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Executive Summary of the Thesis

Study of collisional losses in the Large Hadron Collider for Pb-Pb and p-Pb operation

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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1. Introduction

The Large Hadron Collider (LHC) at CERN is the largest and highest-energy particle accelerator ever built. Inside its 27 km long ring, two counter-rotating beams (B1 and B2) of protons or ions are accelerated up to 7 Z TeV. The achieved stored beam energy is about 400 MJ for protons and 12 MJ for Pb ions, meaning that the beams are highly destructive and all beam losses need to be tightly controlled to avoid magnet quenches or even damage. Therefore about 100 movable collimators are installed. Any beam losses are recorded around the ring by sensitive ionization chambers, called beam loss monitors (BLMs), that trigger a beam dump if losses exceed given thresholds.

The beams are brought into collision at the four experiments ATLAS, ALICE, CMS and LHCb (placed at the four interaction points IP1, IP2, IP5 and IP8). To maximize the statistics in the studied particle physics processes, the luminosity should be maximized. However, the collisions also induce beam losses, which have to be kept within the limits of machine safety.

For about one month per operational year, the LHC is typically operated with fully-stripped lead ions ($^{208}Pb^{+82}$), which are made to collide between themselves (Pb-Pb) or with protons (p-Pb). One of the main aims is that of recreating and studying the so-called quark-gluon plasma, a state of hadronic matter that existed few microseconds after the Big Bang. Four Pb-Pb runs have been executed in 2010, 2011, 2015, and 2018, and two p-Pb runs in 2013 and 2016. The LHC heavy-ion programme is foreseen to continue during Run 3 and 4 with Pb-Pb and p-Pb operation [1, 3].

Apart from the desired hadronic interactions, ultraperipheral electromagnetic interactions are a very frequent phenomenon in heavy-ion collisions and they are responsible for two main effects that introduce luminosity limitations: bound-free pair production (BFPP) and electromagnetic dissociation (EMD) [2, 5]. In BFPP an electron is created in a bound state at one of the ions, whereas in EMD an excited nucleus decays emitting one or more nucleons. As a result, secondary beams with a slightly modified charge-to-mass ratio emerge in both directions from the collision points, at small angles to the main beam. They follow dispersive trajectories, and some eventually hit the machine aperture, causing a localised power deposition given by

$$P_p = \mathcal{L}\sigma_p E_b \ , \qquad (1)$$

where $\mathcal{L}$ is the luminosity, σ_p is the interaction cross section and E_b is the beam energy. The induced heating risks triggering beam dumps or magnet quenches, putting an upper limit on the luminosity [5].

Given the importance of these processes, this work aims both at studying alleviations of BFPP losses at the LHCb experiment, as well as setting up a reliable simulation model that can be used to predict collisional losses in future operation. For the first time, a full analysis of the BFPP losses at LHCb is conducted, adopting the simulation code SixTrack, and a partial mitigation strategy through orbit bumps[1] is proposed. For collisional losses in general, including EMD and inelastic interactions, a new simulation approach is presented and benchmarked with data from previous LHC runs. It relies on the SixTrack-FLUKA coupling to simulate the losses arising around the LHC ring during Pb-Pb and p-Pb collisions. Consequently, a prediction of the collisional losses for the coming heavy-ion runs is also provided.

This executive summary assumes that the reader has a fundamental knowledge of beam dynamics, which can be found in standard accelerator physics textbooks.

2. Simulation tools

The study carried out within this thesis relies on the use of MAD-X, SixTrack and the SixTrack-FLUKA coupling. A brief description of these simulation tools is given in the following.

MAD-X MAD-X is a tool developed for the design and study of particle accelerators, taking as input a description of an accelerator in terms of a sequence of beam elements and their characteristics, e.g. magnetic strengths. With MAD-X it is possible to perform a wide variety of calculations and design tasks, e.g. the calculation and matching of beam optics (i.e. computing the magnetic strengths required to achieve specified optics conditions).

SixTrack SixTrack is a 6D single particle tracking code optimized for element-by-element thin-lens tracking in high energy rings over a large number of turns, e.g. for dynamic aperture studies. SixTrack includes also a collimation module, simulating particle-matter interactions, as well as a machine aperture model and a collimator database. SixTrack allows to simulate so-called lossmaps, i.e. the distribution of the beam losses around the ring resulting from a beam loss scenario given by the initial conditions.

FLUKA FLUKA is a multi-purpose particle-physics Monte Carlo simulation code used to simulate the interaction of particles and nuclei with matter and their transport. The initial particles are tracked through a user-defined 3D geometry, including detailed material composition and electromagnetic fields, as well as the secondaries produced in the induced hadronic and electromagnetic cascades.

SixTrack-FLUKA coupling The SixTrack-FLUKA coupling combines the tracking of SixTrack and the state-of-art physics implementation in FLUKA. When the SixTrack tracking reaches a flagged element, all coordinates are sent to FLUKA to simulate the particle-matter interactions, and the surviving particles are sent back to SixTrack. It includes heavy ions and their complex interactions with matter, which are not implemented in the built-in scattering routine. The SixTrack-FLUKA coupling can be also used to simulate beam-beam collisions and track the resulting products.

3. BFPP losses at IP8

BFPP losses were previously studied and mitigations have been proposed for all LHC experiments except LHCb [5]. Because of a recent request to increase the LHCb luminosity [1, 3], an alleviation strategy must be studied also there. In this section we therefore study the tracking of BFPP particles emerging from IP8, their resulting loss pattern, and investigate a partial mitigation through orbit bumps.

3.1. BFPP beam tracking

SixTrack was used to track BFPP particles from IP8 in B1 and B2, computing the resulting loss patterns. Both the 2018 LHC heavy-ion optics and beam parameters (6.37 Z TeV energy, emittance of 2.3 μm, 1.1 ns bunch length) and the

[1] An orbit bump is a deliberate shift of the beam transverse position in a limited region, not affecting the rest of the ring.

future ones (7 Z TeV energy, 1.6 μm emittance, 1.1 ns bunch length) have been studied.
The dispersive trajectory of BFPP ^{208}Pb^{+81} ions has been mimicked by tracking fully stripped ^{208}Pb^{+82} ions with an effective fractional momentum offset $\delta = \frac{1}{81}$, corresponding to the magnetic rigidity change from the extra electron. The momentum and angular kicks from the interaction are very small and were neglected. The initial spatial distributions, corresponding to the collision points, are narrower than the beam distributions by a factor $\sqrt{2}$ [2]. For each case an initial Gaussian distribution of 10^4 ions was tracked. The momentum spread was neglected, which results in conservative and narrower estimations of the loss patterns.
The results show that the BFPP beams hit the superconducting dipoles MB.B10R8.B1 and MB.B10L8.B2, around the s-coordinates 386.4 m and 365.2 m from IP8 respectively. The standard deviations of the BFPP loss patterns in the different cases are shown in Table 1. This result has been compared to logged BLM measurements in a typical 2018 Pb-Pb fill. In general a very good agreement was found, although the highest measured BLM signals were found slightly downstream of the simulated locations ($\sim$7 m for B1 and $\sim$5 m for B2). This can be fully explained by possible imperfections in the aperture and orbit, the incomplete spatial coverage of the BLMs, and the fact that the BLMs detect losses on the outside of the magnets, downstream of the actual impact position.

3.2. BFPP alleviation through orbit bumps

The studies show that the BFPP losses from IP8 cannot be alleviated in the same way as for IP1 and IP5, by re-directing them into an empty connection cryostat [5]. Instead, the installation of new collimators is required for the full alleviation as at IP2. Since this is not possible in the short term, a partial mitigation by means of an orbit bump has been investigated. For both B1 and B2, an horizontal orbit bump (-5.3 mm on MQML.10R8.B1 and +5 mm on MQML.10L8.B2) has been matched with MAD-X to make the BFPP beam miss the first impact location of its dispersive trajectory in cell 10 and instead be lost in cell 12 (Fig. 1).
New loss patterns, simulated with SixTrack including the implemented orbit bumps, show losses centered at 490.6 m and 468.7 m from IP8, in the superconducting dipoles MB.C12R8.B1 and MB.C12L8.B2 respectively. There the β-

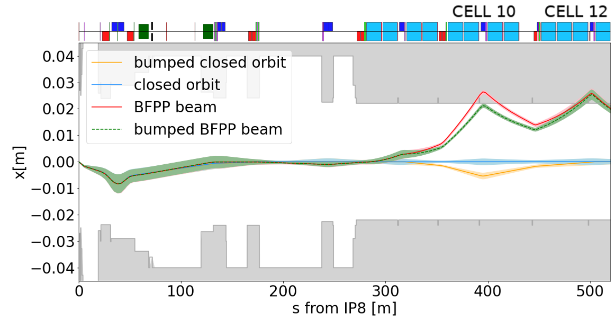

Figure 1: Trajectories on the horizontal plane computed by MAD-X with and without orbit bump for B1 (3σ envelopes). The aperture of the machine is represented by the grey shaded area.

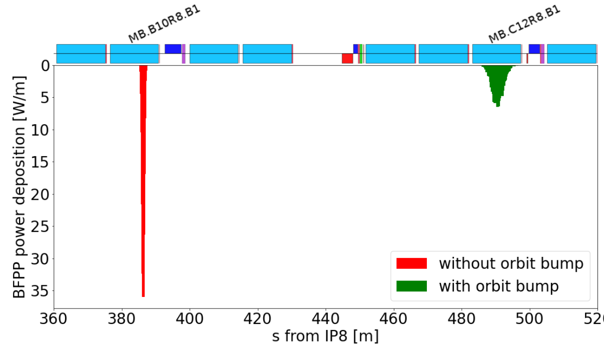

Figure 2: BFPP power deposition on MB.B10R8.B1 (without orbit bump) and MB.C12R8.B1 (with orbit bump) for operating conditions of Pb-Pb 2018 run, simulated with SixTrack.

	without orbit bump (**cell 10**)				with orbit bump (**cell 12**)			
	B1 (s = 386.4 m)		**B2** (s = 365.3 m)		**B1** (s = 490.6 m)		**B2** (s = 468.7 m)	
	1.6 μm	2.3 μm	1.6 μm	2.3 μm	1.6 μm	2.3 μm	1.6 μm	2.3 μm
6.37 Z TeV	0.234 m	0.281 m	0.315 m	0.379 m	1.383 m	1.657 m	1.256 m	1.507 m
7 Z TeV	0.223 m	0.268 m	0.302 m	0.361 m	1.319 m	1.582 m	1.199 m	1.438 m

Table 1: Standard deviations of loss patterns given by BFPP beams without and with orbit bumps for different values of emittance and energy. The most critical cases with the narrowest spot size are highlighted in red.

function is larger, and hence the transverse size of the BFPP beam is larger, meaning that the power deposition is more spread out. The 2018 B1 BFPP losses, with and without orbit bump, are shown in Fig. 2. They are normalized to a power load in W/m for a levelled luminosity of 10^{27} cm^{-2} s^{-1} and a BFPP cross section of 278 b. Also the standard deviations of the new loss patterns in the different cases are shown in Table 1. In addition to the lower peak power load, a risk of symmetric quenches, present in cell 10 and not cell 12, leads to higher beam abort thresholds in cell 12, adding even more margin. As a result, verified with FLUKA studies [4], the levelled luminosity of LHCb can be safely increased by a factor 2–3 in future runs thanks to the proposed orbit bumps, which would be very important for LHCb.

4. Simulation of collisional losses for Pb-Pb and p-Pb operation

For the first time, the FLUKA-SixTrack coupling has been used to setup a simulation of the losses around the LHC during Pb-Pb and p-Pb operation. The interactions in the beam-beam collisions at the IPs were forced by a FLUKA collision source inside a geometry describing the IP pipe. The collision products, studied in detail, were then tracked by SixTrack in the LHC lattice. Repeating this procedure for each IP, beam and interaction creating significant beam losses, and weighting and adding up the resulting losses, a collisional master lossmap is produced.

For Pb-Pb, EMD has the largest cross section after BFPP, while for p-Pb nuclear inelastic interactions dominate. The light ion fragments are primarily lost close to the interaction point where they were created, whereas the heavy fragments, mainly from EMD, travel further, in some cases up to the collimation regions.

4.1. 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 compared to corresponding measurements. The simulation assumptions are summarized in Table 2. For EMD and inelastic interactions, 10^6 events were simulated per beam, experiment and interaction, whereas elastic interactions have been neglected due to their low impact on the losses. For Pb-Pb simulation, BFPP losses have been added up from SixTrack simulations, using the approach in Sec. 3, tracking 10^5 ions per beam and experiment. The simulations were compared to measured BLM signals for two typical fills in the 2018 Pb-Pb and 2016 p-Pb runs.

	Pb-Pb	**p-Pb**
Optics	Run 2 2018	Run 2 2016
Beam energy	6.37 Z TeV	6.5 Z TeV
Normalized emittance	2.3 μm	1.6 μm (Pb) 1.3 μm (p)
Momentum spread	1.06e-4	1.1e-4
Bunch length	1.1 ns	1.1 ns
$\mathcal{L}_{IP1}$ [cm^{-2}s^{-1}]	5.2233e27	8.3562e29
$\mathcal{L}_{IP2}$ [cm^{-2}s^{-1}]	9.9820e26	1.1664e29
$\mathcal{L}_{IP5}$ [cm^{-2}s^{-1}]	5.2296e27	8.7280e29
$\mathcal{L}_{IP8}$ [cm^{-2}s^{-1}]	9.7746e26	8.5087e28
σ_{BFPP} [b]	278	–
σ_{EMD} [b]	223	35.2e-3
σ_{inel} [b]	7.7	2.12

Table 2: Assumptions for 2018 Pb-Pb and 2016 master lossmap simulations.

The results are shown in Figs. 3 and 4. The shown losses, as a function of longitudinal coordinate s, with $s = 0$ at IP1, are labeled as "collimator", "cold" and "warm", depending on whether they occur at a collimator, at a cold superconducting magnet or elsewhere. In both cases the simulations and measurements show very good agreement for all the main clusters and loss peaks, within the uncertainty from the fundamental difficulty in comparing simulated losses on the aperture and the BLM signal caused by the induced particle showers. The only exception is represented by the losses at the collimation regions of 2016 p-Pb master lossmap simulation, which are underestimated by 1-2 orders of magnitude. This shows that for Pb-Pb operation the collisional losses, the only simulated loss source, are the dominating contribution to the collimator losses, while for p-Pb operation other loss sources dominate.

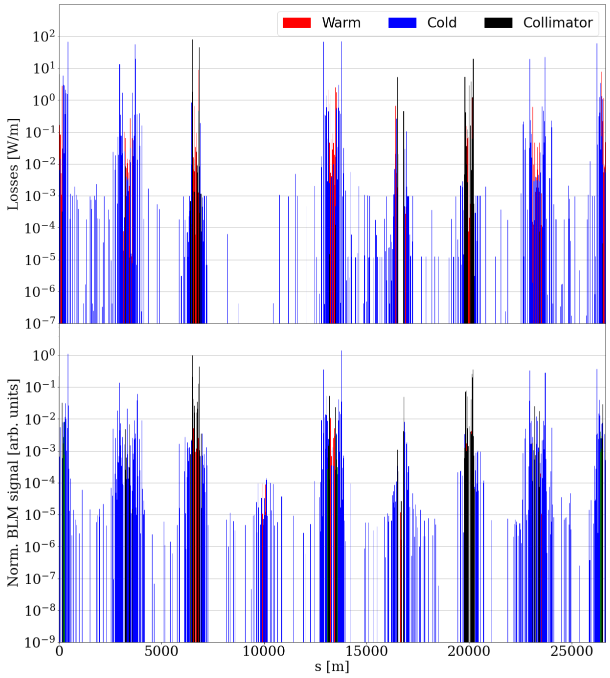

Figure 3: Comparison between simulated (top) and measured (bottom) 2018 Pb-Pb collisional lossmaps. The measured lossmap reports the normalized BLM signals (originally in Gy/s) for fill #7477, at the timestamp $2018 - 11 - 26\ 22:45$.

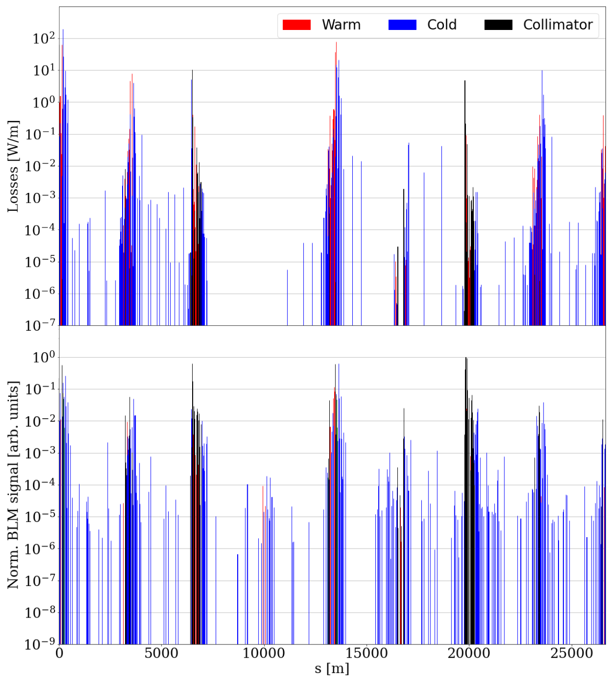

Figure 4: Comparison between simulated (top) and measured (bottom) 2016 p-Pb collisional lossmaps. The measured lossmap reports the normalized BLM signals (originally in Gy/s) for fill #5559, at the timestamp $2016 - 11 - 30\ 11:54$.

	Pb-Pb	**p-Pb**
Optics	Run 3 + BFPP orbit bumps	Run 3
Beam energy	7 Z TeV	7 Z TeV
Normalized emittance	1.6 μm	1.6 μm (Pb) 2.5 μm (p)
Momentum spread	1.06e-4	1.06e-4 (Pb) 1.1e-4 (p)
Bunch length	1.1 ns	1.1 ns
$\mathcal{L}_{IP1}$ [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

Table 3: Assumptions for Run 3-4 Pb-Pb and p-Pb master lossmap simulations.

4.2. Prediction of Pb-Pb and p-Pb collision losses for future runs

The simulation approach presented above has shown an excellent agreement with experimental data 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 all the future changes envisaged in Run 3–4 [1], as well as the orbit bumps proposed in Sec. 3.1 for Pb-Pb simulations. The simulation assumptions are summarized in Table 3. The same procedure and statistics as the benchmark simulations were used.
The results are shown in Figs. 5 and 6. Despite the increased beam energies and luminosities, most of the losses have been found to be below the conservative quench limit of ~ 9 W/m estimated at the design stage of LHC [2]. The few cold loss peaks that exceed this limit are either the BFPP peaks for Pb-Pb, which are safely displaced to an empty cryostat [5], or simulation artifacts due to abrupt steps in the aperture model and the binning of the losses, 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, modelling the actual power load on the superconducting coils.

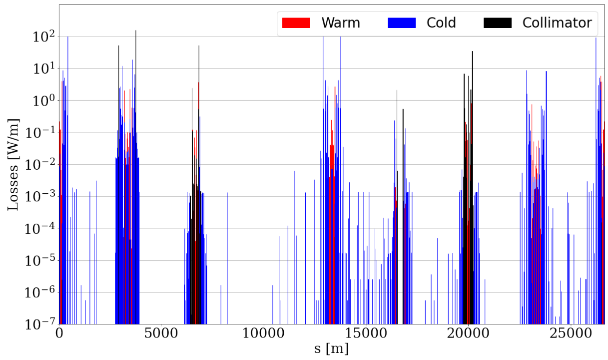

Figure 5: SixTrack-FLUKA prediction of Pb-Pb collisional master lossmap for future runs.

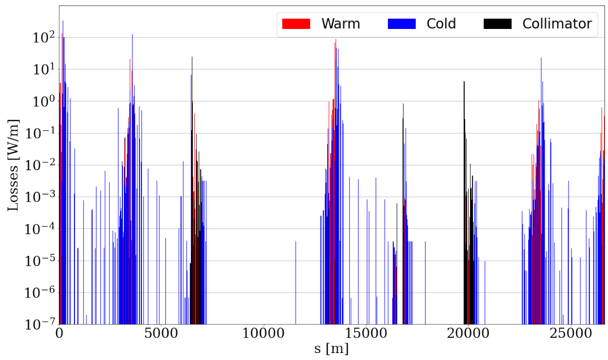

Figure 6: SixTrack-FLUKA simulation of p-Pb collisional master lossmap for future runs.

5. Conclusions

A full study of BFPP losses during Pb-Pb collisions at IP8 has been carried out in this work. These losses impose luminosity limitations due to the risk of quenching impacted magnets. The simulated loss patterns caused by BFPP particles from IP8 have been compared to measured BLM signals. A partial mitigation of these losses has been proposed, by shifting them through an orbit bump from cell 10 to cell 12, where they are more spread out and cause a lower peak power load. This would allow to increase LHCb luminosity by a factor 2–3 in future Pb-Pb runs.
Moreover, a new simulation approach to simulate the losses around the LHC ring during Pb-Pb and p-Pb collisions at all experiments has been presented and validated against experimental data. Simulations with this tool have shown very good agreement with the measurements and hence can be used to estimate the collision losses for future runs.
Finally, a prediction of Pb-Pb and p-Pb collision losses in future operation was done. Most of the losses have been predicted to be below the conservative quench limit. The few losses above are most likely simulation artifacts, but full energy deposition studies are needed to verify the safety of these losses.

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