MULTI-TURN TRACKING OF COLLISION PRODUCTS AT THE LHC*

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Abstract

The luminosity expected at the interaction points in LHC at 7 TeV will be unprecedented, up to $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Part of the debris produced by the collisions is lost locally immediately downstream the Interaction Point (IP), in the matching section and dispersion suppressor.

In this paper, the dynamics of collision debris protons is discussed. First, the loss distributions close to the collision points, simulated with two codes — SixTrack and FLUKA — are compared for different layout configurations. Then, SixTrack is used to simulate the fraction of protons that have undergone inelastic interactions with smaller energy and and betatron offsets, which could travel for several turns around the ring and might be lost in other collimation insertions. A preliminary comparison is made between the resulting loss distribution and measurements.

INTRODUCTION

The long absorbers for physics debris, usually referred to as TCLs, are collimators made of two 1 m-long Copper or Tungsten jaws [1]. During Run 1 of the LHC (2010–2013), one of them was situated downstream both Interaction Points (IP) 1 and 5, before Q5 for each beam. Their goal is to intercept secondary particles and scattered protons coming from the IPs, having undergone collisions at 4 TeV, hence displaying extra kicks and extra momentum offsets. They prevent these particles from being lost in the cold magnets of the straight section (mainly Q5 and Q6) and the Dispersion Suppressor (DS).

The higher energies (for Run 2) and luminosities (for HL-LHC) foreseen for the different LHC upgrades increase the need for protection: another TCL has been installed in each cell 4 of the LHC during LS1, and a third one might be installed in cell 6. A similar layout with three TCLs per beam in IR1 and IR5 is foreseen for the HL-LHC. The positions and effect of these collimators have been simulated for a single pass (one turn) by the particle tracking code SixTrack [2, 3, 4] and the Monte-Carlo code FLUKA , simulating particle-matter interactions [5, 6].

The effects of proton collisions are generated by FLUKA : extra kicks and momentum offsets are applied to the simulated protons (see Fig. 1). Protons with momentum deviations above the arc acceptance of about 1% are lost at the first passage in the matching sections and dispersion suppressors downstream of the IP [7]. Local losses can be simulated with a single-pass tracking and with an aperture check of 10 cm spatial resolution [8]. The number of lost protons simulated by both tools is then converted to protons per second per meter, knowing the number of collisions simulated when creating the initial debris distribution, the number of collisions per second corresponding for a given peak luminosity (see Table 1), and the length of a bin in the loss map.

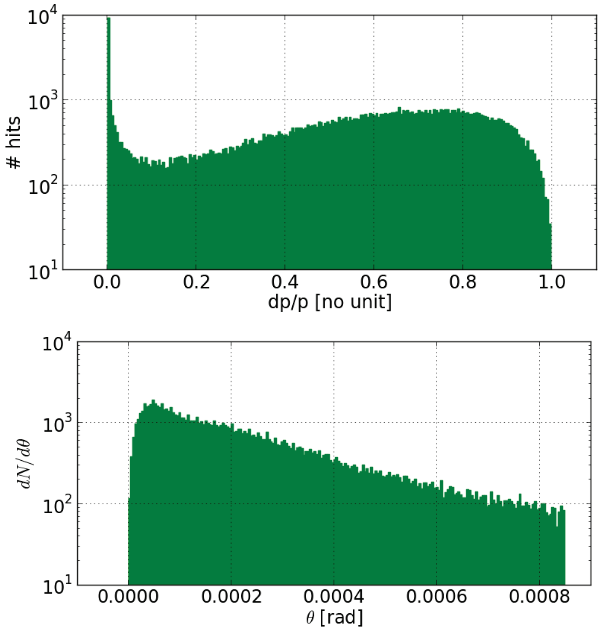

Figure 1: Samples of the distributions of extra momentum offset (dp/p, top) and polar angle from the z axis (bottom) due to collisions, simulated by FLUKA and applied to the protons of the initial distribution.

In this paper, the loss maps immediately downstream of the IRs calculated with FLUKA and SixTrack are compared. Then, multi-turn simulations performed with SixTrack to predict losses around the ring in collisions are discussed and compared with 4 TeV measurement data.

Table 1: Simulation parameters used in both FLUKA and SixTrack simulations.

Energy	7	TeV
Luminosity	10^{34}	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
emittance	3.75	mm.mrad
β^* at IP1/5	55	cm
Crossing angle at IP1/5	295	μrad
σ at IP1/5	16	μm
σ at TCL4	530	μm
σ at TCL5	291	μm
σ at TCL6	84	μm

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* Research supported by FP7 HiLumi LHC – Grant agreement 284404

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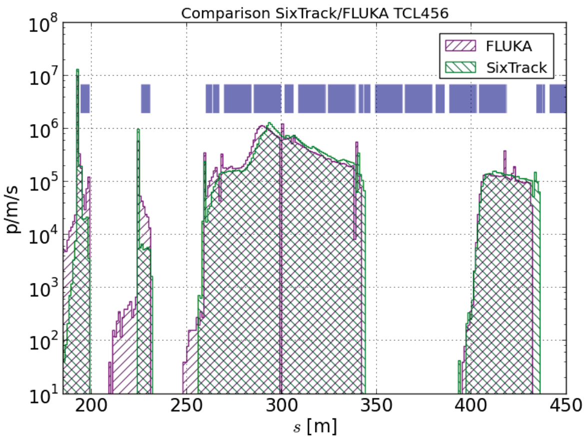

Figure 2: Losses around the DS versus longitudinal position, for FLUKA (purple) and SixTrack (green) simulations, with all TCLs open. The losses are expressed in protons per meter per second, for the design luminosity.

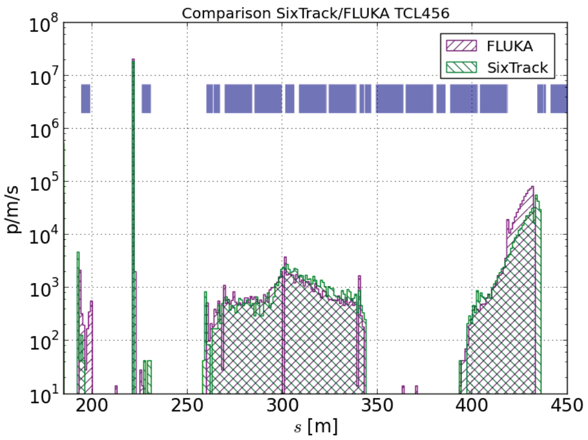

Figure 3: Losses around the DS versus longitudinal position, for FLUKA (purple) and SixTrack (green) simulations, with TCL4, 5 and 6 set at 15, 35 and $10\,\sigma$. The losses are expressed in protons/m/s, for the design luminosity. The highest peak corresponds to the position of the TCL6.

COMPARISON FLUKA / SIXTRACK

SixTrack is a tracking tool [2, 4] optimized to simulate the proton trajectories in magnetic elements (LHC), which also treats their interactions with collimators, generating longitudinal maps of protons lost on the aperture or collimators [3].

These loss maps can also be generated with FLUKA. The results of the two codes for the same inputs and collision point are compared. Tracking simulations of the debris were performed with nominal optics at 7 TeV for the right side of IP5, for a single pass. Relevant simulation parameters are given in Table 1. The comparison for the case with all TCLs open is shown in Fig. 2. Both codes agree well on the considered range: cells 5 and 6, the Dispersion Suppressor (DS), and up to cell 14 of the arc. The triplet region is disregarded in this study because losses are dominated by direct showers from the IP, including other particles than protons, which are only simulated with FLUKA. The amplitude of the different loss clusters agree very well. The longitudinal position at which the losses start rising also agree with a precision of one bin, showing that the optics, the momentum cuts and their effect are consitent.

The TCL4 offers a good protection in cells 4 and 5, but the dp/p cut provided is not enough to protect the entire DS. Only the TCL6 has a dp/p cut low enough to protect the whole DS. The TCL configuration currently considered includes TCLs in cells 4, 5 and 6, set at 15, 35 and $10\,\sigma$ respectively. This configuration was used for the simulations shown in Fig. 3. They show that the whole region of the DS can be protected, up to the beginning of the arc, where once again the required dp/p cut is too low.

For both cases, there are differences that, depending on the loss locations, can reach a factor 2. Some shifts of longitudinal positions of losses are also observed in Fig. 3. This is considered acceptable due to the complexity of the simulations. A detailed comparison of the models used is ongoing. The agreement between the two codes shows that these results can be trusted for further simulations.

MULTITURN SIMULATIONS

Most protons of the initial distribution, generated from collision simulations, have high values of dp/p and transversal kicks. These particles do not survive long: simulations performed with 50 turns showed that 88 % of emerging protons are lost during the first turn, 93 % after turn #5, whereas the last 45 turns represent around 7 % of the total number of particles lost. In this case, 5 turns were already representative, and a dp/p cut of 10 % was applied to the initial distribution to ignore protons that would be lost straight away, before the first TCL.

In order to compare with 2012 data, simulations were performed at 4 TeV, starting at IP1 and IP5, for Beam 1 and Beam 2, with the same initial distribution. It must be noted that the collision debris simulations, used as input to create the initial distribution, does not include elastic proton-proton interaction (not available in FLUKA-generated input yet). The four simulations were summed up over the whole ring in Fig. 4, to recreate a situation similar to what was observed in the LHC during collisions, with the limitations already mentioned. An example of a real LHC loss profile averaged over one hour of data, using the same normalisation, is added for comparison purposes (Fig. 4, green line). Comparison indicates that there is a qualitative agreement for the loss locations; however, the details of peak height show significant quantitative differences. Other limitations include the fact that collisions at IP2 and IP8 were not simulated. The losses at the triplet are dominated by particles with high dp/p, lost during the first turn. A cut was added in simulations to keep only particles likely to survive the first turn, hence underestimating the losses at the triplets.

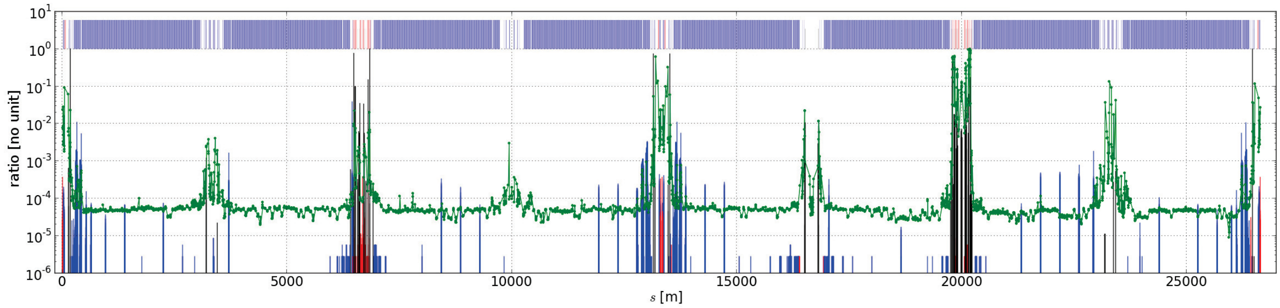

Figure 4: Comparison between simulations and measurements. The Sum of 4 simulated loss maps for debris simulations starting from IP1 and IP5, for B1 and B2, is in blue, red and black. The loss profile of the LHC BLMs, in Gy/s, from the 2012/05/15, averaged between 17:00 and 18:00, with integration window of 1.3 s, is in green. Both plots have been normalised to the losses at the primary collimator TCP.C6R7.B2.

For a complete comparison, the weighted loss maps from beam-gas interactions, possible halo and additional betatron (IR7) and momentum (IR3) losses should be added.

One of the main limitations is that SixTrack simulates the loss locations of primary protons, whereas the observables in the LHC are the signal of the Beam Loss Monitors (BLM). They are ionisation chambers which detect the secondary showers outside the beam pipe (and oustide the cryostat where there is one), generated by protons lost inside on the beam pipe. The shower development depends on the loss location and the material between this location and the BLM. Obviously, one BLM can detect any shower and do not discriminate on the original location; going from proton loss to BLM signal or conversely is complex. The SixTrack simulations are expressed in proton lost per metre per second, while measurements are given as signal in Gy/s. At this stage, the comparison with measurements must therefore be considered very preliminary.

In addition, experience in the LHC showed that the sharing of losses between B1 and B2, and between IR3 and IR7 can evolve from fill to fill, and with time within one fill, as shown in Fig. 6. In this example, the ratio between the two primary collimators of IR7 is similar to the one simulated (Fig. 5) only at the beginning of collisions; at the end of the fill, it is inverted. The contribution of IR3 keeps increasing during the fill; in some cases, the losses are even higher than in IR7. Therefore, a better understanding of the dynamics of losses during the physics fill is needed to perform more detailed comparisons. This is beyond the scope of this paper. Nevertheless, these results are a first step in multiturn debris tracking with known limitations. Further SixTrack studies will be performed to assess the effect of the collision debris.

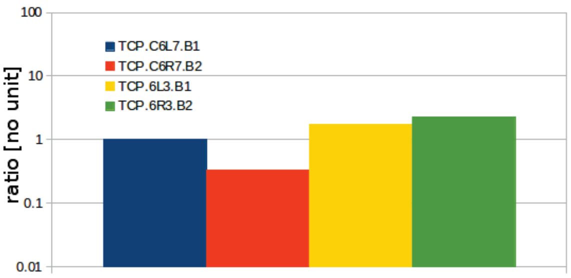

Figure 5: Simulated losses at the TCPs, normalised to the losses at TCP.C6L7.B1. In IR7, losses from B2 are lower than losses from B1; and losses in IR3 (momentum) are higher than losses in IR7 (betatron).

CONCLUSION

Proton loss maps have been simulated with both FLUKA and SixTrack for collision debris in the straight section downstream IP1 and IP5, and they agree well on the considered range. Multi-turn simulations for IP1 and IP5 and both beams have been performed with SixTrack. They were compared with real LHC loss profiles, and showed encouraging results knowing the limitations and the difficulties of comparing to fluctuating real data. Further work implies running multi-turn simulations with the collision debris including elastic proton-proton interaction.

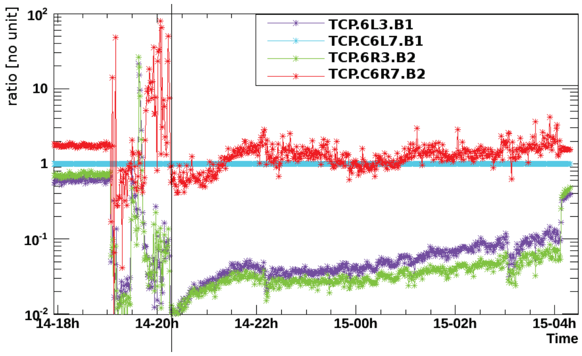

Figure 6: BLM signal at the TCPs normalised to the signal at TCP.C6L7.B1 versus time, during fill #2628, 2012/05/16. The sharing between B1 and B2 in IR7 changes with time. The contribution of IR3 keeps increasing during the fill.

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