CERN-ACC-2013-012

HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Deliverable Report

SIMULATION MODELS FOR BEAM LOSS

Redaelli, Stefano (CERN)

20 November 2012

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package **5: Collimation**.

Grant Agreement No: 284404

HILUMI LHC

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Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures,
Collaborative Project, Design Study

DELIVERABLE REPORT

SIMULATION MODELS FOR BEAM LOSS

DELIVERABLE: D 5.1

Document identifier:	HILUMILHC-Del-D5-1-final
Due date of deliverable:	End of Month 12 (Oct. 2012)
Report release date:	20/11/2012
Work package:	WP5: IR Collimation
Lead beneficiary:	CERN
Document status:	Final

Abstract:

Simulation models for beam losses: setup of simulation models for beam loss halo that correctly describe the halo, the optics and the available LHC aperture after an upgrade. Some of the simulations must allow high statistics of primary beam halo (5-20 million particles).

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The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. HiLumi LHC began in November 2011 and will run for 4 years.

Delivery Slip

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Edited by	A. Szeberenyi	CERN	19/10/12
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Approved by	Steering Committee		15/11/12

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Executive summary

WP5-Collimation team has started the activities toward the design of the new collimation system for the HL-LHC era. The progress of this work package profits from strong collaborations with WP2 and WP10 within HL-LHC, as well as with other teams at CERN, US-LARP and EuCARD. At CERN, models to simulate the multi-turn halo cleaning were successfully setup and the first complete loss maps could be achieved for the ATS optics presently under consideration for HL-LHC. In addition, the tracking simulation models were setup in a way that allows one to compute multi-turn losses from the collision products that, in particular for the high-luminosity experiments, induce significant losses in the matching sections and dispersion suppressors. Manchester and Huddersfield universities have continued their development of the Merlin tracking code for collimation studies. Merlin now has a complete model of the LHC optics and collimators, which is consistent with the state-of-the-art tools developed at CERN. The code has been extended with improved scattering in collimators, with elastic and single diffractive cross sections fitted to recent experimental data. The code is being benchmarked against SixTrack simulations and LHC loss map measurements and it is now essentially ready to be used for simulations of various relevant HL cases.

1. INTRODUCTION

The improved performance of the HL-LHC relies on new optics layouts that will enable reaching β^* values below what can be achieved with the present machine. This can only be achieved by major changes of the machine layouts in the high-luminosity interaction regions, for example by changing the aperture of the triplet magnets that determine the smallest achievable β^*. A new Achromatic Telescopic Squeeze (ATS) scheme is being now considered to achieve β^* below 15 cm at the HL. It is important to address very early on potential collimation issues for these optics scenarios. The complete setup of models for tracking studies has been achieved. This includes simulations of the collimation beam halo cleaning as well as of the physics debris products. These first simulations indicated a potential issue for the ATS optics that will have to be addressed with an upgrade of the collimation system. This new scheme that requires changes of beam orbit and β functions in the arc (as opposed to more standard optics solutions that only require changes in the insertions) induces losses around the ring with a pattern qualitatively different with respect to the present LHC.

2. SIMULATION MODELS FOR HL-LHC OPTICS SCENARIOS

2.1. INTRODUCTION TO SETUP OF HALO CLEANING SIMULATIONS

The setup of beam halo cleaning at 7 TeV with the ATS optics at 15 cm β^* has been setup successfully and has been reported at the second HiLumi annual meeting in Frascati[1] (Nov. 2012). The detailed results are going to be presented at the 4th International Particle Accelerator Conference, IPAC13, in Shanghai, China (May 2013), see Section 2.2 of this report. The standard set of collimator tracking tools based on a SixTrack version with collimation features was updated for setting up the ATS simulations.

These simulations address possible collimation limitations from the betatron cleaning system in IR7. In addition, the developed optics models (optics, layout, aperture) will also be used for simulations of losses around the ring generated by collision products in the high-luminosity insertions. The setup of simulations profited obviously from the optics developments in WP2.

The first simulations results for ATS were achieved which required a definition of a first preliminary baseline for collimator settings in the HL-LHC era, compatible with the new aperture for the ATS layout. This was achieved in strong collaboration with the WP2.

The improvements in the Merlin code have continued with high priority. The LHC loss maps with the standard optics were presented at the International Computational Accelerator Physics conference, ICAP12, Rostock, Germany (Aug. 2012), see section 2.3 of this report. This contribution was granted an oral presentation. Detailed comparisons between Merlin results and SixTrack results as well as between Merlin results and LHC measurements at 3.5 TeV are on-going.

The first simulation setup described here concerns proton beams only. The simulations for ions are being developed.

It is noted that resources from RHUL and Valencia started working on WP5 topics at the end of 2012. They will contribute to the SixTrack simulation effort at CERN. In particular, Valencia will contribute to the simulations of the beam loads at critical collimator locations for HL-LHC layouts. These simulations of beam failures will use the same setup established for halo cleaning and physics debris tracking studies.

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[1] http://indico.cern.ch/event/183635

2.2. PRELIMINARY RESULTS OF HALO CLEANING WITH ATS[i]

SIMULATIONS OF COLLIMATION CLEANING PERFORMANCE WITH HL-LHC OPTICS*

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Abstract

The upgrade of the LHC from the current set-up to high luminosity performances will provide new challenges for the protection of the machine. The different optics considered might create new needs for collimation, and require new collimation locations. In order to evaluate the cleaning performances of the collimation system, different halo cleaning simulations were performed with the particle tracking code SixTrack. This paper presents the cleaning performance simulation results for the high luminosity Achromatic Telescopic Squeeze (ATS) optics considered as baseline for the HL-LHC. The new limitations observed and possible solutions are discussed.

INTRODUCTION

The High-Luminosity LHC (HL-LHC) upgrade project aims to increase the peak luminosity to $5 \times 10^{34}\,\mathrm{cm}^2 \cdot \mathrm{s}^{-1}$ [1]. This can be done by decreasing the size of the beam at the Interaction Point (IP), with values of the beta function down to $\beta^* = 10\,\mathrm{cm}$. One way to achieve this is the so-called *Achromatic Telescopic Squeeze (ATS)* scheme [2]. Its main characteristics is to use a beta beating in the arcs adjacent to the IPs where the low β^* values must be obtained to reduce it further, as shown in Fig. 1.

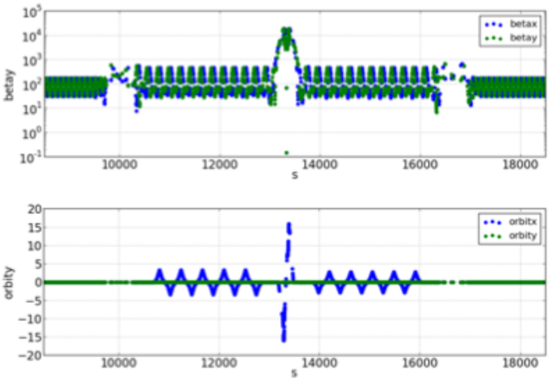

Figure 1: Examples of orbits (top) and beta functions (bottom) in the transverse planes in the arcs 4–5 and 5–6 around IP5, illustrating the differences with the other arcs.

The values of crossing angles and beta functions at the different Interaction Points (IPs) are given in Table 1. While the basic feasibility of this new scheme was successfully addressed during machine development periods at the LHC [4], other aspects need to be studied to see the overall feasibility for HL-LHC. This paper presents the first results of collimation cleaning with ATS.

Table 1: IP Parameters for the ATS Optics SLHCV3.1b [3]

IP	x'[mrad]	y' [mrad]	β_x^*, β_y^* [m]
IP1	0.	0.295	0.15
IP2	0.	0.240	10
IP5	0.295	0.	0.15
IP8	-0.305	0.	10

SIMULATION SET-UP

The cleaning performance simulations were performed using the tracking code SixTrack with the collimation routine [5], for the ATS layout and optics version `SLHCV3.1b` [3] which give the IP parameters in Table 1. The associated aperture model was updated to follow the modifications in IR1/5. The aperture model at the location of the separation dipoles in IR1/5 is still preliminary and does not model the aperture offsets. The nominal 7 TeV collimator settings are used for this first study (cf. Tab. 2). They ensure an adequate protection of the triplets for the optics considered.

The initial particle distribution is a halo at the setting of the primary collimator: 6 units of betatronic standard deviation called σ, in the considered phase space (horizontal or vertical); a normal distribution cut at $3\,\sigma$ for the other plane, and no variation of energy. This is the standard configuration for halo cleaning simulations [5]. A total of 30 millions protons at 7 TeV were tracked per simulation, for the perfect machine with no error.

Table 2: Setting of the Collimators by Type

Type	Location	Setting [σ]
TCP	IR3	12.
TCSG	IR3	15.6
TCLA	IR3	17.6
TCP	IR7	6.
TCSG	IR7	7.
TCLA	IR7	10.
TCSG	IR6	7.5
TCDQ	IR6	8.
TCT	IR1/5	8.3
	IR2/8	30.

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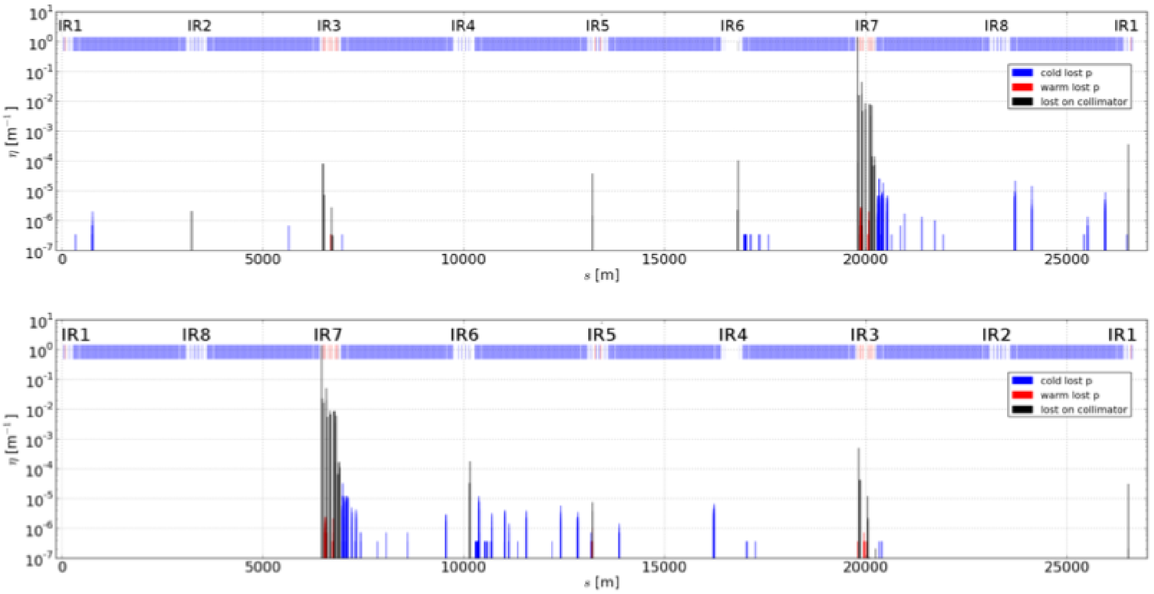

Figure 2: Horizontal loss map for the entire LHC Beam 1 (top) and for Beam 2 (bottom), for 30 million p. The red and blue boxes at the top give the position of warm and cold magnets respectively.

CLEANING SIMULATION RESULTS

The simulated loss map for a horizontal halo shows the local inefficiency around the ring, in Fig. 2 top. The results are the same for the vertical loss map. The local inefficiency η is defined as the loss per meter at a given location, normalised by the total number of protons lost.

The highest losses in cold elements occur in the Insertion Region 7 (IR7), similarly to standard optics, giving the highest inefficiency. The most critical area is the cold magnets in which the inefficiency is the highest (blue peaks right of IR7, see Fig. 3). These losses in the Dispersion Suppressors (DS) are also present in other schemes. However, other peaks, at the same level of the DS peaks (inefficiency $\eta \simeq 10^{-5}\,\mathrm{m}^{-1}$), appear in the arcs, as seen on Fig. 4. This is a specific feature of the ATS scheme which was never observed before with nominal collision optics. These losses, if proven to be above the quench limits, would be concerning because of their numbers: they could not all be cured locally, as the DS losses would.

The same simulations were performed for beam 2 (cf. Fig. 2 bottom). In the arcs downstream IR7, losses occur at negative minimums of the dispersion (maximum in absolute); and always above a certain value of $\delta p/p$.

CHARACTERISATION OF THE LOSS PEAKS DOWNSTREAM IR7

In order to characterise the loss peaks, lost particles have been grouped by loss location. The transverse distribution of the DS losses in IR7 are illustrated in Fig. 5 top. Parti-

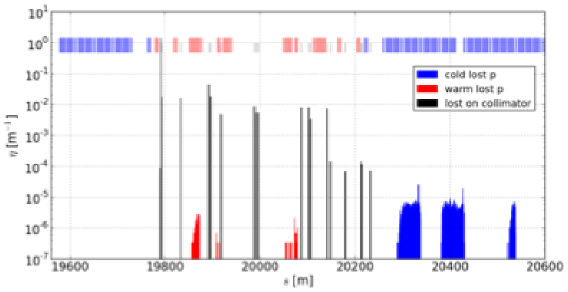

Figure 3: Horizontal loss map for IR7. Every peak in the DS corresponds to a maximum of the dispersion.

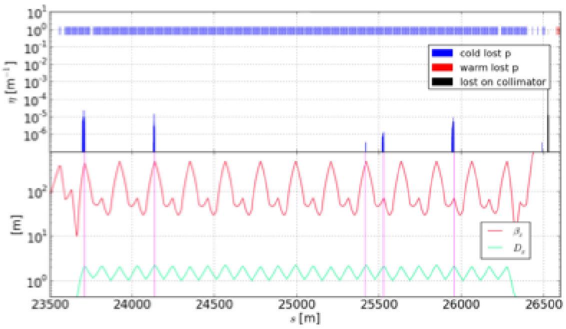

Figure 4: Loss map (top) and values of the beta and dispersion function (bottom) for the arc 81. Every peak inthe arc corresponds to a maximum of the dispersion.

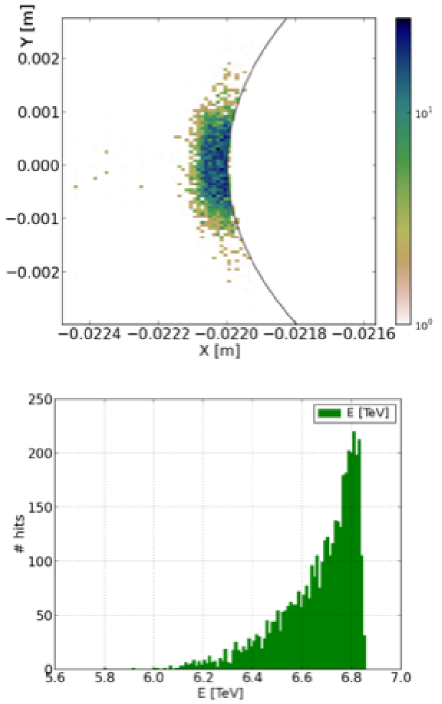

Figure 5: Transverse (top) and energy (bottom) distribution of the losses corresponding in the first peak in the dispersion suppressor right of IR7: 20270 m $< s <$ 20350 m. The black circle represents the aperture of the arc. The highest energy for a lost particle is 6.86 TeV, giving $\delta p/p = -0.02$.

cles are lost on the cold beam screens on the side of positive dispersion function. This is the typical distributions of dispersive losses dominated by single-diffractive interactions at the primary collimator. The energy distribution is also given in Fig. 5 bottom.

All the peaks discussed in the previous section, for both beams, have the same signature: they appear at local maximums of the dispersion function, as shown on Fig. 4. The distributions of the energy of the particles lost in each peak were gathered in Fig. 6. All the lost particles show a $\delta p/p < -0.005$, that is $E < 6.965$ TeV.

POSSIBLE SOLUTIONS

Since all limiting locations are induced by dispersive losses, a natural choice to cure the cleaning issues observed with the ATS optics is to consider local DS collimators in IR7, provided that the achievable momentum cut is sufficient to catch all the critical halo particles.

Solutions involving the installation of local DS collimators in IR7, in association with the new technology of the 11 T dipoles [6], are being considered. Preliminary optics considerations indicate that with collimators at the Q8, Q9 or Q10 locations, already considered in previous scenarios [7], one could achieve momentum cuts of -0.005 to -0.02 which would reduce losses around the ring. Detailed simulations for different layouts are ongoing.

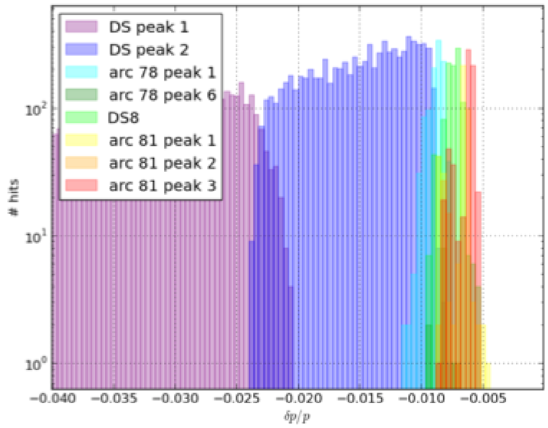

Figure 6: Distributions of the $\delta p/p$ of the particles lost in the main peaks downstream IR7, grouped by peak. The names are arbitrary. There is a clear limit of $\delta p/p$ under which the particles are lost.

CONCLUSIONS

The results for simulation of collimation cleaning with the ATS optics were presented. They indicated a new limitation due to losses in the arcs downstream IR7. Even for a perfect cleaning without optics, orbit and collimator errors, critical loss locations are observed in the arc used for the telescopic squeeze. This is a new feature that is not present in the standard optics, which is limited at the DS locations only. Preliminary studies indicate that DS collimation in IR7 could cure the observed limitation because losses around the ring have a dispersive nature. More simulation works are ongoing to address this.

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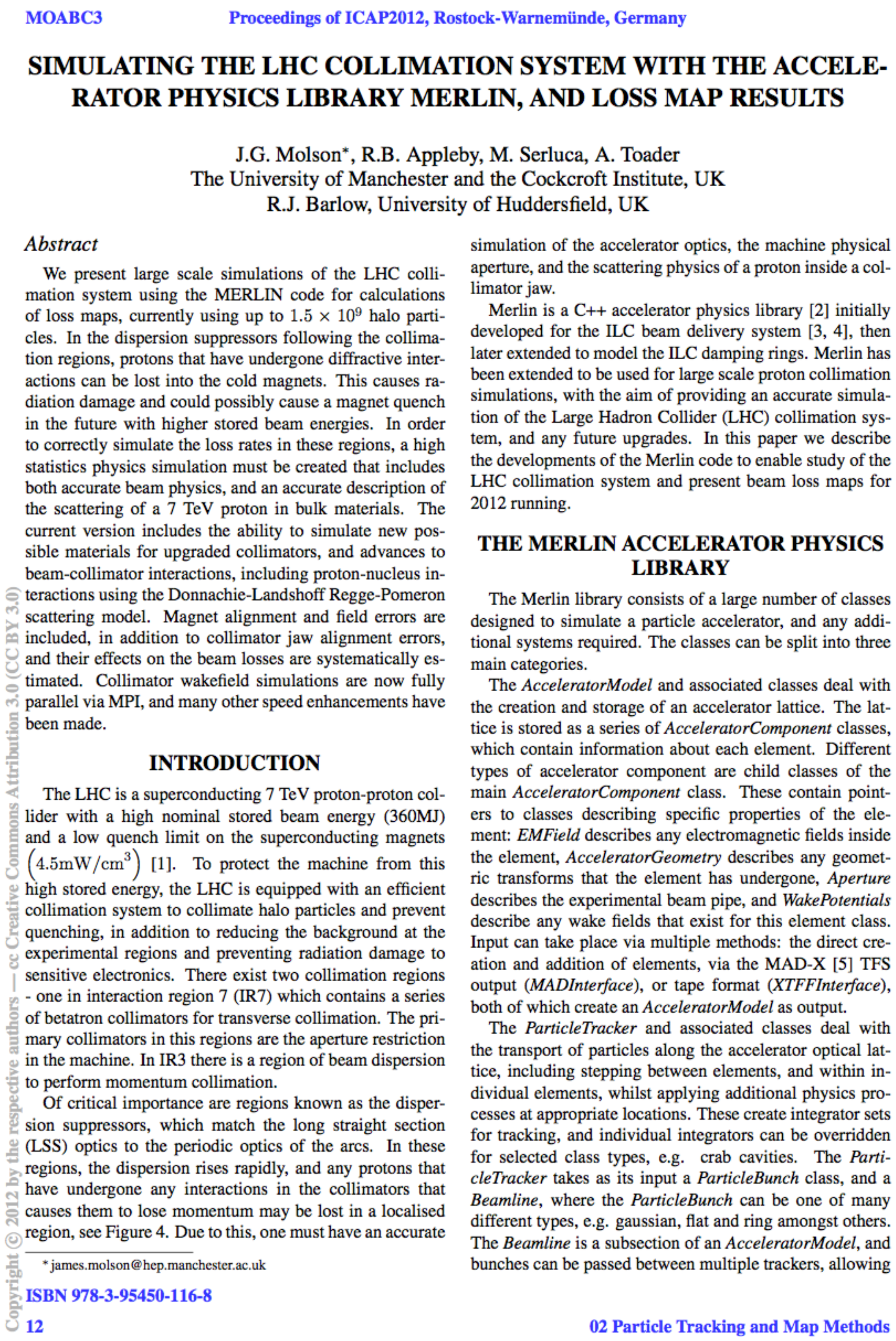
2.3. STATUS OF TRACKING SIMULATIONS WITH MERLIN[ii]



MOABC3 Proceedings of ICAP2012, Rostock-Warnemünde, Germany

SIMULATING THE LHC COLLIMATION SYSTEM WITH THE ACCELERATOR PHYSICS LIBRARY MERLIN, AND LOSS MAP RESULTS

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R.J. Barlow, University of Huddersfield, UK

Abstract

We present large scale simulations of the LHC collimation system using the MERLIN code for calculations of loss maps, currently using up to 1.5×10^9 halo particles. In the dispersion suppressors following the collimation regions, protons that have undergone diffractive interactions can be lost into the cold magnets. This causes radiation damage and could possibly cause a magnet quench in the future with higher stored beam energies. In order to correctly simulate the loss rates in these regions, a high statistics physics simulation must be created that includes both accurate beam physics, and an accurate description of the scattering of a 7 TeV proton in bulk materials. The current version includes the ability to simulate new possible materials for upgraded collimators, and advances to beam-collimator interactions, including proton-nucleus interactions using the Donnachie-Landshoff Regge-Pomeron scattering model. Magnet alignment and field errors are included, in addition to collimator jaw alignment errors, and their effects on the beam losses are systematically estimated. Collimator wakefield simulations are now fully parallel via MPI, and many other speed enhancements have been made.

INTRODUCTION

The LHC is a superconducting 7 TeV proton-proton collider with a high nominal stored beam energy (360MJ) and a low quench limit on the superconducting magnets $\left(4.5\mathrm{mW/cm^3}\right)$ [1]. To protect the machine from this high stored energy, the LHC is equipped with an efficient collimation system to collimate halo particles and prevent quenching, in addition to reducing the background at the experimental regions and preventing radiation damage to sensitive electronics. There exist two collimation regions - one in interaction region 7 (IR7) which contains a series of betatron collimators for transverse collimation. The primary collimators in this regions are the aperture restriction in the machine. In IR3 there is a region of beam dispersion to perform momentum collimation.

Of critical importance are regions known as the dispersion suppressors, which match the long straight section (LSS) optics to the periodic optics of the arcs. In these regions, the dispersion rises rapidly, and any protons that have undergone any interactions in the collimators that causes them to lose momentum may be lost in a localised region, see Figure 4. Due to this, one must have an accurate simulation of the accelerator optics, the machine physical aperture, and the scattering physics of a proton inside a collimator jaw.

Merlin is a C++ accelerator physics library [2] initially developed for the ILC beam delivery system [3, 4], then later extended to model the ILC damping rings. Merlin has been extended to be used for large scale proton collimation simulations, with the aim of providing an accurate simulation of the Large Hadron Collider (LHC) collimation system, and any future upgrades. In this paper we describe the developments of the Merlin code to enable study of the LHC collimation system and present beam loss maps for 2012 running.

THE MERLIN ACCELERATOR PHYSICS LIBRARY

The Merlin library consists of a large number of classes designed to simulate a particle accelerator, and any additional systems required. The classes can be split into three main categories.

The *AcceleratorModel* and associated classes deal with the creation and storage of an accelerator lattice. The lattice is stored as a series of *AcceleratorComponent* classes, which contain information about each element. Different types of accelerator component are child classes of the main *AcceleratorComponent* class. These contain pointers to classes describing specific properties of the element: *EMField* describes any electromagnetic fields inside the element, *AcceleratorGeometry* describes any geometric transforms that the element has undergone, *Aperture* describes the experimental beam pipe, and *WakePotentials* describe any wake fields that exist for this element class. Input can take place via multiple methods: the direct creation and addition of elements, via the MAD-X [5] TFS output (*MADInterface*), or tape format (*XTFFInterface*), both of which create an *AcceleratorModel* as output.

The *ParticleTracker* and associated classes deal with the transport of particles along the accelerator optical lattice, including stepping between elements, and within individual elements, whilst applying additional physics processes at appropriate locations. These create integrator sets for tracking, and individual integrators can be overridden for selected class types, e.g. crab cavities. The *ParticleTracker* takes as its input a *ParticleBunch* class, and a *Beamline*, where the *ParticleBunch* can be one of many different types, e.g. gaussian, flat and ring amongst others. The *Beamline* is a subsection of an *AcceleratorModel*, and bunches can be passed between multiple trackers, allowing

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ISBN 978-3-95450-116-8

situations such as the transfer between different accelerators to be simulated.

A series of *BunchProcess* classes exist to apply additional physics within elements. These can include wakefields, collimation, synchrotron radiation, and others. Templates exist for such classes, and it is straightforward for new users to add additional physics of their choice via this method, without having to adjust other parts of the library.

This modular design allows a user to use as much or as little of the library as they wish. In addition, if one wishes to investigate additional physics relevant to their accelerator system, a new tracking code does not need to be written, but simply a new *BunchProcesses* class can be created. An example simulation run is shown in Figure 1.

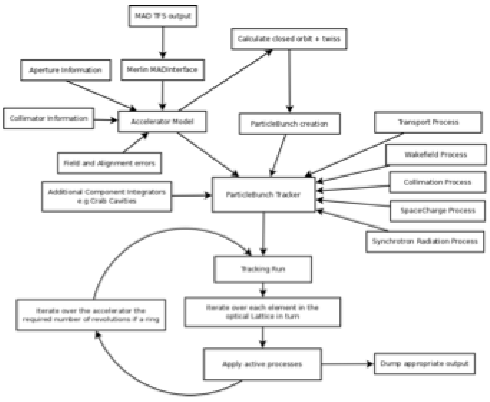

Figure 1: An example logical flow of a Merlin run.

LHC LOSS MAPS RESULTS

Merlin is used to simulate the 2012 as-built optics of the LHC in order to generate loss maps. These can be used to define the maximum possible safe beam current, and indicate areas which may need additional collimators or shielding. The first stage of this calculation is the construction of an accurate optical model of the LHC in Merlin. The machine optics are generated by MAD-X and are used as the input to Merlin. Inside Merlin, the *LatticeFunctions* class calculates beam parameters using Merlin's integrators. A comparison between Merlin and MAD-X of the β-functions and the linear dispersion is shown in Figure 2, and excellent agreement is found in all regions of the machine.

Loss maps can be generated using different optics configurations, e.g. the β-function at the interaction points (β^*), beam crossing angles, and so on. The *CollimationProcess* simulates all proton-collimator interactions and performs all aperture checking. If a proton undergoes an inelastic interaction or touches the beam pipe it is considered lost. If this takes place, the particle is removed from the bunch and the location at which this takes place is recorded. This can be done at any desired longitudinal accuracy, and by default a bin size of 10cm is used.

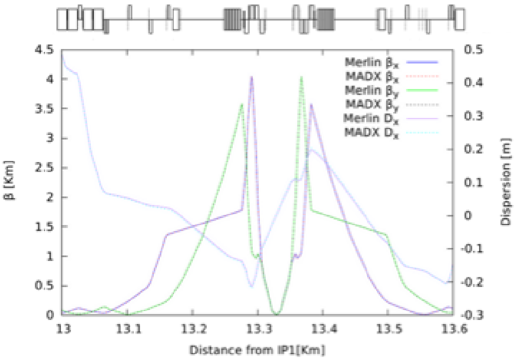

Figure 2: A comparison of optics between MAD-X and Merlin showing the β-functions and dispersion in IR5. Excellent agreement is found for both this region and the entire ring.

Figures 3 and 4 show the example loss map for 2012, 4 TeV running conditions for beam 1. A horizontal beam halo (a ring in x, x' normalized phase space, 0 in y, y') is used, which is then transformed into physical coordinate space. The initial impact parameter with the collimator can be adjusted, and in this case $1\mu m$ is used. Beam is injected at the closest (primary) collimators in IR7, and tracked for 200 turns.

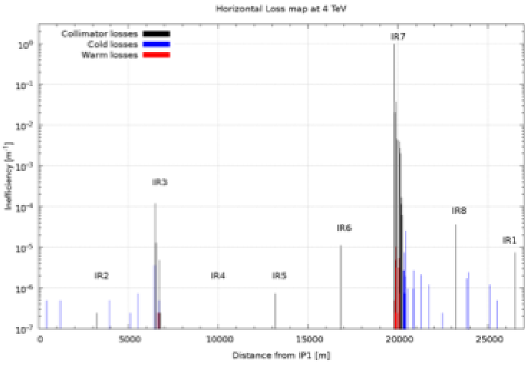

Figure 3: An example collimation loss map for 4 TeV 2012 running conditions. The initial simulated beam halo is a purely horizontal halo.

The loss map variable plotted is cleaning inefficiency around the ring, defined as:

$$\eta = \frac{n_{\rm abs}}{\Delta s \times n_{\rm total}}$$

where η is the inefficiency, Δs is the bin size, $n_{\rm abs}$ is the loss count in that bin, and $n_{\rm total}$ is the total number of losses.

As can be seen, the highest loss locations are in the collimation regions, specifically the IR7 betatron collimation

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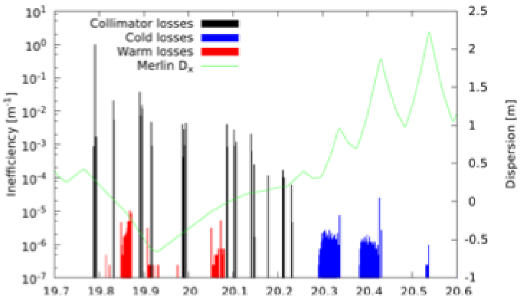

Figure 4: A zoom of the 4 TeV 2012 running conditions loss map focusing on the betatron collimation region in IR7 allowing the losses in the dispersion suppressor to be seen. The horizontal dispersion is also shown as the green line.

region. Figure 4 shows a zoom of this region. Here the effect of dispersion can be seen on the losses. Protons are lost in cold regions following the collimation region, which is minimised in the design.

Lattices have been generated in MAD-X which involve both field and alignment errors on dipole, quadrupole and sextupole magnets, to allow the effects of any lattice errors on losses to be estimated. These error configurations are then corrected using the available corrector circuits in the optical model. Collimators are aligned to the un-errored reference orbit, and then both the magnet errors are added, followed by corrections. Loss maps are generated in this configuration and it is found that as long as corrections are applied there is little quantitative difference to the loss maps generated. This includes both the locations of lost protons and the magnitude of losses.

UPDATED SCATTERING PHYSICS

In order to more accurately simulate the losses in the cold dispersion suppressor regions, more accurate simulation physics must be used over the current generation of codes. New models of proton-proton interactions have been developed, with the aim of expanding these to proton-nucleus interactions. Focus has been on two types of scattering, elastic and single diffractive scattering taking into account both theoretical considerations and experimental high energy physics data. Elastic interactions will give an angular kick to the outgoing proton, increasing the size of the beam halo, with the possibility of the proton exiting the dynamic aperture [6]. Single diffractive interactions can allow a proton to exit with an angular kick, and an energy loss [7]. This energy loss will move the outgoing proton away from the reference momentum, hence on entry to a dispersive region, they will undergo large orbit excursions, and collide with the accelerator beam pipe. Since the fits to these cross sections are mathematically highly complicated, it is faster computationally to pre-generate these distributions in an array, and interpolate them as required. The updated scattering physics will be described in a future publication.

OTHER ENHANCEMENTS

New materials, such as composites are now supported. Since Merlin is a C++ library, this is enabled via creating a new material class which inherits from the base material class, and specific access functions that are defined as virtual can be overridden. For example *GetdEdx()* will return the mean energy loss for the material mixture, whereas *GetElasticCrossSection()* will return the cross section for a randomly chosen nucleus within the material (weighted depending on the material composition). The same function calls are used for both a pure element, and material mixtures in order to model novel collimation materials.

Wakefield calculations are now fully parallel due to a parallel bunch moment calculation. Previously, particles were transferred between threads to a single node, where the wakefield calculation took place. Particles were then redistributed. This gave a speed increase over single threaded operation since standard tracking could take place in parallel. It is not the most efficient method, since a large quantity of bandwidth is required to transfer particles, and whilst this calculation takes place, CPU cores sit idle. Now the mean and standard deviation are calculated in parallel (for bunch slicing), and data is shared via a call to the *Allreduce* function.

CONCLUSION

In conclusion, the accelerator physics code Merlin has been extended in many areas to make detailed studies of the LHC collimation system and calculate halo loss maps. The loss maps have been produced for 2012 4 TeV running, and Merlin is ready to be used for studies of the LHC upgraded collimation system.

ACKNOWLEDGEMENTS

We wish to thank A. Donnachie for his assistance with the scattering physics and allowing usage of his models, and the CERN LHC collimation group for many interesting discussions.

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ISBN 978-3-95450-116-8

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

The simulation models are well advanced to the extent that they can be used to conceive and validate new collimation layouts that can address the potential issue found with the new ATS optics. In particular, it is envisaged to add to the layouts new collimators in the dispersion suppressers of IR7 as a possible cure for the beam losses observed around the ring.

The models will be extended further to follow the ATS optics and layout evolution (an optics version to reach 10 cm is being worked on). As a next step, error models will be added: collimation imperfections (errors on gaps, jaw angles, jaw flatness, etc.) and machine imperfections (orbit and optics errors, aperture misalignments, etc.) will be progressively added.

The simulation setup of beam halo cleaning is going to be used as well for simulations of fast failures at the HL-LHC (Valencia contribution). There is a strong synergy with previous work done within EuCARD-WP8 for the present LHC layout. The detailed comparison between Merlin and SixTrack will continue, with the aim to achieve a comparison for the ATS optics as well as for the standard one. The RHUL team is developing further the existing BDSIM code for HiLumi LHC, including seamless integration of particle interactions and loss (Geant4) with accelerator style tracking and tools to import LHC optics elements into the code. This work complements the MERLIN studies being performed in Manchester and Huddersfield.

It is also noted that the present models will have to evolve further to match the evolving requirements for HL-LHC. In addition, the simulation models do not yet included important hardware that is considered for HL-LHC like the crab-cavity system. Preliminary works (Yi-Peng Sun *et al.*, “Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider”, Phys.Rev.ST Accel. Beams 12:101002, 2009) indicated that this system has minor effects on the LHC collimation performance but more detailed studies should address the final LHC implementation.

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