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PERFORMANCE OF THE COLLIMATION SYSTEM DURING THE 2018 LEAD ION RUN AT THE LARGE HADRON COLLIDER

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Abstract

As part of the Large Hadron Collider (LHC) heavy-ion research programme, the last month of the 2018 LHC run was dedicated to Pb ion physics. Several heavy-ion runs have been performed since the start-up of the LHC. These runs are challenging for collimation, despite lower intensities, because of the degraded cleaning observed compared to protons. This is due to the differences of the interaction mechanisms in the collimators. Ions experience fragmentation and electromagnetic dissociation that result in a substantial flux of off-rigidity particles that escape the collimation system. In this paper, the collimation system performance and the experience gained during the 2018 Pb ion run are presented. The measured performance is compared with the expectation from the Sixtrack-FLUKA coupling simulations and the agreement discussed.

INTRODUCTION

At the CERN Large Hadron Collider (LHC) [1], proton and heavy-ion beams are broght in collisions for high-energy physics experiments. The most recent Pb-Pb collision run took place in 2018, in which $^{208}Pb^{82+}$ ion beams were accelerated to an energy of 6.37 Z TeV [2]. The stored beam energy reached was 13.3 MJ, which is well above the design value of 3.8 MJ [3] and what was previously achieved in Run 2 [4].

The $^{208}Pb^{82+}$ion runs are challenging for collimation despite the lower stored energy reached in comparison to the 300 MJ reached by protons. This is because of the degraded cleaning observed for heavy-ions in comparison to protons throughout Run 2 [5] due to the fragmentation and electromagnetic dissociation (EMD) processes occurring at the collimators. In 2018, no magnet quenches were recorded due to slow losses from circulating beams, but 7 out of 48 fills were dumped by high losses in IR7 caused by orbit oscillations [6].

In this paper, the performance of the collimation system and the experience gained during the 2018 Pb ion run are presented. The measured performance is compared with the expectations from simulations of multi-turn cleaning processes. The understanding of the agreement between simulation tools and measurements is crucial for future operation, where even higher intensities are envisaged [7].

CLEANING PERFORMANCE

Off-momentum and betatron collimation systems are housed in two LHC Insertion Regions (IRs) [8–12], IR3 and IR7, to protect the LHC from normal and abnormal losses. Each system comprises a multi-stage hierarchy with primary (TCPs) and secondary (TCSGs) collimators, as well as absorbers (TCLAs). Tertiary collimators (TCTs), close to the experiments, protect the superconducting triplet magnets and reduce the background in the experiments. Two collimators per beam (TCSP, TCDQ) are installed in IR6 for dump protection.

Table 1: 2018 Physics Collimator Settings. L and R indicates the left and right jaw, respectively

Collimator	Beam	IR	Half-gap [σ]
TCP/TCSG/TCLA	B1	7	5.5(L)-5.0(R)/6.5/10
TCP/TCSG/TCLA	B2	7	5/6.5/10
TCP/TCSG/TCLA	B1/2	3	15/18/20
H TCTs	B1	1/2/5	11/9/9
H TCTs	B2	1/2/5	9/9/9
V TCTs	B1/2	1/2/5	9/9/9
TCTs	B1/2	8	15
TCDQ / TCSP	B1	6	7.4/7.4
TCDQ / TCSP	B2	6	7.4(L)-11.2 (R)
TCL.4/5/6	B1/2	1/5	15/15/out

During beam commissioning, the performance of the collimation system is validated through loss maps (LMs) before high-intensity beams are allowed. The betatron cleaning is checked by inducing transverse losses on a safe low-intensity beam, while the losses are recorded by the beam loss monitoring (BLM) system. Such LMs are done at several points in the LHC operational cycle [13, 14]. The collimator settings used for colliding beams, similar to the proton settings with a few exceptions, are summarised in Tab. 1.

Figure 1 shows the horizontal full ring LM (left) and the IR7 zoom (right) for Beam 1 (top) and Beam 2 (bottom) in collisions. Beam 1 goes from the left to the right while Beam 2 goes from the right to the left. The BLM signal is normalized by the highest measured signal and the losses are classified by their location as cold (blue), warm (red) or collimator (black). The highest cold losses are found in three clusters in the dispersion suppressor (DS) downstream of IR7. An apparent breakage of the cleaning hierarchy was observed in IR7, where the highest measured BLM signal was on a TCSG instead of the TCP. However, it was confirmed experimentally that the TCSG signal was caused by secondary showers and ion fragments and not from primary beam, which was indeed impacting only on the TCP. A summary of the maximum BLM signal in the DS for the studied cases (injection, Flat Top (FT), End of Squeeze (EoS), and physics) is shown in Fig. 2. As in previous Pb-Pb runs, the

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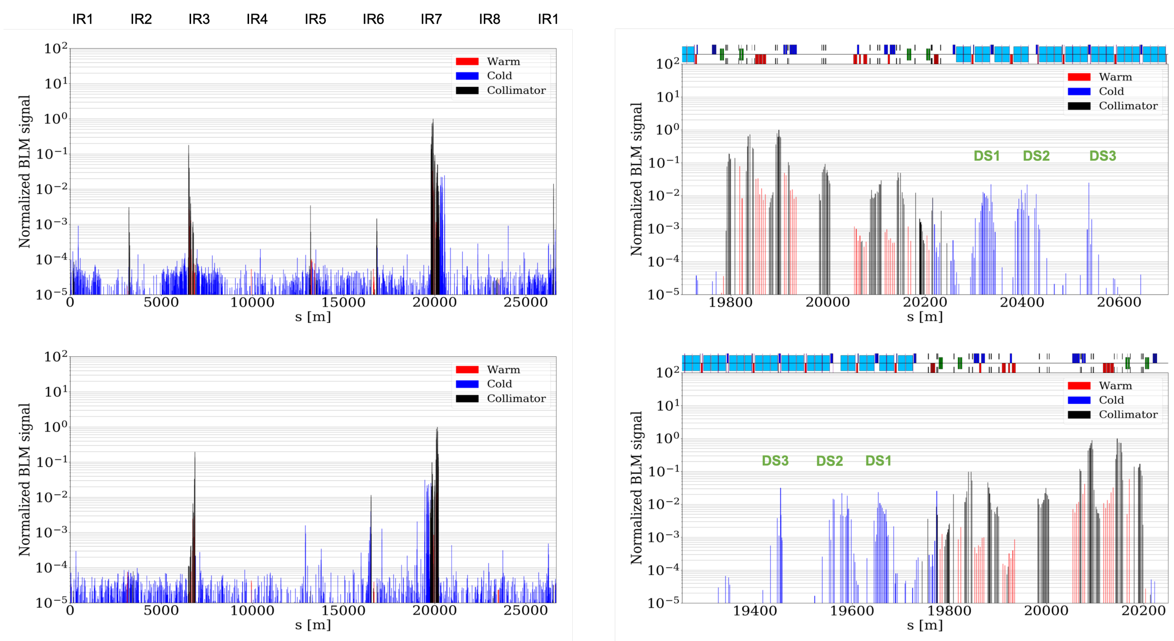

Figure 1: Beam 1 (top) and Beam 2 (bottom) horizontal full ring LM (left) and IR7 zoom (right) for colliding beams. On the left plots the LHC layout is depicted with the dipoles (cyan), quadrupoles (red and blue) and collimators (black) indicated.

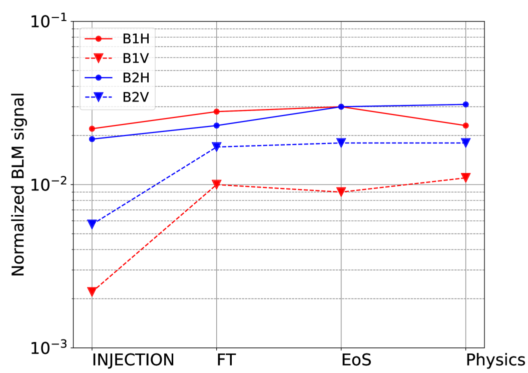

Figure 2: Maximum BLM signal in the DS for both beams and planes all along the cycle.

observed cleaning efficiency was about two orders of magnitude worse than for protons. Furthermore, more cold spikes than for protons, close to maximum values of the dispersion function, are observed around the ring, as well as more losses in IR3. However, these losses remain in the shadow of the DS losses.

The observed losses in the DS of IR7 risk to limit the intensity if appropriate measures are not taken. For future runs, one dipole magnet in the DS in IR7 will be exchanged by two 11 T dipoles with a collimator in between in order to overcome this limitation [15].

COLLIMATOR SETTINGS OPTIMIZATION

The collimator settings for the ion runs are usually chosen to be the same as for the proton runs in all IRs except in the experimental ones, to gain commissioning time. However, during the 2018 commissioning at 6.37 Z TeV, the level of losses observed at some collimators were not compatible with a smooth operation without further optimization. Normalized losses were observed at the horizontal TCT (TCTPH) in IR1 for Beam 1 and at the TCSP in IR6 for Beam 2 at the level of 20% and 90%, respectively.

Based on simulations results performed beforehand, asymmetric TCP settings, with only one of the two TCP jaws inserted at a time, were tested to reduce the losses at the TCTPH in collision. The measured LMs are shown in Fig. 3 (bottom). No losses at the TCTPH were observed when the left TCP jaw was completely retracted. Based on these results, it was decided to open this jaw from 5.0σ to 5.5 σ in operation. However, when performing the re-validation of the configuration before going in collision, losses were still too high at the TCTPH, possibly due to an orbit shift at the TCP. To further reduce these losses, the TCTPH was opened by 2 σ in accordance with simulations. With both mitigation measures in place, the losses at the TCTPH were reduced by 70% with respect to the initial settings.

To simulate the collimation-system performance, the SixTrack-FLUKA coupling framework was used [16–21]. This simulation tracks halo particles through the magnetic lattice and includes the fragmentation of the ions in the LHC collimators and an online aperture check to identify locations of lost particles. The simulations were performed with the 2018 $^{208}Pb^{82+}$ collision optics [2]. An initial $^{208}Pb^{82+}$ ion halo of 6.37 Z TeV was generated at the TCP with 1 µm impact parameter as in Ref. [5]. These simulations did not show problematic losses at the collimators, however, the BLM response is not taken into account and it is therefore

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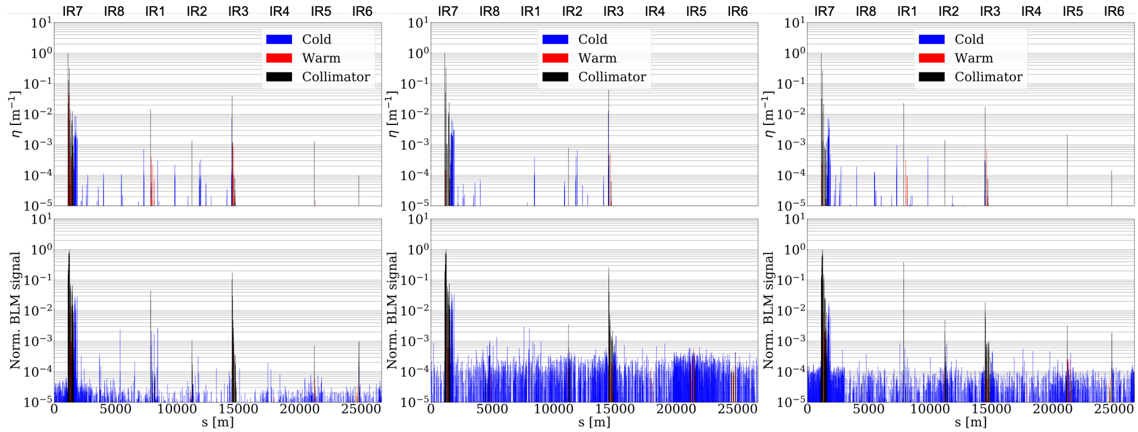

Figure 3: Horizontal simulated (top) and measured (bottom) LM for Beam 1 with both TCP jaws closed to 5σ (left), with only the right TCP jaw closed to 5σ (middle) and with only the left TCP jaw closed to 5σ (right).

hard to use the simulations as a quantitative prediction of the absolute loss levels. Moreover, unknown imperfections could change the measured loss distribution.

The simulations show that 87% of the losses at the TCTPH come from the left TCP jaw. Figure 3 shows a comparison of the measured and simulated horizontal LMs for Beam 1, constructed as in Ref. [5]. A very good agreement of the losses at the collimators for the studied cases is observed. Figure 4 (top) shows the projected horizontal distribution of ions at the TCTPH weighted by the energy. The major contribution to the losses in the TCTPH comes from $^{207}Pb^{82+}$, the heaviest EMD product generated at the TCP. In simulations, by opening the TCTPH by 2 σ the reduction of losses at the TCTPH is about 95%.

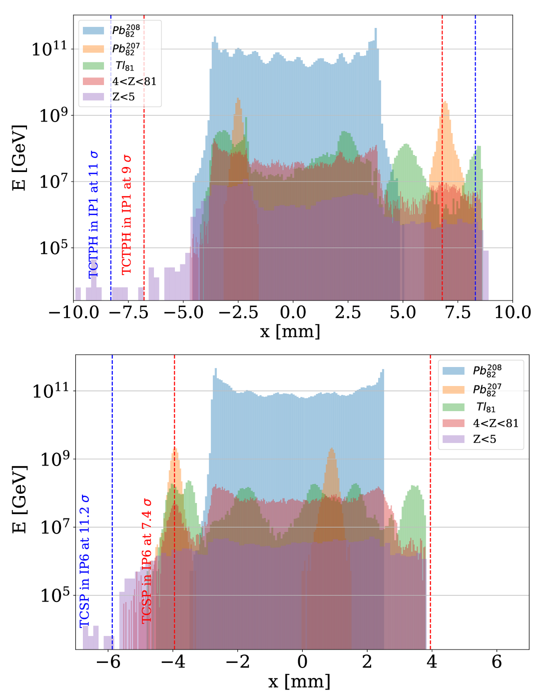

Figure 4: Projected horizontal distribution of energy at the horizontal TCT in IP1 for Beam 1 (top) and at the TCSP in IR6 for Beam 2 (bottom). The initial (red) and final (blue) collimator settings are indicated.

Experimental tests by scanning the jaws individually, showed that the losses at the TCSP were impacting mostly on its right jaw. Different openings of the TCSP were evaluated and the optimum value was found to be 2 mm, about 11.2 σ. With the right TCSP jaw opened to 11.2 σ, the losses were reduced by two orders of magnitude.

In the simulations, the major contribution to the losses at the TCSP was identified again as $^{207}Pb^{82+}$ and the loss peak was removed by opening the right jaw by 1 mm (Fig. 4, bottom). The level of simulated losses for the initial settings was, however, about 2 orders of magnitude lower than measurements. This discrepancy cannot be explained by the neglect of the BLM response. The effect of a beam-orbit offset at the TCSP was investigated but the results do not explain the observed discrepancy. This will be further investigated.

CONCLUSIONS

The cleaning performance of the collimation system in the 2018 Pb-Pb run was similar to previous years, but the stored beam energy was higher and 7 out of 48 fills were dumped by high losses in the betatron-cleaning insertion caused by orbit oscillations at frequencies of about 10 Hz whose origin is under investigation. This underlines the need for a solution for future runs at higher intensity. In the short heavy-ion runs availability is crucial and every fill contributes significantly to the total integrated luminosity. Moreover, the collimation set-up and validation has to be done once at the start of the run to avoid interruptions of the operation for physics.

During beam commissioning, some unexpected high losses were mitigated through optimisation of the collimator settings, motivated by simulations and experimental studies. The SixTrack-FLUKA coupling simulation demonstrated its increasing reliability as a qualitative guide to understanding the origin and location of the losses. Armed with this information, effective mitigation strategies can be formulated and tested before implementation.

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