

HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Deliverable Report

SIMULATION MODELS FOR ENERGY DEPOSITION

Redaelli, Stefano (CERN)

20 November 2012



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DELIVERABLE REPORT

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Abstract:

Simulation models for energy deposition: setup energy deposition models that correctly setup the IR1 and IR5 geometry after the upgrade. Define appropriate interface to the experiments.

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	Name	Partner	Date
Authored by	S. Redaelli	CERN	17/10/12
Edited by	A. Szeberenyi	CERN	19/10/12
Reviewed by	L. Rossi [Scientific coordinator]	CERN	09/11/12
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Executive summary

The simulations of physics debris are important to determine an effective cleaning of losses in the matching sections and dispersion suppressors of the high-luminosity experiments. The setup of models has been focused on the present layout to propose changes that will already take place in LS1. The proposed solution is considered to be valid also for future collimation requirements in the HL-LHC era. Specifically, a new collimation layout in IR1 and IR5, which foresee the addition of 2 new TCL collimators per beam per side of each IR, has been defined and will take place in LS1. The setup of detailed energy deposition models in FLUKA, available so far only for the standard optics, is complemented by tracking models in SixTrack that already include modelling of HL-LHC optics scenarios (ATS option for 15 cm β^). These simulation setups are in a status that can be used to address satisfactorily critical questions for the LHC operation until LS3 as well as to get an insight of possible limitations in the HL-LHC era.*

Simulation models for energy deposition studies in the cleaning insertions IR3/7 are well established and were not addressed by work on model setup performed in this first year. They will be addressed in the context of the simulation setup of new dispersion suppressor collimator layouts based on the 11 T dipole magnets.

1. INTRODUCTION

Within the HiLumi-WP5, models for energy deposition studies must address (1) the analysis of physics debris downstream of the (high-luminosity) experiments, in particular downstream of the TANs; (2) beam loads in the experimental insertions from incoming beam during regular operation (halo cleaning) and abnormal failure cases; (3) beam loads downstream of the collimation cleaning insertions IR3 (momentum cleaning) and IR7 (betatron cleaning). The energy deposition studies are for the moment performed with the FLUKA code, clearly profiting from existing models developed in the past years for the LHC studies. The study in the experimental regions has profited in particular from the recent work developed by HiLumi-WP10: the geometry has been used for the analysis of losses in the matching sections downstream of the triplet and in the dispersion suppressor regions of IR1 and IR5. Losses upstream of the matching section are in the scope of WP10. In addition to the FLUKA geometry setup, beam tracking with SixTrack has also been setup: this faster tracking allows more flexibility in upgrading optics models as well as an analysis of the multi-turn losses around the ring of collision products.

It is important to realize that LHC collimation upgrades towards the HL-LHC will start already before the HL implementation in LS3. The first year of work has been focused on studying improvements that will allow a reliable operation until LS3. In particular, for physics debris studies the simulation work within WP5 has been focused on the present layout of IR1/5. A new layout has been proposed for implementation in LS1 that is expected to be kept until LS3. This is an important milestone. An essential ingredient to achieve this result was the analysis of beam losses from physics debris at the LHC in 2012. The effectiveness of the existing physics debris collimators (TCL) was proved experimentally and this is being benchmarked against simulations. These studies, both the simulation work and the understanding of beam measurements, provide a crucial basis for further improvements to be studies for HL-LHC.

2. IR1/5 GEOMETRY FOR ENERGY DEPOSITION STUDIES (IN COLLABORATION WITH WP10)

The energy deposition simulations for collimation studies in the interaction regions require a complete 3D model of the insertions to cover the machine layout up to the dispersion suppressors. Simulations for the incoming beams rely on detailed halo simulations (loads to the tertiary collimators) and on the geometry upstream of the interaction point. Thanks to the strong collaboration with the WP10 of HL-LHC, simulations were performed to address the energy loads from the collision products for different collimation layouts. An example of FLUKA simulations of particle fluence right side of IR5 is given in Figure 1. The models of the matching sections and of the dispersion suppressors were extended and now feature a better modelling of the orbit configuration from the crossing schemes, allowing to achieve a good agreement with what is calculated with MADX and SixTrack.

The simulations of energy deposition in IR1 and IR5 were triggered from a collimation project request for action in LS1 and this work will continue within the HiLumi scope. A baseline layout was proposed for physics debris collimators (TCL's) in IR1 and IR5 for implementation in LS1 (Collimation Working Group meeting of [July 30th](#), 2012). This study is crucial for the WP5-HiLumi simulations because it represents a first step to understand the losses in the dispersion suppressors with the present collimation layout. Figure 2 gives for example the preliminary estimates of loss density distribution for different settings of the TCL collimators.

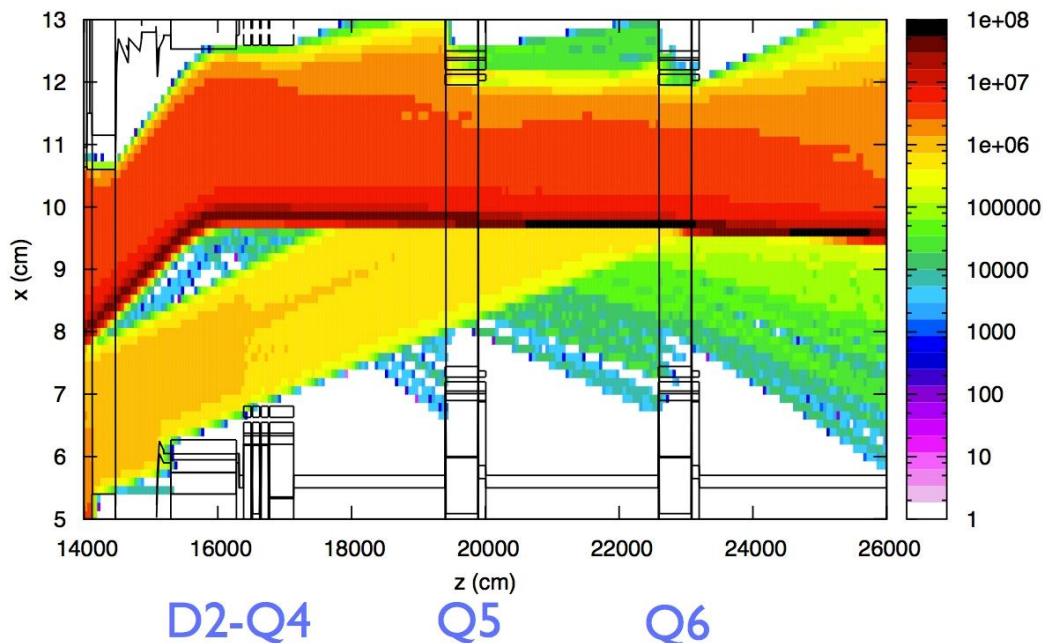


Figure 1: Beam fluence expressed in particles per $\text{cm}^{-2} \text{s}^{-1}$ in the right side of IR5 calculated with FLUKA for a nominal luminosity of $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ at 7 TeV. These simulations are performed with open TCL collimators. Presented at the [Collimation Working Group meeting](#) of July 30th, 2012.

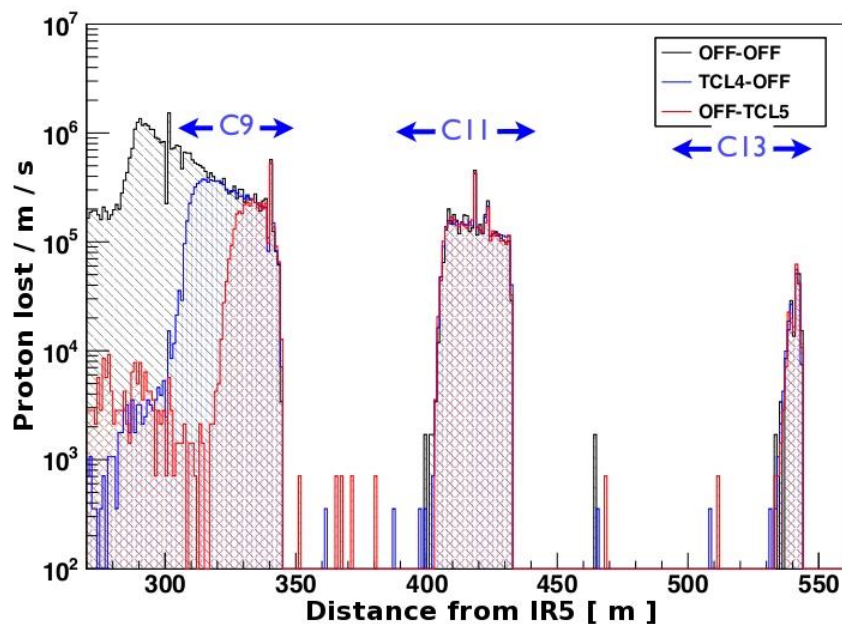


Figure 2: Results of preliminary beam loss calculations from physics debris: proton lost per m per second in the dispersion suppressor of IR5 for different configurations of the TCL collimators. Presented at the [Collimation Working Group meeting](#) of July 30th, 2012

The simulations of energy deposition and background from the incoming beams have not yet started. The simulation tools are however well established and the extension to new layout that will come is essentially ready.

3. MULTI-TURN TRACKING SIMULATIONS OF PHYSICS DEBRIS

The models for single-pass energy deposition studies were complemented by the setup of multi-turn tracking of physics debris by the code SixTrack with collimation features (see G. Robert-Demolaize, R. Assman, S. Redaelli and F. Schmidt, “A new version of SixTrack with collimation and aperture interface”, PAC2005). This simulation setup (1) allows more flexible tracking for parametric studies of different optics configurations and collimator settings; (2) extends the model over longer fractions of the LHC (e.g., allowing modelling the full arcs affected by the “telescopic squeeze” under investigation for HL-LHC optics solutions); (3) allows studying multi-turn losses from physics debris. The multi-turn tracking of physics debris had to be setup from scratch. An example that shows the tracking simulation results for beam loss studies in IR1 is presented in Figure 3. In this example, simple particle distributions with different energy errors are tracked to illustrate the simulation setup and to qualitatively indicate locations of losses for different momentum offsets.

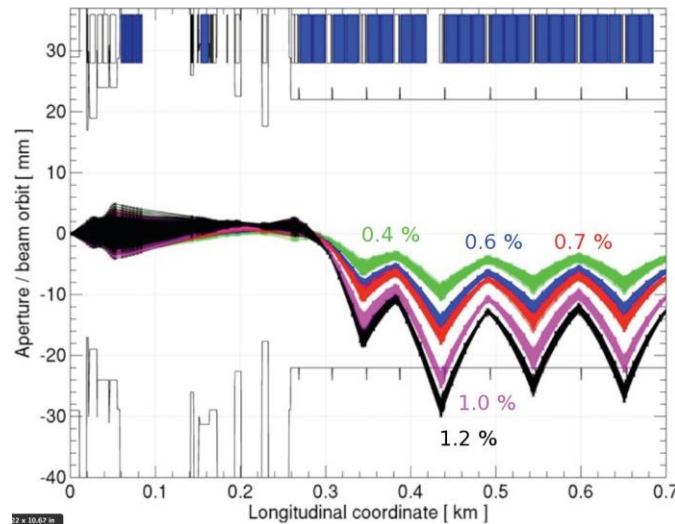


Figure 3: Particle trajectories versus longitudinal coordinate starting in IR1 for bunches with different energy errors. Presented at the 3rd ColUSM meeting of Feb. 23rd, 2012.

The debris tracking simulations rely on external codes (e.g. DPMJET-III/FLUKA) to provide a realistic description of angular and momentum distributions of particles after head-on encounters in interaction points. The change of transverse derivative and energy calculated from the collision process is added to each particle. The simulation setup developed at CERN relies on inputs for the tracking provided by FLUKA that incorporates the dpmjet-III simulation tool. Initial simulations are done without taking into account contributions from elastic interaction (expected to affect only the results of multi-turn behaviour of physics products). First results of this implementation were presented at the [11th ColUSM](#) of Sep. 7th, 2012. The simulation chain involving collision products, particle tracking, aperture checks and loss map generation was successfully setup. A detailed report on these simulations was given at the HiLumi annual meeting in Frascati (A. Marsili *et al.*). An example of loss maps calculated around the ring for the nominal 7 TeV case is given in Figure 4 for collision products generated in IR1. A zoom in the IR1 region is given in Fig. 3. These results are being benchmarked with the FLUKA results described in the previous section.

The complete physics debris simulation chain (tracking with collimators, aperture checks, loss map calculation) was successfully setup at CERN for the first time for the ATS optics for β^* of 15 cm. An example showing the preliminary loss maps on the right side of IR1 is given in Figure 5. This example is used to illustrate the status of setup. The amount of losses will be normalized according to the different HL-LHC luminosity scenarios with and without levelling.

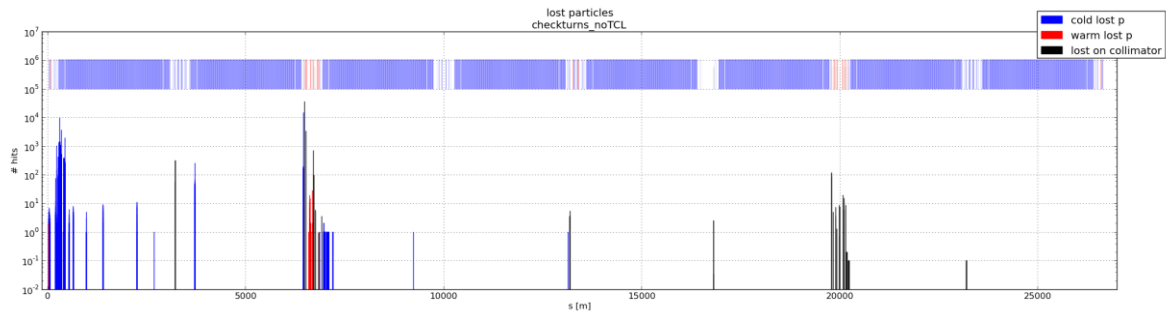


Figure 4: Loss maps around the ring from collision products in IR1 calculated for the nominal 7 TeV machine with $\beta^* = 55$ cm and luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Presented by A. Marsili at the 2nd HiLumi annual meeting in Frascati

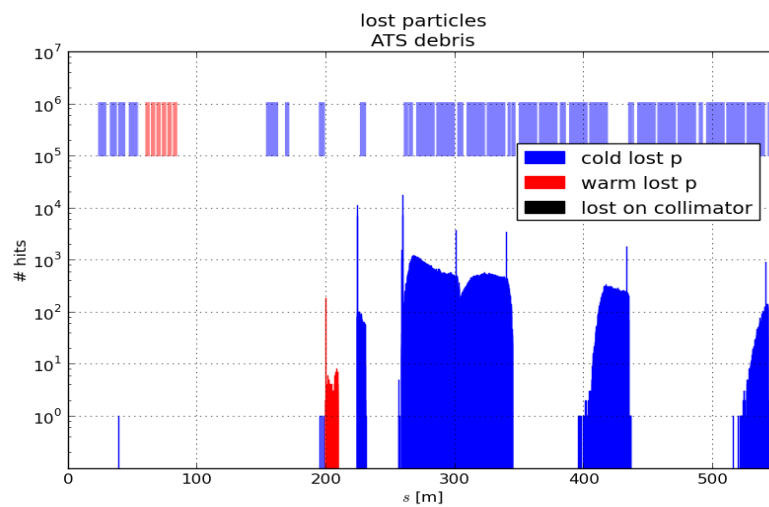


Figure 5: Zoom of FigXX in the matching section and dispersion suppressor on the right side of IR1. Products from inelastic collisions only are considered. Presented by A. Marsili at the 2nd HiLumi annual meeting in Frascati

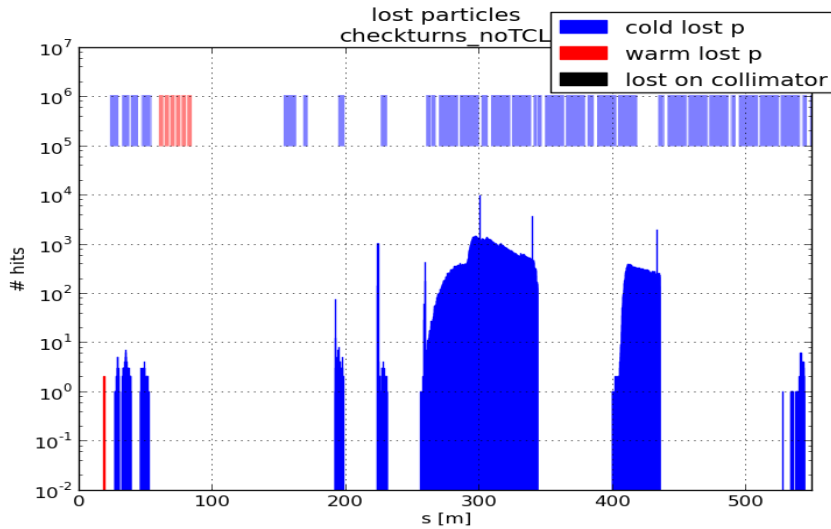


Figure 6: Preliminary simulations of losses in the matching section and dispersion suppressor on the right side of IRI for the ATS optics with $\beta^* = 15$ cm. Products from inelastic collisions only are considered. Presented by A. Marsili at the 2nd HiLumi annual meeting in Frascati

4. MEASUREMENTS OF PHYSICS DEBRIS AT 4 AND PRELIMINARY COMPARISON WITH TRACKING SIMULATIONSⁱ

In order to design new IR collimation schemes, it is equally important to understand in detail the operational limitations at the LHC from beam measurements. To this end, an important participation of WP5 members from CERN and partner institutes to machine studies has taken place during the 2012 run. Particularly relevant for energy deposition studies was the understanding of losses in high-luminosity points for different settings of the existing collimators.

The results of LHC measurements taken in several campaigns during the 2012 operation are subject of a paper submitted to the 4th International Particle Accelerator conference, IPAC13, Shanghai, China (May 2013). This work includes preliminary comparisons with the results of tracking simulations described in Section 3. This work will be expanded including comparisons against FLUKA simulations.

SIMULATIONS AND MEASUREMENTS OF PHYSICS DEBRIS LOSSES AT THE 4 TeV LHC*

A. Marsili[†], R. Bruce, F. Cerutti, S. Redaelli, CERN, Geneva.

Abstract

At the Large Hadron Collider (LHC), dedicated physics debris collimators protect the machine from the collision products at the high-luminosity experiments. These collimators reduce the risk of quenches by stopping physics debris losses. Several measurements have been performed at 4 TeV, with peak luminosity values up to $4 \cdot 10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$ to address the need of these devices and optimize their settings. In this paper, the measurement results are presented and compared with SixTrack simulations of beam losses in IR1 and IR5 for the same conditions.

INTRODUCTION

Installed downstream of the LHC high-luminosity experiments for both beams, the long absorbers for physics debris, usually referred to as *TCLs*, are collimators made of two 1 m-long copper jaws [1]. Their goal is to intercept secondary particles and scattered protons coming from the IPs, having undergone collisions hence displaying extra kicks and momentum offset. They prevent these particles from being lost in the cold magnets of the straight section (mainly Q5 and Q6) and the Dispersion Suppressor (DS).

During LHC operation in 2012, the TCLs were kept at a setting of 10 units of betatron standard deviation (called σ) and proved to be very effective. Dedicated tests were performed to study their effect during collisions, in the range from 10σ to a ‘‘TCL out’’ setting of 60σ (3.6 to 21.6 mm) at different luminosities. These data enable a beam-based optimisation of the TCL settings, and provide

an important reference for benchmarking simulation codes like the particle tracking code SixTrack [2].

RESULTS OF TCL SCANS

The first observations of the TCL scans can be seen on a measured loss map: the signal of the Beam Loss Monitors (BLMs) at their different longitudinal positions s . BLMs are ionisation chambers located outside the LHC cryostat or on the collimator tanks, detecting secondary shower particles. Measurements were performed on the 4th of July 2012. Each TCL was moved from the nominal setting of 10σ to 60σ . The losses on the right of IR1 are given in Fig. 1. The decrease in losses downstream (up to 120 m) shows the actual protection provided by the TCL.

The duration over which the TCL jaws are moved, around 15 min, is quite long with respect to the variation of the luminosity in the LHC. The signal measured by the BLMs is expected to be proportional to the decrease in luminosity. The signals are normalized by the instantaneous luminosity to identify the specific TCL contribution.

In order to evaluate the cleaning provided by the collimator, the ratio of the normalised signal when it is *in* (10σ) over the normalised signal when it is *out* (60σ) was calculated. The results for the four TCLs are shown in Fig. 2. With the TCL in, the losses at the TCL increase by a factor $\simeq 4$; the losses downstream are decreased by a factor down to 0.02 at the most affected location.

* Research supported by FP7 HiLumi LHC – Grant agreement 284404
† amarsili@cern.ch

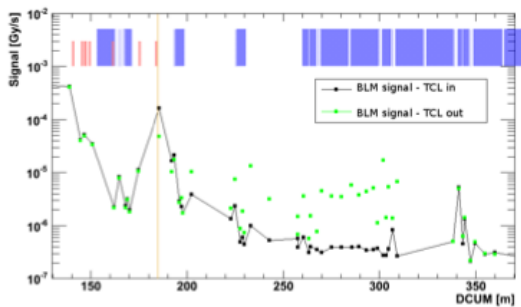


Figure 1: BLM signals on the right side of IP1 ($s = 0$ m) for ‘‘TCL in’’ (black) and ‘‘out’’ (green) with a luminosity of $\simeq 4 \cdot 10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$. Layout elements are illustrated by red and blue boxes. The TCL sits at $s=184$ m (orange line).

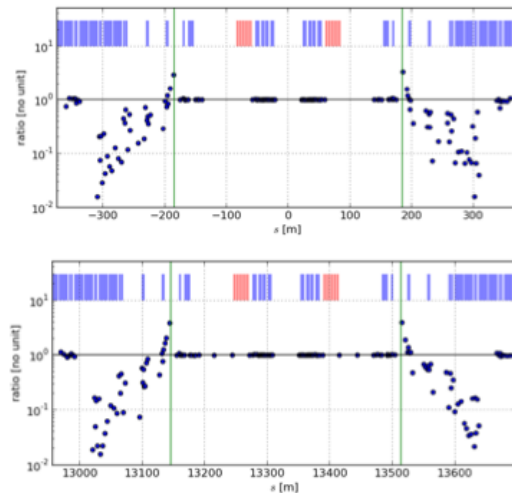


Figure 2: Ratio of the luminosity-normalised losses for TCL at 10σ over 60σ (Fig. 1) in IR1 (top) and IR5 (bottom). TCL positions are given by the green lines.

In Fig. 3, the losses at the quadrupoles Q5 to Q8 measured during the TCL scan are given as a function of half-gap. The curves are normalized to their maximum values, for TCL out. They don't reach zero for elements closer to the IP because of external BLM background signal. Each loss location shows a characteristic evolution. When the TCL moves out, the signal starts rising the furthest away from the TCL (Fig. 3, red curve). When the TCL opens more, the signal at closer BLMs start rising as well (Fig. 3, green curve); this behaviour can be qualitatively explained by the dispersion and momentum spread. The maximum setting for the same cleaning at different loss locations can be read from these plots. Fig. 3 centre (right of IP1) shows that this TCL could be set at 15σ without losing any cleaning. It must be noted that, even though the layouts are symmetric for both sides of IP1 (Fig. 3, top and centre), there are differences in the BLM signals, especially in the setting for which they start rising.

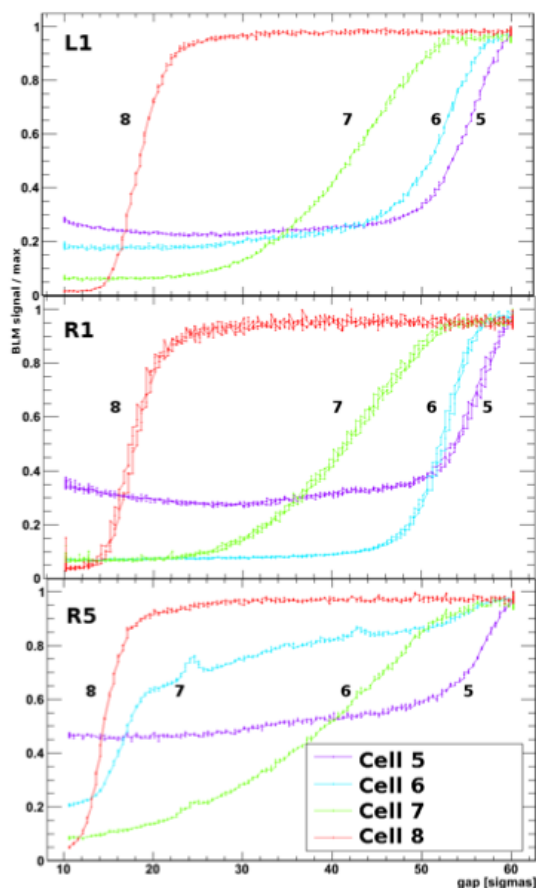


Figure 3: Measured losses normalised by luminosity at Q4 to Q8 magnets versus TCL half-gap, normalized by maximum value for TCL out. Top: Left of IP1, centre: right of IP1, bottom: right of IP5.

PRELIMINARY SIMULATIONS

The collimation simulations were performed with the particle tracking code SixTrack [2]. The initial particle distribution was generated from the products of proton collisions simulated by the particle-matter interaction code FLUKA [3, 4]. Cuts were applied to select the protons (with extra kicks and momentum offsets) that are relevant for losses in the matching section and DS.

Settings between 10σ and 60σ were simulated with 5σ steps. An example of the results for 10σ and 60σ is given in Fig. 4. For each simulated setting, the secondary showers detected by the BLMs were approximated by summing up the protons lost on aperture over 10 m upstream the position of each selected BLM. This is shown in Fig. 5 where the results of the TCL scan is given. The results are normalized to the maximum losses for TCL out, as in Fig. 3. For the Q8 case, the losses are also integrated over 5 m. The losses simulated at the BLM of a DS dipole in cell 8, calculated in a similar way, are given in Fig. 6 together with the measured signal. This is a first attempt to compare the results of these complex simulations against the measurement results, in absence of detailed energy deposition studies of BLM response.

Simulations show a good qualitative agreement with measurements, considering their uncertainty illustrated by Fig. 3. For example, the fact that the Q5 protection is main-

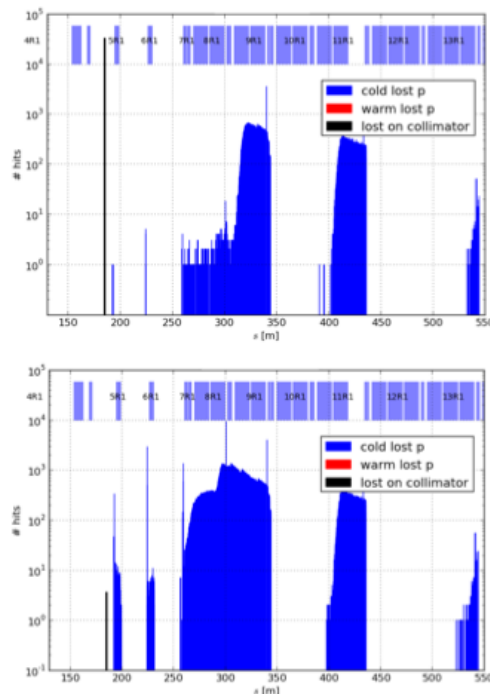


Figure 4: Losses simulated by SixTrack for the losses downstream TCL.5R1.B1 (at 184 m). Top: TCL set at 10σ , bottom: 60σ . The initial distribution had $1.77 \cdot 10^6$ particles, corresponding to 10^7 p-p interactions.

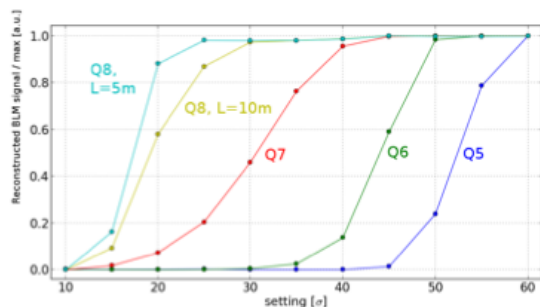


Figure 5: Simulated losses summed on 10m in front of the position of each selected BLM. A different summing length of 5 m has been added for the BLM of Q8, to show the effect of the summing length.

tained for settings up to about 50σ is well reproduced in simulations. This comparison is carried out for the normalized signals; quantitative comparisons require information on the energy deposited to the different BLMs. It should be noted that a difference was found between measurements and simulations of the losses at the TCL itself. Simulated losses vanish above about 40σ whereas measurements indicate decreasing losses up to 60σ . The effects of the chosen cuts of the debris distributions is under investigation.

The ratio of the losses with the “TCL in” over the losses with the “TCL out” was calculated for the simulations, as shown in Fig. 7. Taking simply the ratio of protons hitting the cold aperture, the reduction factor up to the Q8 is overestimated by a factor $\simeq 10$. The behaviour at the Q9 is well reproduced. This can be explained by the nature of the measurements [5]. Several sources of errors in these simulations could explain this discrepancy: 1) the BLMs detect the secondary showers (outside the cryostat) created by the primary particles lost on the beam pipe; 2) the longitudinal range over which protons lost in aperture affect a specific BLM; and 3) the BLM backgrounds are not accounted for in simulations. These aspects are under investigation.

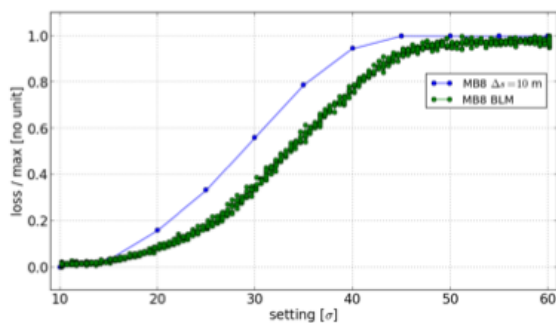


Figure 6: BLM signal and simulated losses summed over 10 m in front of the BLM position versus gap, for the main dipole of cell 8.

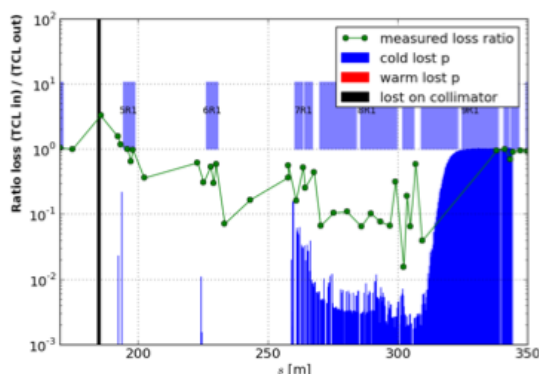


Figure 7: Ratio of the simulated losses for the case “TCL in” (10σ , Fig. 4 top) over the case “TCL out” (60σ , Fig. 4 bottom), for the range of s for which the SixTrack simulations are meaningful. The black line represents the TCL.5R1.B1. The green curve represents the ratio for the measurements in the LHC, as shown in Fig. 2.

CONCLUSIONS

In conclusion, the results of measurements of physics debris collimator cleaning for different collimator gaps were reported. Measurements performed at the LHC at 4 TeV were summarized. The measurements were compared against preliminary results of tracking simulations. The resulting loss pattern of primary protons, simulated with SixTrack, is consistent with the observed BLM signals during a TCL scan in the LHC. The elements closer to the collimator (Q5 and Q6) would be protected even for large values of the setting, whereas further elements in cell 9 need much tighter setting to be protected. This is due to the dominating effect in the IP debris: the momentum offset.

Further work includes gathering results from other LHC measurements, in order to evaluate the uncertainty on the settings due to BLM signal, and reproducing BLM signal more accurately from the simulated losses in 10 cm bins.

ACKNOWLEDGEMENTS

The author wishes to thank L. Lari, D. Mirarchi, B. Salvachua, G. Valentino, the whole collimation team and the operation team for providing data and input.

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5. FUTURE PLANS / CONCLUSION / RELATION TO HL-LHC WORK

Thanks to strong collaborations with other HL-LHC work packages (mainly WP2 and WP10), a satisfactory simulation setup could be established for the studies of energy deposition in IR1 and IR5 for various optics and peak luminosity scenarios. The immediate focus on detailed energy deposition simulations was devoted to a layout improvement that will be implemented for the LHC operation until LS3. Important progress has also been made for the tracking simulations of physics debris, which includes a benchmark against LHC measurements of collision debris cleaning.

Future work will be focused with high priority onto the setup of simulations models with the 11 T dipoles and collimators in the dispersion suppressor regions, with particular focus to the ion case in IR2. Simulations for other IRs (proton physics debris in IR1 and IR5 as well as cleaning simulations in IR7 with DS collimators) will then follow. After that, updated ATS optics cases will be studied for even lower β^* reach.

The present models can be already used for preliminary assessment of the background in the experiments from beam halo cleaning. This work will however follow after the items mentioned above will be satisfactorily addressed.

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ANNEX: GLOSSARY

Acronym	Definition
IR	Interaction region
IP	Interaction point