VALIDATION OF SIMULATION TOOLS FOR FAST BEAM FAILURE STUDIES IN THE LHC

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Abstract

The LHC collimation system protects passively the most sensitive machine equipment against beam losses. In particular, collimators are the last line of defense in case of single-turn failures that cannot be caught by the standard interlock system. The collimator settings are conceived to protect the machine even for very rare events, like beam abort failures with a full machine. Collimator settings are established in simulations through a dedicated tracking setup but also empirically validated by beam measurements at low intensities. A benchmark of simulations is essential for reliably estimating the response of the system for future machine configurations and beam parameters. In the paper, results are presented of tracking simulations for different optics deployed in the LHC Run II at 6.5 TeV and compared with data.

INTRODUCTION

High beam losses at the Large Hadron Collider (LHC) [1, 2] are particularly critical at the present energy of 6.5 TeV due to the large stored beam energy and the potential risk of damaging the machine components.

A collimation system is located along the LHC ring following a multi-stage layout that ensures protection from high beam losses to the most sensitive equipment. Primary (TCP) and secondary collimators (TCSG), followed by tungsten absorbers (TCLA) are located in insertion regions (IR) 3 and 7. Tertiary collimators (TCTs) are installed upstream of the high-luminosity experimental regions to provide local protection of the triplets and reduce the background recorded by the detectors. During the standard operation, TCTs intercept a small fraction of particles. However, they risk to be hit by high-energy primary beam if an accident occurs during the beam extraction process.

In the LHC, the beams are extracted by 15 kicker magnets, called MKDs, that rise from zero to full field in about 3 μs. Therefore, the beam filling scheme contains an "abort" gap of 3 μs to allow all the kickers to fire before the first bunch passes. However, irregularities could lead to an asynchronous beam dump, defined as a case when the MKDs trigger is not synchronised with the abort gap. As a consequence, bunches of particles can be miskicked and sent to magnets as well as collimators [3–5]. For this reason, a stopper (TCDQ) and a secondary collimator (TCSP) are installed at 90° phase advance from the extraction kickers in Point 6 (IR6). They intercept the miskicked beams and protect the machine elements downstream. HiRadMat tests [6] and simulations proved that TCTs at 7 TeV might be damaged by the direct impact of a single pilot bunch (5×10^9 protons): their protection in case of an asynchronous beam dump is thus crucial.

Results of tracking simulations of asynchronous beam dump at the LHC will be discussed in the paper. Losses on the TCTs will be presented for different machine configurations and collimator settings and then benchmarked with measurements in the LHC performed during standard operation and dedicated beam tests in 2015.

SIMULATION SETUP AND PROCEDURE

SixTrack is a multiturn six-dimensional symplectic tracking code optimized to track single particles in high-energy rings [7–9] and it is the standard tool used at CERN for collimation studies [10]. SixTrack simulations of beam cleaning have been successfully benchmarked with LHC data [11].

In order to study fast failure scenarios, SixTrack was adapted to simulate the simultaneous misfiring of all the beam dump kicker magnets in the LHC dump line [12]. A train of 6.5 TeV protons with 25 ns spacing between consecutive bunches was simulated for both beams. Each bunch receives a different kick from each MKD according to the estimated rise of the magnetic field. In simulations were taken into account only the bunches belonging to the zone of angles not caught by the IP6 collimators and still in a range that can hit the TCTs before seeing the full field at the next turn (grey band in Fig.1) . A Gaussian bunch profile of

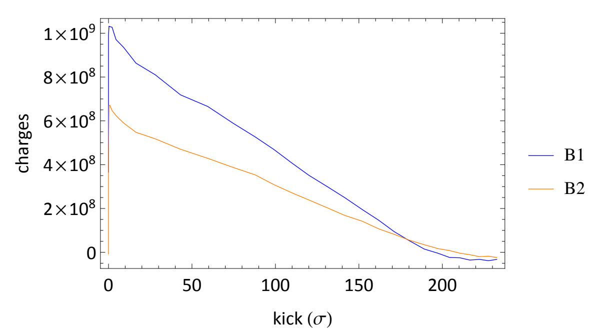

Figure 1: Abort gap population, measured by the abort gap monitors during the asynchronous dump test with tight collimator settings and β^*= 80 cm for both beams, giving as a function of total kick in σ summed over all MKDs.

SixTrack macro-particles is tracked for 3 turns: when the particles pass the MKDs at the second turn, they receive an intermediate kick, which which risks to kick them onto the machine aperture. At the third turn, the MKDs have reached their full field and all remaining particles are extracted. The full LHC collimation system was included in the simulations.

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Three machine configurations of the LHC 2015 proton run at 6.5 TeV were considered: for the first one, the injection optics (β^* = 11 m) is used, while in the other two the optics is squeezed to β^* = 80 cm and the collimators are set either to nominal settings [13] or tighter as in a special study [14]. The experimental procedure to validate the machine protection settings against asynchronous beam dump foresees adding bumps at IR6 collimators to account for orbit drift. In simulation, this was reproduced by further retracting the TCDQs and TCSP by the corresponding amount. The deployed collimator settings used in simulations are listed in Table 1.

Table 1: Collimator Settings used for SixTrack Simulations at 6.5 TeV in Various Machine Configurations. The values are expressed in units of standard deviation [σ] of the beam size, calculated for a normalized emittance of 3.5 μm rad.

Collimator Families	**Flat top** (β^* = 11 m)	**OP squeeze** (β^* = 80 cm)	**MD squeeze** (β^* = 80 cm)
IR7 TCP/TCSG/TCLA	5.5 / 8 / 14	5.5 / 8 / 14	5.5 / 8 / 14
IR3 TCP/TCSG/TCLA	15 / 18 / 20	15 / 18 / 20	15 / 18 / 20
IR6 TCSP - TCDQ	9.1 + 2.4	9.1 + 2.4	9.1 + 2.4
IR1/5 TCTs	37	13.7	10.7
IR2/8 TCTs	37 / 37	37 / 15	37 / 15

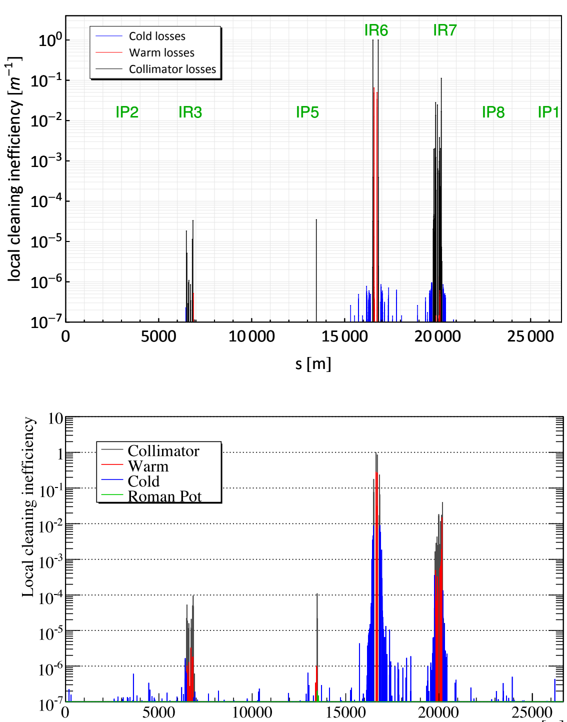

Figure 2: Loss distribution in the ring following asynchronous beam dump at 6.5 TeV with injection optics (β^* = 11 m): SixTrack simulation (top) and measurement performed on 6.9.2015 at 10:59:13 (bottom).

The distribution of particles lost in the ring as simulated by SixTrack for the three considered cases is shown in the top picture of Figs. 2, 3 and 4. The losses at collimators and

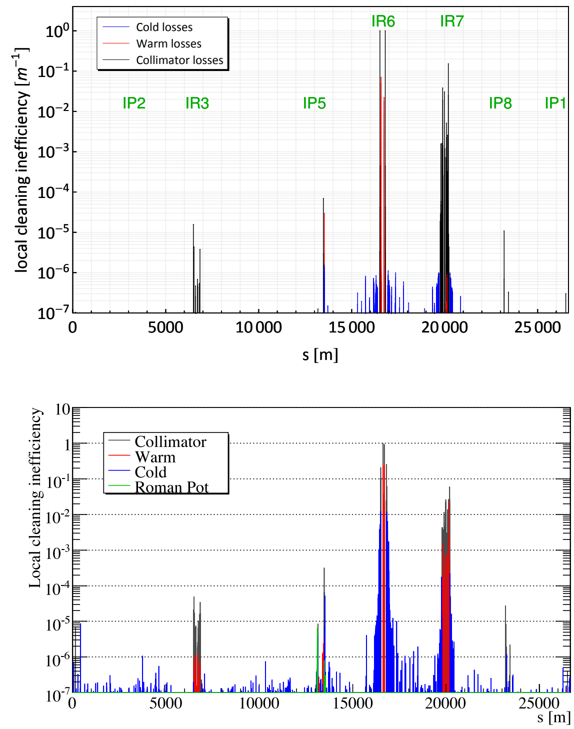

Figure 3: Loss distribution in the ring following asynchronous beam dump at 6.5 TeV with squeezed optics (β^* = 80 cm): SixTrack simulation (top) and measurement performed on 4.7.2015 at 15:42:24 (bottom).

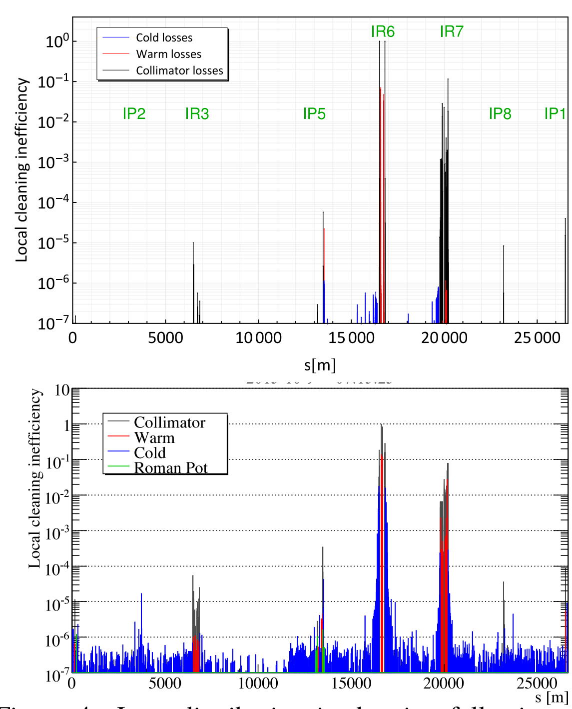

Figure 4: Loss distribution in the ring following asynchronous beam dump at 6.5 TeV with squeezed optics (β^* = 80 cm) and tighter TCT settings in IP1/5: SixTrack simulation (top) and measurement performed on 9.10.2015 at 07:13:25 (bottom).

magnets were summed over all bunches considered in the simulation. Simulations of TCDQ losses are multiplied by

ISBN 978-3-95450-147-2

a factor 7 to take into account not simulated bunches that however in measurement are absorbed by this collimator. As expected, for all the three cases the main loss location is in IR6, but high loss peaks stick out also from collimators in IP7. Losses at IR1/5 TCTs increase when tightening the settings, while the peak in IR8, not visible at flat top when collimators are still opened, appears for squeezed optics. On the other hand, IR3 decreases looking from flat top to squeeze, maybe because particles are caught by IR5.

MEASUREMENTS IN THE LHC

To understand how close the simulation results are to the real behaviour of the machine, measurements of fast beam losses performed in 2015 are used to benchmark the simulation results.

Asynchronous beam dumps in the LHC were mimicked by first turning off the RF system to induce a debunching of a bunch in a bucket next to the abort gap. Once a sufficient abort gap population was reached, a standard beam dump was triggered. Examples of the abort gap distribution at the moment of the dump are shown in Fig. 1. Loss data at flat top and squeeze with nominal collimator settings were taken during asynchronous dump tests performed in a standard LHC configuration, while a dedicated measurement session (MD) was devoted to test the squeezed optics with tighter collimator settings [14]. The signals were recorded by the BLMs and then normalized to the highest value. The signals with an integration time of 1.3 s are collected in the bottom picture of Figs. 2, 3 and 4 for the cases in analysis.

A detailed quantitative comparison between simulated and measured loss patterns is made more difficult by the fact that the presented simulation chain produces lost protons on the aperture, while the BLM signal is mainly caused by the shower particles created by the impact and could be simulated by energy deposition tools. However, a good qualitative agreement can be stated for the three scenarios: the level of normalized losses estimated in simulations in IR6 and IR7 is well reproduced by the measurement as also the higher contribution to the losses in IP7 from Beam 2 (right side of the insertion) due to the worst phase advance with respect to Beam 1. The same trend is visible in IP3, although the discrepancy between simulations and measurements is slightly higher than the other IPs. Reproducing the measured losses in IP1, IP5 and IP8 within factors 3-4 is a very good result considering that showers are not included in SixTrack. The upstream showers are also very likely responsible for the high warm losses in IR3, IR6 and IR7, which are absent in the simulations as shown in [11]. The blue spike sticking out from IP2 in Fig. 4 is noise recorded by a single BLM upstream of IP2 that can be reasonably discarded when compared with simulation.

COMPARISON OF LOSSES IN TCTs

The fraction of the total abort gap population impacting on the horizontal tertiary collimators in IP1 and IP5 measured during the asynchronous dumps is compared with SixTrack simulations for the same collimators in all the configurations considered for this study. In order to have a meaningful comparison, the BLM signals were converted from Gy/s to the estimated number of protons impacting the TCT as detailed in [15] and then normalized to the abort gap population at the time of the dump. It should be also noted that the simulated bunches were all equally populated, while the population was not fully homogeneous during the measurement (Fig. 1). Therefore, each simulated bunch was normalized to the measured population profile of the abort gap over the corresponding 25 ns interval and in the end the losses at the TCTs were summed over all bunches and normalized to the total abort gap population.

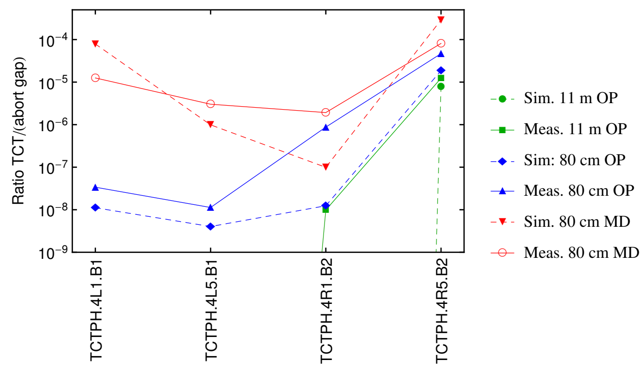

Figure 5: Fraction of the total abort gap population impacting on the TCTs in IR1/5 during the asynchronous dump in simulation and measurement for the cases discussed.

By looking at the ratio for single TCTs in Fig. 5, it can be stated that the overall accuracy of the simulations with respect to the measurements is good: all results are within the expected uncertainties except for TCTPH.4R1.B2, which should be investigated more in detail. Possible explanations for the discrepancy could be errors on the BLM placement or electronics, causing a different BLM response, or errors on the assumed collimator setting.

CONCLUSIONS

Safe machine operation at the LHC must be guaranteed even in the rare case of a beam failure. The asynchronous beam dump is one of the most critical scenarios that may expose the aperture to large beam losses. A comparative study of simulated and measured losses on tertiary collimator following an asynchronous beam dump test has been discussed for different configuration of LHC adopted in 2015.

An overall good agreement between beam loss measurements and prediction from SixTrack simulations was found, also in view of various uncertainties except at one collimator. The possibility to rely on a tool that allows to reproduce in simulation possible beam accidents and predict losses on sensitive equipment, as collimators, is of undisputed importance in view of the upcoming upgrades at the LHC.

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ISBN 978-3-95450-147-2