this new family are multiplied by the highest factor out of all the BLM detectors in it.

At the same time, selected BLM detectors that were found to limit only in one of the configurations were put in dedicated BLM thresholds families for protection, having at least two detectors per beam to cover the horizontal and vertical losses for the channelling case, and one detector per plane for the amorphous and volume reflection cases.

The number of these dedicated families is kept short in order to minimize the machine protection impact and optimize the implementation of the changes, which must happen as soon as possible after the start of Pb ion operation, shortly after the validation loss maps are performed. The final chosen factors in each family are a compromise between the needed factors of all the BLM detectors belonging to it. It is ensured that there are enough families to allow for the protection on channelling, amorphous and volume reflection collimation.

Figure 6 shows the power loss at which the dedicated Pb ion BLM thresholds families for protection would limit for each one of the analysed loss maps with crystal collimation. CH is for optimal channelling, AM for amorphous and VR for volume reflection. The name of each family identifies the beam loss scenario and the collimator type monitored.

Even though this contribution is focused on RS09 (around 1.3 s integration time) values at top energy, the same analysis is performed for all the RS and at injection energy.

In order to verify that the thresholds are correctly set, the beam power loss during operation was followed up closely. As an example, Fig. 7 shows the peak power loss for all 2024 Pb ion fills around the moment that the beams are brought into collision, the most critical in terms of losses at the betatron collimators.

The limits set for the channelling and amorphous/volume reflection regimes for operation are included. The cases that led to beam dumps are indicated with crosses. Note that during the first days of operation the peak power loss is higher, reaching values above 1 kW. This is due to beam tests and tuning of settings. During standard operation, the peak power loss is generally below 0.1 kW, increasing slightly as the circulating intensity does.

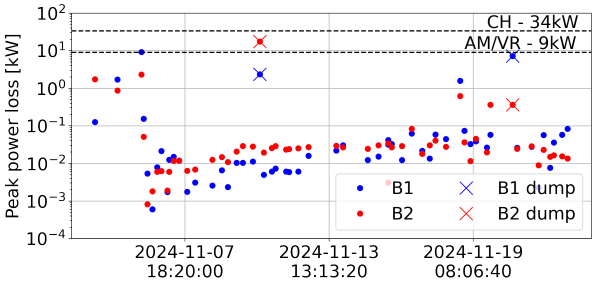

Figure 7: Peak power loss around the moment that the beams are brought into collision during the 2024 Pb ion operation.

There were only two beam dumps due to beam losses at this moment of the cycle. The first one, at a power loss of around 18 kW in B2, and the second one at a power loss of around 8 kW in B1. A beam loss pattern recognition algorithm using BLM signals, described in [18], was used to estimate the fraction of losses happening in each crystal configuration. It was found that in the first case, which occurred following a beam instability, around 14 kW was lost with the beam halo hitting the crystals in channelling conditions, while the rest of the losses occurred with a different angle, out of the channelling conditions. This would explain the dump at around half the expected limit for pure channelling losses. For the second case all of the losses occurred with the crystals out of channelling, during a loss map. This confirms that the BLM thresholds at the betatron collimation region were indeed adjusted to the intended values. There were no other beam dumps due to losses at the betatron collimators and no additional changes were required for the BLM thresholds in this region during 2024 Pb ion operation.

CONCLUSION

Pb ion operation during LHC Run 3 has seen an increase of instantaneous luminosity and stored beam energy, following the upgrades for HL-LHC. The betatron collimation system had to be updated in order to reduce the leakage to downstream superconducting magnets, that would risk quenching. This was done with the introduction of crystal collimators that send the halo particles to dedicated absorbers when they are in optimal channelling, creating new beam loss patterns, completely different to those generated by the standard collimation system. The BLM signal thresholds at the collimators are based on the BLM signals measured during the collimation loss maps. Therefore, they had to be adjusted to ensure protection and allow Pb ion operation following the change in regular beam loss patterns, also when the crystal collimators lose the channelling conditions. These new thresholds in the betatron collimation region performed as expected during 2024 operation and no further changes were required.

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