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SIMULATIONS AND MEASUREMENTS OF CLEANING WITH 100 MJ BEAMS IN THE LHC

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Abstract

The CERN Large Hadron Collider is routinely storing proton beam intensities of more than 100 MJ, which puts extraordinary demands on the control of beam losses to avoid quenches of the superconducting magnets. Therefore, a detailed understanding of the LHC beam cleaning is required. We present tracking and shower simulations of the LHC's multi-stage collimation system and compare with measured beam losses, which allow us to conclude on the predictive power of the simulations.

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The CERN Large Hadron Collider is routinely storing proton beam intensities of more than 100 MJ, which puts extraordinary demands on the control of beam losses to avoid quenches of the superconducting magnets. Therefore, a detailed understanding of the LHC beam cleaning is required. We present tracking and shower simulations of the LHC's multi-stage collimation system and compare with measured beam losses, which allow us to conclude on the predictive power of the simulations.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN is designed to collide proton beams at an unprecedented energy of 7 TeV with and a stored energy of about 362 MJ. The machine parameters, both nominal and achieved in 2011 and 2012, are given in Table 1. Even though the design parameters are not yet reached, a maximum of 146.5 MJ has been stored in operation. Because of the large stored energy, the two counter-rotating LHC beams, called B1 and B2, are highly destructive. Beam losses can cause both quenches of superconducting magnets and possibly material damage. Therefore, the machine aperture must be protected and beam losses tightly controlled. For this purpose, a multi-stage collimation system has been installed [1, 2, 3, 4]. Most collimators have two movable jaws, one on each side of the beam. The collimators are mainly grouped in the insertion regions (IRs) called IR3 (momentum cleaning) and IR7 (betatron cleaning).

The collimators in the cleaning insertions are primary (TCP), secondary (TCS) and absorbers (TCLA). Tertiary collimators (horizontal TCTH and vertical TCTV) are in place in front of the experiments in IR1, IR2, IR5, and IR8. Dump protection devices (TCS6 and TCDQ) in IR6 shield the machine in case of beam dump failures. Some important settings are shown Table 1.

The cleaning performance is qualified regularly with provoked losses at a low, safe intensity [5, 6, 7]. The loss pattern, measured with a system of beam loss monitors (BLMs) installed around the ring, is studied to make sure that sensitive equipment is properly protected.

The efficiency of the collimation system, required to safely operate below the quench limit, is extraordinary and requires that we can quantitatively predict local beam losses. In this paper we present results of simulations with SixTrack [8, 9] of the LHC cleaning performance. We simulate the machine used during the previous physics runs and make quantitative comparisons with measurements of losses. For this purpose, we perform also a second stage of simulations with FLUKA [10, 11] of the particle showers induced by the losses that reach the BLMs.

Table 1: Proton running conditions for physics in the LHC in 2011, 2012, and for nominal design parameters.

	2011	2012	Nom.
E (TeV)	3.5	4	7
N. of bunches	1380	1380	2808
Average bunch intensity (10^{11})	1.2	1.4	1.15
TCP cut (σ)	5.7	4.3	6.0
TCS cut (σ)	8.5	6.3	7.0
TCLA cut (σ)	17.7	8.3	10.0
TCT cut (σ)	11.8	9.0	8.3
Peak stored energy (MJ)	128	146.5	362
Peak luminosity $(10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	0.35	0.77	1.0

SIXTRACK SIMULATIONS

SixTrack is a multi-turn tracking code that accounts for the full six-dimensional phase space in a symplectic manner. SixTrack does a thin-lens element-by-element tracking through the magnetic lattice. The particle coordinates are checked against a detailed aperture model with 10 cm longitudinal precision. If the aperture is hit, the particle is considered lost, except at collimators, where a built-in Monte Carlo code [9] is used to simulate the particle-matter interaction. When an inelastic event occurs inside a collimator, the particle is considered lost, otherwise the scattered particle is reinserted in the tracking.

The starting conditions are an assumed primary halo with betatron actions large enough to hit the TCPs at impact parameters of a few microns [12]. The details of the generation of starting conditions can be found in Ref. [13]. This approach significantly increases the efficiency of the simulation, since the beam core is not tracked and no diffusion is included. Typically we track 64×10^6 particles for 200 turns, which is sufficient for all of them to be lost. Different simulations are performed for initial losses in the horizontal and vertical planes and the two beams.

STUDY OF 2011 RUN

Qualitative comparison

To benchmark the simulations, we consider the LHC configuration used in the 2011 physics run (see Table 1). We study the qualification loss maps rather than the losses during high-intensity physics fills, since only one beam is excited at a time. Furthermore, the collisional loss rate is

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negligible, meaning that the losses are dominated by the betatron halo.

Fig. 1 shows the losses around the ring as simulated by SixTrack in a perfect machine and measured during a 2011 qualification loss map, with different colors for losses in a cold or warm element or on a collimator. In both cases, the initial beam loss occurs in B1 in the horizontal plane. The simulated losses are binned in 1 m intervals. Both simulations and measurements are normalized to the highest loss. There is an excellent qualitative agreement between simulation and measurement. The main losses in IR7 decay along the insertion. A small tail, 4–5 orders of magnitude lower than the TCP loss, leaks to the cold dispersion suppressor (DS) downstream of IR7. This location of the highest local cold loss in the ring is the limiting location for the LHC intensity reach [4]. The second most important loss location is IR3. We note that the simulation accurately predicts all potentially limiting cold loss locations.

Significant quantitative deviations are found at some locations, in particular in IR6 and on the TCTs, where differences of a few orders of magnitude are observed. However, the BLMs do not measure the direct proton losses shown for the simulation, but the showers produced by them. The BLM signal per lost primary proton could vary significantly between loss locations, depending on the local geometry, and therefore one cannot expect a high level of accuracy when comparing the weighted convolution of all upstream showers in a BLM with the proton loss locations.

Quantitative comparison

In order to compare quantitatively with the BLM measurements we use FLUKA to simulate the showers at some selected locations. We consider first the IR7 DS using a detailed FLUKA geometry including collimators, magnets and BLMs. The loss distributions from SixTrack are used as starting conditions. Details are given in Refs. [14, 15].

Some key results are shown in Fig. 2 and compared with the averages over 7 different loss maps from 2011. Both simulations and measurements are normalized to the BLM with the highest signal. The highest signal in cell 8 (the most critical location) is found on the same BLM in simulations and measurements. In cell 11, the BLM with the measured maximum is only the second highest in simulation. The magnitudes of the signals agree within a factor 2, which we consider an excellent agreement, especially since the initial impact distribution on the TCPs is not well known and, as far as cell 8 is concerned, the contribution of the shower from the Long Straight Section (LSS), not included in the calculation, is expected to play a role increasing the predicted signal.

We study also the TCTs in ATLAS and CMS with simulations done in reduced FLUKA models, including only the collimators and the BLMs attached to them. Both the TCTs and the TCPs are simulated. In SixTrack, we include the influence of random collimator imperfections (errors on tilt angles, beam center, gap, and jaw curvature in IR7) using the parameters in Ref. [13] in 30 seeds. The FLUKA simulations are done for a perfect machine assuming the same BLM response.

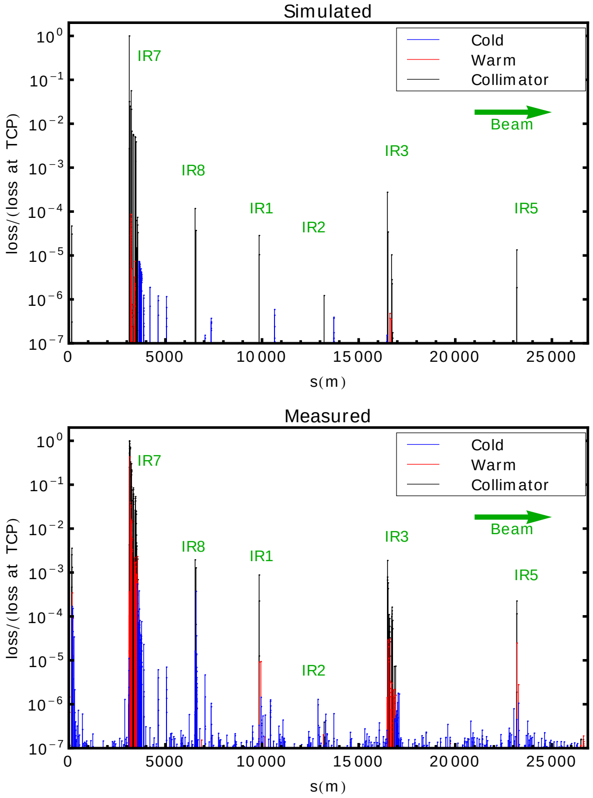

Figure 1: Simulated loss locations from SixTrack binned in 1 m intervals (top) and measured BLM signals from a qualification loss map on April 12, 2011 (bottom). The initial losses occur in both cases in the horizontal plane in B1.

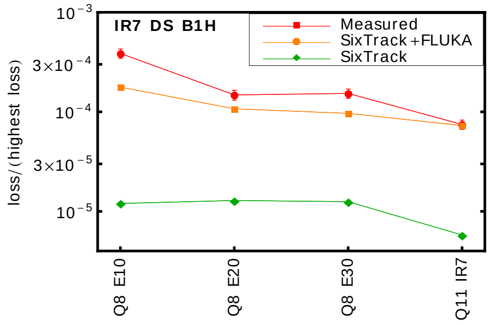

Figure 2: The ratio of BLM signal, or particles lost, at the BLMs with the highest signal in the IR7 DS, to the highest signal in the LSS, in simulations and measurements for the 2011 machine for horizontal losses in B1.

The simulated energy deposition in the BLM per lost proton is found to be a factor 3.6–7.4 higher at the TCTs than at the TCPs, since more of the shower develops in the jaws due to different materials and impact distributions. The BLM response is simulated only for the case of the B1H and B1V loss maps—since it was found to be similar

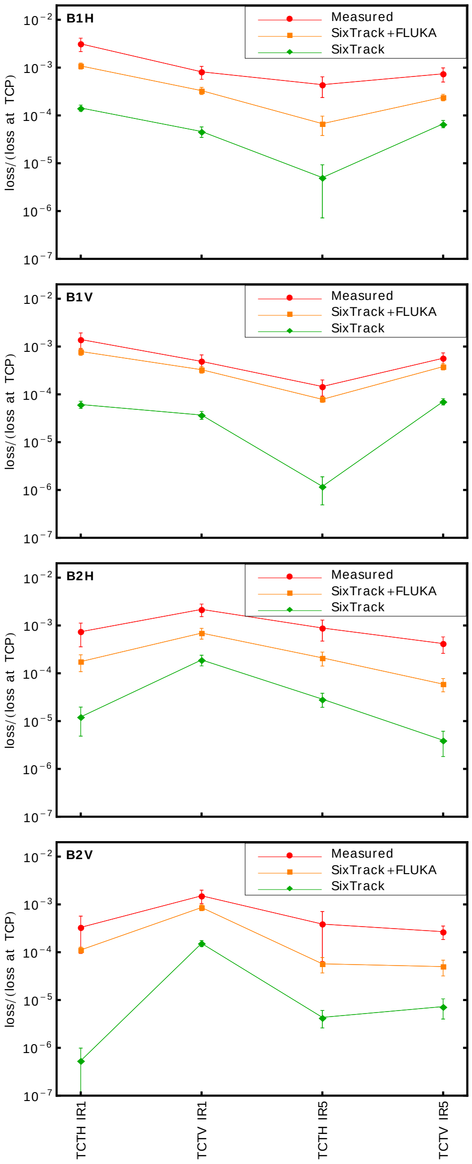

Figure 3: The ratio of BLM signal, or particles lost, on horizontal and vertical TCTs to the TCPs in simulations and measurements in the 2011 machine.

in IR1 and IR5 in spite of slight variations in the impacts, we apply the same response to B2 for the corresponding plane. Furthermore, we account for the cross talk between the BLMs at the TCTH and TCTV, which are situated only about one meter apart.

The simulated ratios of losses at TCTs and TCP, from primary SixTrack losses and from FLUKA, are shown in Fig. 3 for both beams and planes together with the measured average BLM ratios from the 2011 loss maps. The simulation consistently underestimates the measurements by about a factor 1.5–4 in most cases, although discrepancies by up to a factor 7 are found. We consider this a good agreement in view of the high complexity of the two-step simulation, including multi-turn effects in the 27 km ring, and the fact that the leakage shown in Fig. 1 spans more than 7 orders of magnitude. It should be noted that we do not include optics imperfections, which can further increase the leakage out of IR7 [13].

Regardless of the plane of the initial IR7 loss, the measured maximum TCT loss is recorded at the IR1 TCTH for B1. In B2, the maximum loss occurs on the IR1 TCTV for both planes. This is accurately reproduced by the simulations. The fact that more losses are seen in IR1 in both cases implies a higher contribution to the experimental background from collimation losses than in IR5.

Other comparisons between SixTrack and measurements are shown in Ref. [16], for the case of losses during a non-perfect beam extraction, and in Ref. [17], where the energy dependence of betatron losses is studied. In both cases a very good qualitative agreement is found.

CONCLUSIONS

We show simulations with SixTrack of the cleaning performance of the LHC collimation system. When comparing simulated beam loss locations with BLM measurements during provoked losses in the LHC, a qualitatively very good agreement is found with all significant loss locations predicted by the simulation. At some selected loss locations around the ring, the showers induced by the impacting protons are simulated with FLUKA for a quantitative comparison with measurements. It is found that the combined simulation in most cases underestimates the measured losses by a factor 1.5–4 and reproduces very well the measured loss pattern. We consider this a very good agreement given the complexity of the simulation.

Our results are important for the quantitative understanding of beam losses from the leakage out of a multi-stage collimation system. They give an increased confidence in our simulation programs, which are used also as a design tool to determine improved collimator configurations in future running scenarios.

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