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SIMULATIONS AND MEASUREMENTS OF COLLISIONAL LOSSES WITH Pb BEAMS AT THE LHC

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Abstract

For about one month per operational year, the Large Hadron Collider (LHC) at CERN works as a heavy-ion collider. Four one-month Pb-Pb runs have been executed so far as well as two p-Pb runs. The LHC heavy-ion programme is scheduled to continue in the future, featuring increased luminosity and beam energy. Beam losses caused by ions fragmenting in the collision process risk introducing performance limitations. Losses occur immediately downstream of the collision points as well as at other locations in the ring, through multi-turn beam dynamics processes and interactions with ring collimators. This paper presents first simulations of collisional loss patterns for nuclear beams using a new simulation approach that relies on the SixTrack-FLUKA coupling simulation tool, including nuclear fragmentation and electron capture in the collisions. Simulations of the 2018 Pb-Pb and 2016 p-Pb runs are compared against experimental data and the prediction of collisional losses for future Pb-Pb and p-Pb runs is shown.

INTRODUCTION

The Large Hadron Collider (LHC) [1] has been designed to accelerate two counter-circulating beams (B1 and B2) of protons or ions up to 7 Z TeV. The unprecedented amount of energy stored in these beams, so far about 400 MJ for protons and 12 MJ for Pb ions, makes it necessary to tightly control all beam losses to avoid magnet quenches and equipment damage. Therefore, about 100 movable collimators are installed, mainly in the momentum and betatron cleaning regions (in the insertion regions IR3 and IR7, respectively) [2]. Beam losses are recorded around the ring by sensitive ionization chamber beam loss monitors (BLMs), that trigger a beam dump if losses exceed given thresholds [3, 4].

For about one month per operational year, the LHC is typically operated with fully-stripped lead ions ($^{208}\mathrm{Pb}^{+82}$), colliding either Pb-Pb or p-Pb. These nuclear beams collide at the experiments ATLAS, ALICE, CMS and LHCb (placed at the four interaction points IP1, IP2, IP5 and IP8). Four Pb-Pb runs have been executed in 2010, 2011, 2015, and 2018 [5–7], and two p-Pb runs in 2013 and 2016 [8–10]. The LHC heavy-ion programme is foreseen to continue during Run 3 and 4 with Pb-Pb and p-Pb operation [11, 12].

Beam losses caused by ions fragmenting in the collision process risk introducing performance limitations. Apart from the desired hadronic interactions, ultraperipheral electromagnetic interactions are frequent and they are responsible for two main effects: bound-free pair production (BFPP) and electromagnetic dissociation (EMD) [13, 14]. In BFPP an electron-positron pair is created and the electron is captured in a bound state at one of the ions, whereas in EMD an excited nucleus decays, emitting one or more nucleons. Because of these interactions, secondary beams with a slightly modified charge-to-mass ratio emerge in both directions from the IPs, at small angles to the main beam. Following dispersive trajectories, they might be lost on the aperture downstream of the collision point and might generate beam losses leading to beam dumps or magnet quenches, putting an upper limit on the luminosity [10, 13–16]. For Pb-Pb, BFPP has the largest cross section (281 b at 7 Z TeV [13]) followed by EMD, while for p-Pb nuclear inelastic interactions dominate [12]. The lighter ion fragments are primarily lost close to the collision point where they are created, whereas the heavy fragments, mainly from EMD, travel further, in some cases up to the collimation regions IR3 and IR7.

Given the importance of these processes, this study aims at setting up a reliable simulation model that can be used to predict collisional losses in future operation. In this approach, the coupling [17–19] of the two simulation codes SixTrack [20–23] and FLUKA [24–27] is used to generate the off-rigidity ions created in both Pb-Pb and p-Pb collisions and to track them through the LHC lattice until they are lost on the machine aperture or on the ring collimators. The simulated loss patterns are compared with measured LHC data both for 2018 and 2016 operating conditions. Consequently, a prediction of the collisional losses for the coming heavy-ion runs is also provided.

SIMULATION SETUP

The SixTrack-FLUKA coupling combines the 6D single particle magnetic tracking of SixTrack and the state-of-the-art physics implementation of the multi-purpose Monte Carlo simulation code FLUKA. When the SixTrack tracking reaches a flagged FLUKA element, all particle coordinates are sent to FLUKA to simulate the particle-matter interactions in a full 3D geometry of the concerned element, after which the surviving particles are sent back to SixTrack. FLUKA simulates the complex interactions between ions and matter.

The final-state ions resulting from EMD and nuclear inelastic collisions at the IPs are generated in FLUKA and distributed in space as the collision point distribution, which is narrower than the beam distribution by a factor of $\sqrt{2}$ in both the transverse and longitudinal planes, while the angular spread is unchanged [13]. These particles are subsequently tracked by SixTrack along the LHC lattice, in which also all collimators are included as FLUKA elements.

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Table 1: Assumptions for 2018 Pb-Pb and 2016 Master Lossmap Simulations

	Pb-Pb	**p-Pb**
Fill number	7477	5559
Optics	Run 2 2018	Run 2 2016
Beam energy [Z TeV]	6.37	6.5
Normalized emittance [µm]	2.3	1.6 (Pb) 1.3 (p)
Momentum spread	1.06e-4	1.1e-4
Bunch length [ns]	1.1	1.1
$\mathcal{L}_{IP1}$ [cm^{-2}s^{-1}]	5.2e27	8.4e29
$\mathcal{L}_{IP2}$ [cm^{-2}s^{-1}]	1.0e27	1.2e29
$\mathcal{L}_{IP5}$ [cm^{-2}s^{-1}]	5.2e27	8.7e29
$\mathcal{L}_{IP8}$ [cm^{-2}s^{-1}]	9.8e26	8.5e28
σ_{BFPP} [b]	278	–
σ_{EMD} [b]	223	35.2e-3
σ_{inel} [b]	7.7	2.12

For Pb-Pb simulations, BFPP losses are simulated by tracking off-momentum ions ($\delta = \frac{1}{81}$, corresponding to a 1-electron capture) in SixTrack, initially distributed as the collision points[1]. For p-Pb simulation, BFPP interactions have been neglected due to their much lower cross section.

In order to produce a so-called collisional master lossmap, the obtained losses for each beam, IP and physics process are converted to a power load (multiplying them by the cross section and luminosity) and added up.

SIMULATION OF 2018 Pb-Pb AND 2016 p-Pb MASTER LOSSMAPS

In order to benchmark the proposed simulation approach, simulated master lossmaps of 2018 Pb-Pb and 2016 p-Pb runs were produced. For EMD and inelastic interactions, 10^6 events were simulated per beam, experiment and interaction, for BFPP 10^5 events, whereas elastic interactions have been neglected due to their low impact on the losses, as for protons [28]. The results were compared to measured BLM signals for two typical fills in the 2018 Pb-Pb and 2016 p-Pb runs. The simulation parameters, extracted from these fills, are summarized in Table 1.

The results are shown in Figs. 1 and 2. The shown losses, as a function of longitudinal coordinate s with $s = 0$ at IP1, are labeled "collimator", "cold" and "warm", showing if they occur at a collimator, at a cold superconducting magnet or elsewhere. Simulations and measurements show generally good qualitative agreement for all the main clusters and loss peaks, despite the large uncertainties when comparing simulated losses on the aperture and the BLM signals. The main discrepancy is that the measured losses at the collimation

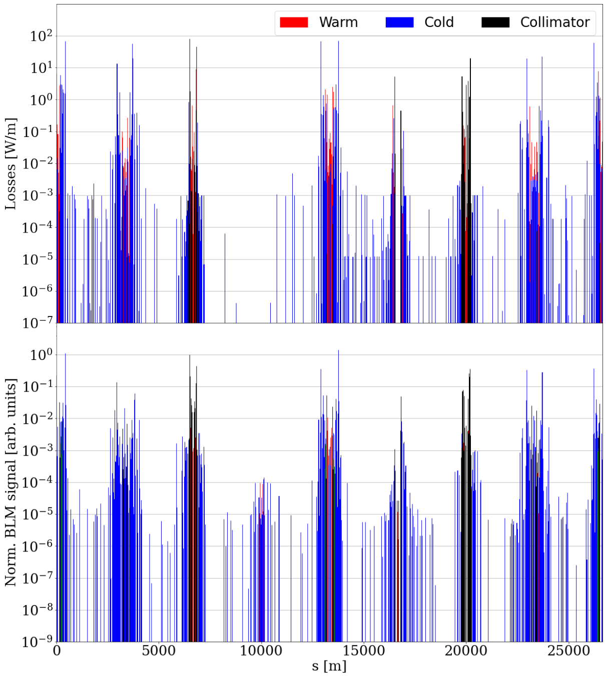

Figure 1: Comparison between simulated (top) and measured (bottom) 2018 Pb-Pb collisional lossmaps. The measured lossmap reports the normalized BLM signals (originally in Gy/s) for fill #7477, at the timestamp $2018-11-26\ 22:45$.

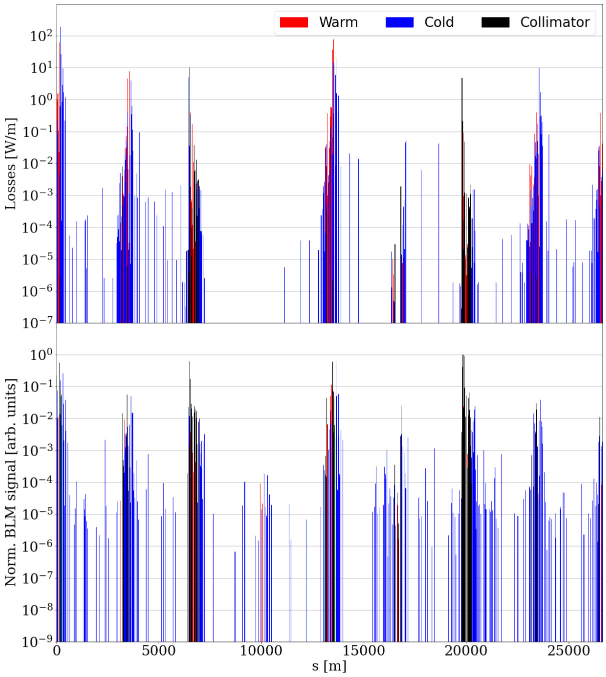

Figure 2: Comparison between simulated (top) and measured (bottom) 2016 p-Pb collisional lossmaps. The measured lossmap reports the normalized BLM signals (originally in Gy/s) for fill #5559, at the timestamp $2016-11-30\ 11:54$.

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[1] Given the negligible angular and momentum kicks associated with BFPP, the behaviour of BFPP particles can be mimicked by tracking fully-stripped Pb ions with a momentum offset corresponding to the change in magnetic rigidity due to the extra electron.

Table 2: Assumptions for Run 3-4 Pb-Pb and p-Pb Master Lossmap Simulations [12]

	Pb-Pb	**p-Pb**
Optics	Run 3 + BFPP orbit bumps	Run 3
Beam energy [Z TeV]	7	7
Normalized emittance [µm]	1.6	1.6 (Pb) 2.5 (p)
Momentum spread	1.06e-4	1.06e-4 (Pb) 1.1e-4 (p)
Bunch length [ns]	1.1	1.1
$\mathcal{L}_{IP1}$ [cm^{-2}s^{-1}]	6.4e27	16e29
$\mathcal{L}_{IP2}$ [cm^{-2}s^{-1}]	6.4e26	5e29
$\mathcal{L}_{IP5}$ [cm^{-2}s^{-1}]	6.4e27	16e29
$\mathcal{L}_{IP8}$ [cm^{-2}s^{-1}]	1e27	2e29
σ_{BFPP} [b]	281	–
σ_{EMD} [b]	226	35.5e-3
σ_{inel} [b]	7.8	2.13

regions (IR3: ~ 6000–7000 m, IR7: ~ 19000–21000 m) of 2016 p-Pb master lossmap simulation are underestimated by 1-2 orders of magnitude. This shows that for Pb-Pb operation the collisional losses, the only simulated loss source, constitute the dominating contribution to the collimator losses, while for p-Pb operation other loss sources, most likely betatron losses not included in the simulation, dominate.

PREDICTION OF COLLISIONAL LOSSES FOR FUTURE Pb-Pb AND p-Pb RUNS

The simulation approach presented above shows a very good agreement with experimental data, excluding betatron losses, and hence it can be used to estimate the beam losses in future operation. Pb-Pb and p-Pb master lossmaps have been simulated for future runs, including relevant future beam, hardware, and optics changes envisaged for Run 3–4 [11, 12]. Moreover, the orbit bumps proposed in [29] to partially mitigate the BFPP losses at LHCb have been included in Pb-Pb simulations. The simulation parameters are summarized in Table 2. The same procedure and statistics as the benchmark simulations were used.

The results are shown in Figs. 3 and 4. Despite the increased beam energies and luminosities, most of the cold losses are found to be well below the conservative quench limit of ~ 9 W/m estimated at the design stage of LHC [30] (more recent studies suggest about a factor 3 higher quench limit [31]). The few cold loss peaks that exceed this limit are either the BFPP losses for Pb-Pb, which have been studied and safely impact an empty cryostat thanks to orbit bumps [14], or simulation artifacts due to abrupt steps in the aperture model and the binning, that are not likely to cause a real danger of quenching. Nevertheless, to verify this, it would be useful as future work to study the highest losses with full energy deposition studies in FLUKA, modelling the actual power load on the superconducting coils.

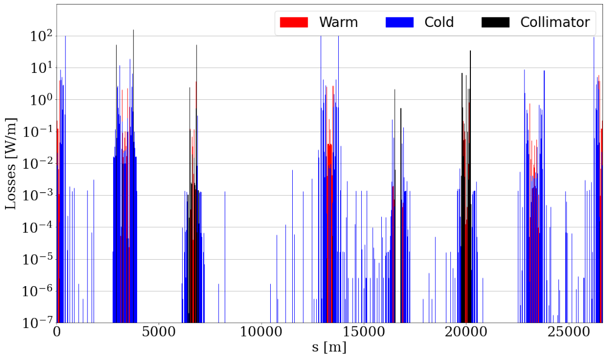

Figure 3: SixTrack-FLUKA prediction of Pb-Pb collisional master lossmap for future runs.

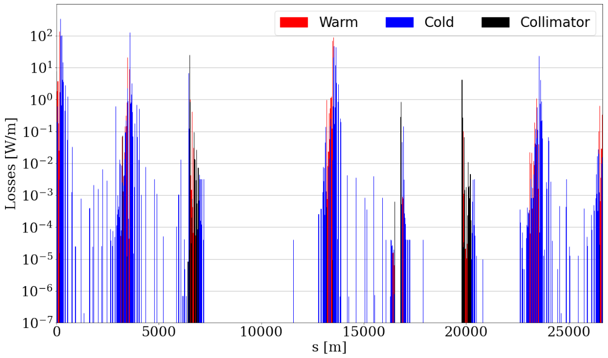

Figure 4: SixTrack-FLUKA simulation of p-Pb collisional master lossmap for future runs.

CONCLUSION

When colliding fully-stripped lead ions, interactions causing nuclear fragmentation or electron capture give rise to off-rigidity secondary beams, which can be lost on the machine aperture and cause localised power deposition. This risks to quench magnets and could limit the achievable luminosity. A new simulation approach relying on the SixTrack-FLUKA coupling to simulate heavy-ion collisional losses has been described. The tool used to study the losses around the LHC ring during Pb-Pb and p-Pb collisions at all experiments has been presented and validated against experimental data. Simulation results showed very good agreement with measurements, within the limitation of comparing simulated losses on the aperture and BLM measurements of the particle showers outside of the cryostats. The simulation setup was then used to predict Pb-Pb and p-Pb collisional losses in future operation. Most of the losses are predicted to be below a conservative quench limit. The few loss locations above the limit are caused by BFPP, for which mitigations have been studied. Furthermore, these loss spikes are likely overestimating the energy deposition density due to limitations of the simulation. Full energy deposition studies using FLUKA should be done to verify the safety.

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