IMPACT OF BEAM LOSSES IN THE LHC COLLIMATION REGIONS

E. Skordis*, R. Bruce, F. Cerutti, A. Ferrari, P. G. Ortega, P. D. Hermes,
A. Lechner, A. Mereghetti, S. Redaelli, V. Vlachoudis
CERN, Geneva, Switzerland

Abstract

The upgrade of the LHC energy and brightness, from the 2015 restart at close to design energy until the HL-LHC era with considerable hardware development and layout renewal, poses tight challenges in terms of machine protection. The collimation insertions and especially the one dedicated to betatron cleaning (IR7), where most of the beam halo is intercepted to spare from losses the cold sectors of the ring, will be subject to a significant increase of radiation load, whose leakage to the nearby dispersion suppressors must be kept sustainable. The past LHC run, while displaying a remarkable performance of the collimation system, offered the opportunity for a demanding benchmarking of the complex simulation chain describing the beam losses and the macroscopic effects of the induced particle showers, this way strengthening the confidence in the reliability of its predictions. This paper discusses the adopted calculation strategy and its evolution options, showing the accuracy achieved with respect to Beam Loss Monitor measurements in controlled loss scenarios. Expectations at design energy, including lifetime considerations concerning critical elements, will also be presented.

INTRODUCTION

The design stored energy of the Large Hadron Collider (LHC) [1] of about 362 MJ per beam is capable of causing catastrophic damage to the machine. However, even a very small fraction of that can induce both quenches of the superconducting (SC) magnets as well as material damage. Consequently, the inevitable proton losses have to be adequately intercepted before touching the machine aperture.

The collimation system installed in the LHC [2, 3] proved to be capable of sustaining up to 1MW of impacting protons for 1 s [4, 5] and protecting the machine from damage and quench. However the collimators themselves are not designed to absorb the entirety of the energy of the halo protons but rather divert it to an area with less sensitive equipment. The most exposed area is the insertion region (IR) 7 [6], where 3 different kinds of collimators, primaries (TCP), secondaries (TCSG) and active absorbers (TCLA), hierarchically extract the beam halo particles and absorb part of the primary, secondary and tertiary shower. The rest of the energy is deposited in the other LHC elements and eventually in the tunnel walls. A tiny but potentially harmful fraction leaves the IR7 straight section and reaches the dispersion suppressor (DS) where the SC magnets are installed.

To be able to make accurate predictions of the collimation performance in future running scenarios, and ensure that magnets are sufficiently protected, it is crucial to have a reliable and well-benchmarked simulation chain. Sixtrack [7, 8] and FLUKA [9-11] are the two simulation tools used for the tracking of the protons and the calculation of the secondary particle shower development and its effects, respectively. In order to validate the predictions, Beam Loss Monitor (BLM) signals are also simulated and compared against measurements for well-defined scenarios such as the collimation quench test in 2013 [2]. The goal of this paper is to present the updated results of the energy deposition calculations for the IR7 and the BLM benchmark with the most recent developments in the simulation procedure.

SIMULATION CHAIN

Tracking of Protons around the LHC Ring

The first necessary step of the simulation chain is to track the halo protons around the ring and create a map of proton hits in the collimators. The tracking is done using Sixtrack, a six-dimensional phase space multi-turn tracking code that uses thin-lens element-by-element tracking through the magnetic lattice.

Together with a detailed aperture model, Sixtrack has been using its own built-in Monte Carlo code to deal with interactions, other than nuclear inelastic events, between beam particles and collimator jaw material. In this way a distribution of inelastic interactions in the LHC collimators is produced as initial condition for FLUKA [12]. Nowadays, the development of the Sixtrack-FLUKA active coupling [13] takes advantage of the specialized and highly benchmarked interaction models of FLUKA as well as of the detailed geometrical models of the collimator devices to describe all kinds of interactions in a consistent way, improving the simulation accuracy.

Particle Shower Simulations

As a second step, the general purpose particle physics Monte Carlo code FLUKA is used in order to calculate the values of interest (e.g. thermal load in critical elements, power density in the SC coils, dose in the warm magnets, BLM signals etc.) from the particle showers initiated by protons interacting with the collimators. All the relevant elements in the IR7, including collimators, magnets, BLMs, device supports, cables, tunnel walls, etc. are modelled in detail and then accurately assembled by the LineBuilder [14] to create a geometry of several hundreds of meters (Fig. 1).

---

*eleftherios.skordis@cern.ch

IR7 WARM SECTION RESULTS

4TeV Collimation Quench Test

One of the intriguing challenges of this chain of simulations, exploring the far periphery of the phase space populated after many generations of particles originated by TeV protons, is to be able to benchmark its results. The feedback that one can get from the machine, as far as beam losses are concerned, is the signal of the BLMs. The 2013 collimation quench test provided an interesting testing scenario given the relatively well known initial beam conditions. The full list of adopted parameters can be found in Ref. [4].

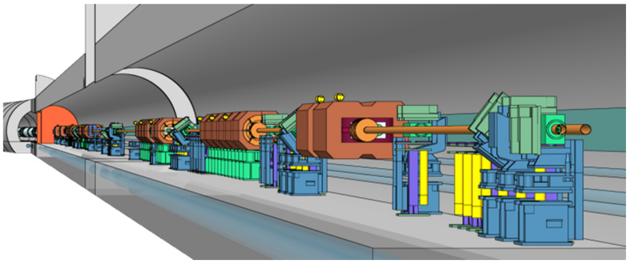

Figure 1: FLUKA model of the IR7 warm section.

The IR7 warm section's FLUKA geometry is illustrated in Fig. 1, starting from the Beam 2 primary collimators (TCP) on the right up to the beginning of the cold section (on the left, behind the shielding wall). In Fig. 2 the experimental BLM signals of the last 40 µs of the quench test are compared with the simulation results. Over that time, which is the shortest BLM integration time, the peak proton loss rate of 1.05 MW that was measured by the beam current transformers (BCT) is considered unchanged. Normalising the simulation results by that loss rate, an excellent agreement is observed both in terms of absolute signal comparison, spanning a few orders of magnitude, and pattern. The latter is well reproduced over more than 100 BLMs which are spread over 400 meters, from the Beam 2 TCPs (at about 200 m right of IP7) all the way to the BLMs of the Beam 1 TCPs at the opposite location. Figure 2 also compares the use, in the first step, of independent SixTrack runs and of the SixTrack-FLUKA coupling, which turn out to be consistent apart from a minor improvement by the latter in the underestimation observed towards the left end of the Long Straight Section. For this study such a consistency is not surprising, since the relevant interactions in the collimators (i.e. nuclear reactions including diffractive events) were anyway simulated by FLUKA, in the second step, for both cases.

Table 1 reports the calculated sharing of the beam energy deposition. Only 10% of it is deposited in the collimator jaws while 40% is distributed between the passive absorbers (TCAP), the warm dipoles (MBW) and quadrupoles (MQW), and the vacuum chamber of the concerned beam. Roughly one third is absorbed by the tunnel walls and less than 0.1% leaks to the cold section. The 0.5% deposited in air is relevant for ozone production that may contribute to the corrosion of metals.

Table 1: Sharing of beam energy deposition in IR7. Missing energy means energy converted to mass or carried away by neutrinos.

Absorbing material	**Beam energy deposition (%)**	**Absorbing material**	**Beam energy deposition (%)**
TCP+TCSG Jaws	10	Collimator support + tank	4
TCAP	13	Beam pipe support	1
MBW	8.5		
MQW	9.5	Tunnel wall	33
Beam 2 pipe	8.6	Other elements	4.4
Air	0.5		
Cables	0.9	**Total**	**93.5**
Cold section Elements	0.1	*Missing energy*	*6.5*

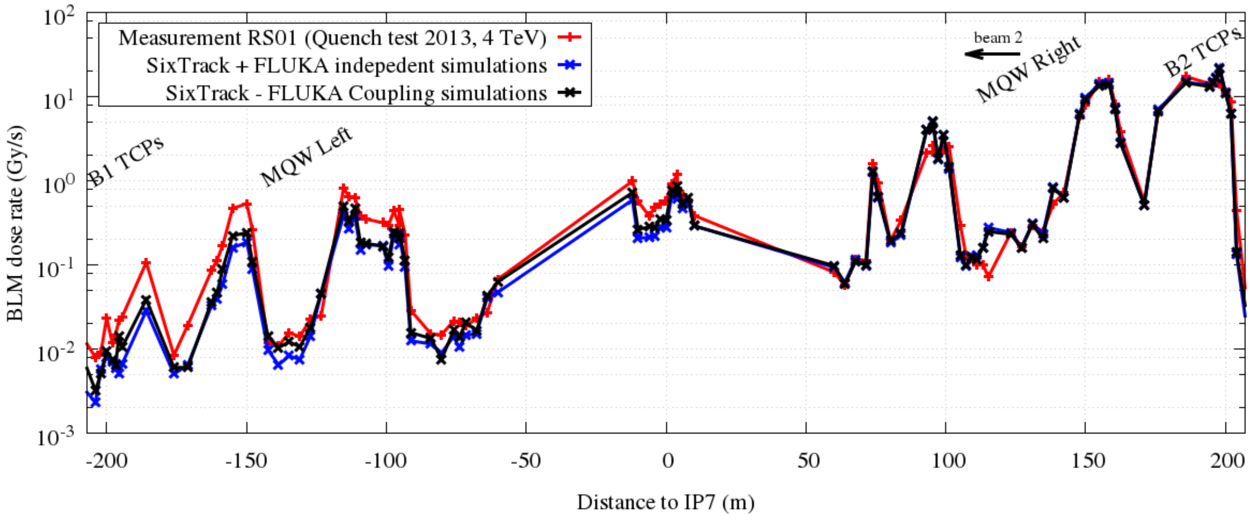

Figure 2: Absolute BLM signal comparison at the peak loss rate of the 2013 Collimation Quench Test, data (RS01 corresponding to 40 µs integration time) vs predictions for the two different simulation strategies discussed in the text.

7 TeV Nominal Cleaning

With the beam energy increasing to its design value, the sharing of the energy deposition is only marginally affected. However, when taking a deeper look at the dose accumulated in the MBW and MQW coils (whose insulation resin is a weak point), it was found that, without intervention, some of the magnets could have reached their lifetime before the next shutdown [15]. Simulations were carried out at 7 TeV for nominal collimator settings [1]. In Fig. 3 the dedicated tungsten shielding, which was installed on the front face of the IR7 MBWs return coils, is shown together with its simulated protection effect, prolonging by 3 times the period to reach the critical dose limit. An analogous measure was adopted for the most exposed MQW magnets.

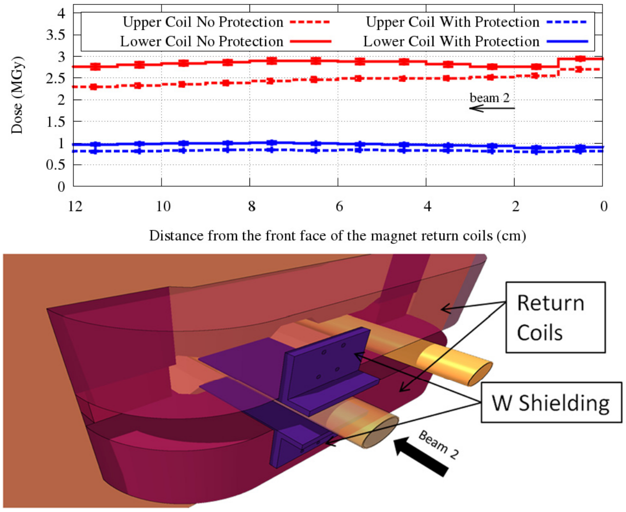

Figure 3: Accumulated peak dose profile (top) in the IR7 MBW front face return coils for 1.15×10^{16} lost protons (~30 fb^{-1}) with and without tungsten protection, and respective FLUKA geometry model (bottom).

IR7 COLD SECTION RESULTS

Even though the efficiency of the collimation system allows less than 1 per mille of the energy to leak in the cold section, the risk of quench is increasing as the beam energy and intensity of the LHC are raised. Therefore, a deep understanding of the energy deposition in the SC coils and its effects is required.

4 TeV Collimation Quench Test

For the aforementioned quench test, a peak power density of about 25 mW/cm^3 was predicted on the front face of the first bending dipole in cell 9 (see Fig. 4). If one scales this value by a factor 3 to tentatively compensate for the local underestimation of the BLM signals in the simulation, the fact that no quench occurred during the test is still compatible with the expected quench limit of 115-140 mW/cm^3 [16].

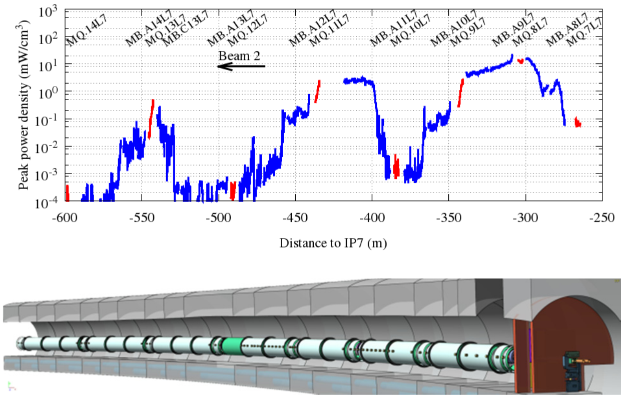

Figure 4: Peak power density profile in the IR7 DS SC coils at the peak loss rate of the 2013 4 TeV Collimation Quench Test (top). Respective FLUKA geometry of the cold section starting from the last TCLA up to cell 14 (from right to left, according to the concerned beam direction).

7 TeV Nominal Cleaning

The dedicated calculation at top energy for nominal collimator settings [1] yields the maximum power density at the same location. At nominal LHC beam intensity, it amounts to 2-3 mW/cm^3 for the 0.2h beam lifetime taken for design purposes as the shortest one to be sustained during 10s without quench occurrence (corresponding to a proton loss rate of 4.5 10^{11} s^{-1}). The application of the same correction factor brings this value still below the latest estimates of the respective quench limit [17, 18]. However, in an operational scenario with relaxed collimation settings [19], which may be needed due to impedance constraints, a further increase of about a factor 6 is predicted by simulations. This suggest to refer to the experience of the upcoming new LHC run at 6.5 TeV, prior to the possible decision of implementing mitigation measures, as the envisaged installation of a collimator between two shorter higher field dipoles [20].

CONCLUSION

Taking into consideration the complexity of the simulation chain, the very satisfactory BLM pattern reproduction presented in this study inspires confidence in the predictive power of the available simulation tools. They allow a quantitative assessment of the weak points of the LHC, as far as radiation impact is concerned, and the identification of suitable actions to ensure an unobstructed machine operation.

ACKNOWLEDGMENT

The authors of this paper would like to acknowledge the members of the LHC BLM, operation, magnet and collimation teams.

REFERENCES

[1] LHC design report v.1. CERN-2004-003.

[2] R.W. Assmann, “Collimators and Beam Absorbers for Cleaning and Machine Protection” Proceedings of the LHC Project Workshop - Chamonix XIV, Chamonix, France, 261 (2005).

[3] R.W. Assmann et al., “The Final Collimation System for the LHC” Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland, 986 (2006).

[4] B. Salvachua et al., “Collimation quench test with 4 TeV proton beams”, CERN-ACC-NOTE-2014-0036 (2014).

[5] B. Salvachua et al, “Handling 1 MW Losses with the LHC Collimation System”, IPAC’14, Dresden, Germany.

[6] B. Salvachua et al, “Estimate of Warm Magnets Lifetime in the Betatron and Momentum Cleaning Insertions of the LHC”, IPAC’13, Shanghai, China.

[7] F. Schmidt. CERN Report No. CERN/SL/94-56-AP, 1994.

[8] G. Robert-Demolaize et al. PAC05, page 4084.

[9] A. Ferrari, P. Sala, A. Fassò, and J. Ranft, CERN Report No. CERN-2005-10, 2005.

[10] G. Battistoni, S. Muraro, P. R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso, and J. Ranft, AIP Conf. Proc. 896, 31 (2007).

[11] V. Vlachoudis, Proceedings of the International Conference on Mathematics, Computational Methods and Reactor Physics (MC 2009), Saratoga Spring.

[12] R. Bruce, et al., “Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider”, Phys. Rev. ST Accel. Beams 17, 081004 (2014).

[13] A. Mereghetti et al, “Sixtrack-Fluka Active Coupling for the Upgrade of the SPS Scrapers”, IPAC’13, Shanghai, China.

[14] A. Mereghetti et al, “The FLUKA LineBuilder and Element Database: Tools for Building Complex Models of Accelerator Beam Lines”, IPAC’12, New Orleans, Louisiana, USA.

[15] P. Fessia, “LHC PICs: What are we talking about?”, Proceedings of the Review of LHC and Injector Upgrade Plans (RLIUP) Workshop, Archamps, France, 29-31 October 2013.

[16] B. Auchmann et al, “Testing Beam-Induced Quench Levels of LHC Superconducting Magnets in Run 1”, IPAC’14 special issue of PRST-AB (submitted).

[17] B. Auchmann et al, “Lessons Learnt from Quench Tests at the LHC – Implications for the Setting of BLM”, BIQ’14 proceeding, CERN September 15-16.

[18] P.P. Granieri et al, “Steady-State Heat Transfer in the LHC Superconducting Coils: Status of Experiments and Modelling”, BIQ’14 proceeding, CERN September 15-16.

[19] B. Salvachua et al, “Cleaning Performance with 11T Dipoles and Local Dispersion Suppressor Collimation at the LHC”, IPAC’14, Dresden, Germany.

[20] HL-LHC Preliminary Design Report, Chapter 5: Collimation system, 28 November 2014.