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COMPARISON BETWEEN RUN 2 TID MEASUREMENTS AND FLUKA SIMULATIONS IN THE CERN LHC TUNNEL OF THE ATLAS INSERTION REGION

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Abstract

In this paper we present a systematic benchmark between the simulated and the measured data for the radiation monitors useful for Radiation to Electronics (R2E) studies at the Large Hadron Collider (LHC) at CERN. For this purpose, the radiation levels in the main LHC tunnel on the right side of the Interaction Point 1 (ATLAS detector) are simulated using the FLUKA Monte Carlo code and compared against Total Ionising Dose (TID) measurements performed with the Beam Loss Monitoring (BLM) system, and 180 m of Distributed Optical Fibre Radiation Sensor (DOFRS). Considering the complexity and the scale of the simulations as well as the variety of the LHC operational parameters, we find a generally good agreement between measured and simulated radiation levels, typically within a factor of 2 or better.

INTRODUCTION

The scope of this paper is to present a systematic benchmark between the simulated and the measured data for the radiation monitors useful for Radiation to Electronics (R2E) [1] studies at the Large Hadron Collider (LHC) at CERN [2]. For this purpose, the Total Ionizing Dose (TID) measurements performed with: (i) the Beam Loss Monitoring (BLM) system [3], and (ii) 180 m of Distributed Optical Fiber Sensor (OF) [4] are compared against those simulated using the FLUKA Monte Carlo code (version 4.1.1, CERN distributed) [5–7].

More specifically, the benchmark study has been performed for the Long Straight Section (LSS - up to Cell 7) and Dispersion Supressor (DS - up to Cell 11) at the high luminosity Interaction Point 1 (IP1 - ATLAS detector). Moreover, the simulation has been extended into the ARC (up to Cell 17) of IP1 to test several hypotheses. A similar approach can be used for other IPs.

RADIATION LEVELS IN LUMINOSITY-DRIVEN INTERACTION POINTS

The main source of radiation in the LHC tunnel in IP1 are inelastic proton-proton collisions in the center of the ATLAS experiment ($z = 0$ m) whose debris partially propagates in the tunnel leading to radiation showers. As anticipated, the discussion in this paper is focused on the TID, relevant for cumulated damage and lifetime degradation on machine equipment. The TID is defined as the energy deposited per unit mass by electromagnetic or hadronic showers via ionisation, and is measured by the BLM detectors and simulated with FLUKA.

Due to the origin of the showers, the BLM measurements are assumed to scale with luminosity, which is a measure of the number of inelastic collisions taking place in the IP. Still, there are several operational parameters of the LHC that can also affect the radiation levels near IP1. The ones examined in this study (but more play role, e.g. the crossing angle) are: (i) Target Collimator Long (TCL)settings: aperture size (and usage) of the collimators protecting beam elements, e.g. the cold magnets in half-cell 8 and 9, and (ii) Roman Pots (RP) [8] settings: devices used to measure the total cross section of two particle beams in a collider.

ANALYSIS STRATEGY

Experimentally, the measured data is stored continuously over the entire Run 2 period (from 2015 to 2018) of data taking. Several selection criteria are considered to identify time periods that allow for a direct comparison between measured and simulated data. The first selection criterion is for the radiation monitor data to correspond to the STABLE BEAMS beam mode, as this one corresponds to the delivery of beam to the experiments yielding collision debris. Subsequently, within this single fill, some parameters (such as the collimator settings or the roman pots usage) alternate between two predefined values (e.g., open/closed or in/out) while others are changed quasi-continuously, as the LHC performance has been improved.

The comparison of measured TID per unit integrated luminosity (fb^{-1}) for different periods of operation with the same configuration of LHC parameters exhibits a very stable profile [9]. This result allows to merge different fills corresponding to periods with identical operational conditions, yielding larger data sets (tens of fb^{-1}) per configuration. Moreover, the symmetry around IP1 allows to reduce the study to only one side of the tunnel.

The simulations employed in this study are able to (statically) replicate a given LHC configuration, meaning that quasi-continuous changes like the crossing angle anti-levelling [10] cannot be reproduced, hence the need to identify time periods with constant LHC settings as described above.

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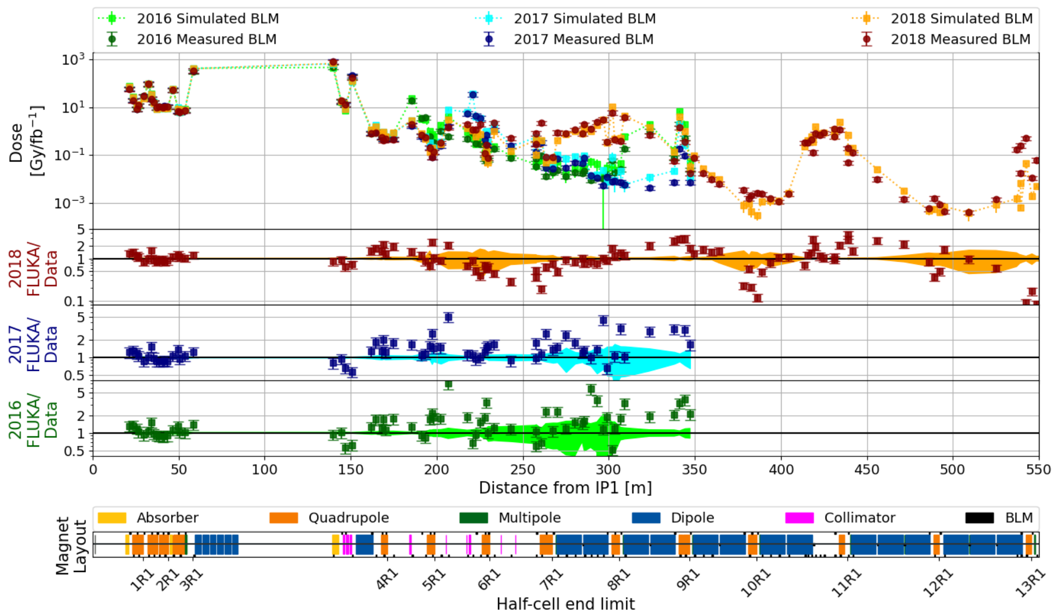

Figure 1: Top pannel: Comparison between BLM data and FLUKA predictions for the tunnel in the right side of IP1 (ATLAS detector) for 3 years of Run 2 operation with different configurations: 2018 with LSS+DS+ARC TCL456: 15s-35s-park RP: IN (red), 2017 with LSS+DS TCL456: 15s-35s-20s RP: IN (blue), and 2016 with LSS+DS TCL456: 15s-15s-open RP: OUT (green). Center pannels: The ratio of FLUKA simulated values to the BLM measurements. Lower pad: Machine beamline layout, with markers at the cell limits right of IP1.

TOTAL IONIZING DOSE RESULTS

Beam Loss Monitor (BLM) Benchmark

Within the large LHC FLUKA geometry, the BLMs [3] are explicitly modelled and the scored TID is deposited in their active volume (N_2 gas) and compared to the measured values. Previous studies of this kind for Run 2 [11, 12] have used a similar simulation procedure, but the experimental data consisted of at singular LHC fills (corresponding to at most 0.65 fb^{-1}). Similar studies have been performed for the BLM benchmark for Run 1 (2012) of the LHC, when it was operated at 4 TeV [13]. The FLUKA simulation usually employed in such studies originally covered only the LSS up to 269 m, but it has been extended up to 700 m (Cell 17), whereas only shown in Figure 1 up to 500 m (Cell 13). The experimental errorbars considered in this analysis, namely a 30% systematic error, are derived from a similar benchmark study in the more controlled CHARM facility [14].

There are several general considerations to be made about the results in Figure 1, regardless of the LHC configuration, out of which the most important is the global good agreement within a factor of 2 between data and FLUKA simulations. In general, the obvious outliers are considered to arise due to inaccurate geometry modelling. For the highly irradiated BLMs near the Inner Triplet (IT) up to 70 m, there is an excellent agreement (i.e. within the errorbars). The largest TID is recorded at the BLM next to the TAN collimator [15], as it absorbs the flux of forward high energy neutral particles (predominantly neutrons) that are produced at the collision points, generating plenty of secondary showers and thermal neutrons, leading to a high TID area.

The comparison between the different years of operation reflects the impact of the LHC machine parameters on the radiation levels in a local region downstream, if not globally. Three years of Run 2 with different configurations are shown in Figure 1. The results are virtually identical up to Cell 5, where the TCL6 open aperture leads to higher radiation levels between half-cell 7 and half-cell 8 (e.g. with impact on the Quench Protection System [16]). Regionally, there are some systematic trends that can be observed: the BLMs in the DS region are overestimated by a factor of 2 for the configurations with TCL6 operated with closed aperture (2016 and 2017), which could be coupled to the significantly lower radiation levels in half-cells 8 and 9, and also leading to poorer simulation statistics as well; the agreement improves when TCL6 is opened (2018).

There is a reasonable agreement for monitors further downstream, such as those in half-cell 11, but there are discrepancies still to be investigated in half-cell 13. The very large simulation statistical errors after 550 m (not shown), especially those larger than 20%, indicate that the simulation procedure is not able to achieve statistical convergence beyond half-cell 13.

Based on the very good scaling with luminosity, it is clear that the collision debris are the main source of radiation in the LSS. In the LHC ARC, the beam-residual gas interaction becomes the main source of radiation (for a detailed analysis of the measured BLM signals in the ARC, see [17]). This study answers as well a long-standing question about LHC operation: at which point are the collision debris no longer dominant for losses? From these results, the collision debris are no longer the main source of radiation only after 550 m

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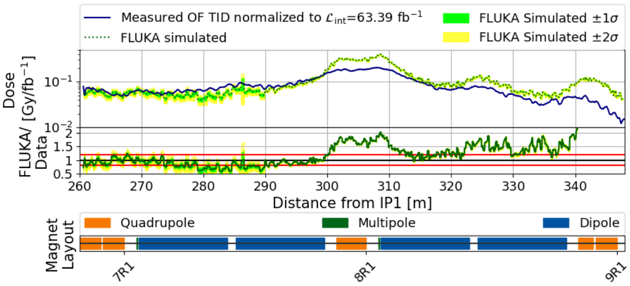

Figure 2: Top pannel: Comparison between OF measured data (blue) and FLUKA predictions (green) for the DS in the right side of IP1 (ATLAS detector) for 2018. Center pannel: The ratio of FLUKA simulated values to the measured data. Lower pad: Machine beamline layout.

(end of half-cell 13), in the ARC region. Nevertheless, small local radiation peaks could be distinguished even further in BLM data [17] in half-cells 15 and 17, which are considered to be also luminosity-driven.

Distributed Optical Fibre Radiation Sensor (DOFRS) Benchmark

When deployed in the machine tunnels, the OF sensors operate in a complex mixed-field radiation environment; for this reason, they have been qualified [18] in conditions as close as possible to the ones encountered during operation [4]. The previously mentioned CHARM study [14] quantified the expected agreement level to a 30% systematic uncertainty.

Compared to the online monitoring done in the Proton Synchrotron Booster (PSB) [19], the OF deployed in 2018 in the DS region right of IP1 provides only passive measurements (the details of this new sensing technique will be reported elsewhere) collected during the three technical stops. The TID per unit fb^{-1} in the three time periods is consistent with each other and only the cummulative (annual) value is used here for the comparison.

Following the updated OF implementation of CHARM [14], the FLUKA model at the LHC consisted of a cylinder made of SiO_2 with a size of 1 x 1 x 50 cm^3 (X x Y x Z). The longitudinal direction is chosen to match the measured data resolution of 1 m [19], whereas the transversal size is the main responsible of simulation artefacts, such as self-shielding or build-up effects, since the actual size of 125 μm is too small to computationally achieve sufficient statistics.

The results of Figure 2 exhibit a good agreement, with a (TID weighted) ratio average of 1.3±0.3 (standard deviation). There seems to be an overestimation particularly near the magnet interconnects which are not yet explicitly modelled in the simulation geometry, leading to less material budget absorbing radiation.

UNCERTAINTIES AND LIMITATIONS

Considering the complexity of the IP1 LHC layout, the observed level of agreement between measured data and simulations can be regarded as highly satisfactory. The main sources of uncertainty is considered to be the geometry mismodelling, precision misalignments, etc.

It is generally considered that for the complex and large accelerator, the elements are modelled correctly within a 10 cm accuracy and only the radiation monitors may have up to a 1 m shift[13]. Locally, some radiation monitors are placed in the close proximity of strong gradients of radiation, implying that even a slightly shifted position could significantly change the overall agreement (e.g. 1 m gives almost a factor of 10 at 205 m[1] from IP1).

CONCLUSIONS

This study aimed to test the understanding of the loss pattern and the mechanism generating the losses, as well as to validate the use of simulation tools like FLUKA and their predicting power in the difficult scenario of the LHC accelerator, which consists of a complex radiation field and for a radiation source propagating into a geometry that spans hundreds of meters. The general level of agreement that results from this study is a factor of 2 or better, with local outliers.

These benchmarking results are of paramount importance to test the consistency between the two independent tools used for assessing the radiation levels in the LHC accelerator environment: (i) radiation monitors, and (ii) FLUKA simulations. Used for the design of future accelerators and for the lifetime usage of several beam elements, the FLUKA Monte Carlo code can provide a much more detailed description of the radiation field compared to what the measurements can offer, e.g. the total TID received by sensitive equipment or cables, and one must make sure that this equipment will withstand the radiation levels they will actually receive during operation. The FLUKA simulations benchmarked in this way allows to trust to similar levels of precision also all the other predictions that they provide (such as particle energy spectra, R2E-relevant quantities in positions where no radiation monitors are present and other quantities.)

The estimated annual TID levels below the beamline (where electronics racks are often located) varies due to the accelerator operation (e.g. collimator apertures) is in the range of [0.25, 16] kGy up to 150 m and of [20, 250] Gy up to 350 m, assuming a total of 80 fb^{-1} delivered LHC luminosity per year. Such levels are the highest present in the LHC tunnels and placing equipment here requires dedicated analysis to asses the feasibility of the installation, often involving the development and qualification of radiation tolerant systems.

Possible improvements consists in correcting all possible discrepancies by identifying the source of inconsistencies, either from the measurement side (radiation monitor not functioning properly, error in the data analysis chain, etc.) or on the simulation side (position inaccuracy, equipment mismodeling, etc.).

[1] e.g. for BLMEI.06R1.B1E10_XRP.A6R1

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