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LHC physics debris collimation studies and their impact on AFP detectors acceptance

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Summary

The ATLAS Forward Proton (AFP) group is proposing to upgrade the forward region of ATLAS by installing forward proton detectors at 220 m and 420 m from the interaction point on both sides of the LHC ATLAS experiment. For this purpose, at both the 420 m and 220 m locations, it is proposed to install movable beam pipes which will host silicon tracking and fast timing detectors (i.e. four independent detector stations). The experimental acceptance at 220 m is dependent upon the setting of two collimators designed to protect the LHC straight section and dispersion suppressor around ATLAS (and CMS) from the physics debris generated at the two high luminosity experiments. This note presents the result of tracking studies showing that the installation of a new collimator in front of the Q6 magnet (or the displacement at this of location of the second of the already existing collimators) would ensure an improved protection of the LHC machine while allowing the AFP experiment at 220m.

1 INTRODUCTION

The ATLAS Forward Proton (AFP) group is proposing to upgrade the forward region of ATLAS by installing forward proton detectors at 220 m and 420 m from the interaction point on both sides of the LHC ATLAS experiment. For this purpose, at both the 420 m and 220 m locations, it is proposed to install movable beam pipes which will host silicon tracking and fast timing detectors (i.e. four independent detector stations). The detectors are designed to operate at intermediate and high instantaneous luminosities of up to 10^{34} $cm^{-2}s^{-1}$. The primary goal is to enhance the ATLAS baseline physics programme, particularly the search for and identication of new particles such as Higgs bosons and supersymmetric particles. At the moment of writing, the proposal is undergoing an internal review within the ATLAS management.

The installation of forward proton detectors at 420 m around both ATLAS and CMS was investigated in detail by the FP420 R&D Collaboration in [1]. All details about the AFP proposal can be found in [2, 3].

At 220 m a system similar to that developed for FP420 is proposed. The 220 m region is less demanding from an engineering perspective since a cryogenic bypass is not required. However, the experimental acceptance at 220 m is dependent upon the setting of two collimators designed to protect the LHC straight section and dispersion suppressor around ATLAS (and CMS) from the physics debris generated at the two high luminosity experiments. Such two collimators (at about 140 m and 190 m from the IP) are foreseen to be in a closed position, as needed for machine protection, for luminosity higher than a few 10^{33} $cm^{-2}s^{-1}$.

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2 IR layout and present collimation scheme

The layout of the first 250 m on the right side of ATLAS is shown in Fig. 1, in which the proposed location of the AFP detectors at 220 m is indicated. The two collimators presently foreseen for operation at high LHC luminosity runs are also indicated. Throughout the note these two collimators will be labelled as TCL4 and TCL5. The location for a possible new collimator (TCL6), that will be discussed later in this note, is also indicated. For the issues discussed here, the layout of the left side of ATLAS is practically symmetric, whereas both sides of CMS have differences due to the presence of TOTEM [4] during LHC low luminosity runs.
Both TCL4 and TCL5 are installed on the beam pipe hosting the LHC beam that emerges from ATLAS (CMS), after the beam pipes divided. TCL4 has been designed to protect the separation dipole D2 from physics debris and also the first matching section quadrupole Q4 and possibly other downstream magnets. TCL5 has been designed to protect Q5 and possibly other superconductive elements down to the dispersion suppressor (DS) at about 400 m. TCL5 was proposed in the year 2000, before any proposal for a TCL4, and the details can be found in [5], where the authors proved with simulations the need for the protection of Q5 and estimated the beneficial effects of TCL5 in terms of beam losses reduction in the DS region. At the end of their note, they assess the need for a TCL4 collimator without presenting detailed studies. The TCL5 studies were performed using the LHC optics Version 6.1 and the presented results give as 15 σ_x a convenient collimator half gap for guaranteeing the LHC protection.
Given the TCL4 and TCL5 interference with the proposed AFP physics, the availability of

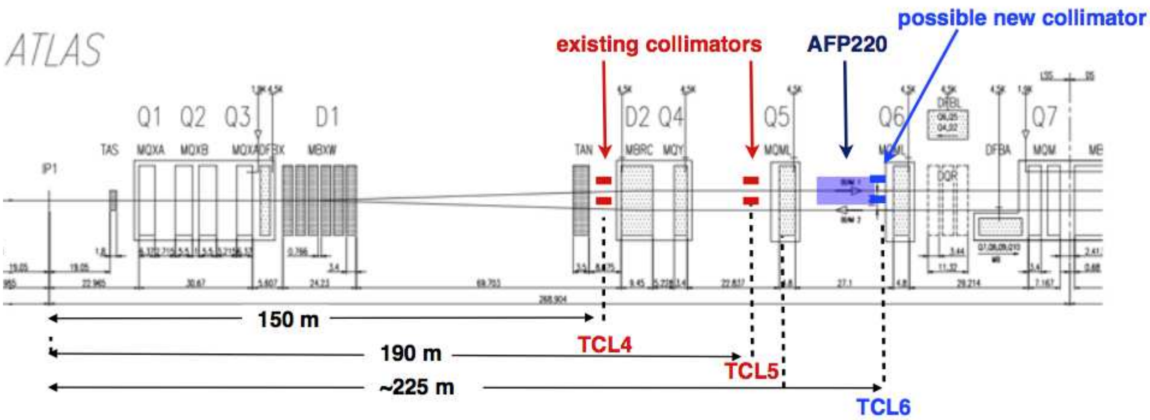

Figure 1: Layout of the straight section on the right side of ATLAS.

the new LHC optics Version 6.503 and the lack of information about the TCL4 effectiveness, the AFP collaboration decided to carry out a new study in order to investigate a physics debris protection scheme that allows safe LHC operation as well as full forward protons acceptance at 220 m. In the following sections, we present the result of analytical considerations accounting for the new LHC optics and of numerical simulations aimed at generating beam loss patterns for different collimation settings.

3 Optimal collimator settings as studied with beam optics calculations

According to linear beam dynamics, the transverse motion of particles has two amplitude terms. The betatronic one is described by the betatron functions $\beta_{x,y}(s)$ variation along the accelerator structure. A second term is proportional to the particle momentum offset with respect to the reference momentum dp/p, with the dispersion function $D_{x,y}(s)$ as proportionality factor. Considering the horizontal plane, the maximum excursion of a particle with momentum offset dp/p as function of location s is equal to:

$$x_{max}(s) = \sqrt{\beta_x(s)\epsilon_x + \left[\frac{dp}{p} \cdot D_x(s)\right]^2}, \tag{1}$$

where ϵ_x is the geometric horizontal emittance describing the particle mapping of the horizontal phase space. The horizontal trajectories of a 7 TeV proton and of three off-momentum protons (with $dp/p = -1 \cdot 10^{-3}, -1 \cdot 10^{-2}$ and $-1 \cdot 10^{-1}$ respectively), as calculated with PTC [6] using the MADX LHC optics V6.503, are shown in Fig. 2. Since in all four cases the tracking starts at IP1 with (x,x',y,y') = (0,0,0,0), there is no betatronic contribution and the particle deviation from the reference orbit is only due to the energy dependent term of Eq. 1.

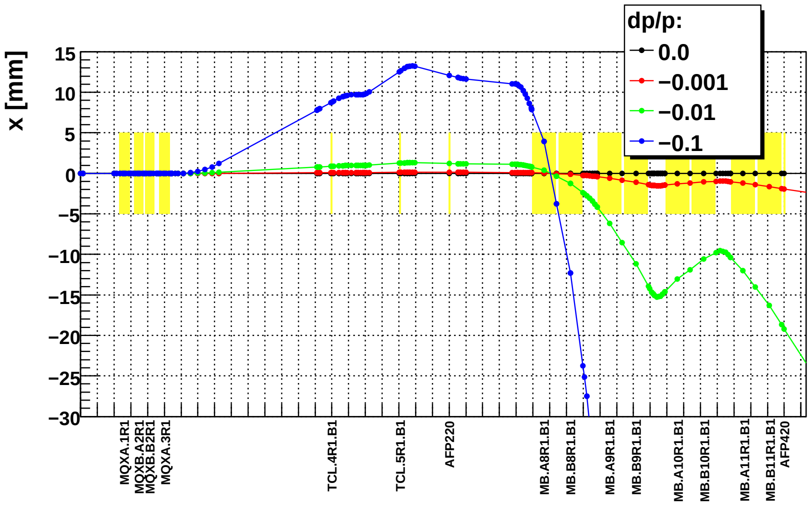

Figure 2: Horizontal trajectory of a 7 TeV proton and of three off-momentum protons, as simulated with PTC. For all particles the initial coordinates are at (x,x',y,y') = (0,0,0,0).

Assuming a collimator at a location $s = s_c$ with a full gap centered around the reference beam closed orbit, it is possible to determine the minimum collimator half gap ($x_c(s)$ *or* $y_c(s)$) necessary to intercept a particle with momentum offset dp/p. Considering the horizontal plane, such a quantity defined in units of the betatronic beam size $\sigma_x(s) = \sqrt{\epsilon_x \beta_x(s)}$ results:

$$\frac{x_c(s)}{\sigma_x(s)} = \frac{D_x(s)}{\sigma_x(s)} \cdot \frac{dp}{p} = \frac{D_x(s)}{\sqrt{\beta_x(s)\epsilon_x}} \cdot \frac{dp}{p} = \frac{1}{\epsilon_x} \cdot D_x^n(s) \cdot \frac{dp}{p}, \tag{2}$$

where $D_x^n(s) = D_x(s)/\sqrt{\beta_x(s)}$ is called the *normalized dispersion* function. The normalized dispersion and the collimator half gap, as defined in Eq. 2, are shown in Fig. 3 and Fig. 4 respectively, for the two LHC beams outgoing from IP1. It must be noted that in this case D_x is the *unmatched* dispersion function (different from the periodic lattice dispersion) accounting for the fact that protons experience a $D_x = 0$ at the location where they are generated (the IP). The necessary collimator half gap has been plotted for three values of the proton momentum offset with respect to 7 TeV ($dp/p = 2 \cdot 10^{-2}, 5 \cdot 10^{-2}$ and $10 \cdot 10^{-2}$) that cover the range of particles that needs to be intercepted in order to minimize the risk of quenching superconductive elements in the long straight sections and dispersion suppressors. The location of the two existing collimators (TCL4 and TCL5) and of a possible additional collimator (TCL6) are indicated. As an example these calculations indicate that, for intercepting a proton with $dp/p = 2 \cdot 10^{-2}$ (black line in the figure), TCL5 needs to be closed to less than $10 \cdot \sigma_x$ whereas it would be enough to keep TCL6 at about $35 \cdot \sigma_x$.

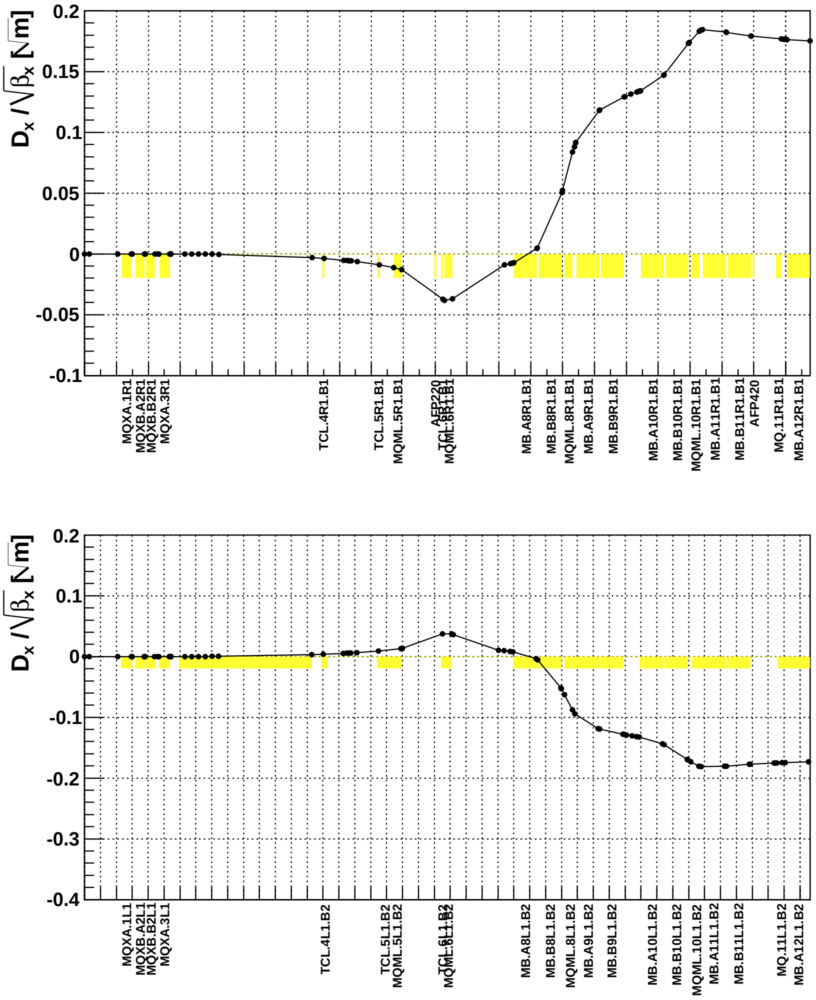

Figure 3: Normalized horizontal dispersion in the straight section on the right side of ATLAS for Beam 1 (top) and on the left side for Beam 2(bottom).

4 Numerical simulations setup

In order to confirm the analytical calculations discussed above, a set of numerical simultions have been implemented.

4.1 Simulation strategy and tools

The numerical simulations consisted in tracking distributions of protons, representing a sample of forward protons generated by p-p collisions, downstream, in the LHC straight section and dispersion suppressor. The tracking included the best available approximation of the LHC physical aperture and were performed with different collimator settings in order to evaluate the effectiveness of the machine protection. Two tracking codes have been used and compared:

- PTC (Polymorphic Tracking Code) [6], that is based on a 'thick lens' model of the accelerator elements and offers an exact Hamiltonian of the magnetic elements; in such a way the trajectory of off-momentum protons is described in the best approximation available for the LHC model; the simulations performed with PTC considered any aperture limit, including collimators, as black absorbers.

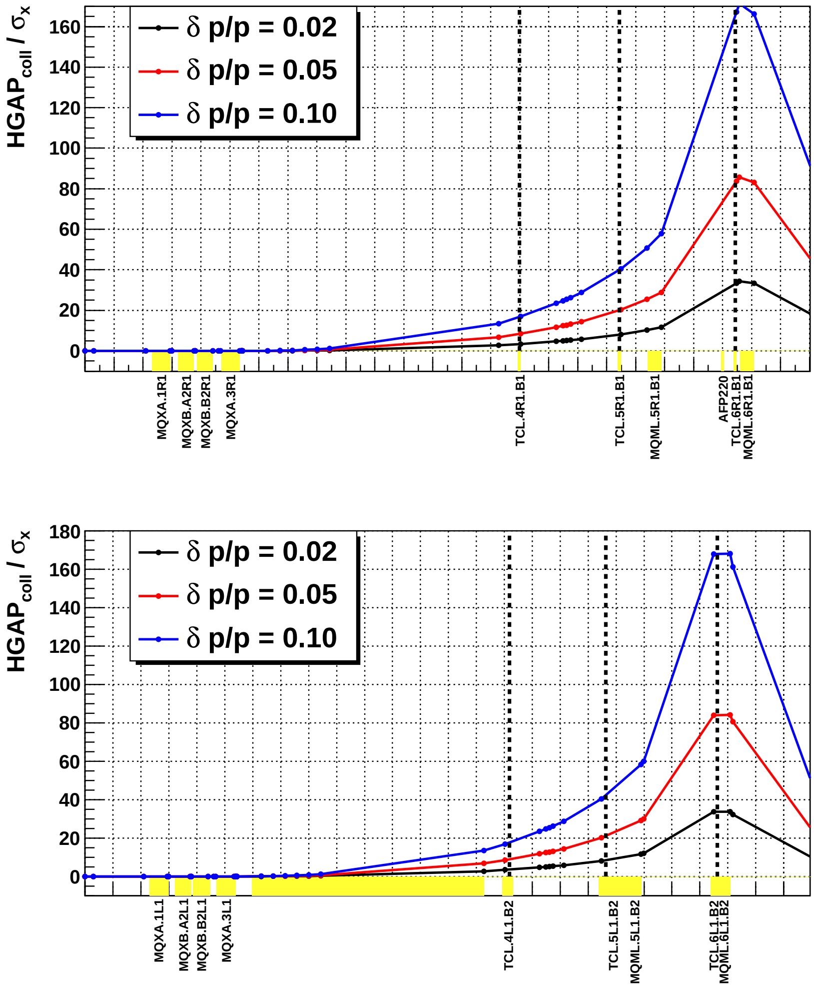

Figure 4: Collimators horizontal half gap necessary to intercept protons with 3 different momentum offsets as function of collimator position, for Beam 1 (top) and Beam 2 (bottom).

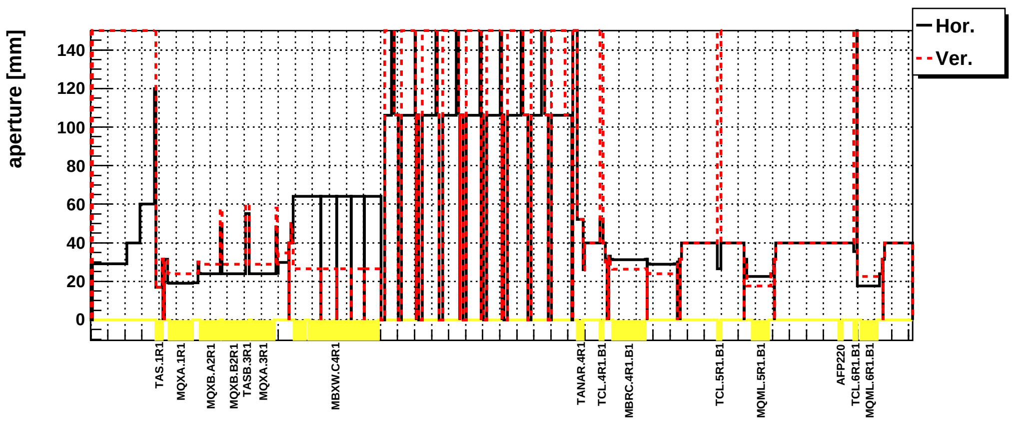

Figure 5: Aperture model in the first 230 m from IP1 (Beam 1), used for both the PTC and SIXTRACK simulations.

- SIXTRACK [7], that is based on a 'thin lens' model of the accelerator elements; in particular, a special version of the code including the COLLTRACK tools, that has been designed for fast multi-turn tracking and extensively used for designing the LHC collimation system; SIXTRACK is supposed to be less accurate in tracking protons with more than 10% momentum offset, but has the advantage of simulating elastic and inelastic scattering on the collimators. Therefore, with respect to PTC, it does not neglect the contribution of scattered protons to the losses on the downstream superconducting elements.

Both codes have been interfaced to the MADX LHC optics V6.503 and were given the same LHC aperture model. The aperture model used for the right side of IR1 is shown in Fig. 5. The plot covers the region from s=0 to s=230 m, even though the aperture has been modeled and considered by the tracking up to 450 m. The considered aperture model was the one available in MADX at the moment of the simulations and may well be replaced by better approximations for future studies. Despite some uncertainties (e.g. vertical aperture of experimental beam pipe before the TAS) the studies presented here focus on comparisons between different codes and different collimator settings and the results significance must be considered as unbiased.

4.2 Initial proton distribution and normalization

The Monte Carlo code DPMJET [8] has been used for simulating p-p interactions at 7 TeV. The simulations were performed for other purposes [9] and for the studies presented here the forward protons were used for the tracking with PTC and SIXTRACK.
The initial energy distribution of a sample of such protons is shown in Fig. 6. The full particle sample (red dotted line) exhibits a long tail of the energy distribution, extending well below 50% of the 7 TeV colliding beam energy. In addition, the energy distribution accounting for a cut of protons absorbed by the first TAS (black solid line) indicate that above 1 TeV the energy spectrum is unchanged. Therefore, in order to increase the statistics of the tracking loss maps, all protons intercepted by the TAS were neglected.
The angular and transverse distribution of the initial protons were obviously smeared for the colliding beam divergence and RMS size (16 μm) and centered around the nominal crossing angle (142.5 μrad) and position (x=0, y=-0.5 mm at ATLAS).

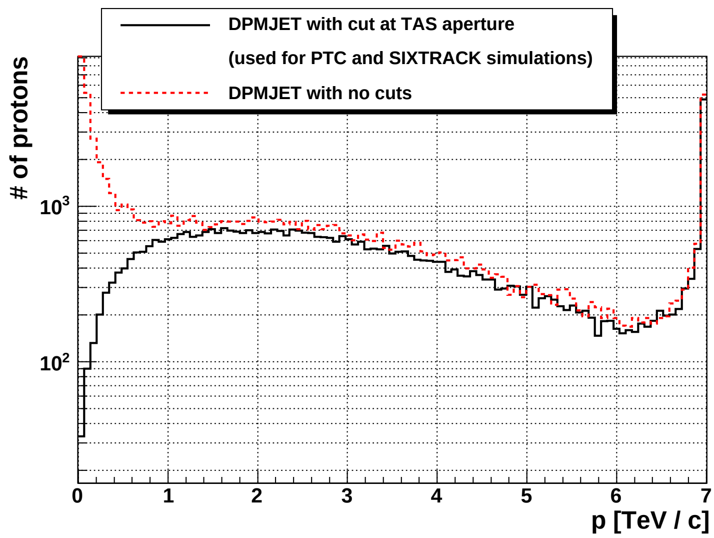

Figure 6: Momentum distribution of protons arising from DPMJET simulations with and without a cut of all protons lost on the first TAS. For this plot, in both cases, 48e3 protons have been considered.

The DPMJET simulation runs provided about $5 \cdot 10^5$ forward protons in the direction of each LHC beam. For the PTC and SIXTRACK loss map studies very little differences were found after tracking $5 \cdot 10^5$ and $5 \cdot 10^4$ protons, indicating a negligible statistical error. Therefore $N_0 = 5 \cdot 10^4$ protons were used for most of the studies presented here.

All loss map results presented below will be expressed as number of protons lost per meter and per second at LHC nominal luminosity. The normalization is calculated as follows. DMJET was run with a total cross section for p-p interaction at 7 TeV $\sigma_{tot} = 100\, mb$. At the nominal LHC luminosity $\mathcal{L}= 10^{34}\, cm^{-2}s^{-1}$ this corresponds to about 35 total events per bunch crossing and $N_{fp} \approx 12$ forward proton events per bunch crossing. Consequently, starting from $N_0 = 5 \cdot 10^4$ forward protons generated by DPMJET, the correspondent proton losses per unit length N_{p0} given by PTC or SIXTRACK will be converted to:

$$N_p = \frac{N_{p0}}{N_0} \cdot N_{fp} \cdot f_{rate} \quad [p/m/s] \tag{3}$$

where $f_{rate} = 40 \cdot 10^6$ is the number of bunch crossings per second for the LHC at nominal luminosity and nominal filling scheme.

5 Numerical simulation results

This section will present and discuss all tracking results with the aim of

- comparing with previous studies
- assessing the effectiveness of the presently installed TCL collimators
- proposing an alternative collimation scheme that ensures the LHC protection and simultaneously a sufficient acceptance of the AFP detectors

5.1 Comparison with previous studies

The results of loss maps performed to study the necessity of a collimator for protecting Q5 was presented by Baichev and Jeanneret in [5]. In their publication the authors included a table with proton loss values at each element after the collimator, for a collimator half-gap between 15 and 20 σ_x. Such a loss map pattern is shown in Fig. 7 together with three loss maps produced with PTC:

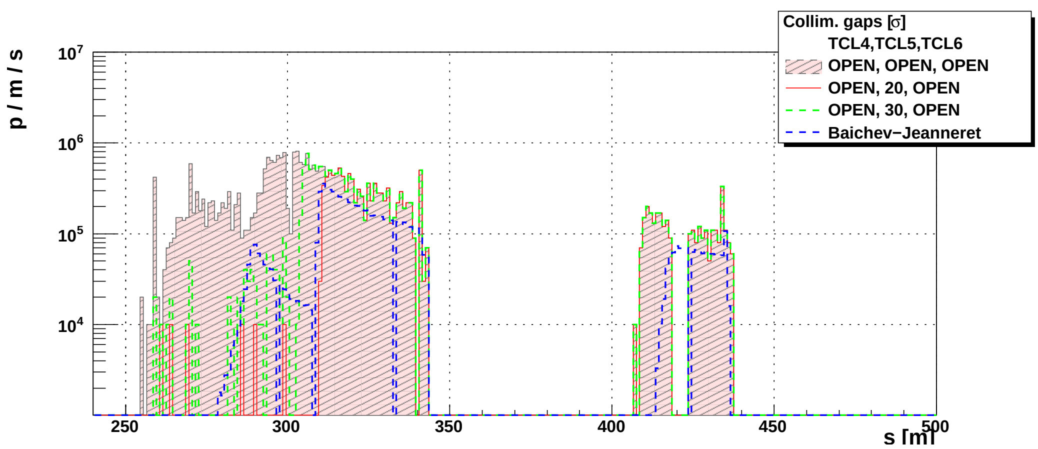

Figure 7: PTC loss maps for two different TCL 5 settings compared to Baichev-Jeanneret results and to the case with no collimators.

- without any collimator (black line),
- with TCL5 at 20 and 30 σ_x (red and green lines respectively).

It must be noted that, apart from the different tracking codes, the new results with PTC account for the last LHC optics (V6.503) and aperture models. Baichev and Jeanneret used the optics model available in 2000 (V6.1). In addition, as discussed above, the PTC loss maps are produced starting from DPMJET distributions generated with a total cross-section of 100 mb that corresponds to about 12 forward protons per bunch crossing. In their normalization, Baichev and Jeanneret quote a rate of $3.5 \cdot 10^8$ inelastic events per second that gives about 8.75 protons per bunch crossing.
Considering such differences, it can be assessed that PTC reproduces with a good agreement the old results.

5.2 PTC loss maps without collimators

For all results presented in this document, the loss maps refer to forward protons generated at IP1 and tracked along the LHC Beam 1 direction (right side of ATLAS) for 450 m in the dispersion suppressor region. For the LHC design, the majority of the DPMJET protons surviving this region will be lost in the cleaning insertions IR3 and IR7.
The first set of loss maps produced with PTC has been performed without TCL collimators installed in the lattice and the estimated number of protons per meter and per second at nominal LHC luminosity is shown in Fig. 8. Like in many of the figures that will be presented, the horizontal blue line at $8 \cdot 10^6\, p/m/s$ indicates an estimation of the quench level threshold for the superconductive magnets in the studied region. Such a value assumes that all protons have a momentum of 7 TeV. This approximation is the one used for all machine protection studies before the LHC provides any data.
The average momentum offset (with respect to 7 TeV) of the lost protons and the number of lost protons weighted for the proton momenta are shown in Fig. 9 and 10 respectively. The three plots yield the following considerations:

- a few peaks of Fig. 8 in the final focusing triplets region (s=0-80 m) exceed the estimated quench limit. However, since most of the protons lost in this region have very low momentum, all peaks fall below the quench limit when normalizing for the proton momentum, as evident in Fig. 10.
- the TAN absorber at about 140 m indeed intercepts a large number of forward protons as indicated by the peak reaching 10^8 protons per meter per second; but it cannot quench.
- the losses along the Q5 quadrupole at about 190 m approach the estimated quench limit and require a protection;
- the estimated losses from about 250 m to the dispersion suppressor result in an order of magnitude safety with respect to the estimated quench limit.

The calculated energy deposition expressed in Watt per meter is shown in Fig. 11. The values resulting form the loss maps are well in agreement with the LHC Design Report [10], stating that the deposited energy in the triplets can reach the level of 10 Watts per meter.

5.3 PTC loss maps with single collimators

The loss maps produced with PTC for different settings of the TCL4 collimator, while maintaining all other collimators wide open, are shown in Fig. 12 for all the region on the right side of ATLAS. The plots indicate that TCL4 at $30\,\sigma_x$ (blue line) is sufficient to protect all

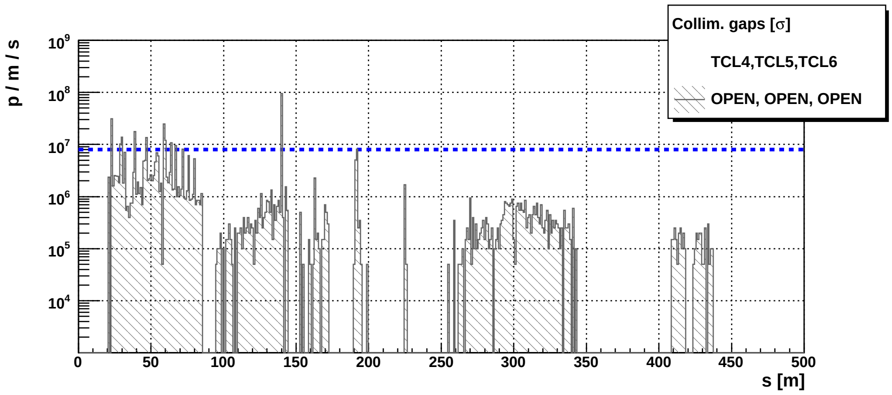

Figure 8: PTC loss maps with no TCL collimators installed in the IR1 straight section. The horizontal blue line indicate the estimated quench limit assuming 7 TeV protons.

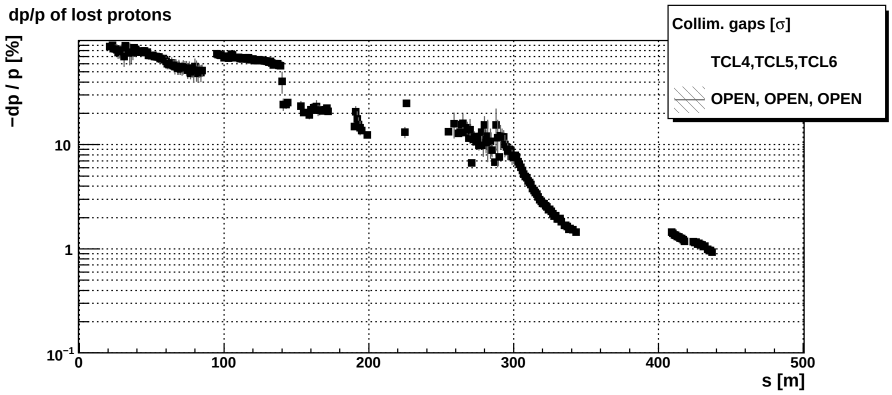

Figure 9: Average momentum offset with respect to 7 TeV of the protons lost according to the distribution of Fig. 8

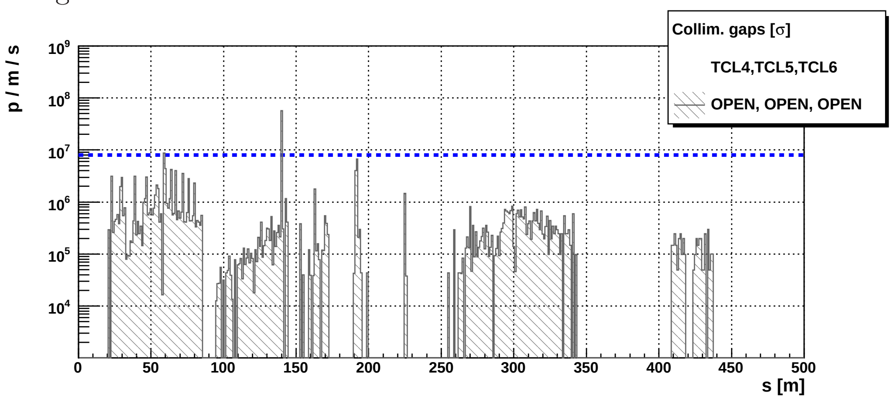

Figure 10: PTC loss maps with no TCL collimators installed in the IR1 straight section, scaled to the factor p/p_0 where p is the lost protons momentum and p_0=7 TeV. The horizontal blue line indicate the estimated quench limit assuming 7 TeV protons.

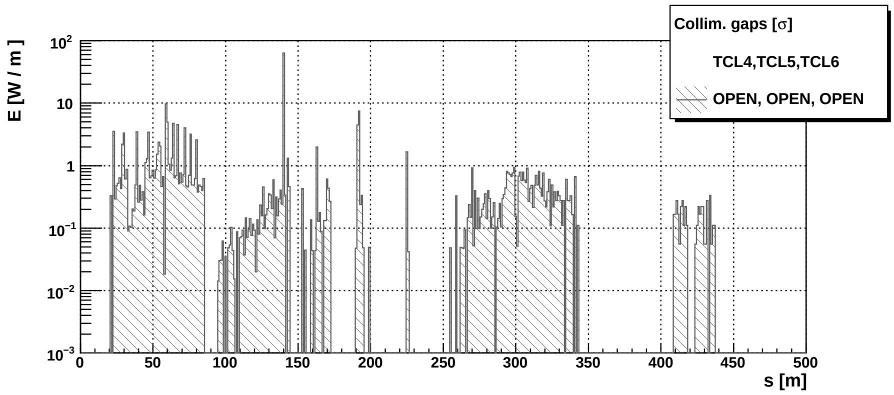

Figure 11: Energy deposition corresponding to the loss map shown in Fig. 8. Hence, it should be better if p/p_0 is considered (see Fig. 10).

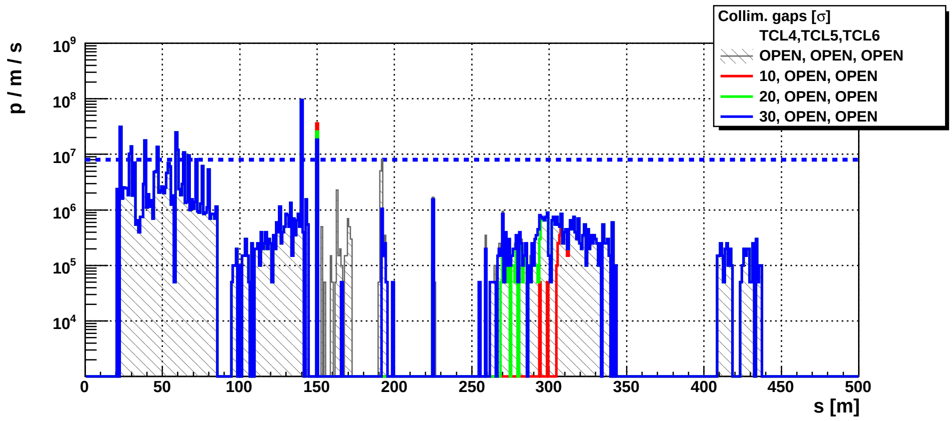

Figure 12: PTC loss maps with different settings of the TCL4 collimator installed at about 140 m from IP1. The horizontal blue line indicate the estimated quench limit assuming 7 TeV protons.

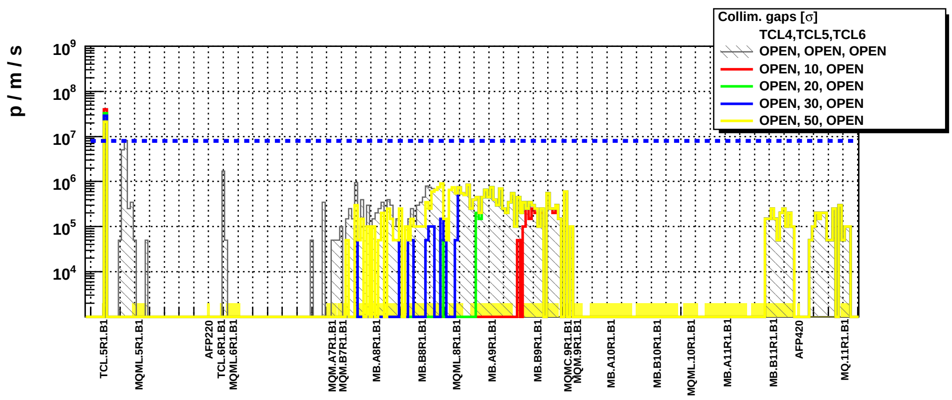

Figure 13: PTC loss maps with different settings of the TCL5 collimator installed at about 190 m from IP1. The horizontal blue line indicate the estimated quench limit assuming 7 TeV protons.

magnets (Q4 included) in the region from 150 m to 180 m from the interaction point. For the same settings the losses on the Q5 magnet are reduced by a factor of 10. On the other hand, even an extreme closure of TCL4 (e.g. red line in the figure) only partially reduces the integrated losses from 250 m downstream.

The loss maps produced with PTC for different settings of the TCL5 collimator, while maintaining all other collimator wide open, are shown in Fig. 13. In this case, the plots indicate that TCL5 at 50 σ_x (yellow line) is sufficient to protect all magnets (Q5 and Q6 included) in the region from 190 m to 250 m from the interaction point. For the same settings the integrated losses in the region from 250 m to 350 m are slightly reduced, whereas the peak losses remain, as without collimators (black line), one order of magnitude below the estimated quench limit. In this second region, even when the TCL5 collimator is closed to 10 σ_x (red line), the peak losses remain unchanged even though the integrated losses are reduced by about a factor of 5.

It is very relevant to notice that neither TCL4 or TCL5 have any effect on the losses after 350 m from the IP, even when closed to 10 σ_x.

5.4 PTC loss maps with different collimator schemes

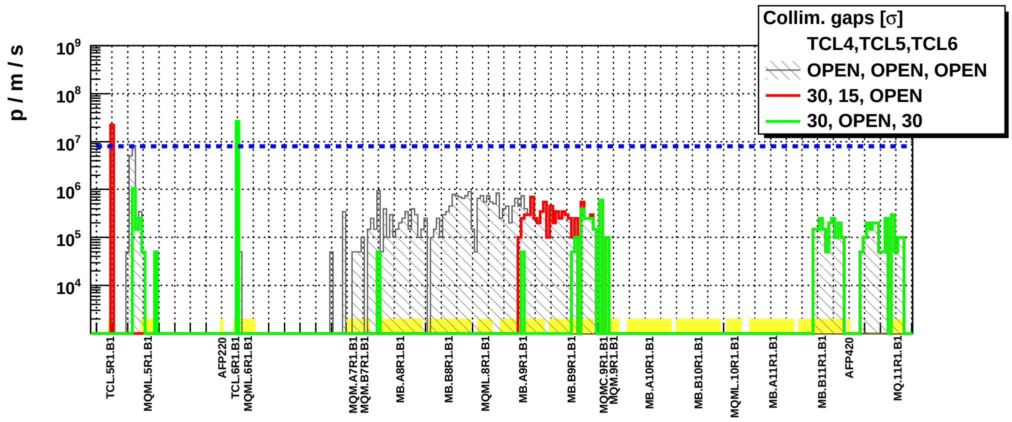

Figure 14: Comparison between loss maps with the presently foreseen collimation scheme (red) and a first alternative scheme (green) implying the displacement of TCL5 in front of Q6.

This section discusses two possible collimation schemes that, according to the simulations, guarantee the same LHC protection as with the existing scheme and allow enough forward proton acceptance at the AFP detectors proposed at 220 m. Both proposals envisage the presence of a collimator (TCL6) at about 230 m, in front of the Q6 quadrupole.

The first alternative implies the displacement of the TCL5 collimator from the slot just upstream of Q5 to the one upstream of Q6. The loss maps produced with PTC with both TCL4 and a new TCL6 at 30 σ_x is shown in Fig. 14 (green line) and compared to the situation without collimators (black) and with a possible configuration of the present scheme (red, TCL4 at 30 σ_x and TCL5 at 15 σ_x). This alternative configuration results in the reduction of a factor 10 (w.r.t. the case of no collimators) of the peak losses on Q5 and reduces by a factor of 3 (w.r.t. the existing solution) the integrated losses in the region from 250 m to 350 m. This solution would not require the production of a new collimator.

The second alternative implies the fabrication of a new collimator and its installation in front of Q6, while leaving in place the TCL5 collimator. The loss maps produced with PTC while setting TCL4 at 30 σ_x, TCL5 at 50 σ_x and a new TCL6 at 40 σ_x is shown in Fig. 15 (green line) and compared to the situation without collimators (black) and to the first alternative presented above (red). This second alternative would guarantee a full cleaning of the losses in the Q5

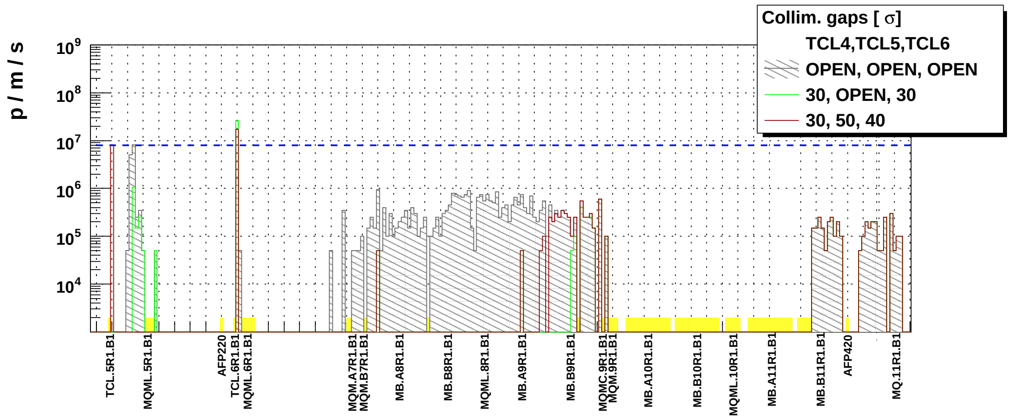

Figure 15: Comparison between loss maps with a second alternative scheme (green) implying the installation of a new collimator in front of Q6 and the first alternative presented in Fig. 14.

region, while reducing by a factor of about 2 (w.r.t. the existing solution, red line in Fig. 14), the integrated losses in the region from 250 m to 350 m.

As discussed later in the note, both alternatives would allow enough forward proton acceptance at the AFP detectors proposed at 220 m.

5.5 PTC-SIXTRACK comparison

As mentioned above, PTC is based on a "thick lens" accelerator model and offers an exact Hamiltonian to calculate the effect of the accelerator elements on the tracked particles. Therefore it is considered very accurate in describing the orbit of all particles, including the ones with a large momentum offset. However, the PTC tool suite used for the simulations presented here does not include a model for the scattering on collimators, as included in SIXTRACK. In this section we will compare loss maps produced with the two different codes in order to validate PTC as the most appropriate for these particular studies.
The trajectories of particles along the right side of IP1, with 2 % and 30 % momentum offset with respect to 7 TeV as simulated by PTC and SIXTRACK are shown in Fig. 16 and Fig. 17 respectively. If in the first case the two programs agree almost perfectly, in the second SIXTRACK underestimates the dispersive (energy dependent) part of the trajectory. Such underestimation of course biases the loss map results.
Such a difference is confirmed by Fig. 18 that shows the result of loss maps with PTC (black solid line) and SIXTRACK with all collimators installed in the lattice. SIXTRACK was used with the same aperture model as PTC and with two different routines for calculating the loss maps from the tracking results:

- the same used for PTC and coded specifically for these studies (red solid line)
- the one used extensively by the CERN LHC collimation team for many collimation studies (blue dashed line)

These two routines used with the SIXTRACK tracking results agree almost perfectly both in terms of peak and integrated losses. On the other hand, PTC exhibits a different loss pattern in the few meters after the IP and in the region between about 100 and about 150 meters from the IP. This can be attributed to the more accurate PTC tracking of off-momentum particles. It must be noted that this difference has little influence on machine protection issues, since all proton losses not detected by SIXTRACK in the 100-150 m region are then scored on the TAN absorber and do not reach any superconducting element downstream.

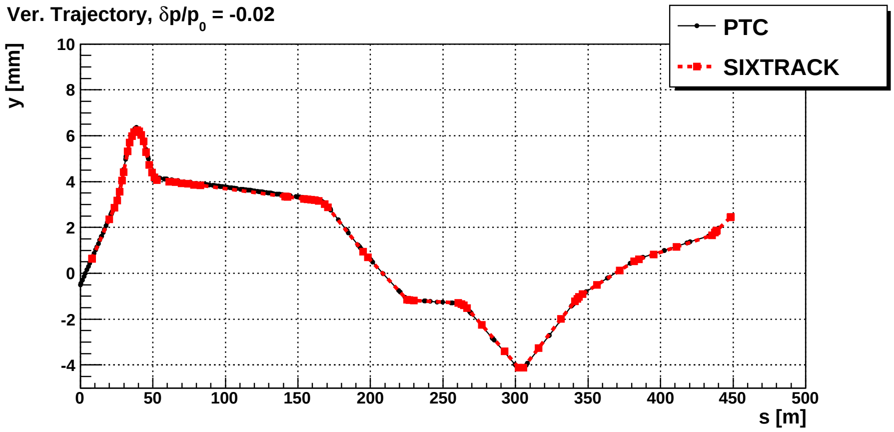

Figure 16: Vertical trajectory of a proton generated at (x,x',y,y') = (0,0,0,0) and with 2 % momentum offset, as simulated by PTC and SIXTRACK.

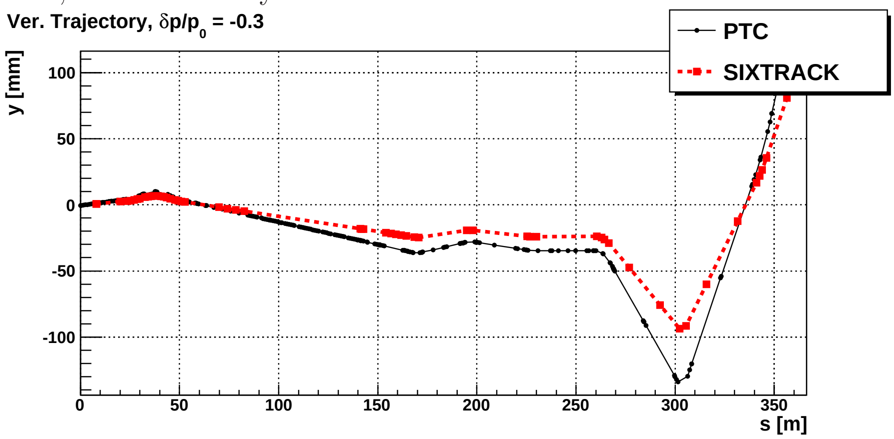

Figure 17: Vertical trajectory of a proton generated at (x,x',y,y') = (0,0,0,0) and with 30 % momentum offset, as simulated by PTC and SIXTRACK.

The same kind of loss maps, while setting TCL4 at 30 σ_x, TCL5 at 50 σ_x and a new TCL6 at 40 σ_x is shown in Fig. 19. This corresponds to the second alternative to the present scheme with two collimators, presented above. In this case it must be noted that the difference between PTC and SIXTRACK is negligible when looking at the losses after the TAN absorber at about 140 m. As a consequence, one can assess that the effect of neglecting the effect of scattering on the TCL collimators in PTC is not relevant in determining the best collimator settings. This assessment is confirmed by the histograms in Fig. 20 and Fig. 21 resulting from the SIXTRACK simulations. The first histogram is a count of the protons impacting on the collimators for different collimation settings when considering 48000 protons generated at the IP. For the same IP protons and the same collimator settings, the second histogram indicates the fraction of protons that emerge from the collimators (i.e. scattered and not absorbed). All values are below 5 %.

6 AFP acceptances

The motivation for the revised collimation scheme comes from the impact of the TCL5 collimator on the acceptance of the 220 m detector station. To illustrate the impact, the acceptance curves for TCL5 at 10σ_x and the other collimators open (the nominal configuration) is shown in figure 22. In this plot, the acceptance is defined as the fraction of Higgs events produced by central exclusive production with a given mass to be tagged by the forward detectors. The blue

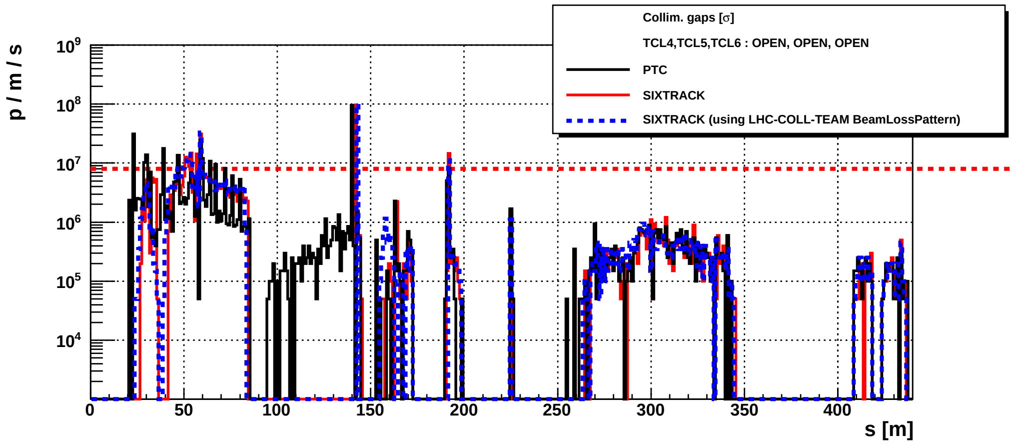

Figure 18: Loss maps comparison between PTC and SIXTRACK with no collimators added to the lattice.

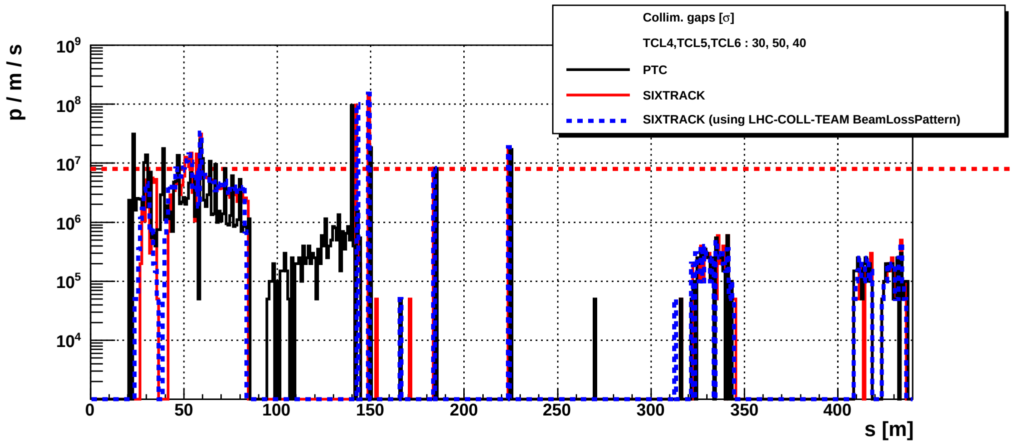

Figure 19: Loss maps comparison between PTC and SIXTRACK with TCL collimators half gaps at 30, 50 and 40 σ_x (*Alternative 2* discussed above).

line denotes the acceptance of the protons by the 420 m detectors on both sides, the red denotes acceptance of the protons by the 220 m detectors on both sides and black denotes the combined acceptance by requiring proton acceptance by the 220 m detector on one side and the 420 m detector on the other. The acceptances are calculated with the EXHUME [11] Monte Carlo for the Higgs production and the beam transport code PTC [6]. The acceptance for lower Higgs mass is dominated by protons tagged at 420 m, and so does not depend on the setting of the TCL5 collimator. However, the protons from higher Higgs mass events are primarily detected at 220 m, and the TCL5 at $10\sigma_x$ collimates many of these protons before the detector (and as a result impacts the 220 m / 420 m acceptance).

The new collimation scheme proposed in this note reduces the problem by allowing TCL5 to be opened. To show this, the acceptance curves for TCL4 at $30\sigma_x$, TCL5 at $50\sigma_x$ and TCL6 at $40\sigma_x$ is shown in figure 23. The plot shows the 420 m acceptance is not changed, but the acceptance for 220 m and for 220 m / 420 m is significantly improved, demonstrating the success of the scheme.

6.1 Simulation uncertainties

All the analytical calculations and tracking simulations that have been presented above refer to an ideal linear model of the LHC optics and any machine imperfection has been neglected.

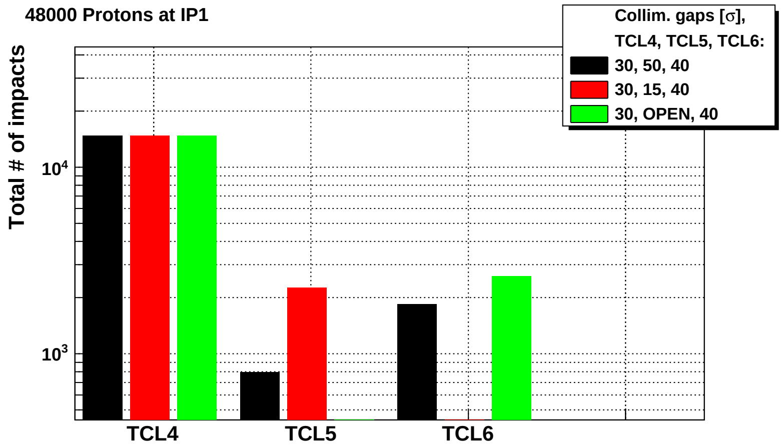

Figure 20: Total number of protons impacting on the 3 collimators as calculated by SIXTRACK when considering 48000 protons at the IP and different collimator settings.

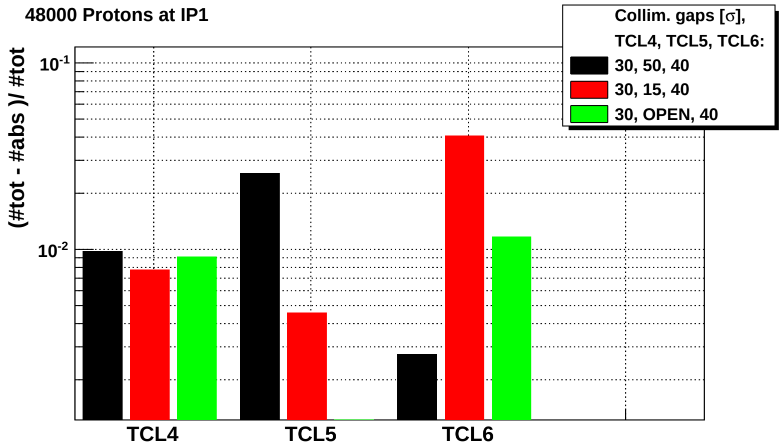

Figure 21: Fraction of protons not absorbed by the collimators as calculated by SIXTRACK when considering 48000 protons at the IP and different collimator settings.

As a consequence, the effect of non linear contribution of magnetic field errors and magnetic elements misalignment have not been considered. However, since such uncertainties contribute to both the presently considered collimation scheme and the proposed alternatives, the relative comparison between the different schemes can be considered very accurate.

7 CONCLUSIONS

The analytical calculations and tracking simulations presented in this note provide two alternative collimation schemes to the one presently foreseen in the ATLAS (and CMS) straight section regions. According to these studies, the two alternatives would guarantee the LHC protection from physics debris and enough acceptance for the detectors proposed at 220 meters from the IP. Both alternatives imply the installation of a collimator between the Q5 and Q6 magnets, as close as possible to Q6. This looks possible after studying the present LHC layout and a visual inspection in the tunnel. However, a detailed study of the collimator integration is necessary for validating the proposal.

The overall study interpretation depends on the estimated quench limit for the supercon-

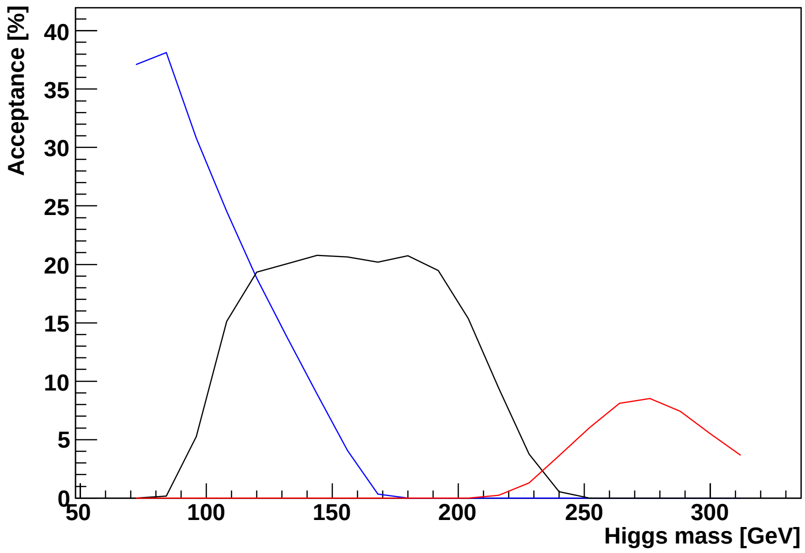

Figure 22: The acceptance curves for TCL5 at $10\sigma_x$ and the other collimators open. In this plot blue denotes the 420/420 acceptance, red denotes the 220/220 acceptance and black denotes the 220/420 acceptance. Note the difference in scale to figure 23.

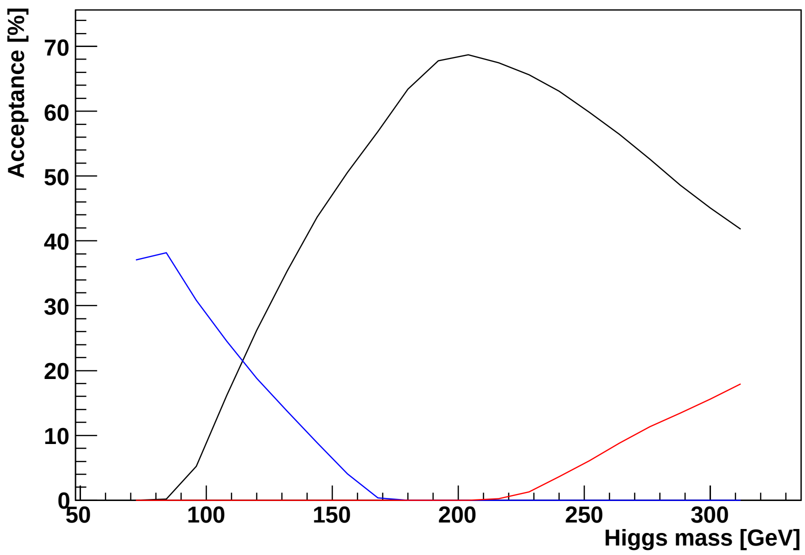

Figure 23: The acceptance curves for TCL4 at $30\sigma_x$, TCL5 at $50\sigma_x$ and TCL6 at $40\sigma_x$. In this plot blue denotes the 420/420 acceptance, red denotes the 220/220 acceptance and black denotes the 220/420 acceptance. Note the difference in scale to figure 22.

ducting elements and the early LHC runs will give information about the accuracy of such estimation.

Even though the studies considered a perfectly linear model of the LHC optics, the relative comparison among loss maps produced with different collimation schemes is considered accurate. Indeed, the numerical simulations reproduced nicely the results of Baichev-Jeanneret performed with a different tracking code and p-p generator. In addition, the two independent codes PTC and SIXTRACK exhibited very consistent results when using the same LHC model in terms of optics and aperture.

The absolute simulation accuracy can be improved by considering magnetic field errors measured in the laboratory and magnet elements misalignment measured in the LHC tunnel. The results could also be improved by using the accelerator optics as measured during the early LHC runs.

A complete estimation of the effect of the physics debris on the LHC elements can be achieved by modeling the electromagnetic and hadronic showers resulting from the scattering of the of the proton on the TCL. This can be done with Monte Carlo codes such as Geant4 and FLUKA, with the showers initiated from the PTC loss maps in the collimators.

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References

[1] The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC, JINST 4 T10001, hep-ex/0806.0302 (June 2008)

[2] C. Royon [RP220 Collaboration], ”Project to install roman pot detectors at 220 m in ATLAS”, arXiv:0706.1796 [physics.ins-det].

[3] AFP LOI [AFP group], private ATLAS document.

[4] TOTEM Collaboration, CERN-LHCC 2004-002 (2004)

[5] I. Baichev, J.-B. Jeanneret and G.R. Stevenson, *Beam losses far downstream of the high luminosity interaction points of LHC - intermediate results*, LHC-Project Note 208, CERN, 2000

[6] E. Forest, F. Schmidt and E. McIntosh, “Introduction to the Polymorphic Tracking Code”, CERN-SL-2002-044-AP, KEK report 2002-3, July 2002.

[7] R. Assmann *et al*, The proceedings of PAC03, pag. 3496.

[8] S. Roesler, R. Engel, J. Ranft: ”The Monte Carlo Event Generator DPMJET-III” in Proceedings of the Monte Carlo 2000 Conference, Lisbon, October 23-26 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz eds., Springer-Verlag Berlin, 1033-1038 (2001).

[9] V.Talanov, Private communication

[10] The LHC design report, CERN-2004-003 (2004)

[11] J. Monk and A. Pilkington, Comput. Phys. Commun. **175** (2006) 232 [arXiv:hep-ph/0502077].

[12] "The FLUKA code: Description and benchmarking" G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso', J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6–8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)