# SIXTRACK SIMULATIONS OF BEAM CLEANING DURING HIGH-BETA OPERATION IN THE LHC

R. Bruce*, CERN, Geneva, Switzerland

## Abstract

The 1000 m high-beta run in the LHC provided very clean conditions for observing experimental backgrounds. In AT-LAS, a much higher background was observed for Beam 2 than for Beam 1, suspected to be caused by upstream showers from beam losses on collimators or aperture. However, no local beam losses were observed in the vicinity. This paper presents SixTrack simulations of the beam cleaning during the high-beta run. The results demonstrate that, for the special optics and collimator settings used, the highest loss location in IR1 is at the TAS absorber just in front of the ATLAS detector, where no beam loss monitor is installed. Furthermore, the highest losses are seen in Beam 2. The results could thus provide a possible explanation of the AT-LAS observations, although detailed shower calculations would be needed for a quantitative comparison.

## INTRODUCTION

The schematic layout of the the CERN Large Hadron Collider (LHC) [1] is shown in Fig. 1. It has two counter-rotating beams (B1 and B2) and consists of 8 arcs and 8 straight insertion regions (IRs). At the end of its first proton physics run, in 2012, the LHC collided 4 TeV beams using an optical $\beta$-function $\beta^*$ =60 cm at the high-luminosity experiments ATLAS [2] and CMS [3]. This value was optimized to be as low as possible [4], for highest luminosity, in order to increase the rate of rare events.

Downstream of ATLAS and CMS, the forward physics experiments ALFA [2] and TOTEM [5] are installed, which are specialized at measuring the proton-proton cross section from elastic scattering. In order to accurately measure the scattering angles of outgoing protons, TOTEM and ALFA require a minimum angular divergence at the interaction point (IP). So instead of the small $\beta^*$ used in the high-luminosity runs, which imply a large angular divergence at the IP, these experiments benefit from a very large $\beta^*$.

Therefore, short special physics runs were performed with a particular high-$\beta$ optics, where the largest value used was $\beta^*$ =1 km during LHC fill 3216 on October 24 in 2012 [6]. This run was carried out at low intensity for machine protection reasons and used special collimator settings. The primary collimators (TCP) in the betatron cleaning insertion IR7 [7] were used to scrape down the beam to about 2 $\sigma$ [8] ($\sigma$ is defined as the local beam size calculated using the standardized normalized emittance of 3.5 $\mu$m and the ideal $\beta$-function) and then retracted by about 0.5 $\sigma$. This removed the beam halo in the scraping range and allowed to minimize the background at the forward-physics experiments. Other scrapings were performed using the TCP in the momentum
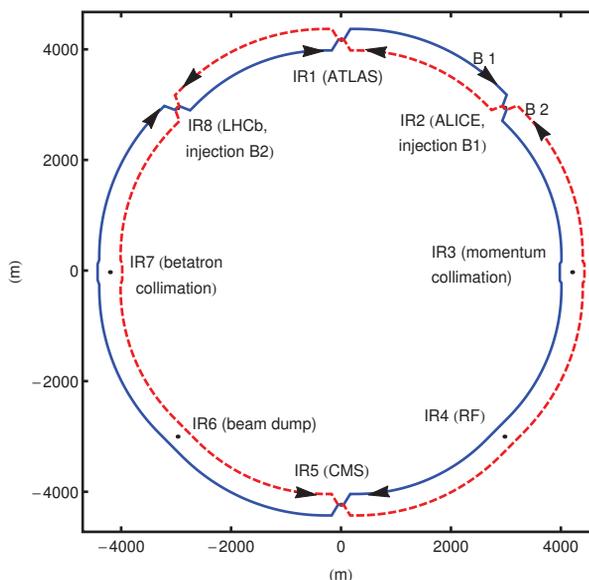
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* roderik.bruce@cern.ch

Figure 1: The schematic layout of the LHC (the separation of the two rings is exaggerated). The two beams are brought into collision at the four experiments ATLAS, ALICE, CMS and LHCb. Figure taken from Ref. [9].

cleaning insertion IR3, to remove the off-momentum tails. Cycles of TCP scraping and subsequent retraction had to be repeated several time, after a re-population of beam tails that reached the TCP cut.

## BACKGROUND IN HIGH-$\beta$ RUN

Beam-halo induced background occurs in the LHC experiments when halo protons initially hit a TCPs and then scatter back into the beam to an oscillating orbit, which leads to a final loss position on collimators or the machine aperture close to the experiments [10]. The unwanted background signals are caused by secondary shower particles that enter the detectors.

ATLAS and CMS were acquiring data during the high-$\beta$ run. The low intensity and low luminosity provided very clean conditions to observe beam-halo induced background, since, during the scraping by the collimators, this was by far the dominating beam loss process. However, some intriguing observations were made by ATLAS [11]. A clear increase of background was observed in the counter-clockwise rotating B2 in strong correlation to beam scraping in IR3. This background was much stronger than what was observed in B1 and when the beam was scraped in IR7. Furthermore, during the IR3 scraping, no beam loss monitors (BLMs) close to ATLAS indicated local losses, that could be the origin of the observed background.

A possible explanation to the observations can be guessed from the normalized aperture obtained with the $\beta^* =1000$ m optics, shown in Ref. [6]. It can be seen that the tightest aperture restriction is found at the TAS absorber, which is installed between the experimental detector and the inner triplet that provides the final focusing, and where no BLM is installed. If the beam-halo losses occurred there when the beam was scraped in IR3, it would explain both the background observations and the absence of BLM signals on the incoming B2 side of ATLAS. The rest of this paper investigates this assumption through simulations.

## SIXTRACK SIMULATION SETUP

We use SixTrack [12, 13] to simulate the distribution around the LHC ring of lost protons that leak out of the collimators. SixTrack is a thin-lens particle tracking code, which follows 6D trajectories of relativistic particles in circular accelerators in a symplectic manner. It has a built-in Monte Carlo code to simulate the proton-matter interaction in the collimators. A particle is considered lost either when it hits the aperture—the particle coordinates are checked against a detailed aperture model with 10 cm longitudinal precision—or if it interacts inelastically inside a collimator. The exception to this rule is single diffractive events, where the incident proton could survive and exit the collimator. These protons, which often have significant energy offsets, are tracked further.

The simulation output contains coordinates of all loss locations, and the results are usually expressed in terms of the local cleaning inefficiency

$$\eta = \frac{N_{\text{loc}}}{N_{\text{tot}}\Delta s}, \tag{1}$$

where $N_{\text{loc}}$ is the number of protons lost locally over a distance $\Delta s$, and $N_{\text{tot}}$ is the total losses on collimators. SixTrack results have been found to be in very good agreement with measured loss patterns for the LHC [9].

The simulation starts with a halo distribution sampled at the front face of a selected collimator (see Ref. [9] for details). For the studies in this paper, we start at the horizontal TCPs in both IR3 and IR7 and in B1 and B2. It should be noted that the sampled halo distribution corresponds to an on-momentum beam, while the IR3 halo is expected to be significantly off-momentum. The error introduced by this on the simulation results is estimated to be relatively small as long as the energy offsets acquired in the scattering inside the collimator are large compared to the initial energy offset, and the aperture bottlenecks under study are significantly larger than the opening of the collimator in units of the local betatronic beam size. For normalized apertures smaller than the collimator opening, the on-momentum sampling would produce large errors. A more general halo sampling with a matched off-momentum beam is under development and the results presented in this paper should possibly be revisited using such a code.

The tracking is performed for 200 turns, which is enough for most initial halo particles to be lost on the collimators

or aperture. We use the $\beta^* =1000$ m optics, which had to be converted to thin-lens for this study, and the collimator settings that were in place at the end of the scraping before moving out the TCP. Most collimators were kept at the standard top-energy operational settings [4,9] in mm. Because of a small $\beta$-beat induced by the squeeze to $\beta^* =1000$ m, the effective normalized setting was up to 10 % different. The exceptions, where special settings were applied, were the TCPs that were used for scraping, which went down to $5.9\ \sigma$ in IR3 and $2\ \sigma$ in IR7, and the tertiary collimators (TCTs) that were set at $17\ \sigma$ in IR1 and IR5, and at $26\ \sigma$ in IR2 and IR8.

## SIMULATION RESULTS

Figure 2 shows on top the simulated residual loss distribution, expressed in $\eta$, around the LHC for the case of primary beam impacts on the TCP in IR3 in B2. As can be seen, the largest losses are observed at the IR3 TCP, while those at the IR7 horizontal TCP are about a factor 2 below. This comes from the fact that, due to the low intensity where an efficient cleaning was not needed to avoid quenches, the secondary collimators (TCS) in IR3 were kept at their standard setting of $15.6\ \sigma$. This leaves a retraction of about $10\ \sigma$ between the IR3 TCP and TCS, meaning that most out-scattered particles avoid the TCS and that the IR3 collimation effectively works as a single-stage cleaning system. The out-scattered protons tend instead to hit the IR7 TCP, which was kept at a tight opening of about $4.3\ \sigma$ during the IR3 scraping. However, the leakage to IR7 is likely overestimated due to the on-momentum halo approximation.

A significant leakage to IR1 is observed, which is shown in detail in the lower part of Fig. 2 together with the layout. It should be noted that the highest cleaning inefficiency is $\eta \approx 0.01$, which is observed at the TAS. This unusually high value would not be tolerable with higher beam intensities. Some losses are also observed at the TCTs and in the triplet.

As a comparison, the corresponding loss distribution for the case of primary losses on the IR7 TCP is shown in Fig. 3. In this case, most losses are concentrated in IR7, where the TCSs were kept at $6.3\ \sigma$, which means that they are still quite efficient at intercepting protons that leak out of the TCPs. The leakage out of IR7 is therefore much smaller than for the case of IR3. The losses on the IR3 TCP are almost two orders of magnitude lower than on the IR7 TCP. These losses cause again a corresponding leakage to IR1, which can be seen on the lower part of Fig. 3. It shows a similar pattern as the losses in Fig. 2 but with levels that are consequently almost two orders of magnitude lower.

The corresponding simulations for B1 show much lower losses in IR1 than the B2 cases, as can be seen in Table 1, where the highest values of $\eta$ in IR1 are summarized for the different simulation cases. In B1, the beam coming from IR3 has to travel over a large part of the ring before reaching IR1, and it is likely that particles are lost in IR7 on the way. In B2, there are only few collimators between IR3 and IR1 and thus a much higher fraction of particles can reach IR1.
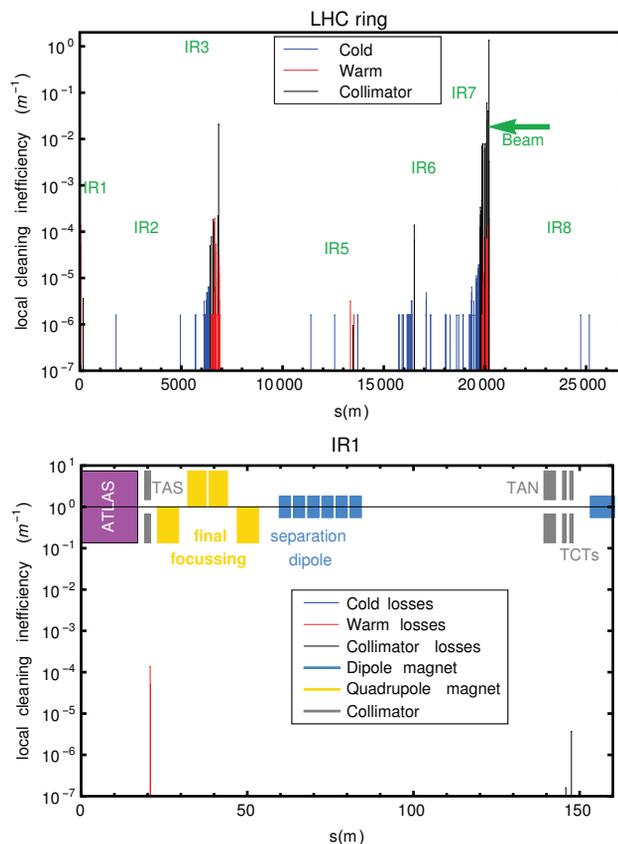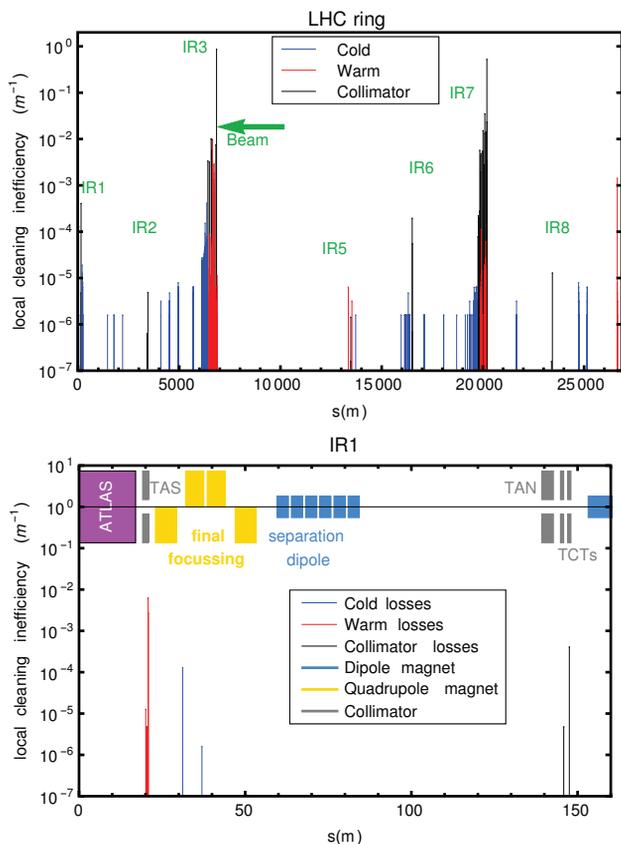
Figure 2: The loss distribution around the LHC ring (top) and in IR1 (bottom) as simulated with SixTrack for the case of primary beam impacts on the primary B2 collimator in IR3.

Table 1: Highest Local Cleaning Inefficiency in IR1 as Simulated with SixTrack, for a Horizontal Beam Halo Impacting in IR3 or IR7, for Both Beams. We show both the value of $\eta$ and the element where it occurs.

| Initial halo loss | $\eta$ (m$^{-1}$) | Element |
|---|---|---|
| IR3 B1 | $3.1 \times 10^{-6}$ | TAS L1 |
| IR7 B1 | $6.2 \times 10^{-6}$ | TAS L1 |
| IR3 B2 | $6.3 \times 10^{-3}$ | TAS R1 |
| IR7 B2 | $1.4 \times 10^{-4}$ | TAS R1 |

## CONCLUSIONS

SixTrack simulation results of the beam cleaning during the LHC $\beta^*$ =1000 m run in 2012 show that, when the primary beam loss occurs in IR3 in B2, there is a significant leakage to the TAS in front of the ATLAS experiment. The corresponding leakage from IR7 is much lower, which is the case also for losses in B1. These results are consistent with the ATLAS observations [11] of a clear beam-halo background in strong correlation with B2 scrapings in IR3. The TAS is not equipped with BLMs, which means that the predicted loss location cannot be verified from measurements. In order to quantitatively estimate the leakage of particles

Figure 3: The loss distribution around the LHC ring (top) and in IR1 (bottom) as simulated with SixTrack for the case of primary beam impacts on the primary B2 collimator in IR7.

into the ATLAS detector, further shower simulations would be needed, analogue to Ref. [10].

It should be noted that the simulations were performed using the approximation of an on-momentum halo, which could potentially induce errors for the IR3 simulations. These cases could be studied again when a new version of SixTrack, including an off-momentum halo sampling, becomes available.

## ACKNOWLEDGMENTS

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