STUDY OF THE 2015 TOP ENERGY LHC COLLIMATION QUENCH TESTS THROUGH AN ADVANCED SIMULATION CHAIN

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Abstract

While the LHC has shown record-breaking performance during the 2016 run, our understanding of the behaviour of the machine must also reach new levels. The collimation system and especially the betatron cleaning insertion region (IR7), where most of the beam halo is intercepted to protect superconducting (SC) magnets from quenching, has so far met the expectations but could nonetheless pose a bottleneck for future operation at higher beam intensities for HL-LHC. A better understanding of the collimation leakage to SC magnets is required in order to quantify potential limitations in terms of cleaning efficiency, ultimately optimising the collider capabilities. Particle tracking simulations combined with shower simulations represent a powerful tool for quantifying the power deposition in magnets next to the cleaning insertion. In this study, we benchmark the simulation models against beam loss monitor measurements from magnet quench tests (QT) with 6.5 TeV proton and 6.37Z TeV Pb ion beams. In addition, we investigate the effect of possible imperfections on the collimation leakage and the power deposition in magnets.

INTRODUCTION

The Large Hadron Collider (LHC) [1] has been designed to store about 362 MJ per proton beam and 3.8 MJ per Pb ion beam of energies up to 7Z TeV. While in 2015 operation the stored ion energy has already exceeded the design by reaching 9.5 MJ [2], the High Luminosity (HL) LHC upgrade [3,4] envisages an even further increase, aiming at 700 MJ and ~12 MJ per beam for protons and ions, respectively. Even a small fraction of this energy is sufficient to induce both quenches of the superconducting (SC) magnets as well as material damage. In order to avoid such events, the unavoidable beam losses should be properly handled in a controlled way by a sophisticated intercepting mechanism.

The collimation system installed in the LHC [5, 6] has proven to be a reliable solution, being able to sustain up to 1MW of impacting protons for 1 s [7, 8] preventing damage and quenching of the SC magnets. The betatron cleaning system, installed in insertion region (IR) 7, consists of three kinds of specially designed collimators, primaries (TCP), secondaries (TCSG) and active absorbers (TCLA), are hierarchically installed to extract the beam halo particles by absorbing part of the shower and redirecting the rest to less sensitive equipment. While tiny, the fraction of energy leaving the IR7 straight section and reaching the dispersion suppressor (DS), where the SC magnets are installed, could prove pernicious.

A dependable well-benchmarked simulation chain is vital in order to allow for accurate predictions of the cleaning efficiency of the collimation system in future scenarios, and ensure the sufficient protection of the magnets. Two simulation codes, Sixtrack [9, 10] and FLUKA [11-13], have been established as the standard tools for the tracking of the particles in the accelerator lattice and for studying the effect of the secondary particle shower development, respectively. The most robust way of validating the computations is to compare against the signals of the Beam Loss Monitors (BLMs) for well-controlled loss cases such as the collimation quench tests (CQTs). This study presents the latest developments of the simulation tools as well as the benchmark of particle shower simulations against CQTs with 6.5 TeV protons [14] and 6.37Z TeV Pb ions [15] carried out in 2015.

SIMULATION CHAIN

Beam Particle Tracking in the LHC

As far as collimation losses are concerned, the simulation chain involves a first step which is the tracking of the initial halo particles through the machine optics over multiple turns and the identification of the impact positions in the respective aperture restriction. To this end, Sixtrack, a six-dimensional phase space multi-turn tracking code capable of handling thin-lens element-by-element tracking through the magnetic lattice, is utilised.

When particles arrive at the collimators, their information (phase space coordinates, type, momentum) is exchanged between Sixtrack and FLUKA with the latter handling the interaction processes. This is achieved through the Sixtrack-FLUKA active coupling [16, 17] mechanism for both protons and heavy ions [18, 19] and allows for the utilisation of the highly specialised particle interaction models in FLUKA, in addition to the detailed geometrical models of the collimator devices. Particles are no longer tracked either when they have a deep inelastic interaction that did not produce secondaries (e.g. protons or heavy ions) above a certain magnetic rigidity or when they are found, with the use of a detailed aperture model and an online aperture check, to have unacceptable spatial amplitudes.

Lastly, the details of the particles are dumped on their first impact with a collimator belonging to the region to be further studied in the second step. This is repeated each turn until the particle is lost. This method ensures that the

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effect of the multi-turn passage of particles through the collimator is taken into consideration.

Particle Shower Simulations

In order to evaluate critical quantities relevant to the interaction of the beam particles with the machine elements (e.g. power density in the SC coils, BLM signals, thermal loads and dose to critical elements etc.) the general purpose particle physics Monte Carlo code FLUKA is used. The setup of the particle shower simulations involved the development of dedicated source routines able to handle the importation of the primary and secondary (mainly for ions) particles impacting on collimators. Moreover, the modelling and assembly of the majority of the machine elements in the IR7, including magnets, collimators with their supports, BLMs, tunnel details etc., was pedantically performed for several hundreds of meters of geometry. The beam line was assembled by means of an external tool called LineBuilder [20], which embeds the different magnets and other elements in a model of the LHC tunnel. The resulting geometry setup spanned over several hundred meters of beam line (see Fig. 1).

One of the most challenging parts of this study is to establish a scenario in which simulation and experimental data can be one-to-one compared. The beam loss feedback from the machine, most readily accessible to users, is the BLMs signals. The 2015 CQTs (settings can be found in Ref [14, 15] for protons and Pb ions respectively) provide an excellent study case for simulation benchmarking where the origin of beam losses is well understood and are high enough to allow the study in areas that under normal operation the losses would be undetectable.

2015 PROTON QUENCH TEST

Warm Section

The majority of the energy of the protons lost in IR7 is deposited in the tunnel and machine elements of the Long Straight Section (LSS), especially around the locations where collimators are installed [20]. While the LSS elements are less sensitive, instantaneous power deposition to collimators could affect their performance while long-term effects (e.g. yearly dose to the insulation resin of the normal conducting coils, DPA to collimators etc.) are connected with the lifetime of some components. For this reason it is important to have a proper quantitative understanding of the losses and a well benchmarked warm section simulation tool.

In Fig. 1 (red curve) the cumulative dose recorded by BLMs for the duration of the CQT are shown against the simulated ones (blue curve) normalised according to the total number of protons lost during the CQT recorded by the Beam Current Transformers (BCT). The absolute signals, which vary by several orders of magnitude, and overall pattern are remarkably well reproduced, with a few ten percent, for more than 120 monitors distributed over 400 meters of beam line.

Cold Section

Because of the low fraction (less than one per mille) of the energy deposited in the cold section, most of the processing power is spent in the warm section. As a result, it would require years of CPU time to be able to acquire enough statistics to calculate BLM signals or the power deposited in the SC coils. For this reason, an extra step in the chain is necessary, where low-energy showers are not explicitly simulated, but the information of highly energetic particles, that arrive in the cold section, are stored. This distribution then serves as input for a dedicated third simulation step, where showers in the region where the cold magnets are operating, are simulated.

The simulated BLM signals are shown in Fig. 1 (black curve), continuing the calculated BLM pattern for the warm section. While the absolute values up to -300 m are

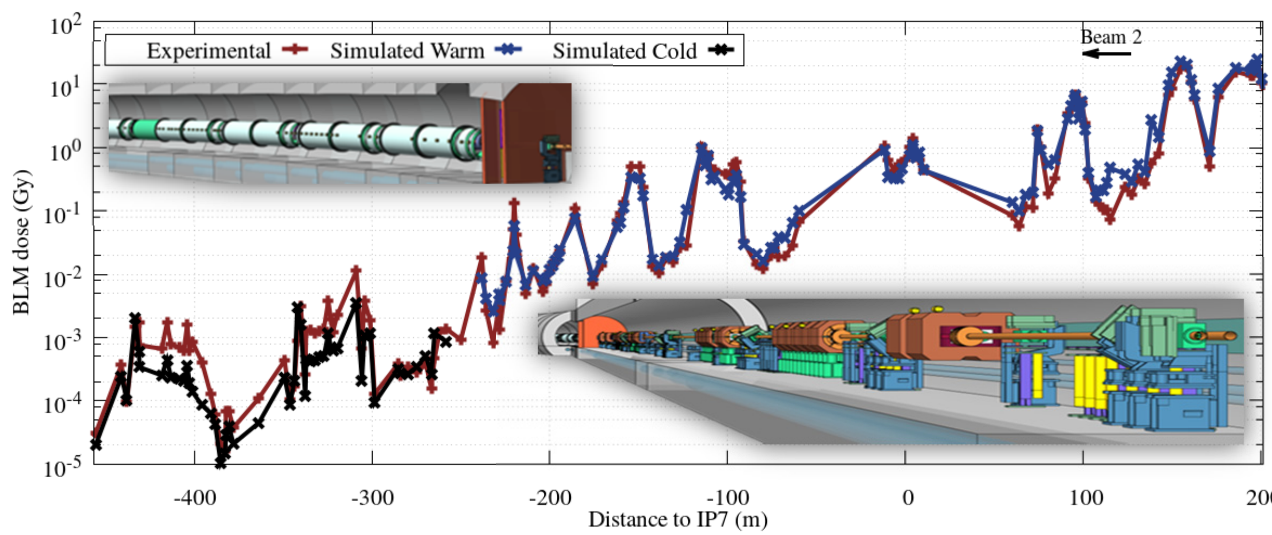

Figure 1: Simulated and measured BLM signals for the 2015 proton CQT at 6.5 TeV. Renderings of the IR7 and dispersion suppressor geometry models in FLUKA are shown in bottom right and top left corners, respectively. The beam direction is from the right to the left. The beam 2 primary collimators are located at around 200 m from the IP.

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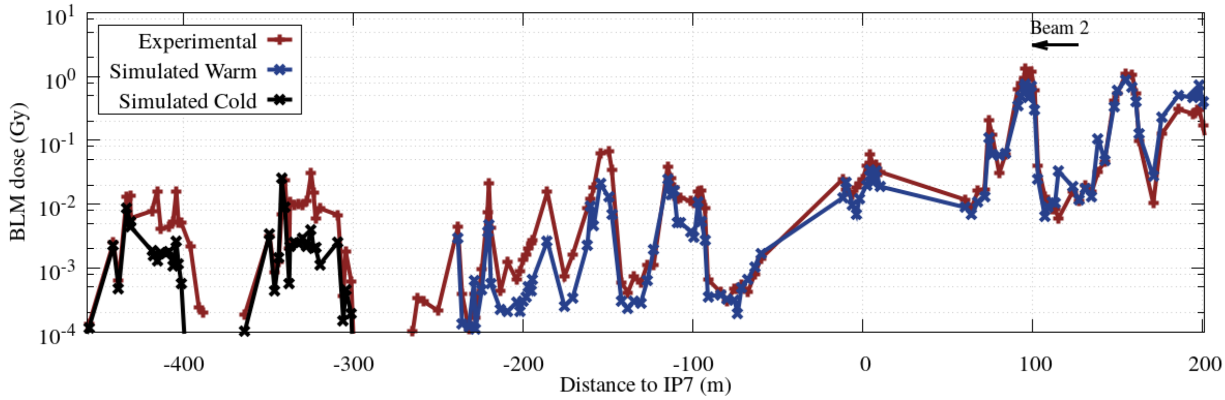

Figure 2: Cumulative BLM signals of the 2015 6.37 ZTeV Pb Ion CQT, Experimental vs Simulated

reproduced within a few percent, an overall underestimation of about a factor of 3 is observed in the SC magnets of cell 8-12 (from -450m to -300m). A similar value was observed in the past studies for 4 TeV protons [21, 22].

This discrepancy hints at an underestimation of the amount of protons leaking from the insertion region to the dispersion suppressor. A possible reason could be machine imperfections (i.e. misalignments of the collimator jaws), which were not taken into account in the simulations. Previous studies [22, 23] as well as new preliminary investigations of these imperfections show that they can increase the predicted losses by a factor of 2.

The longitudinal peak power density profile radially averaged of the innermost SC coils was also evaluated and is presented in Fig 3. The highest value, which is observed in the first SC dipole magnet in cell 9, amounts to 7 mW/cm^3 for the maximum loss rate of 585 kW achieved at the end of the CQT but no quench occurred. Considering the underestimation of measured BLM signals, the actual power density in the coils could have been as high as 20 mW/cm^3.

2015 ION QUENCH TEST

For the simulations of the Pb ion CQT the tools had to undergo extensive updates in order to support the importation of information of ions and secondary fragments between the FLUKA simulation steps. In the following, we present, for the first time, a benchmark against BLM signals of ion collimation losses in the LHC. The same strategy as for protons was adopted to simulate particle showers in the warm and cold sections. In addition, the high total energy carried by the heavy ions and the different interaction mechanisms of ions with matter present extra challenges that affect the achievable statistical convergence of the results.

In an analogous way to Fig. 1, Fig. 2 presents a comparison of the BLM signals for the ion CQT. The overall agreement between experiment and simulations, while less good than for the protons CQT, is satisfactory (better in the warm section than the cold) and provides a solid bases for further investigation of discrepancies. It is also clear that the uncertainties (and underestimation) in the cold section of the proton CQT are inherited in the ion case, further suggesting that the initial discrepancy is not due to the modelling of the interactions but rather physical imperfections of the machine, or local problems with the geometry, currently under study.

A quench of the second SC dipole in cell 9 (MB.B9L7) occurred during the ion CQT at a beam loss rate of only 15 kW due to the worse collimation cleaning efficiency for ions compared to protons. The peak power density achieved in the SC coils is estimated between 25-30 mW/cm^3 in the same magnet, when scaling the peak value found in Fig. 3 by a factor of 4-5 due to the BLM underestimation.

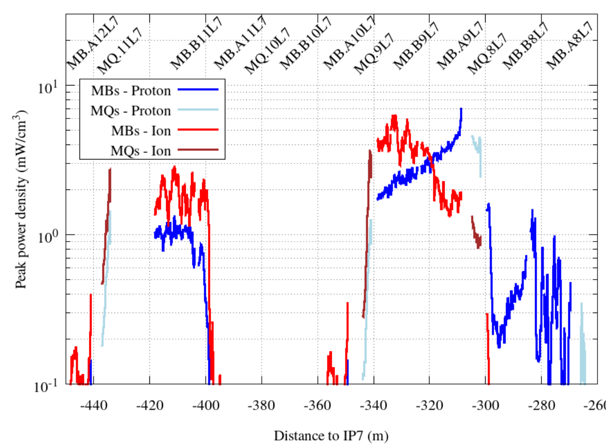

Figure 3: Simulated peak power density profile in the IR7 SC coils at the peak loss rate of the 2015 CQT for 6.5 TeV proton and 6.37 ZTeV Pb Ion

CONCLUSION

Given the complex and multi-step process, the benchmark against BLM measurements and the estimation of the peak power density in the SC coils presented in this study, provide invaluable feedback on the accuracy of the simulation tools. It offers a robust way of quantifying possible limitations and of the effects from imperfections of the machine and allows for further quantitative investigations of possible upgrades/improvements in view of the HL-LHC upgrade.

REFERENCES

[1] LHC design report v.1. CERN-2004-003
[2] J. M. Jowett *et al.*, "The 2015 Heavy-ion run of the LHC", in Proc. IPAC'16, Busan, Korea, May 2016, pp. 1493–1496.
[3] G. Apollinari *et al,*. "High Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report", CERN- 2015-005, 2015.
[4] The HiLumi LHC Collaboration, "HL-LHC Preliminary Design Report, Chapter 5: Collimation system", CERN-ACC-2014-105, 28 Novermber 2014.
[5] R.W. Assmann, "Collimators and Beam Absorbers for Cleaning and Machine Protection" in *Proc. of the LHC Project Workshop - Chamonix XIV*, Chamonix, France, 261, 2005.
[6] R.W. Assmann *et al.*, "The Final Collimation System for the LHC" in *Proc. of the European Particle Accelerator Conference 2006*, Edinburgh, Scotland, 986, 2006.
[7] B. Salvachua *et al.*, "Collimation quench test with 4 TeV proton beams", CERN-ACC-NOTE-2014-0036, 2014
[8] B. Salvachua *et al.*, "Handling 1 MW Losses with the LHC Collimation System", IPAC'14, Dresden, Germany, 2014, pp 174-177
[9] F. Schmidt, "SixTrackVersion 4.2.16 Single Particle Tracking Code Treating Transverse Motion with Synchrotron Oscillations in a Symplectic Manner", CERN, Geneva, Switzerland, Rep. CERN/SL/9456, 2012.
[10] G. Ripken and F. Schmidt, "A symplectic six-dimensional thin-lens formalism for tracking", CERN, Geneva, Switzerland, Rep. CERN/SL/95–12(AP), 1995.
[11] G. Battistoni *et al.*, "Overview of the FLUKA code", *Annals of Nuclear Energy*, vol. 82, pp. 10-18, Aug. 2015.
[12] A. Ferrary, P. R. Sala, A. Fassò, and J. Ranft "FLUKA: a multi-particle transport code", Rep. CERN-2005-10, INFN/TC 05/11, SLAC-R-773, Oct. 2005.
[13] V. Vlachoudis, "FLAIR: a powerful but user friendly graphical interface for FLUKA", in *Proc. International Conference on Mathematics, Computational Methods & Reactor Physics*, La Grange Park, IL: American Nuclear Society, p. 1–11, 2009.
[14] B. Salvachua *et al.*, "Collimation quench test with 6.5 TeV proton beams", CERN-ACCNOTE-2016-0015, 2016.
[15] P. D. Hermes *et al.*, "LHC Heavy-Ion Collimation Quench Test at 6.37Z TeV", CERN-ACC-Note-2016-0031 MD, 2016
[16] A. Mereghetti *et al.*, "Sixtrack-Fluka Active Coupling for the Upgrade of the SPS Scrapers", IPAC'13, Shanghai, China, pp 2657-2659
[17] A. Mereghetti *et al.*, "SixTrack for Cleaning Studies: 2017 Updates", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper THPAB046, this conference.
[18] P. D. Hermes *et al.*, "Simulation Of Heavy-Ion Beam Losses With The Sixtrack-Fluka Active Coupling", IPAC'16, Busan, Korea, pp 2490-2493
[19] P. D. Hermes, "Heavy-Ion Collimation at the Large Hadron Collider: Simulations and Measurements", PhD thesis, University of Munster, 2016
[20] 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, pp 2687-2689
[21] E. Skordis *et al.*, "Impact Of Beam Losses In The LHC Collimation Regions", IPAC'15, Richmond, USA, pp 2116-2119
[22] 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.
[23] C. Braco "Commissioning Scenarios and Tests for the LHC Collimation System", PhD thesis, EPFL, Lausanne, Switzerland, 2009.

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