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# SIMULATIONS AND MEASUREMENTS OF BETATRON AND OFF-MOMENTUM CLEANING PERFORMANCE IN THE ENERGY RAMP AT THE LHC

N. Triantafyllou*, R. Bruce, M. D'Andrea, K. Dewhurst, B. Lindstrom, D. Mirarchi, S. Redaelli, F. F. Van der Veken, CERN, Geneva, Switzerland

*Abstract*

The Large Hadron Collider (LHC) is equipped with a multi-stage collimation system that protects the machine against unavoidable beam losses at large betatron and energy offsets at all stages of operation. Dedicated beam validations and an understanding in simulations of the collimation performance are crucial for the energy ramp from 450 GeV to 6.8 TeV because complex changes of optics and orbit take place in this phase. Indeed, the betatron functions are reduced in all experiments for an efficient setup of the collisions at top energy. In this paper, simulations of the betatron and off-momentum cleaning during the energy ramp are presented. A particular focus is given to the off-momentum losses at the start of the ramp. The simulation results are benchmarked against experimental data, demonstrating the accuracy of newly developed simulation tools.

## INTRODUCTION

The Large Hadron Collider (LHC) features a multi-stage collimation system designed to protect the superconducting magnets from quenching and sensitive aperture restrictions from damage from particle losses [1, 2]. It consists of more than 100 collimators, all consisting of two movable jaws with the beam passing in the centre, ordered into well-defined families. In the dedicated collimation insertions (IRs) – IR3 dedicated to momentum cleaning and IR7 to betatron cleaning – primary collimators (TCPs) are the closest to the beam and intercept the primary beam halo; secondary collimators (TCSGs) intercept the secondary particles scattered out of the TCPs, and the absorbers (TCLA) dispose of products from the showers produced by the interactions of halo particles with upstream collimator materials. In the experimental regions, tertiary collimators (TCTs) provide local protection around the Interaction Points (IPs) and minimize the physics background from beam-halo losses. In addition, the dump-protection collimators (TCSPs, TCDQs) in IR6 provide protection in case of asynchronous damp failures. The collimation system for beam 1 (B1) and beam 2 (B2) share the same setup. The majority of the collimators are installed IR3 (9/beam) and IR7 (19), and clean particles with high momentum and betatron offsets, respectively. In IR3, the dispersion is significantly higher than in IR7, and TCPs are only present in the horizontal plane. In contrast, in IR7, TCPs are installed in horizontal, vertical, and skew planes.

The system is setup through dedicated beam-based alignment procedures to ensure that the collimators are set precisely around the local orbit [3]. The cleaning performance is then qualified during the beam commissioning, before allowing high intensity in the machine, in order to validate that sensitive components are protected. The beam commissioning of the LHC typically takes place yearly, after extended periods of downtime during which there are no beams in the accelerator or significant modifications to the hardware. The validation of the cleaning performance is achieved by exciting low-intensity beams to induce artificial losses around the machine and assessing the resulting loss distribution at beam loss monitors (BLMs) [4, 5] throughout the ring. The resulting distribution of losses around the ring is referred to as loss map [6]. More detail on the procedure of the collimation qualification through loss maps can be found in Ref. [7–9]. In this paper, two types of loss maps will be discussed: betatron loss maps and off-momentum loss maps. Betatron loss maps are done by blowing up the beam using the transverse damper (ADT) in both the horizontal and vertical planes [10]. If the system is correctly setup, this causes primary losses in IR7. Off-momentum loss maps, on the other hand, are generated by shifting the RF frequency by a few hundred Hz, leading to primary losses in IR3.

There is always some particle leakage from the collimators into the machine aperture. To quantify the collimation performance, the local cleaning inefficiency is defined as [6, 11]: $\eta = N_{\mathrm{loc}}/(N_{\mathrm{tot}}\Delta s)$, where $N_{\mathrm{loc}}$ the local losses over a distance $\Delta s$ and $N_{\mathrm{tot}}$ the total number of losses in the collimation system. The inefficiency is most critical in the dispersion suppression regions (DS) downstream of the IR7, since it is where the largest losses in cold magnets occur [6].

Qualification loss maps are conducted at several stages of the LHC cycle, typically following significant changes of energy, optics, reference orbit, or collimator settings. This paper provides a review of the LHC collimation system's performance at injection and during the energy ramp in the 2023 commissioning. This investigation is considered crucial due to the complex evolution in optics and closed orbit that occurs during this part of the cycle [12]. The measurements are compared against simulations conducted using the newly developed tools, Xsuite [13–15] and its tracking engine Xtrack [16]. These simulations mark the first of their kind during the LHC ramp and also the first off momentum loss maps using dynamic RF sweep in Xtrack.

## MACHINE CONFIGURATION

The studies presented in this paper were conducted for the 2023 machine configuration, taking as input the validation loss maps [17]. The standard LHC cycle starts with injection

* natalia.triantafyllou@cern.ch

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of proton beams at 450 GeV, followed by an energy ramp to 6.8 TeV, where the beams are later brought in collision. The studies in this paper were performed at injection or during the energy ramp. The chromaticity was consistently set at 10 units, except for the off-momentum loss maps at injection energy, where it was adjusted to 5 units. The octupole current increased from 0 A at injection energy to 197 A at flat top. The evolution of the collimator settings is shown in Table 1. The off-momentum cut is found to be $3.2{\times}10^{-3}$. The optics version Proton_2023 [18] was used.

Table 1: Overview of the Collimation Settings for Normalised Emittance of 3.5 µm During the Energy Ramp

| Elements | Initial | Final |
|---|---|---|
| TCP7/TCSG7/TCLA7 | $5.7\sigma/6.7\sigma/10\sigma$ | $5\sigma/6.5\sigma/10\sigma$ |
| TCP3/TCSG3/TCLA3 | $8\sigma/9.3\sigma/12\sigma$ | $15\sigma/18\sigma/20\sigma$ |
| TCDQ/TCSP | $8\sigma/7.4\sigma$ | $7.3\sigma/7.3\sigma$ |
| TCT1/5/8/TCT2 | $13\sigma/13\sigma$ | $18\sigma/37\sigma$ |

## SIMULATION SET UP

The simulations of cleaning performance presented in this paper are conducted with the Xsuite tool, which provides single particle tracking in the 6D phase space through the elements of the accelerator using symplectic maps. The interaction of the particles with the collimation system is provided by the Xcoll package which provides an internal implementation [19–21] of the original K2 code [22] to simulate proton-matter interactions.

It is noted that in the simulations, a particle is considered lost in the following two scenarios [6]: if it intersects the machine aperture, modelled with a 10 cm resolution, or if it undergoes an inelastic interaction within a collimator. In measurements, the BLMs record shower particles produced by the interaction of lost protons with the adjacent materials. This introduces an unavoidable uncertainty between simulations and measurements.

### *Betatron Loss Maps*

Separate loss map simulations were conducted for the vertical and horizontal planes. The initial particle distribution combines a Gaussian 2D distribution in the non-collimated plane, and a "direct halo" [6] in the collimation plane. This is sampled directly at the jaws of the primary collimator in IR7 and it is matched to the machine optics. It extends from the collimator surface to 1 µm within the jaw volume and is uniformly populated. In this approach all particles encounter the collimator at the first turn, optimizing simulation efficiency. However, it simplifies the beam dynamics and does not account for the diffusion bringing the halo onto the collimators. The simulated betatron loss maps in this study were obtained by tracking $20{\times}10^{6}$ particles for 200 turns, which has been demonstrated to yield statistically reliable results [19] even at locations of low losses.

### *Off-momentum Loss Maps*

For accurate off-momentum loss maps, a dynamic change in RF frequency and complex beam dynamics need to be considered beyond just initializing the beam on the collimator [23]. Past studies at flat top mimicked the dynamic RF sweep by introducing a time-dependent phase which was added to the RF frequency in Sixtrack [23]. However, this is not feasible in Xtrack because the tracking map for the cavities is implemented such that all particles are assumed to be synchronous to the longitudinal reference orbit. This is not the case during an RF sweep, as the reference trajectory will lengthen/shorten. Therefore, the RF sweep is mimicked in Xtrack by introducing a shift $\Delta\zeta$ to all the particles, as: $\Delta\zeta = L(\Delta f_{\mathrm{RF}})/(f_{\mathrm{RF}} + \Delta f_{\mathrm{RF}})$. where $L$ the ring circumference and $\Delta f_{\mathrm{RF}}$ the change in RF frequency. Note that the sweep during tracking is applied faster than in the real machine, but adiabatically, i.e. over a timescale that is slower than the synchrotron oscillation period. This is necessary to avoid displacing the center of the bucket too rapidly, which could cause captured particles to cross the separatrix. For the LHC, 50 mHz/turn is adequate for most particles.This implementation does not affect the Xcoll routine that handles the collimators [19] and takes as inputs the particles' positions simulated in Xtrack.

The initial distribution used for simulating the off-momentum cleaning combines the following characteristics. In both transverse planes, the particles are uniformly-populated in a band from 3.5 to 5.7 $\sigma$ [1] in normalised phase space, with uniformly distributed phases between 0 and $\pi/2$. To account for the real transverse distribution, the losses are weighted as a function of their starting amplitude. Based on past measurement, we assume here a double Gaussian in both transverse planes, for which the parameters can be found in Table 6.14 of Ref. [24]. In the longitudinal plane, a Gaussian distribution matched to the non-linear bucket is used [25].

Figure 1 shows the simulated time profile of losses in IR7 and IR3 primary collimators during a -200 Hz RF sweep. For this, 15000 particles were tracked for LHC B1 using Xsuite and Xcoll for 4000 turns. It is evident that for small frequency shifts, the losses are concentrated in IR7, and the primary bottleneck is the TCP7. Beyond a shift of approximately 160 Hz, the primary collimators in IR3 (TCP3) become the primary loss location. Lower losses are then still observed in IR7, which can be attributed to the leakage of secondary particles from IR3. The above-described pattern aligns with theoretical estimations and experimental observations as shown in Ref. [26].

The off-momentum loss maps are constructed from the above simulation by recording the losses in all the locations around the ring. The average values from B1 and B2 were used for both planes. When constructing the loss maps,

[1] Particles at transverse amplitudes smaller than $3.5\sigma$ will never reach the TCP3/7 during a typical RF sweep of about 250 Hz [26], and the TCP cuts the beam at $5.7\sigma$.

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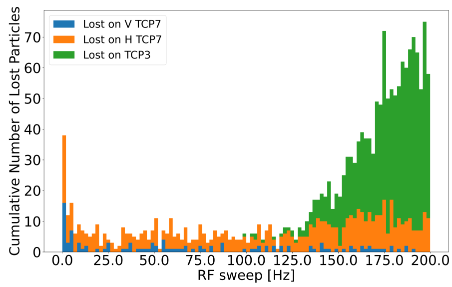


Figure 1: Histogram showing the time profile of losses in TCPs in IR3 and IR7 as simulated during an RF sweep of -200 Hz during 4000 turns for B1. Each coloured segment's height within a bin shows the particles lost for that category, while the full bar height represents the total loss.

counts of lost particles at each location are scaled based on the weight of the particles lost there.

Lastly, we compare the simulation to measured loss map data from only the last second of the RF sweep, considering a 1.3 s BLM integration time. A typical RF sweep during the measurements at injection shifts by ~25 Hz/second, equating to 2.2 mHz/turn. The implemented, in Xtrack, RF sweep's shift is 50 mHz/turn, 22.5 times quicker than the actual conditions. In the construction of the off-momentum loss maps presented below only the losses from the equivalent of the final 3 seconds are retained to ensure sufficient data without compromising statistical accuracy. Particles from the off-momentum halo are not expected to impact the results significantly, and therefore are not considered here.

## BETATRON CLEANING PERFORMANCE DURING THE RAMP

This section focuses on the betatron loss maps during the energy ramp. Figure 2 compares the betatron loss maps at 2.5 TeV during the ramp in the horizontal plane for beam 1 that were measured during the LHC commissioning in 2023 (top) and simulated losses using Xsuite and Xcoll (bottom). For both cases, the distribution of losses is shown for the full ring and for a zoom in IR7. Simulations are performed statically at the same energy, as the dynamic variations during the ramp are considered negligible over the time scale of the ADT excitation of 1-2 s.

Overall there is good qualitative agreement between measurements and simulations: the highest losses are observed in IR7 as expected, and the loss patterns in that region are very similar, although it should be noted that the BLMs are affected not only by the losses directly at their location, but also by showers from upstream losses. However, the simulations show higher losses in IR3 compared to IR6, while the measurements show the opposite. This behavior has been identified in previous studies, however, the reason is not yet clear. The local inefficiency in the IR7 DS ($s$ = 20265 m to 20543 m) is about 7 times lower in the simulations with respect to the measurement.

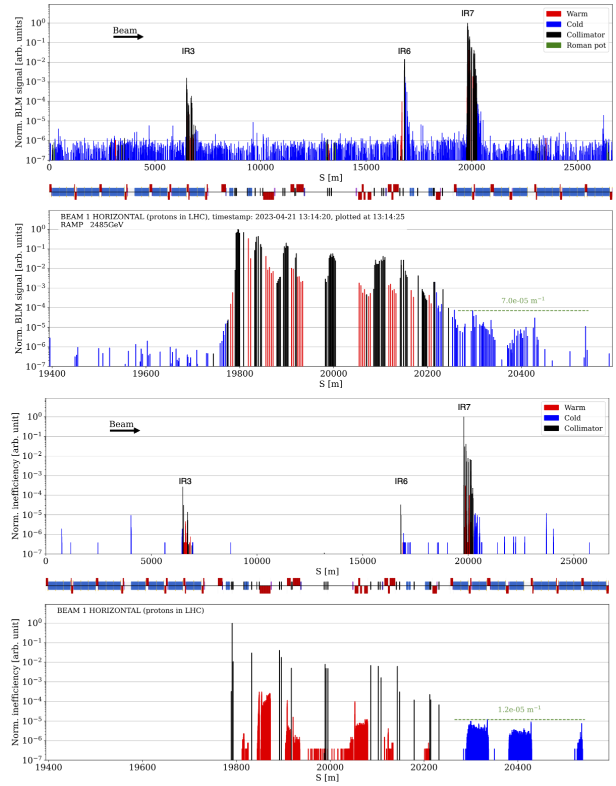


Figure 2: Example horizontal loss maps for B1 at around 2.5 TeV as obtained from measurements (top) and Xsuite simulation (bottom), with a zoom in IR7. The losses are normalized to the maximum losses observed in the collimators.

The simulated betatron cleaning inefficiency in the DS during the energy ramp is shown in Fig. 3 for B1 (top) and B2 (bottom) and compared to the measurement results. There

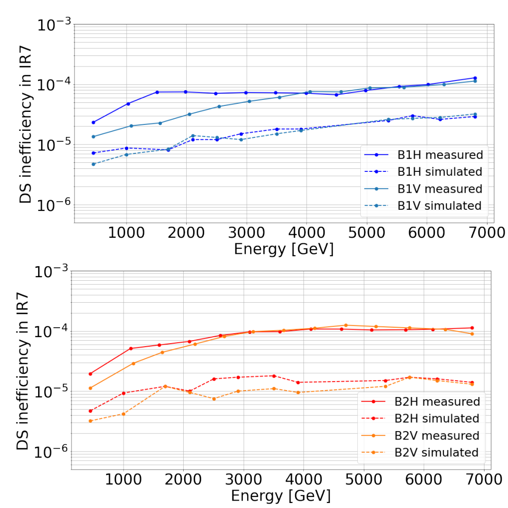


Figure 3: Normalised local inefficiency in the DS in IR7 for B1(top) and B2 (bottom), during the energy ramp for the machine configuration of commissioning 2023. Results from measurements (solid lines) and Xsuite simulations (dashed lines) are shown. The inefficiency values are normalized to the maximum losses observed in the collimators.

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is a very good overall qualitative agreement between measurements and simulations. In particular, for B1 the DS inefficiency in IR7 appears to continuously increase while for B2 it increases until about 3 TeV after which it reaches a plateau. However, quantitatively, the simulations underestimate the normalised DS inefficiency by a factor of 2-4 for B1 and from 3-11 for B2. For B1 an additional discrepancy is observed: in the measurements the inefficiency evolution differs between the vertical and horizontal planes at the start of the ramp up to 3 TeV, while the simulations show these values to be closely aligned. For B2, a similar discrepancy is observed, but it occurs in the middle of the ramp, from 2.5 TeV to 5 TeV.

These results indicate that simulations underestimate the machine's normalized local inefficiency. Such discrepancies, though less pronounced, have been observed previously [6, 23]. This can be attributed to differences in loss map construction: machine measurements use BLMs outside the magnet cryostat, sensitive to the shower development, while simulations count protons lost in the aperture. Accounting for the local BLM response is likely to improve the agreement [6]. Furthermore, simulations assume a nominal machine without orbit misalignment, beta-beating, and collimator imperfections. Last, note that the presented results are obtained with the new tools, and benchmarking with Sixtrack+K2 is underway. Early findings suggest a good agreement between the two simulation tools [20].

## OFF-MOMENTUM CLEANING AT INJECTION

Figures 4 and 5 compare the positive and negative off-momentum betatron loss maps at injection (injection protection out) that were measured during the 2023 commissioning (top) and simulated with the Xsuite and the implemented dynamic RF sweep (bottom). The positive off-momentum loss maps were performed with a sweep of -200 Hz while the negative 250 Hz. Although the simulations were conducted separately for B1 and B2, they are presented together for direct comparison with the measured loss maps, where both beams are affected simultaneously. The losses are normalized to the maximum losses observed in the collimators.

From Fig. 4 it can be clearly seen that there is very good alignment between measurements and simulations. In both cases, the highest losses appear in IR3, followed by IR7, while other main collimation areas are reproduced (TCTs and TCDQ/TCSP). Furthermore, the simulated values of normalised cleaning inefficiency on both sides of IR3 are very close to the measured values. For the negative off-momentum loss maps the results are very similar, and are summarised in Fig. 5 with a focus on the IR3 region. Once again, the inefficiency values between measurement and simulations are in excellent agreement

## CONCLUSIONS

This paper reviewed the LHC collimation system's performance during the 2023 commissioning, particularly during the energy ramp. Simulation results obtained with the Xsuite and Xcoll tools were compared with LHC measurements. The findings show good qualitative agreement, especially in areas like IR7 and IR3. However, quantitative differences were noted in the betatron loss maps, which are likely due to the BLM response that is not included in the simulations. Future work should investigate these discrepancies to refine our understanding and models.

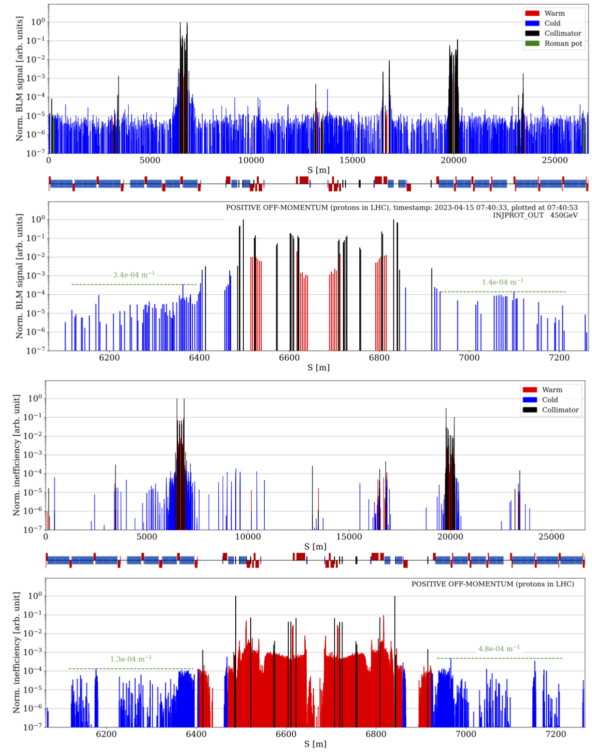


Figure 4: Off-momentum loss maps at injection as obtained from measurements (top) and Xsuite simulation (bottom), for an RF sweep of -200 Hz. Both plots have a zoom in IR3. The losses are normalized to the maximum losses observed in the collimators.

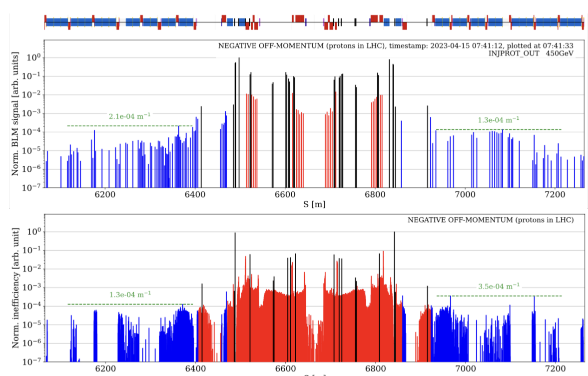


Figure 5: Off-momentum loss maps at injection energy as obtained from measurements (top) and Xsuite simulation (bottom), for an RF sweep of 250 Hz, focusing in IR3.

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