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BENCHMARKING OF THE RADIATION ENVIRONMENT SIMULATIONS FOR CMS EXPERIMENT AT LHC

I. L. Azhgirey*, I. A. Kurochkin, A. D. Riabchikova
NRC "Kurchatov Institute" - IHEP, Protvino, Russia
D. Bozzato, A. E. Dabrowski, P. Kicsiny, J. Wanczyk, CERN, Geneva, Switzerland
S. Mallows, KIT, Karlsruhe, Germany

Abstract

Radiation Simulations group of the Beam Radiation Instrumentation and Luminosity Project of the Compact Muon Solenoid (CMS) experiment provide for CMS radiation environment and radiation effects simulation and benchmarking of these calculations by comparison with CMS data and Large Hadron Collider (LHC) radiation monitors. We present some results of such benchmarking and the reliability analysis of the simulation procedures for radiation environment calculations at LHC.

INTRODUCTION

The optimization of the radiation environment and estimation of the radiation stability of materials and electronic equipment in the CMS experiment [1] are based primarily on the Monte Carlo simulation predictions [2]. The FLUKA simulation framework [3, 4] is a main software for precision radiation transport through detector and experimental hall.

The CMS FLUKA model is a key element of the simulations. It includes not only CMS subdetectors, but also elements of the LHC (beamline, vacuum elements, interface of experiment with machine) and experimental cavern with the CMS infrastructure. The current version of the CMS FLUKA model contains more than 15000 lines of code.

CMS needs to monitor the radiation levels in the experiment to benchmark the Monte Carlo simulations.

Radiation measurements are not trivial in the mixed and complicated CMS radiation environment. The one method approach can provide only a limited set of data about radiation environment. A set of different methods and cross-check of measurements give us a more detailed understanding of the radiation environment.

SYSTEMATIC UNCERTAINTY

For certain locations in the CMS detector where the CPU time required is exceptionally high (e.g., particle rates in outer muon chambers or residual dose rates after long cooling times), results are released with up to 10-20% statistical uncertainty. However, for most quantities at locations in the central detectors, the statistical uncertainty can be assumed negligible.

Systematic uncertainties are difficult to quantify and depend heavily on which quantity is estimated (e.g., dose, neutron fluence, spectrum, etc.), as well as the region of interest. There can be several contributions to the systematic uncertainty in the simulation:

- Accuracy of geometrical model.
- Reliability of primary event generators.
- Imperfections of baseline software.
- Spatial or energy resolution of simulations.

Imperfection of event generators and simulation physical models presently are out of our consideration. In our case accuracy of the material budget, or CMS model geometry, looks like the main uncertainty contribution to the result. It contains simplified geometries and material compositions for a simple and accurate representation of the CMS detector and the underground cavern.

Radiation environment in the CMS cavern is initiated by the sequence of the sources of scattered radiation, starting from the primary interaction at the Interaction Point (IP), and then reproducing on every aperture limitation that intercepts secondary particles, created at IP. There are: vacuum chamber and vacuum equipment, endcap and forward calorimeters, and collimators, protecting the superconducting magnets around the CMS experimental region. Intensity of these sources is defined by fraction of energy of primary interaction, scattered on these sources. Particles, escaping into the CMS cavern, have many generations of ancestors during development of the nuclear-electromagnetic cascade, starting in IP. Thereby radiation environment on the periphery of the cavern often is determined by near-beam elements configuration, located far (more than 20 m) from the point of interest.

It is recommended for CMS subsystems to assume simulation predictions are reasonable within a factor of 1.5 for central tracker and 2 in the central detectors, considering the sum of all possible uncertainties. A factor 3 is recommended for the outer muon chambers and electronics in the cavern. These "safety factors" came not only from simulations uncertainty, but they also include usual uncertainty in the predictions of the radiation tolerance of the detectors.

BENCHMARKING WITH RAMSES

To verify the accuracy of the CMS FLUKA model, benchmark simulations against the real measurement data are regularly performed, often by using data taken from different radiation monitors located in the CMS cavern.

RAMSES (The Radiation Monitoring System for the Environment and Safety) is a system consisting of hundreds of monitors installed all around CERN. Its main task is to monitor the ambient dose equivalent rates in experimental areas [5]. These monitors are air-filled ionization chambers.

*igor.azhgirey@cern.ch

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Ten RAMSES monitors are in the CMS cavern. Data from 9 of them (see Fig. 1) were used for benchmarking of the FLUKA simulation [6]. Tenth monitor had a very low level of signal.

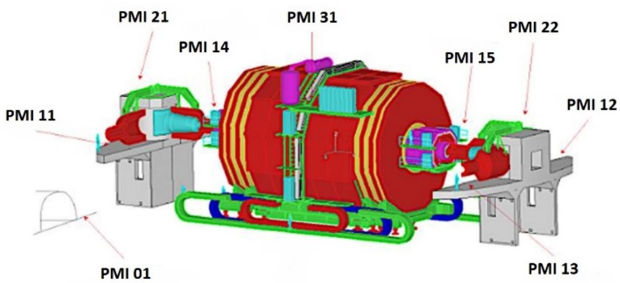

Figure 1: RAMSES monitors locations in CMS.

There are two pairs of monitors which are located symmetrically at the opposite Z-ends of the cavern (Z axis is directed along the beam line). There are PMI11 vs PMI13, and PMI14 vs PMI15. It implies that simulation results inside such pairs are completely the same for symmetrical model. PMI14 and 15 are located on the cavern balcony over Forward Hadron Calorimeter. In these areas they can see high energy neutrons escaping from the CMS Forward Shielding region. Monitors PMI21 and 22 are located at the very ends of the cavern on the top floor (X5) and have lower exposition. PMI31 has smallest value, it is due to location in the calm region shadowed by the Muon system iron yokes from the main sources of radiation. CMS FLUKA model v.3.32.0.0 was used for simulations.

The particle spectra scored at the monitor locations were folded with the PMI response function (RF) [7]. In this study, the number of events in 2017, corresponding to 49.79 fb^{-1} of collected luminosity [8], is used to compare with integrated dose measured by the RAMSES monitors in the cavern for that year. Charge collected in chambers was converted to the dose. Conversion factor is based on a calibration with Cs-137 gamma source; hence it is not meant to be applied for the prompt radiation. The systematic uncertainty for dose values is problematic to define. Neutrons give the main contribution to the monitor response for all locations. Results of the comparison are presented in Table 1.

Table 1: Charge Generated in RAMSES Monitors in 2017 and Ratio of the Simulated Values to Measured

Monitor	Charge [μC]	Ratio, sim/meas
PMI01	58.90	1.40
PMI11	58.01	1.22
PMI12	54.65	1.23
PMI13	50.59	1.39
PMI14	281.27	1.10
PMI15	202.79	1.53
PMI21	47.35	1.58
PMI22	37.15	1.85
PMI31	3.54	3.34

In general, the results validate the reliability of the CMS FLUKA model estimations. The ratio deviates the most for PMI31 monitor. It indicates the material budget description imperfection. CMS FLUKA model does not contain accurate specification of the electronic equipment around the Muon Barrel subdetector, apparently it is important for this detector location.

BENCHMARKING WITH BLM

The Beam Loss Monitoring (BLM) system [9] is a safety system at LHC that is implemented to protect the infrastructure close to the beam line from excessive radiation damage caused by the lost beam particles. It consists of about several thousands of the air-filled gas ionization chambers that are mounted outside of the beam pipe at regular distances continuously measuring the amount of lost beam particles and their approximate location along the LHC.

We present results of a simulation benchmark study conducted with measurements of two ionization chambers used as beam loss monitors in the CMS forward zone inside the CMS Collar Shielding in 2018 [10]. Detectors are represented by air cylinders in CMS FLUKA model. Real monitors are shown on Fig. 2, and part of the CMS FLUKA model with BLM inserted – on Fig. 3.

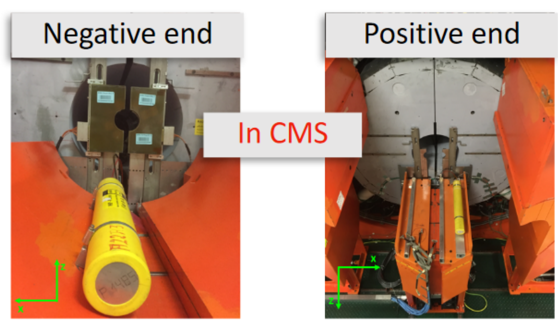

Figure 2: BLMs in CMS.

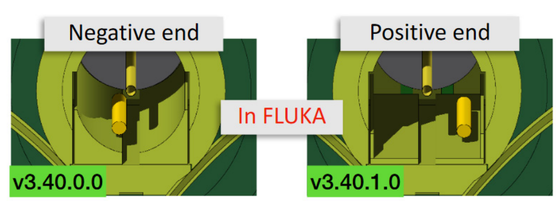

Figure 3: BLMs in CMS FLUKA model.

Simulation over measurement charge ratios of the BLM detectors were performed per proton fills in 2018. Particle fluences inside the BLM volumes are simulated and converted into charge quantities using pre-simulated detector RF [11]. Simulations were done using CMS FLUKA Run 2 models v3.40.0.0 (BLM -Z) and v3.40.1.0 (BLM +Z) and are normalized by the total delivered luminosity of each fill, and the inelastic cross section of σ_{inel} =79.5 mb [12]. On the Fig. 4 blue dots represent simulated over measured charge ratios for the BLM on the negative end, whereas red dots show them for the BLM on the positive end. Statistical uncertainties are up to 1%. Offset between the two bands

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of ratios is ascribed to various systematic uncertainties including the assumed response functions of the detectors, the modelling of the surrounding geometry and the high gradient of the radiation field. Detailed analysis of the result is given in [10].

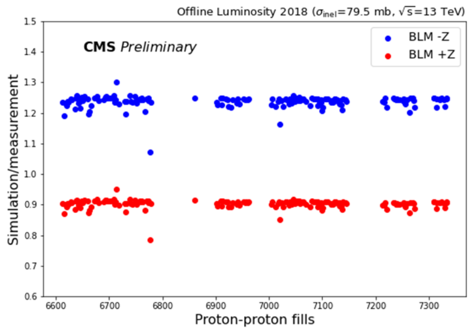

Figure 4: The ratio of the simulated charge in BLM to the measured one for proton-proton fills in 2018.

Agreement of the BLM data with FLUKA simulation results is rather good considering the complexity of radiation sources in this region.

MONITORS FOR THE CMS PHASE-2

CMS collaboration plans to develop radiation monitoring instrumentation for the Phase-2 operation [13].

The system of 32 gas filled proportional chamber based neutron monitors is designed to provide continuous monitoring information about neutron fluence at various points of the CMS experimental cavern during Phase-2 operation [14]. Monitors are working in pairs – main and complementary ones. RF of the complementary monitor is close to the RF of the main one below 100 keV and much lower at high energies. Thus, the difference between the two properly normalized responses of the main and complementary monitors is almost free of contribution from the low energy neutrons. It allows to measure fast neutron fluence additionally to the individual data from each monitor.

For radiation monitoring BRIL CMS prefers to use commercially available monitors certified for installation in the accelerator environment with mixed radiation field. Two monitor types from those are proposed in the Phase-2 upgrade of the CMS. There are RAMSES monitors and the LHC Radiation Monitor (RadMon).

RadMon was developed at CERN [15, 16] to monitor the Total Ionising Dose (TID), the Single Event Effect (SEE) and the Displacement Damage (DD). Each RadMon has 9 radiation sensors installed on the board: 2 radiation sensitive p-channel MOS-FETs (RadFETs) with different oxide thickness for the TID measurements, 3 photodiodes in series for the measurements of 1 MeV equivalent neutron fluence and a Toshiba SRAM memory to measure the cumulative fluence of hadrons with energy higher than 20 MeV and thermal neutrons through different voltage settings [17]. For the Phase-2 operation CMS plans to install ten additional RadMons in regions which were not covered by existing LHC operated monitors.

CONCLUSIONS

We present results of benchmarking of the Monte Carlo simulations of the radiation field in the CMS experimental cavern with data from LHC radiation monitors located around CMS detector. The results validate the reliability of the FLUKA simulations of the radiation environment based on the CMS FLUKA model, both for the high intensity and moderate intensity radiation regions of the CMS cavern.

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