



Full Length Article

Measurements and FLUKA Monte Carlo simulations of steel, aluminium, and copper activation at the CMS experiment at the Large Hadron Collider at CERN

Bartosz Idzior^{a,b},^{*} Tommaso Lorenzon^{b,c}, Davide Bozzato^b, Robert Froeschl^b,
Frank Hartmann^{a,b}

^a Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

^b European Organization for Nuclear Research (CERN), Geneva, Switzerland

^c Universitat Politècnica de Catalunya – BarcelonaTech (UPC), Barcelona, Spain

ARTICLE INFO

Keywords:

Activation
Monte Carlo
FLUKA
CMS
Radiation protection
Benchmark

ABSTRACT

The complex radiation environment at CERN's Large Hadron Collider significantly impacts the radiation protection studies, necessitating innovative approaches. The computational tools currently employed to evaluate radiological quantities for personnel and equipment safety are under continuous development and require systematic validation. The availability of well-documented beam history, luminosity data and detector geometry facilitates large-scale comparisons between FLUKA Monte Carlo simulations and experimental measurements. In this study, thirty-eight activation samples of three materials were positioned and irradiated in the CMS experimental cavern in various locations, and were subsequently analysed by gamma spectrometry and compared to simulation predictions. The FLUKA Monte Carlo code was used to score fluence spectra, which were then weighted using the activation cross section. The time evolution was applied using the newly developed tool to determine the induced activation. A comparison of the calculated and measured specific activities lies within a factor of two for the majority of radionuclides in copper, aluminium, and stainless steel samples, which can be considered good agreement for such a large and complex setup. The present study has identified discrepancies observed for ^{60}Co and ^{51}Cr in steel. This benchmark demonstrates the reliability of the FLUKA Monte Carlo code for activation calculations and provides a reference for the computational method developed and used to establish radiological zoning of materials.

1. Introduction

Four major experiments (ATLAS, ALICE, CMS, and LHCb) at CERN's Large Hadron Collider (LHC) study proton–proton and heavy-ion collisions at a centre-of-mass energy of 13.6 TeV per charge, probing fundamental questions about the Universe [1]. These high-energy collisions produce intense secondary particle showers that activate surrounding materials and accelerator components [2]. The resulting induced radioactivity presents significant challenges for maintenance operations, detector upgrades, and radiation protection planning, requiring careful radiological assessment and operational constraints. Except for the ALICE experiment, heavy-ion collisions are treated as a cooldown period because of the far lower number of secondaries per second produced compared to proton–proton collisions.

The Radiation Protection (RP) group at CERN is responsible for ensuring the safety of personnel and maintaining the highest radiation

protection standards, in line with national and international recommendations [3–5]. A major focus is placed on scheduled long-term operational phases such as Year-End Technical Stops (YETS) (stops of the order of 3–4 months starting typically in December) and Long Shutdowns (LS), when access to accelerator and experimental areas is required. In addition to dose estimates for planned exposure situations, the characterisation and handling of activated materials become an important aspect of radiation protection, directly impacting maintenance, dismantling, and upgrade activities.

The CERN RP group generally uses the FLUKA Monte Carlo code [6–8], to model particle transport and interactions with matter in order to support radiation safety assessments and compute various operational radiation protection quantities. The results provide support for planning and decision-making. An important application is the establishment of a radiological zoning for the clearance of detector and infrastructure components from further regulatory control [9].

^{*} Corresponding author at: European Organization for Nuclear Research (CERN), Geneva, Switzerland.
E-mail address: bartosz.idzior@cern.ch (B. Idzior).

However, due to the evolving detector geometries and complex beam dynamics of the LHC experiments, the simulations must be validated against experimental data.

This paper describes a benchmark of Monte Carlo simulation predictions for the Compact Muon Solenoid (CMS) experiment with activation in the CMS cavern [10]. Thirty-eight samples, representing three materials commonly used in the accelerator and detector components, were installed in various locations of the cavern and left in position for several months of beam irradiation. They were then analysed by means of gamma spectrometry with High Purity Germanium (HPGe) detectors. Benchmark simulations were performed with the FLUKA code using the newly developed Mesh-Enabled Fluence Weighting (MEFW) tool [11]. This benchmark serves as a foundation for comparisons of the future activation assessments for the other LHC experiments.

2. Experiment

The CERN RP group designs activation campaigns that involve the placement of small material samples in regions where benchmark measurements are required for the verification of operational radiation protection studies. Radioactivity levels must be measured, as they directly impact the operational procedures at accelerator facilities and the handling of material exiting radiation areas. As a general RP standard, the samples are made of aluminium 6060, stainless steel 304L, and oxygen-free electronic grade high purity copper (C10100), selected to represent materials commonly found in the experimental areas. They measure approximately 6 cm in diameter and 0.5 cm in thickness for copper and stainless steel; 6 cm in diameter and 1.5 cm in thickness for aluminium and weigh approximately 100 g each.

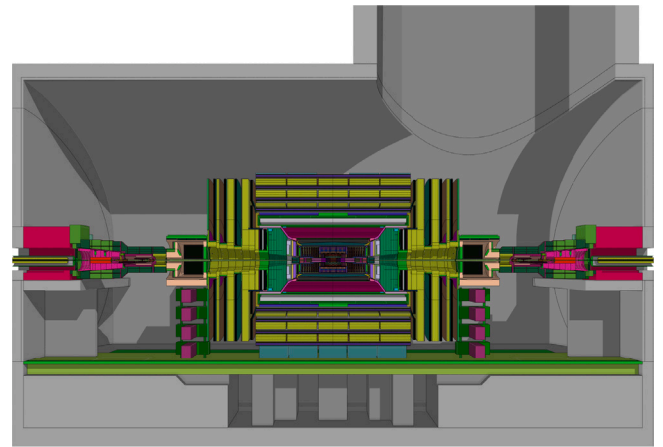
2.1. Facility

The CMS experiment is located on CERN's French site, in a cavern approximately 100 m underground. It is designed to track charged particles, measure momenta, energies, and identify particle species to study the Standard Model and search for new physics.

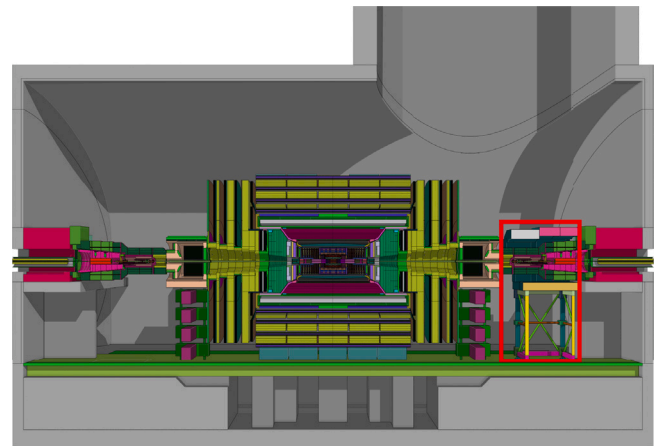
The CMS detector has a cylindrical geometry oriented along the beam line, measuring about 25 m in length and 15 m in diameter, with beam-beam collisions occurring at its geometric centre, called the interaction point (IP). The shape of the CMS barrel is determined by the steel return yoke, which is responsible for half of the volume in this region, and consequently almost all of the density. Heavy lead-tungstate electromagnetic calorimeters and hadronic calorimeters with brass plates as absorbers also drastically reduce radiation levels outside the barrel. At increasing distances from the IP along the beam axis, forward shielding structures are installed on both sides of the detector to suppress the neutron-induced background in the experimental cavern (Fig. 1(a)) originating from a copper collimator — Target Absorber Secondaries (TAS). In 2024, additional shielding, the so-called New Forward Shielding (NFS), was placed on the right side of IP (Z- end of the cavern), surrounding the existing rotating shield, as illustrated in Fig. 1(b). The NFS occupies 216 m^3 of the cavern and weighs 240 t [13]. Electronic racks are located along the cylindrical barrel on both sides of the detector, parallel to the beam line. Finally, balconies along the two cavern walls provide access to the electronics and the other detector components. The above-mentioned elements are implemented in the FLUKA geometry. The details of the CMS geometry can be found in [10,14].

2.2. Experimental setup

A total of thirty-eight samples were installed in the cavern on balconies and inside electronic racks at the beam level, labelled and marked in Fig. 2(a), and on the floor level attached to air pads, marked in Fig. 2(b). The composition of stainless steel, copper, and aluminium samples and placement locations are summarised in Table



(a) CMS geometry in years 2022 and 2023.



(b) CMS geometry in 2024 with the NFS marked red.

Fig. 1. Vertical cross section parallel to the beam line of the two CMS cavern configurations as viewed with the FLUKA graphical interface, Flair [12]. The NFS is represented in the red box.

1. The chemical and radioanalytical analyses were performed by an external laboratory. Placement locations for all materials were tailored to radiological zoning estimations. A naming scheme was adopted in this study to identify a given set of activation samples: the set identifier is “SAM X”, where “X” is an integer identifier specifying a particular location, as marked in Figs. 2(a) and 2(b).

Thirty-two disc samples were installed at the end of LS2 in 2022, in 14 different locations. Table 2 reports sample coordinates in the CMS geometry reference frame. Additionally, during the YETS 2024/2025, two sets of samples (SAM 15 and SAM 16) were installed in the same locations as the existing sets, SAM 3 and SAM 2, respectively. The same locations were chosen to compare with previous measurements before the installation of the NFS, which modified the detector geometry on the Z- side.

In December 2024, at the beginning of the YETS, samples were extracted from the cavern and transferred to the CERN Radiation Protection Analytical Laboratory for activation measurements via gamma spectrometry with an HPGe detector. Energy spectra were measured over a duration of 10 000 s. Energy and efficiency calibrations were performed for the specific sample geometries with the Apex-Gamma and LabSOCS software [15]. The extended geometry and self-attenuation of the samples were taken into account in the analysis of gamma spectrometry measurements. The detection thresholds and Minimum Detectable Activity (MDA) values were determined for each radionuclide

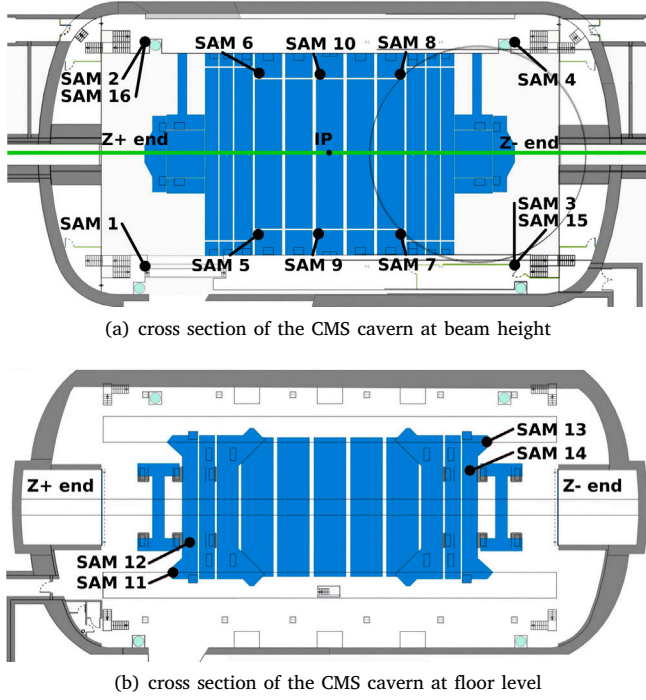


Fig. 2. Cartographies illustrating the location of the installed sets of samples in the CMS experimental cavern at beam height and at floor level. Detector parts are depicted in blue, and concrete walls are in grey. The green line indicates the beam axis. The numbered locations of the samples are marked in black.

Table 1

Measured density (with relative uncertainty in %), placement locations, and chemical composition (weight percentage) of the activation samples used in CMS.

Stainless steel 304L					
Density: 7.95 g/cm ³ (0.02%)		Locations: 1-16			
Element	Mass [%]	Element	Mass [%]	Element	Mass [%]
Fe	7.19×10^1	V	7.38×10^{-2}	Al	1.02×10^{-3}
Cr	1.77×10^1	Cu	2.60×10^{-2}	W	1.75×10^{-4}
Ni	8.10×10^0	P	2.44×10^{-2}	Mg	1.18×10^{-4}
Mn	1.33×10^0	Mo	4.20×10^{-3}	Na	5.00×10^{-7}
Si	5.20×10^{-1}	S	3.35×10^{-3}		
Co	2.48×10^{-1}	Ca	1.13×10^{-3}		
Aluminium 6060					
Density: 2.70 g/cm ³ (0.02%)		Locations: 1-8, 15, 16			
Element	Mass [%]	Element	Mass [%]	Element	Mass [%]
Al	9.73×10^{-1}	Mn	5.45×10^{-3}	Zn	4.72×10^{-4}
Si	8.70×10^{-3}	Fe	4.48×10^{-3}	Cr	3.49×10^{-4}
Mg	7.18×10^{-3}	Cu	7.20×10^{-4}	Ti	1.95×10^{-4}
Oxygen-free electronic grade copper					
Density: 8.96 g/cm ³ (0.02%)		Locations: 1-10, 15, 16			
Element	Mass [%]	Element	Mass [%]	Element	Mass [%]
Cu	1.00×10^2	Si	2.40×10^{-6}	As	1.00×10^{-6}
S	6.40×10^{-6}	Mg	1.80×10^{-6}	Pb	2.90×10^{-7}
Ni	2.50×10^{-6}	Ag	1.10×10^{-6}	Bi	2.00×10^{-7}

according to ISO 11929 [16]. Each sample was marked with a sample-specific cooldown time calculated as the difference between the end of the proton physics run and the gamma spectrometry measurement reporting time.

Table 2

Coordinates of the SAM positions in the CMS geometry reference frame. The X axis points horizontally towards the centre of the LHC ring, the Y axis points upwards, and the Z axis follows the beam direction. All coordinates are given in centimetres.

SAM	X [cm]	Y [cm]	Z [cm]
SAM 1	1061	-45	1748
SAM 2	-1059	-37	1752
SAM 3	1060	-12	-1750
SAM 4	-1061	1	-1751
SAM 5	789	-20	692
SAM 6	-772	-10	725
SAM 7	771	-4	-692
SAM 8	-814	-58	-705
SAM 9	789	-20	114
SAM 10	-771	-17	-114
SAM 11	523	-866	1140
SAM 12	159	-866	1056
SAM 13	-520	-866	-1175
SAM 14	-164	-866	-1068
SAM 15	1060	-12	-1750
SAM 16	-1059	-37	1752

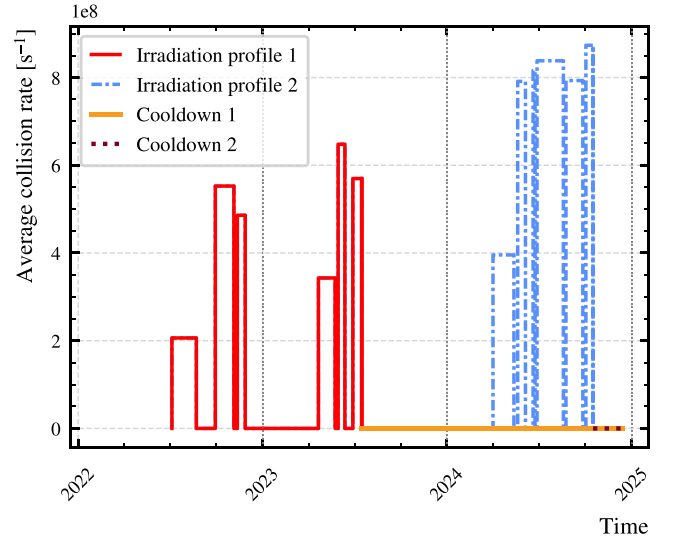


Fig. 3. The average collision rate over time at the CMS experiment, with two marked irradiation profiles used for data post-processing.

3. Beam data acquisition and processing

The prompt source term for simulation, corresponding to the average proton-proton collision rate, was derived from the instantaneous luminosity in the CMS experiment. The delivered luminosity data were retrieved from the CERN data logging system, averaged over user-defined time intervals, and converted into an average collision rate using the inelastic proton-proton cross section $\sigma_{\text{inel}} = 80 \text{ mb}$ [17].

Samples installed in 2022 remained in the cavern for three years, including two years of operation in the configuration without the NFS and one year after its installation. Samples SAM 15 and SAM 16, installed in 2024, were present in the cavern exclusively during operation with the NFS installed.

For this reason, the irradiation profile was separated into two sets, shown schematically in Fig. 3. The first set spans from 2022 to the end of proton collisions in September 2023, followed by a cooldown extending to the week of the gamma-spectrometry measurements. The second set covers the year 2024, with an analogously represented cooldown period. While the cooldown durations are shown only at the week level in the figure, the precise sample-specific values were used in the activity calculations.

4. Computational approach

4.1. Mesh-enabled fluence weighting tool

FLUKA provides several methods for calculating induced activation in materials. Among these, the RESNUCLEi tally tracks residual nuclei that stop in a given region, and the USRTRACK estimator records the differential fluence spectrum for each region based on track length. Many workflows calculate the build-up of radioactivity from fluence weighted with radionuclide production cross sections using the Bateman equations [18]. These alone are not sufficient for modern RP assessments, which require mesh-based spatial coverage.

To address this, the MEFW tool was developed to improve the workflow and enable the computation of radiological quantities inaccessible through FLUKA's built-in capabilities. The spatial distribution of particle fluence is recorded across regions or meshes using a combination of USRBIN cards — each covering one energy bin of a given particle type. Additionally, a dedicated FLUKA user routine is prepared in the pre-processing step and linked to the FLUKA executable. This routine restricts the scoring of the fluence to the energy bin of the given USRBIN card. This approach allows the fluence distribution within a detector to be calculated once (for example, on a three-dimensional mesh) and reused for various studies, eliminating the need for repeated simulations, provided the geometry remains unchanged.

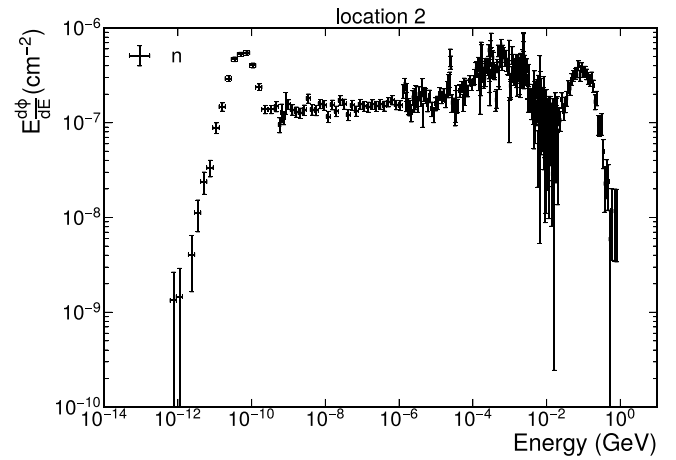
The output files are parsed for the post-processing step: a Python script is used to construct the mesh-based fluence spectra. An extended version of the JEREMY code suite [19] is also used to evaluate a range of radiological quantities in an n-dimensional mesh. These quantities include production yields as well as quantities that are non-linearly dependent on fluence, like specific activities. The isotope production cross sections were calculated using FLUKA for all particles and energies [2], except for neutrons with energies below 20 MeV, which were retrieved from the JEFF-3.1 library [20]. If the RESNUCLE scorer were applied to a set of hypothetical regions that together represent the given bin, the resulting radionuclide inventory would be nearly identical to that obtained with the tool, with any differences arising only if different neutron cross section data are used.

The results can be visualised as two-dimensional maps or projections. As material compositions, irradiation histories and cooling times are all defined at the post-processing stage, one simulation dataset can support multiple independent studies. This significantly reduces the computational load on computing cluster resources and the overall workload of the RP group.

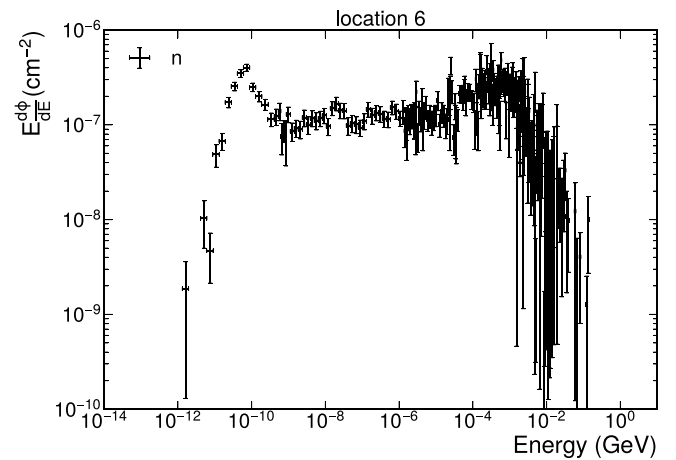
5. Monte Carlo simulation

The installation of the NFS in 2024 introduced geometry modifications, and to reconstruct the effect of its installation, two simulations that differed only in detector configuration were performed using the FLUKA Monte Carlo code (version 4–5.0). Neutrons were transported down to an energy cut-off of 0.01 meV using pointwise neutron cross sections from the JEFF-3.3 library, while charged hadrons, electrons, and photons were transported down to 1 MeV. Electromagnetic transport of electrons, positrons, and photons was also enabled.

Sample locations were surveyed in collaboration with the Geodetic Metrology group. The instrumentation used had a measurement capability of 0.3 mm at one sigma level, exceeding the precision required for this study. Due to a consistent radiation gradient in selected sample locations and expected slow statistical convergence, each region of interest was designed to cover a volume of 0.125 m³, to score particle fluence for protons, neutrons, and charged pions. For samples 11–14, located on the floor, the regions were defined with half the volume of the other regions to avoid including the floor material. The regions containing the investigated samples were defined in the FLUKA geometry as air-filled volumes, while the actual sample material was assigned at the post-processing step. This approach offers a high degree



(a) Neutron energy spectrum in location 2.



(b) Neutron energy spectrum in location 6.

Fig. 4. Isolethargic neutron energy spectra in locations 2 and 6 normalised per 1 collision.

of flexibility, enabling the same Monte Carlo simulation to be reused for multiple material and irradiation configurations, for example, for future operational radiation protection studies.

The two simulations required approximately 2500 CPU days on CERN's High Throughput Computing (HTC) batch system — HTCondor [21] to complete with sufficiently high statistical precision.

The simulation output was processed with the MEFW tool. For each sample location, FLUKA output files were combined to construct particle energy spectra. Fig. 4 provides examples of the neutron spectra at locations 2 and 6, demonstrating the influence of the CMS detector construction on their energy distribution. Location 2 features a high-energy neutron peak caused by the TAS region and reduced shielding in the forward region. This peak is not visible in the barrel region of the plot for location 6 due to dense steel shielding or the return yoke [10]. Production yields and the resulting specific activities were computed. The radionuclide decay calculation required the detailed material composition of each sample, the exact sample-specific cooling times between the end of the proton physics run and the reporting time of gamma spectrometry measurements, and the irradiation profile describing the irradiation history of a given sample.

This process was repeated for both geometry configurations and their corresponding irradiation profiles. The computed radionuclide activities were then summed to estimate the total activity.

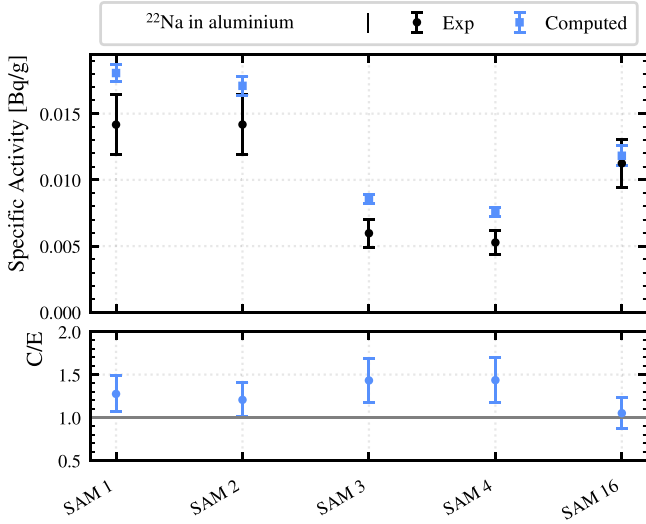


Fig. 5. Specific activity of ^{22}Na in aluminium 6060 expressed in Bq g^{-1} for computed (C) and experimental (E) values in the aluminium samples at different locations and their ratio.

5.1. Uncertainty calculation

Both experimental measurements and simulation results are affected by uncertainties. Measurement uncertainties of radionuclide-specific activities were provided in the gamma spectrometry reports by the software. However, estimation of simulation uncertainties is less straightforward due to the multi-step post-processing workflow and the use of multiple radioactive decay data libraries.

Systematic uncertainties originate from the choice of physics models, transport algorithms, and cross section data libraries. Additional bias may be introduced by the geometry implementation in FLUKA and by imprecise knowledge of the material compositions of the CMS detector. These effects are acknowledged qualitatively but are not quantified nor included in the reported uncertainties.

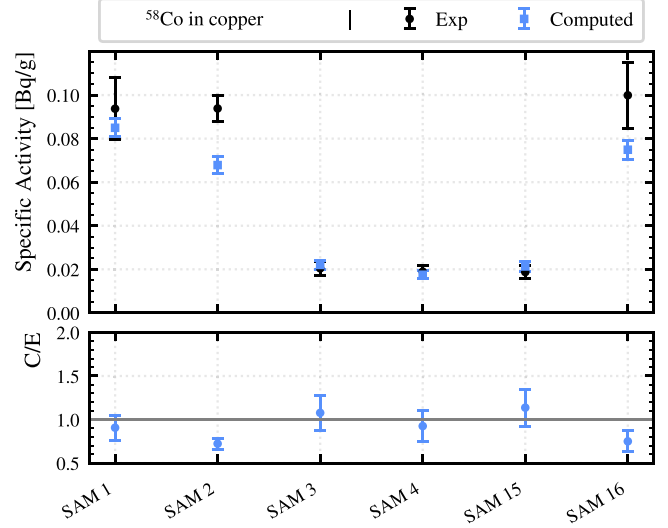
The statistical uncertainty of the simulation results was estimated by subdividing the raw simulation output into several independent batches. Each one was processed separately following the procedure described above. The resulting distribution of batched estimates was used to evaluate the uncertainty of the radionuclide activities, with the uncertainty of the mean computed using the unbiased sample estimator. One-sigma statistical uncertainties are reported for all datasets and shown in the figures.

6. Results and discussion

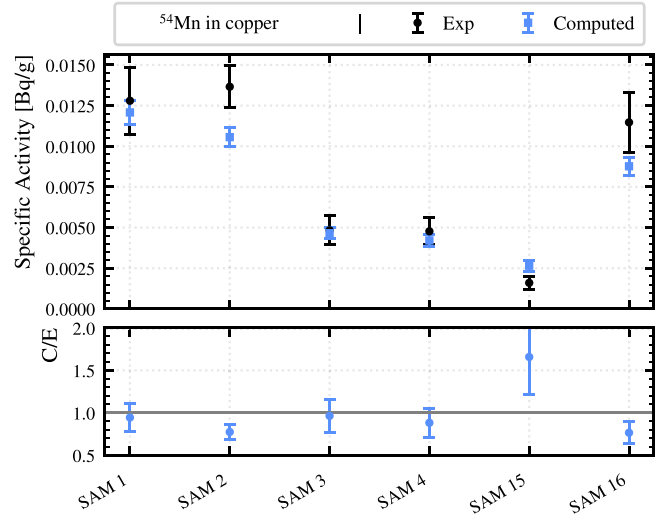
Gamma spectrometry reports include the radionuclides identified in the spectrum, that is, those whose activity is above the detection limit. On the other hand, the FLUKA simulations coupled to the MEFW tool yield the full radionuclide inventory. The comparison was limited to radionuclides detected by gamma spectrometry. A selection of representative examples is discussed, while a complete list of experimental (E) and calculated (C) mass-specific activities is provided in the supplementary spreadsheet attached to the online version of the paper.

The achieved ratio of the computed and experimentally measured values is within a factor of two, with the exception of ^{60}Co and ^{51}Cr in stainless steel. This level of agreement is reasonable considering the complexity of this study and geometry. The most significant radionuclides, which may restrict the operational activities (e.g. ^{22}Na for aluminium and ^{54}Mn for stainless steel), have been well estimated.

Small discrepancies between experimental and computed specific activity can be noticed, especially for SAM1 and SAM2 in Figs. 5,



(a) Specific activity of ^{58}Co in oxygen-free electronic grade copper



(b) Specific activity of ^{54}Mn in oxygen-free electronic grade copper

Fig. 6. Specific activity of radionuclides in aluminium 6060 and oxygen-free electronic grade copper expressed in Bq g^{-1} for computed (C) and experimental (E) values in the aluminium samples at different locations and their ratio.

6(a), 6(b) and 7. However, analysing the ratio plots, a 20% difference is satisfactory for small activity levels reaching a maximum $1.69 \times 10^{-1} \text{ Bq g}^{-1}$ of ^{54}Mn in stainless steel 304L. Concerning the higher discrepancies for ^{60}Co and ^{51}Cr in stainless steel samples (Figs. 8(a) and 8(b)), the simulation results are conservative from the RP point of view. The maximum difference between simulated and experimental measurements is found to be a factor of six apart from SAM 9 and 10, for which measured specific activity is very low: $8.05 \times 10^{-4} \text{ Bq g}^{-1}$ and $8.07 \times 10^{-4} \text{ Bq g}^{-1}$ respectively. These discrepancies were previously identified in an analogous FLUKA benchmark [2]. It may be the result of several factors, which could be investigated in future benchmarks.

6.1. Specific activity distribution reflecting CMS geometry and NFS efficiency

The first conclusion can be derived from observation of samples placed on the opposite side of the beam axis in a horizontal plane. By comparing the values of SAM1 with SAM2, and SAM3 with SAM4 in

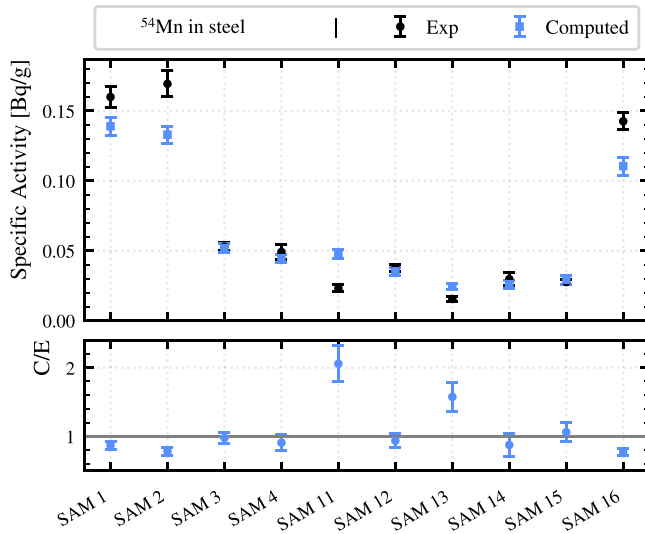


Fig. 7. Specific activity of ^{54}Mn in stainless steel 304L expressed in Bq g^{-1} for computed (C) and experimental (E) values in the aluminium samples at different locations and their ratio.

Figs. 5, 6(a), 6(b), 7 and 8(a), a radially symmetrical radiation field in the experimental cavern can be identified. Additionally, a similar pattern is also visible for samples SAM5–SAM8 in Fig. 8(a).

Following this approach, one can inspect samples on the opposite sides of the cavern along the beam axis (SAM1, 2, and 16 versus SAM3, 4, and 15). For example, in Figs. 6(a), 6(b), 7, 8(a) and 8(b) the impact of the NFS is noticeable, as the shielding affects all materials on the side where it was installed, reducing the amount of radioactive material and confirming shielding design studies [22].

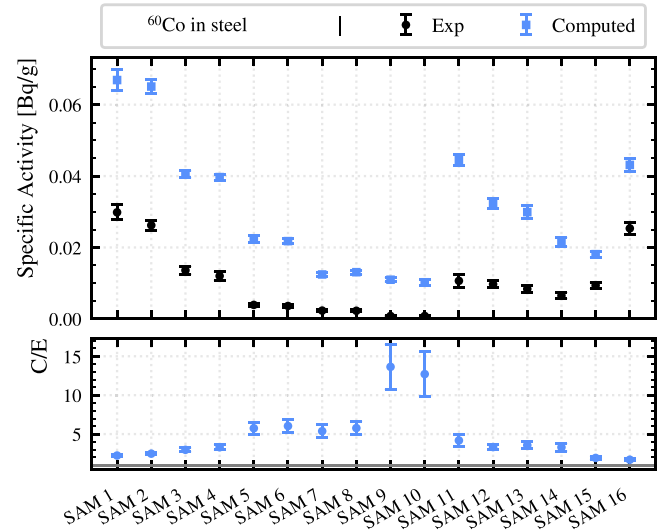
The MEFW tool has been designed to assess radiological quantities and establish new in-situ clearance procedures for materials, which are tailored to the LHC experiments during LS3. This new approach offers greater flexibility and potential than existing Monte Carlo code toolchains. For example, if a new material or cooldown time were to be requested, a new simulation would need to be set up. With the new workflow, these parameters can be modified in the MEFW tool's post-processing step, reducing the time required to perform the same study by approximately a factor of seven, that is, from weeks to a few days.

7. Conclusions

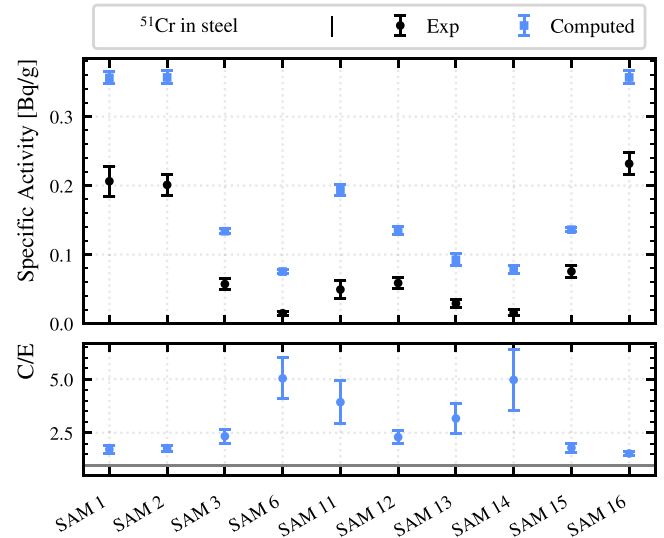
The benchmark study of FLUKA Monte Carlo simulations against CMS activation measurements provides a reliable reference for future radiological zoning calculations. The complex geometry of the detector and the irradiation conditions make accurate activation simulations challenging, requiring validation with experimental data.

In this study, thirty-eight activation samples of three materials were placed at various locations and irradiated in the CMS cavern. The radionuclide inventories were determined by gamma spectrometry. The measurements were compared with FLUKA simulations coupled to the Mesh-Enabled Fluence Weighting tool, allowing accurate geometry reconstruction and implementation of the irradiation profile.

The results show good overall agreement between simulation and experimental data, while highlighting deviations for ^{60}Co and ^{51}Cr in stainless steel samples, suggesting potential needs for further investigation. The present study provides a foundation for subsequent activation studies and benchmark campaigns during LS3 for CMS and other experiments at CERN.



(a) Specific activity of ^{60}Co in stainless steel 304L



(b) Specific activity of ^{51}Cr in stainless steel 304L

Fig. 8. Specific activity of radionuclides in stainless steel 304L expressed in Bq g^{-1} for computed (C) and experimental (E) values in the aluminium samples at different locations and their ratio.

CRedit authorship contribution statement

Bartosz Idzior: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tommaso Lorenzon:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Davide Bozzato:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Froeschl:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Frank Hartmann:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the accelerator operation staff, and the experimental groups at CMS, CMS BRIL group, CERN Radiation Protection Analytical Laboratory group, and the Geodetic Metrology group (BE-GM) for their input and helpful support in the experiment.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.nima.2026.172138>.

Data availability

Data will be made available on request.

References

- [1] L. Evans, P. Bryant, LHC machine, J. Instrum. 3 (08) (2008) S08001, <http://dx.doi.org/10.1088/1748-0221/3/08/S08001>.
- [2] D. Bozzato, Monte Carlo Simulations and Benchmarks for the Radiological Characterization of the LHC Experiments (Ph.D. thesis), Karlsruher Institut für Technologie (KIT), 2023, <http://dx.doi.org/10.5445/IR/1000159308>.
- [3] Ordonnance sur la radioprotection (ORaP), RS 814.501, 2017, Swiss Federal Legislation, Radiological protection ordinance of 26 April 2017, state as of 1 January 2022; English translation available, URL <https://www.fedlex.admin.ch/eli/cc/2017/502/en>.
- [4] ICRP, Recommendations of the international commission on radiological protection, 1991, ICRP Publication 60. Ann. ICRP 21(1-3).
- [5] CERN, Code F rev. Radiation protection - radiation protection manual radioprotection - manuel de radioprotection, 2006, Safety Code F.
- [6] C. Ahdida, D. Bozzato, D. Calzolari, F. Cerutti, N. Charitonidis, A. Cimmino, A. Coronetti, G.L. D'Alessandro, A.D. Servelle, L.S. Esposito, R. Froeschl, R.G. Alfá, A. Gerbershagen, S. Gilardoni, D. Horváth, G. Hugo, A. Infantino, V. Kouskoura, A. Lechner, B. Lefebvre, G. Lerner, M. Magistris, A. Manousos, G. Moryc, F.O. Ruiz, F. Pozzi, D. Prelicpean, S. Roesler, R. Rossi, M.S. Gilarte, F.S. Pujol, P. Schoofs, V. Stránský, C. Theis, A. Tsinganis, R. Versaci, V. Vlachoudis, A. Waets, M. Witorski, *New capabilities of the FLUKA multi-purpose code*, Frontiers Phys. 9 (2022) 788253, <http://dx.doi.org/10.3389/fphy.2021.788253>.
- [7] G. Battistoni, T. Boehlen, F. Cerutti, P.W. Chin, L.S. Esposito, A. Fassò, A. Ferrari, A. Lechner, A. Empl, A. Mairani, A. Mereghetti, P.G. Ortega, J. Ranft, S. Roesler, P.R. Sala, V. Vlachoudis, G. Smirnov, Overview of the FLUKA code, Annals Nucl. Energy 82 (2015) 10–18.
- [8] FLUKA.CERN Collaboration, FLUKA, 2025, Official website of the FLUKA code. URL <https://fluka.cern>. (Accessed 26 January 2026).
- [9] D. Bozzato, P. Dyrce, R. Froeschl, A. Infantino, T. Lorenzon, M. Tisi, H. Vincke, Advanced simulation techniques for radiation protection studies at the large hadron collider, Radiat. Phys. Chem. 218 (2024) 111573, <http://dx.doi.org/10.1016/j.radphyschem.2024.111573>, URL <https://www.sciencedirect.com/science/article/pii/S0969806X24000653>.
- [10] The CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (08) (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [11] B. Idzior, D. Bozzato, R. Froeschl, Mesh-Enabled Fluence Weighting Tool, Tech. Rep., CERN, Geneva, 2024, URL <https://cds.cern.ch/record/2955712>.
- [12] V. Vlachoudis, FLAIR: A powerful but user friendly graphical interface for FLUKA, in: Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics, M&C2009, Saratoga Springs, New York, 2009.
- [13] CMS Collaboration, New forward shielding installed, 2024, URL <https://cms.cern/news/new-forward-shielding-installed>.
- [14] The CMS Collaboration, CMS physics technical design report, volume II: Physics performance, J. Phys. G: Nucl. Part. Phys. 34 (6) (2007) 995, <http://dx.doi.org/10.1088/0954-3899/34/6/S01>.
- [15] F. Bronson, Validation of the accuracy of the LabSOCS software for mathematical efficiency calibration of Ge detectors for typical laboratory samples, J. Radioanal. Nucl. Chem. - J. RADIOANAL. NUCL. CHEM 255 (2003) 137–141, <http://dx.doi.org/10.1023/A:1022248318741>.
- [16] International Organization for Standardization, ISO 11929-3:2019 determination of the characteristic limits (decision threshold, detection limit and coverage interval) for measurements of ionizing radiation – fundamentals and application – part 3: Applications to unfolding methods, 2019, International Standard. URL <https://www.iso.org/standard/43856.html>.
- [17] The TOTEM Collaboration, First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies, Eur. Phys. J. C 79 (2019) 103, <http://dx.doi.org/10.1140/epjc/s10052-019-6567-0>.
- [18] H. Bateman, The solution of a system of differential equations occurring in the theory of radioactive transformations, in: Proc. Cambridge Philos. Soc., vol. 15, 1910, pp. 423–427.
- [19] R. Froeschl, M. Magistris, F. Leite Pereira, C. Theis, Computation of Radioactivity in Particle Accelerators and Propagation of Uncertainties with the JEREMY Code, Tech. Rep., CERN, Geneva, 2024, URL <https://cds.cern.ch/record/2886086>.
- [20] A. Koning, R. Forrest, M. Kellett, R. Mills, H. Henriksson, Y. Rugama, JEFF report 21: The JEFF-3.1 nuclear data library, 2006.
- [21] Center for High Throughput Computing, HTCondor high throughput computing software collection, 2026, University of Wisconsin–Madison. <https://htcondor.org/>. (Accessed 04 August 2026).
- [22] I.L. Azhgirey, D. Bozzato, A.E. Dabrowski, I.A. Kurochkin, S. Mallows, A.D. Riabchikova, Physical design of the radiation shielding for the CMS experiment at LHC, JACoW IPAC 2021 (2021) 2246–2248, <http://dx.doi.org/10.18429/JACoW-IPAC2021-TUPAB320>, URL <https://cds.cern.ch/record/2811873>.