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PHYSICAL DESIGN OF THE RADIATION SHIELDING FOR THE CMS EXPERIMENT AT LHC

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Abstract

The design of the radiation shielding for the CMS experiment at the LHC requires a simulation of the radiation environment using a model of the CMS experimental setup, accelerator components and the experimental hall infrastructure. The radiation simulations are used to optimize the design of the CMS detectors components and the interface of the CMS detector with LHC accelerator. The Beam Radiation Instrumentation and Luminosity Project of CMS is responsible for giving important input into the optimization and upgrade of radiation shielding used in CMS and the radiation environment simulations software infrastructure.

This contribution describes the organization of this work, the simulation software environment used for this part of CMS experiment activity and recent radiation simulation results used to optimize the forward shielding for CMS.

INTRODUCTION

The LHC will be upgraded to enable baseline operation for the HL-LHC period (Phase-2) at an instantaneous luminosities of 5×10^{34} cm^{-2} s^{-1} [1]. The accelerator will operate at energy of 7 TeV per beam and a distance between bunches of 25 ns. This will allow ATLAS and CMS to collect integrated luminosity order 300 fb^{-1} per year and up to 3000 fb^{-1} during the HL-LHC projected lifetime of ten years, assuming machine efficiency is around 50%. In the case of the ultimate instantaneous luminosity, the delivered luminosity can be achieved up to 4000 fb^{-1}, so experimental hardware for Phase-2 operation must be designed to operate at least up to this value. The extreme radiation levels expected in Phase-2 require technologies with the higher radiation robustness. The consideration of the radiation effects is a key to the overall success of the CMS experiment.

RADIATION EFFECTS

The radiation effects (RE) result in the aging of the detector elements and the losses of efficiency of physical measurements at CMS. RE can be classified as cumulative and instantaneous. Cumulative effects may include bulk (lattice) damage of silicon detectors; damage to electronics resulting in degraded performance and signal-to-noise ratio (S/N); light transmission loss in scintillators and fibers, resulting in calibration issues; structural damage; buildup of activation, which leads to access restrictions for maintenance. Instantaneous effects include higher occupancy rates, which can cause saturation in detectors, create readout or trigger problems, and make pattern recognition difficult. The instantaneous radiation effects generated can be caused directly by charged particles or photons converted to electrons, or by neutron reactions where the resulting photon is subsequently converted. Electronic devices that are sensitive to cumulative effects, i.e., those that scale with absorbed dose or displacement damage, will exhibit failure when the dose or fluence reaches tolerance limits. Thus, it is possible to predict the time at which the failure of the characterized unit of equipment will occur. However, for electronic devices that are sensitive to single events, the failure can occur at any moment in time, and the probability is defined in terms of a cross section.

Instantaneous effects occurring in electronics caused by a single energetic particle are referred to as single event effects (SEEs). Single event upsets (SEUs) are soft errors, and are generally non-destructive, as they normally appear as transient pulses in logic or support circuitry, or as bit flips in memory cells or registers. Several types of hard errors, potentially destructive, can appear, including single event latch-up (SEL) that can cause serious effects such as high operating current, complete burnout of the power MOSFET, frozen bits, etc. Possible nuclear interactions that cause SEUs are hadron-silicon scattering at high energy (>20 MeV), low-energy neutron scattering on silicon, and thermal neutron capture on boron.

The BRIL project is responsible for research on the radiation environment at CMS.

CMS BRIL PROJECT

The Beam Radiation Instrumentation and Luminosity project in the CMS experiment [2] at CERN is responsible for various detector systems that measure when a beam is present at the LHC [3], the beam conditions at the CMS detector, the radiation products in the CMS experimental cavern, and the luminosity. The BRIL Project is also responsible for maintaining and improving the radiation simulation infrastructure. This software infrastructure is used by BRIL to estimate the radiation levels in the CMS detector and experimental cavern, and is also provided to CERN's Radiation Protection group (HSE/RP) for specialized simulations related to all aspects of the induced radioactivity.

The possible radiation effects are numerous and complicated in the CMS experiment. The optimization of the

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radiation environment and the estimation of the radiation stability of materials and electronic equipment in the CMS experiment are based primarily on the predictions of the Monte Carlo simulation. The radiation simulation plays a central role in the design of Phase-2 of the CMS detector and in planning for its longevity and maintenance. The radiation damage is already an important factor for Phase-1 LHC. The CMS needs to monitor the radiation levels in the experiment to control lifetime of electronics and sensitive elements of the detector and to benchmark the Monte Carlo simulations. Details of the radiation fields is crucial to verify the simulation model.

SIMULATION SOFTWARE

The simulations of expected CMS radiation levels were performed for Phase-1 and Phase-2 planning. Simulations are an iterative process; they are not only used to provide reference radiation field maps for the latest detector design but are used as an integral part of the design process, providing feedback for configurations, shielding arrangements, and component designs.

Simulations are performed by the BRIL Radiation Simulation group (RadSim) with specialized software based on a complex dynamic model of the CMS experiment, its infrastructure and interface with the LHC. RadSim uses two MC simulation packages, FLUKA [4, 5] and MARS [6], to transport particles through the CMS to calculate radiation levels in the detectors and the CMS cavern.

The FLUKA output is usually averaged over all simulated primary events and normalized per primary event. Cross sections for low-energy neutron transport are handled with a group-wise approach, in which energy range is divided into several discrete groups, and the effects of elastic and inelastic reactions on neutrons are modeled using the transition probabilities between groups. MARS is an inclusive code with a simplified description of low-energy neutron transport. Currently, it is mainly FLUKA, which is used for precision radiation transport through the detector and experimental hall. The MARS code is used for internal checks and fast turnarounds. GEANT4 [7] is used by other CMS subsystems for specific background studies.

A Python-based web plotting tool allows CMS members to access preliminary simulated data and generate their own 2D flux maps according to a specified region, particle type, and simulation parameters [8].

PYTHIA and DPMJET [9, 10] are used to simulate primary pp, pA or AA events in the region of the beams crossing.

As a rule it is necessary to predict a wide range of quantities related to the various radiation effects. Radiation maps of integrated fluxes for various types and groups of particles, such as charged hadrons, as well as for energy deposition quantities, such as absorbed dose and non-ionizing energy loss (NIEL), are required for the entire CMS cavern. Energy spectra, angular distributions, and timing data are also required for specific studies.

It is also important to estimate the machine-induced background radiation (MIB) relative to the collision radiation at the location of various radiation detectors, which are operated by the BRIL project and used to monitor the MIB and luminosity during LHC operation [11].

MIB simulation uses another set of input data [8]. For inelastic local beam-gas interactions in the straight section around the CMS, the radiation source can be calculated with FLUKA of MARS using preliminary simulated residual gas profiles. FLUKA needs a two-steps simulation, MARS can do it in one step due to simplified detector description and fast inclusive simulation algorithm. For elastic distant gas interactions along the cold LHC ring, the source at TCT (Target Collimator Tertiary at 150 m to CMS) was calculated using the STRUCT code, and then the particle transport was simulated using MARS [8]. For Beam Halo interactions, the source at the TCT was determined using the SixTrack code, and particle transport to the CMS was simulated using FLUKA [12].

The SESAME tool [13] was developed, which enables the separation of prompt and decay simulation steps and the transformation of the geometry model in-between, which includes the ability to rotate, move, remove and add components. This is useful for estimates residual radiation with an open CMS configuration.

CMS FLUKA Model

The CMS FLUKA model is a key element of the simulations. It includes not only CMS sub-detectors, but LHC elements (vacuum chambers, vacuum equipment, interface of experiment with machine) and an experimental cavern with CMS infrastructure. The FLUKA geometry description is constantly updated to include current changes to detector configurations such as new shielding and beam pipe elements, as well as general modeling improvements, including more detailed material composition, more detailed representation of the structure of sensitive elements of detectors, and the implementation of previously omitted elements. Future configurations should also be maintained at key stages as upgrade configurations evolve. Ideally, geometric models of past configurations should be retained for benchmarking purposes.

Collecting, processing, and implementing geometry updates is a time-consuming task. Obtaining information related to the material budget necessitates a substantial amount of research and communication. Maintaining up-to-date representations in FLUKA of past, current, and future CMS configurations requires complex file merging.

The current version of the CMS FLUKA model contains over 15,000 lines of code. For CMS FLUKA models [14], a four-level version numbering scheme is used, where a new tag is given for each change in the input files that may affect the result. This includes simulation parameters, user-files, magnetic field maps and geometry updates.

Since the model has been developed over more than 20 years of CMS experimentation and many people have been involved in the model development process, it is important to maintain the general style of describing geometry. Special software was developed to clean up the CMS model from duplicates and unused elements, which should increase reliability of simulations.

A large number of baseline, auxiliary, obsolete and test versions of the CMS FLUKA model led to the need to create a special database of CMS models.

SHIELDING DESIGN

In almost all cases, there are two important components to each issue: first, correct simulation of the sources of various radiation fields, typically as a result of geometric or material changes; secondly, detailed modelling of potentially susceptible components of the detector, which often requires fine knowledge of their isotopic structure of materials and surroundings. The RadSim's activities are between detector and engineering designers, on the one hand, and detection and analysis activities, on the other. It is also often the case that a proposed detector change could have a detrimental effect on a completely different system.

It is impossible to simplify the calculation of the shielding efficiency either in geometry or in physics. For example, radiation effects in the external barrel muon chamber are determined by low-energy electrons, whose ancestors are generated in the CMS/LHC interface regions and are coming into barrel region after multiple reflections from the experimental cavern walls. The description of this process includes modelling of the initial interaction of hadrons in the TeV energy range, nuclear-electromagnetic cascades, multiple production of neutrons, thermalization and capture, production of soft photons and conversion into electrons.

Calculation of the shielding effect needs exact simulation of the radiation effect change in the region of interest after development of the geometry model of the whole object. The complex structure of secondary and tertiary sources of scattered radiation in the CMS region does not allow using simple approaches of the shielding efficiency estimation. Thus, reinforcement of the thin rotating shielding unit in the forward region of the experiment gives more than one order of magnitude improvement in neutron fluence, but in the regions of interest – near electronic racks – the effect is moderated, near factor 2-3 only.

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

Systematic uncertainties are difficult to quantify and are highly dependent on how much is being estimated (e.g., dose, neutron fluence, hadron spectrum, etc.), and also from the region of interest. There can be several contributions to the systematic uncertainty in the simulation:

- Geometrical model and material budget
- Design imperfections (gaps, etc.)
- Event generators
- Imperfection of particles transport algorithms
- Spatial or energy resolution (bin size)

The material budget is often the main contributor to the uncertainty of the result.

CONCLUSION

The organization, approaches and software used by the CMS BRIL RadSim group for the physical design of radiation shielding for the CMS experiment have been summarized in this report.

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