LHC COLLIMATION WITH A REDUCED BEAM PIPE RADIUS IN ATLAS

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Abstract

To increase physics performance, an upgrade of the ATLAS detector has been requested. As a consequence, a new beam pipe with a smaller radius needs to be installed inside the experimental detector. Based on SixTrack simulations, we investigate the effect from collimation of a reduced beam pipe in the ATLAS experiment. Several running scenarios are studied with a range of different beam pipe radii and in each case we conclude on the minimum allowed aperture, which does not cause beam losses inside the detectors.

INTRODUCTION

The first year of operation of the Large Hadron Collider (LHC) [1] at CERN has been very successful but to further increase performance, plans to improve the experimental detectors as well as the machine are being discussed. One important upgrade concerns the detector of the ATLAS experiment [2]. A higher performance can be achieved if new layers are added to the inner pixel detector close to the beam. In order to fit the enhanced pixel detector, a new beam pipe with the radius reduced from 29 mm to 22.5 mm has to be installed inside the experiment.

With this decrease of aperture, several performance limitations of the might machine arise, which have to be carefully examined before a decision on the upgrade is taken [2]. In this article we investigate the consequences for LHC collimation if a smaller pipe is installed.

The LHC uses a multi-stage cleaning system [1, 3, 4] to provide passive machine protection and intercept unavoidable beam losses caused by a continuous re-population of the halo as well as single events where particles are scattered onto an unwanted trajectory. If the aperture is decreased anywhere in the machine, new bottlenecks could be introduced that might intercept parts of the beam halo. Even if the an aperture limitation is outside the cut of the primary collimators, it could catch particles in the secondary or tertiary halo leaking out of the cleaning insertions. If the aperture limit is inside an experiment, it could lead to increased background signals. It is therefore very important to assess this risk.

SIMULATION SETUP

To simulate the proton leakage out of the cleaning insertions, the SixTrack code [5] was used. SixTrack performs a thin-lens optical tracking element by element through the lattice. When a collimator is reached, a Monte Carlo code is used to simulate the particle-matter interaction, taking into account multiple Coulomb scattering, ionization, single diffractive scattering, and point-like elastic and inelastic scattering. When inelastic scattering occurs, the particle is considered lost. The coordinates of all particles are also checked against a detailed aperture model with 10 cm precision longitudinally to determine loss locations outside the collimators.

To make the simulation more CPU efficient, a pencil beam impinging on the collimators was used as starting condition. An impact parameter of 1 μm was assumed as in Ref. [6]. Tracking was performed over 200 turns, which is sufficient to study the multi-turn effects involving several scattering events in different collimators. No diffusion mechanisms were included as this is unimportant over the short timescale considered. A total of 6.4×10^6 halo particles were simulated for each studied case.

Several machine configurations were considered with different energies and optics. They are summarized in Table 1. For most scenarios, both beams and planes were studied in separate simulations and a scan was performed over a range of different apertures inside the ATLAS experiment. Several aperture values were used: 29 mm (presently installed ideal beam pipe), 22.5 mm (upgrade design request), 15.45 mm (guaranteed beam stay clear radius for upgrade when accounting for mechanical errors and tolerances [2]) and several lower values in steps of 1 mm.

In the rest of the LHC ring, outside the ATLAS detector, a perfect design aperture was assumed. This is an unrealistic worst-case scenario and the real situation is therefore expected to be significantly better.

SIMULATION RESULTS

As an example of a result from a SixTrack simulation, where the primary halo was represented by a pencil beam on the primary horizontal collimator in IR7, the losses from IR7 to the end of the ring are shown in Fig. 1 for two different values of the ATLAS beam pipe radius. For the larger aperture (15.45 mm), corresponding to the guaranteed beam stay clear of the upgrade proposal, there are no losses inside the detector (the black peak at the end of the ring corresponds to a TCT [tertiary collimator]). For the smaller pipe radius of 4.45 mm (this value is evidently much smaller than the minimum real aperture) a clear loss spike appears in the detector. Operating with such a small aperture would not be possible.

A scan over many different pipe radii for the case of 450 GeV and injection optics is shown in Fig. 2. Here the maximum local cleaning inefficiency η (defined as the ratio of the local losses per meter to the total losses on the pri-

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Table 1: Smallest aperture values where losses were observed in the SixTrack simulations for different machine configurations. Where available, the ratio between the $n1$ aperture and this aperture is shown.

Scenario	Energy (TeV)	Optics	Ap. w. loss (mm)	Ap. w. loss (σ)	n1 aperture/ Ap. w. loss
1	0.45	$\beta^* = 11$ m	5.45	18	1.25
2	3.5	$\beta^* = 11$ m	3.45	31	
3	3.5	$\beta^* = 3.5$ m	6.45	75	
4	7.0	$\beta^* = 11$ m	2.45	31	
5	7.0	$\beta^* = 0.55$ m	7.45	66	1.45

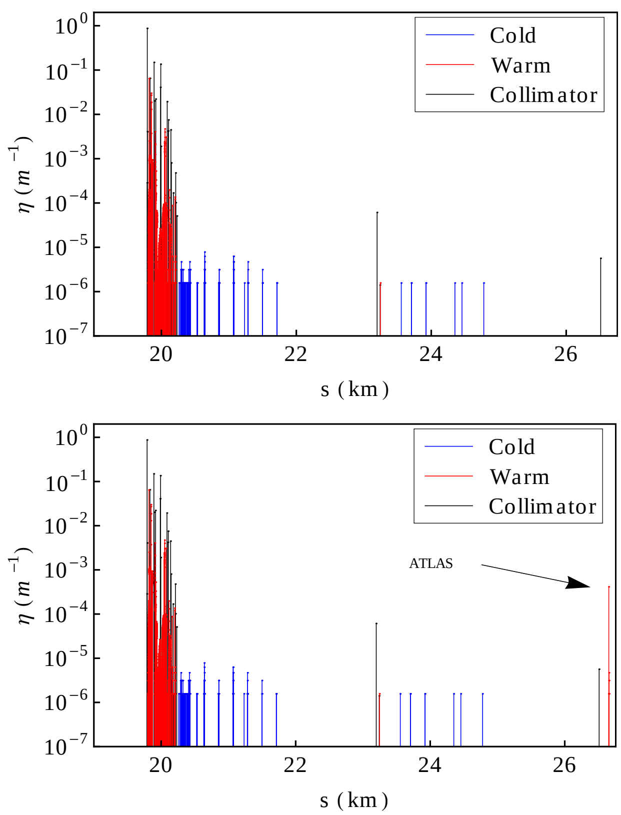

Figure 1: Simulated cleaning inefficiency (ratio of particles lost locally per meter to the total number of losses), for 450 GeV injection optics, in IR7 and downstream in beam 1. The ATLAS beam pipe radius was reduced from 29 mm to 15.45 mm (top) and to 4.45 mm (bottom). The initial halo particles were a pencil beam impacting on the horizontal primary collimators in IR7 with 1 μm impact parameter. The losses on collimators, warm elements and cold elements are represented by different color coding. The large loss location around 20 km comes from the betatron collimation in IR7. With the smaller pipe radius, a clear loss spike is observed in the ATLAS detector.

mary collimator) inside the detector is shown as a function of the pipe radius. This max occurs at the entrance of the detector, since the β-function has a local minimum at the collision point. A binning of 10 cm was used, over which the losses were averaged to calculate η.

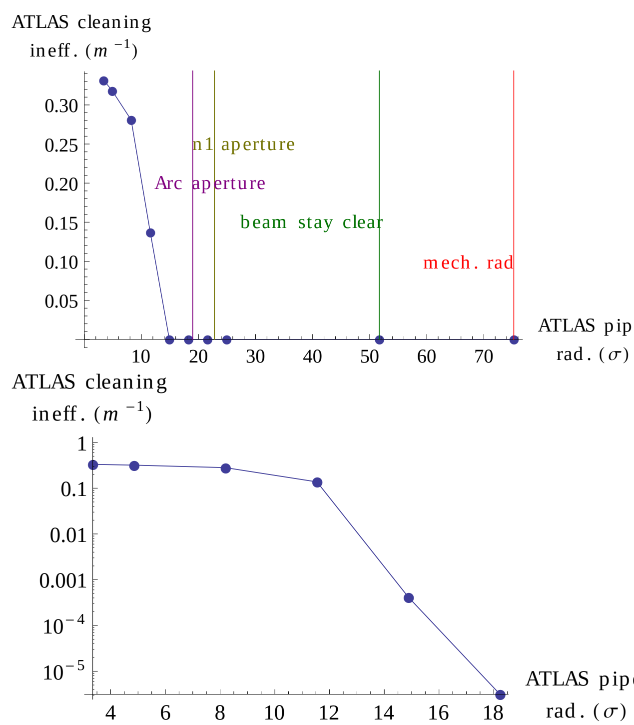

Figure 2: Maximum local cleaning inefficiency in the ATLAS detector (using 10 cm bins) for 450 GeV injection optics as a function of the beam pipe radius (top). Vertical lines show the design aperture for the upgrade, the guaranteed beam stay clear radius and the $n1$ aperture [7], which is the worst possible aperture, and the aperture of the arc. Losses start appearing only below this aperture. Assuming a full phase coverage, any miskicked beams would then hit the arc aperture and not the detector. The bottom plot shows the non-zero losses on a logarithmic scale.

Fig. 2 shows also the design aperture of the upgraded beam pipe, beam stay clear, and the aperture coming from an $n1$ calculation as provided by Ref. [7]. The $n1$ value is defined as the maximum acceptable primary collimator opening, in units of beam σ, that still provides a protection of the mechanical aperture against losses from the secondary beam halo. With the standard assumptions on the secondary halo, the minimal aperture if the β-beat, orbit error, and mechanical errors all add up in the pessimistic direction is a factor 1.2 larger than $n1$. We call this value the

$n1$ aperture. Provided that the upper limits and tolerances and machine imperfections are realistic, the real aperture can not be smaller than the $n1$ aperture. In fact, it is likely to be significantly larger [8].

In Fig. 2, no losses appear above a radius larger than 18 σ. This is no guarantee that the detector will be completely free from losses. It shows rather that within the statistical uncertainty of the simulation (losses at specific locations have approximately a Poisson distribution) and the resolution of the simulation, no losses are to be expected. A cleaning inefficiency which is non-zero but lower than the resolution (6.4×10^6 primary particles gives a resolution of $1/(6.4 \times 10^6) = 1.6 \times 10^{-7}$) cannot be ruled out.

In Fig. 2 we show also the mechanical aperture of the LHC arc for the case of a perfect machine without imperfections. As can be seen, the maximum arc aperture is still smaller than the $n1$ aperture of the ATLAS detector. This is important from the point of view of machine protection, since another potential risk with a decreased aperture is that the detector could be hit by mis-kicked beams during an asynchronous beam dump. However, it is clear from Fig. 2 that this cannot happen since the detector is in the shadow of the arc.

At top energy and collision optics the situation is different, since the available aperture in the ATLAS detector is much larger due to the smaller β^*. On the other hand, the β-function blows up in the triplet and the TCTs are expected to intercept many more halo particles [9]. A possible increase in background may therefore come from particles scattered out of the TCTs. In order to make the simulations more efficient, the starting halo particles were therefore a pencil beam impacting directly on a TCT. The results of the aperture scan are shown in Fig. 3.

The results show that again that no losses appear at the $n1$ aperture and that the arc aperture is smaller than the $n1$ aperture. The results are qualitatively representative for the other simulated cases as well. All results are summarized in Table 1. In summary, no obstacles from collimation were found for operating the machine in these conditions.

CONCLUSIONS

We have presented simulations with SixTrack of the LHC cleaning if the radius of the beam pipe inside the ATLAS detector is reduced. Several machine configurations have been studied for a range of different apertures. A worst-case scenario was assumed, with a perfect machine outside ATLAS. In the studied cases, the largest aperture where losses appear inside the detector is below the guaranteed design aperture so no increase of background can be expected within the simulation accuracy. Furthermore, the largest possible arc aperture is smaller than the worst-case aperture in the detector, meaning that any mis-kicked beam should hit the arc first. Therefore, no obstacles from the point of view of collimation were found. It should be noted that the case of a high-β optics has not been studied in detail but for this case, additional constraints on the beam-pipe alignment are necessary [2].

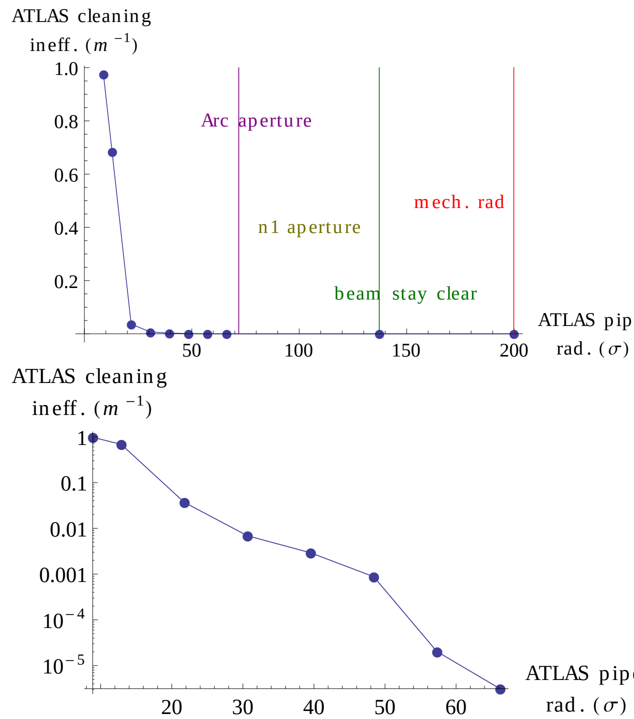

Figure 3: Maximum local cleaning inefficiency, normalized by TCT losses, in ATLAS (using 10 cm bins) for 7 TeV collision optics as a function of the beam pipe radius (top), shown with the design aperture for the upgrade, the guaranteed beam stay clear radius and the $n1$ aperture [7]. The bottom plot shows the non-zero losses on a logarithmic scale.

We have not treated the possible background created by showers from protons interacting inelastically in the TCTs. This has to be done separately, for example by inserting the results presented in Ref. [10] in a simulation of the detector.

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