Measurements and estimates of the radiation levels in the CMS Experimental Cavern using Medipix and RAMSES monitors, and the FLUKA Monte Carlo code

Supervisor: David Stickland, Ph.D.
Senior Research Physicist at Princeton University, USA

Kraków, July 2019
Aware of criminal liability for making untrue statements I declare that the following thesis was written personally by myself and that I did not use any sources but the ones mentioned in the dissertation itself.

.................................................................

(signature)
The subject of the master thesis and the internship by Joanna Wańczyk, student of 5th year major in technical physics

The subject of the master thesis: Measurements and estimates of the radiation levels in the CMS Experimental Cavern using Medipix and RAMSES monitors, and the FLUKA Monte Carlo code

Supervisor: David Stickland, Ph.D.
Supervisor on the faculty: Krzysztof Malarz, D.Sc., Ph.D.
Reviewer: Agnieszka Obłąkowska-Mucha, Ph.D.
A place of the internship: CERN, Geneva in Switzerland

Programme of the master thesis and the internship

1. First discussion with the supervisor on realization of the thesis.
2. Collecting and studying references describing monitors and tools used in the project.
3. The internship:
   - research into RAMSES monitors, working out access to Timber database,
   - development of software to obtain and process RAMSES data,
   - estimation of the ionizing dose deposited in the air-filled volume in RAMSES locations using FLUKA,
   - comparison of RAMSES measurements over various time periods to understand the effect of additional shielding added over time,
   - comparison of RAMSES measurements with FLUKA predictions,
   - get acquainted with the Medipix technology and its implementation status for the CMS cavern,
   - perform Monte Carlo simulations in order to choose best locations for installation,
   - participation in calibration of remaining cameras and their installation during the Technical Stop,
   - development of operational scripts for data acquisition purposes using MARS API,
   - data acquisition in the last part of Run II, between TS2 and LS2,
   - refinement of analysis techniques in relation to Medipix based on pattern recognition of particle tracks,
   - analysis of data collected to provide first neutron flux estimates,
   - comparison, where appropriate, of RAMSES, Medipix data with measurements from RADMON neutron monitors and FLUKA predictions,
   - conclusions and discussion with supervisor for final approval,
   - preparation of the internship report.
4. Typesetting the thesis.
Dean’s office delivery deadline: July 2019

.............................. (Supervisor) ..............................

.............................. (Head of Department) ....................
Abstract

Highlights of the work performed for the BRIL project which include FLUKA simulations, background measurements and investigations, and benchmarking activities. Activation simulations with a simple fix for the well known silver isomer problem in FLUKA were performed for the tracker bulkhead region and compared with measurements of the residual dose rates taken in (E)YETS 17/18. Measurements from the RAMSES monitors are compared with FLUKA predictions for the mixed radiation field. Using non-standard FLUKA output, timing information for simulated particles arriving at ME4/2 have been produced with an extensive simulation run. First analysis has been performed, demonstrating how the information can be used to help determine the source of background and support future shielding studies. Changes in the year to year RAMSES readings are investigated to understand the effect of various shielding elements added. Lastly, the Medipix based neutron camera was investigated to obtain the neutron flux.
Acknowledgements

I would like to thank the BRIL group for the opportunity to take part in all exciting projects and the possibility to work in a very inspiring environment. Especially, the Radiation Simulation team for their constant help and many constructive discussions: Sophie Mallows, Igor Azhgirey, and Igor Kurochkin. Thank you Arkady Lokhovitskiy for the work we did together with your friendly and open-minded attitude.

I would also like to express my gratitude to the RP group for their expertise and help with operations in the CMS cavern (Robert Froeschl, Juan Carlos Armenteros Carmona, Anna Cimmino, Markus Widorski and Evangelia Dimovasili)

Anne Dabrowski, David Stickland and Karl Gill for their enduring support, providing me with the possibility to learn from FLUKA experts in the 20th FLUKA Course at Stellenbosch University and to carry out my Master’s Thesis within the BRIL group.

I would like to thank my thesis advisor Krzysztof Malarz, for constant support and encouragement throughout my studies. Last, but not least I would like to thank my family and Marcin without whom this work would never be possible.
# Contents

1 Introduction ............................................................... 6
   1.1 CERN ................................................................. 6
   1.2 Large Hadron Collider ............................................. 7
   1.3 Compact Muon Solenoid experiment .............................. 8
   1.4 Beam Radiation Instrumentation and Luminosity ............ 10
      1.4.1 Luminosity measurement ...................................... 10
      1.4.2 Radiation simulation ........................................... 11
   1.5 Outline of work performed in thesis .......................... 11

2 Radiation and particle detection ...................................... 13
   2.1 Interactions of particles with matter ........................ 13
      2.1.1 Photon .......................................................... 13
      2.1.2 Neutron .......................................................... 14
      2.1.3 Charged particles interactions .............................. 14
   2.2 CMS radiation environment ....................................... 15
   2.3 Relevant Radiation Protection aspects ......................... 16
   2.4 FLUKA simulation package ....................................... 17
      2.4.1 The CMS geometry model ...................................... 19
   2.5 RAMSES monitors .................................................. 20
      2.5.1 Ionization chamber .............................................. 22
   2.6 The Medipix-based neutron camera .............................. 22

3 Radiation levels studies .................................................. 25
   3.1 Benchmark of the residual radiation in the CMS Cavern ... 25
   3.2 Benchmark of the prompt radiation background in the CMS Cavern with RAMSES measurements ................................................. 33
   3.3 Background in Muon Chamber ME4/2—investigation with FLUKA 39
      3.3.1 Cavern asymmetries impact cross-check .................... 46
   3.4 Radiation level changes with RAMSES measurements ........ 48
   3.5 Neutron flux measurement with the Medipix3RX-based cameras 55
List of Abbreviations

BRIL Beam Radiation Instrumentation and Luminosity. 10

CMS Compact Muon Solenoid. 8

CSC Cathode Strip Chamber. 9

ECAL Electromagnetic Calorimeter. 8

HCAL Hadron Calorimeter. 8

HF Hadron Forward Calorimeter. 9

HO Hadron Outer Calorimeter. 9

IP Interaction Point. 8

LHC Large Hadron Collider. 7

LS Lumisection. 30

ME Muon Endcap. 39

PP Polypropylene. 22

RAMSES The RAdiation Monitoring System for the Environment and Safety. 20

RP Radiation Protection. 16

RS Rotating Shielding. 16

YE Yoke Endcap. 39

YETS Year End Technical Shutdown. 25
Chapter 1

Introduction

The Large Hadron Collider brings highly energetic particles into collision that generates exceptional conditions for particle physics experiments. In 2012, the accelerator potential was confirmed by the discovery of the Higgs Boson [7]. That fundamental particle was created during proton-proton collisions along with millions of others, taking advantage of the enormous energy of a few TeV per colliding particle and converting it into mass in the hadronization process. Each of those particles interacts with matter as it traverses the detector elements. Those phenomena are used in particle physics experiments to investigate the primary event. This is performed by building complex detector systems comprising of various detection units made of different materials. This approach provides a wide range of distinct and detailed information about the event and its components. However, it is not possible to directly separate the processes that are intended to provide vital information from many others that occur. As a result, hostile radiation conditions are present on the experimental sites. It is of high importance to have a deep understanding of this environment and be able to foresee the impact on the experiment. To achieve that, powerful simulation packages are used to estimate the radiation levels and their composition. It is important that measurement data can be used to validate simulation estimates. Within the CMS experiment, several different types of radiation monitor are used to monitor, regulate and predict the radiation impact. This is necessary for the sake of a robust operation and a safe working environment.

The thesis begins with an introduction to the laboratory where most of the presented work was performed. Details about the experiment and its environment are provided. The research group is introduced along with its main functions and projects.

1.1 CERN

The European Organization for Nuclear Research is the biggest nuclear physics laboratory in the World. Founded in 1954 at the Swiss-French border just outside Geneva. From that time on, it has gathered thousands of professionals from around the globe to work on state-of-the-
art experiments. CERN’s mission is to advance human knowledge boundaries and push the frontiers of technology, through international collaboration. The last 65 years of operation have been marked with an abundance of milestones. From discoveries of new particles and confirmation of complex theories of particle physics to the technological spin-offs for the benefit of all people in everyday life. As a result of CERN constantly pushing the limits of science the LHC was created, providing the first look into matter above the scale of 1 TeV.

1.2 Large Hadron Collider

The LHC is a two-ring-superconducting-hadron accelerator, having almost 27 km in circumference it is the biggest machine ever built. This remarkable size provides enormous energies per accelerated particle. It was designed to reach 14 TeV in centre of mass-energy in the crossing points (for colliding protons). There are four such points around the ring, each of them is home to one of the four main experiments:

(a) ATLAS (A Toroidal LHC ApparatuS)—general purpose detector, investigating a wide range of problems in physics.

(b) ALICE (A Large Ion Collider Experiment)—conducts research related to collisions with lead ions. It is designed to study the physics of strongly interacting matter at extreme energy densities, particularly the quark-gluon plasma.

(c) CMS (described in the next section 1.3)

(d) LHCb (Large Hadron Collider beauty)—focuses on the CP (Charge Parity) violating phenomena in the beauty and charm decays as well as searches for physics beyond the standard model through rare decays.

In figure 1.1 all the experiments mentioned above are illustrated on the LHC ring, which is presented with its entire injection chain. The acceleration process starts from a hydrogen-filled cylinder, the extracted hydrogen atoms are stripped of electrons, leaving only protons in the beam. In the first stage, which is the LINAC2 (linear accelerator) they reach an energy of 50 MeV. Then, they are injected into the Proton Synchrotron Booster, which is made up of four superimposed synchrotron rings that accelerate them to 1.4 GeV for the injection into the Proton Synchrotron (PS). In the PS they reach 25 GeV and then travel to the last stage of the pre-acceleration—the Super Proton Synchrotron (SPS). They reach 450 GeV and they are ready to be injected into the LHC where they are accelerated to the final collision energies, currently 13 TeV. The beams are guided by superconducting dipole electromagnets which keep the beams stable and precisely aligned. Before they enter the detector they are squeezed closer together by quadrupole magnets to make collisions more probable.

1 TeV — Tera electron-volts $= 10^{12} \times (1.6 \times 10^{-19})$ J
1.3 Compact Muon Solenoid experiment

CMS is a general purpose detector on the LHC ring. It has a cylindrical layout, built up from tight layers wrapped around the interaction point (IP). The first layer from the middle is the Tracker in which charged-particle trajectories (tracks) and origins (vertices) are reconstructed from signals (hits). It consists of 10 layers of silicon microstrip detectors, providing the required granularity and precision. There are also three silicon pixel detectors layers in the most inner part which measure primary and secondary vertices as well as the impact parameter.

The next layer is the Electromagnetic Calorimeter (ECAL). It is made of lead tungstate scintillating (PbWO$_4$) crystals. The scintillation light is detected by silicon avalanche photodiodes in the barrel region and vacuum phototriodes in the end cap region. The calorimeter is fast and radiation hard, it covers pseudorapidity up to $|\eta| < 3.0$. The electromagnetic showers are detected as clusters of energy recorded in neighboring cells, from which the energy and direction of the particles can be determined.

Around the ECAL the Hadron Calorimeter (HCAL) is installed. It is hermetic (no gaps) and has a coarse segmentation, consisting of several layers of the brass absorber and plastic scintillator tiles. The signal from the HCAL is sufficient to separate charged and neutral hadron...
energy deposits. Besides, it provides an indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos (by the missing energy measurement). For that to be possible, the HCAL design maximizes material inside the magnet coil in terms of interaction lengths. There is an additional layer outside the coil—hadron outer (HO) detector, made of scintillators. The HCAL is complemented by hadron forward (HF) calorimeters situated at $\pm 11$ m from the interaction point that extends the angular coverage on both sides up to $|\eta| \approx 5$.

All the layers mentioned above are surrounded by the large superconducting solenoid, creating an axial and uniform magnetic field of 3.8 T over a length of 12.5 m and a radius of 3.15 m. It provides the bending power in the calorimeters allowing for the separation between charged- and neutral-particle energy deposits.

The magnet is also necessary for a good performance of the next layer—the Muon Chambers. The muon bending angle at the exit of the 4 T coil determines the measurement of its momentum. The magnetic flux is returned through a yoke consisting of three layers of steel interleaved with four muon detector planes. The latter consists of three types of gaseous detectors: drift tube (DT) chambers, cathode strip chambers (CSC) and resistive plate chambers (RPC). In the barrel region DT and RPC are used, covering very large area up to the range $|\eta| = 1.2$. In the endcap region, CSCs are used, interleaved with RPC plates. The reconstruction involves a global trajectory fit across the muon detectors and the inner tracker.

Figure 1.2: The representation of CMS and its layers [17]
All those parts form a great and robust machine, but still compact, compared to detectors of similar weight (in total 14000 tones). CMS is almost 29 m long and has a diameter of 15 m and it is symmetric with reference to the interaction point [8, 26].

1.4 Beam Radiation Instrumentation and Luminosity

The BRIL project operates as a part of the CMS experiment. Its duties are associated with the luminosity measurement as well as the instrumentation of the beam radiation and its effects. BRIL members maintain and operate several independent detectors specialized in luminosity measurement, monitoring of the beam conditions, and particle fluxes. They provide active protection of the CMS sub-systems from serious radiation damage.

1.4.1 Luminosity measurement

The LHC is designed to provide an absolute luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Precise luminosity measurement describes the accelerator performance. After calibration, it is a crucial element in the physics analyses connected to the CMS experiment. Regardless of the detector type, luminosity ($L$) is defined by the rate of quantities (e.g., hits, tracks) registered in that detector:

$$R = L \times \sigma,$$

(1.1)

where $\sigma$ is the inelastic cross section of the process producing that rate. The instantaneous luminosity is usually given in cm$^{-2}\text{s}^{-1}$ or using inverse barns$^2$ for example Hz/$\mu$b. Several independent detectors are used to measure real-time luminosity within the BRIL project:

- The Pixel Luminosity Telescope (PLT)—is a dedicated standalone luminosity monitor. It comprises of eight 3-plane silicon-pixel telescopes per end. It is installed close to the IP, only 1.75 m away and 5 cm in radius from the beamline. The luminosity measurement is based on the threefold coincidences count (on each plane). The PLT provides online bunch-by-bunch measurements to LHC and CMS with a statistical precision of 1% every 1.5 s.

- The Fast Beam Conditions Monitor (BCM1F)—is a system for bunch-by-bunch measurement of beam background flux and collision products. It is a diamond-based detector, with an excellent arrival time resolution of 1 ns. It is installed at a radius of 6.94 cm from the beamline, 1.8 m away from the IP.

- The Hadron Forward Calorimeter (HF)—previously described in section 1.3 as one of the central CMS subsystems. It was a primary method used at CMS for the real-time

$^2|\text{b}| = 10^{-24}$ cm$^2$
bunch-by-bunch luminosity measurements. For those measurements, only the outer part of HF is used as it has the most stable contribution.

- The Silicon Pixel Detector—the innermost part of the CMS. It operates only under stable beams conditions, hence it is used rather as an offline luminometer.

- The Drift Tubes (DT)—one of the segments of the CMS Muon Chambers. The luminosity measurement uses the rate of muon track stubs in the muon barrel track finder.

The first two above listed items are dedicated systems for luminosity measurement. The rest use the data from existing parts of the CMS detector to perform a luminosity measurement. RAMSES monitors are additionally used as a measurement stability crosscheck.

There is a complementary safety system BCML1/2 that can send the signal to abort the beam. They use pCVD diamond sensors installed on a circular collar around the beam pipe. By monitoring the current in the sensors induced by the crossing particles, it provides safe operation. They are installed several centimeters in radius for the beam pipe. The BCML1 is located inside the Tracker volume and the BCML2 is outside the HF (~ 2.4 m away from the IP).

1.4.2 Radiation simulation

The Radiation Simulation team works within the BRIL project. It investigates and endeavors to diminish the hazardous radiation effects on sensitive devices and materials.

One of their tasks is to maintain and develop the CMS geometry models for FLUKA and MARS simulation packages (introduction in the following section 2.4). Based on these virtual descriptions, estimations of collision and machine induced radiation background can be performed as well as activation studies. The team distributes supplementary tools enhancing access to simulation data (RadSim Web Plotting Tool [22]) and facilitating performance of specialized simulations (SESAME [25], FOCUS [12]). It is also involved in all main CMS sub-system design and upgrades, supporting engaged groups with simulation estimations.

1.5 Outline of work performed in thesis

The BRIL project has a diverse set of responsibilities to the CMS project and must therefore use and develop a wide range of software packages and detectors to fulfil its mandate.

The work in this thesis focuses on the validation of the FLUKA for predicting radiation levels in the CMS cavern, with measurements of the residual radiation field in a shutdown period, the use of ionization chambers to monitor the background radiation in the outer cavern (in a region where uncertainties associated with simulation are expected to be higher) and a comparison with corresponding FLUKA estimates, a comparison of FLUKA estimates with a
more comprehensive estimators (information timing information) with measurement data to better understand the origin of background radiation arriving at the CMS Muon Chamber "ME4". Furthermore, the analysis of measurements with newly installed BRIL Medipix3RX radiation monitor detector is presented.

Validating the ability to predict the residual radiation levels and prompt radiation in the cavern using CMS FLUKA set up is important for maintenance work on the detectors in shutdown periods and for designing shielding to suppress background.

The selection of software and detectors that were used and analysed the work for the thesis are described in more detail in Chapter 2 along with a summary of the relevant physical processes involved.
Chapter 2  

Radiation and particle detection

2.1 Interactions of particles with matter

In this section, all relevant particle physics phenomena are included, which allow the understanding of the detectors used in the projects as well as the collected data. They are divided into groups to give an overview.

2.1.1 Photon

A photon is one of the fundamental particles and is described in the standard model as a force-carrying gauge boson. It is responsible for the electromagnetic force.

Photons traveling with the speed close to the speed of light (exactly \(c\) only in the vacuum), can easily traverse relatively thick layers of various materials. However, it is dependent on the energy of a photon as well as the thickness of the layer, the density of the material and its absorption cross-section. The total absorption shows an exponential decrease of intensity with increasing distance [20]. As the photon travels through a medium it can interact via three main processes:

(a) Compton scattering—if the photon energy \(h\nu\) is smaller than the binding energy of the electron, it undergoes classical scattering without any change in energy. However, if the photon energy is greater than the binding energy, it loses some energy which is transferred to the recoiled electron.

(b) Photoelectric effect—the energy of a quantum \(h\nu\) is completely absorbed by the atom and transferred to one of its electrons. It obtains the kinetic energy of \(E_k = h\nu - J\), where \(J\) is the binding energy of that electron.

(c) Pair production—when a photon travels near a nucleus and has sufficient energy it can create a particle and its antiparticle. The most common is the production of the lightest possible pair (1 MeV of the total rest mass energy)—electron and positron: \(\gamma \rightarrow e^- + e^+\)
2.1.2 Neutron

A neutron, as its name indicates, does not have any charge, hence it does not undergo Coulomb interactions, which are the main energy loss mechanisms for the charged particles. It is classified as hadron, as it is composed of three quarks. Thus, it is mainly subject to strong interactions with an encountered nucleus, while penetrating matter. Neutron-nucleus interaction probabilities depend on the energy and can vary dramatically. What is more, there are large oscillations of several orders of magnitude visible in the cross-section which correspond to resonances. Generally, neutrons can travel long distances in matter without any interactions thus are invisible to common detectors. They can be detected effectively only by creating an ionizing (hence detectable) secondary particle. In that process, the following neutron interactions can be utilized [28]:

(a) inelastic scattering—a fraction of neutron kinetic energy is shared with a nucleus in the collision. The nucleus returns to its ground state by emitting radiation (significant from 1 MeV)

(b) elastic scattering with a nucleus—in most of the cases resulting in a recoiled proton. This process is the most probable out of all herein listed.

(c) radiative neutron capture—the nucleus absorbs the neutron and finds itself in an excited state, which decays by gamma emission.

(d) neutron capture followed by emission of a charged particle or followed by fission.

If a neutron follows the most probable scenario, it loses energy until its energy is equal to the thermal energy of the surrounding matter. The energy transfer in the scattering is determined mainly by the mass of the collided nucleus. The lower the nucleus mass, the higher the energy transfer. Having that in mind, the lightest element is used to thermalize neutrons—hydrogen. Hydrogen-rich materials are widely adapted for shielding, for example, concrete and polymers.

2.1.3 Charged particles interactions

Charged particles pass through matter interacting mainly with atomic electrons, creating electron and ion pairs along their path. Their energy loss per unit length due to the ionization is described by the Bethe-Bloch formula (for particles heavier than an electron):

\[
- \frac{dE}{dx} = K \frac{Z}{A} \frac{\gamma^2}{\beta^2} \ln \left( \frac{2m^2 \gamma^2 \beta^2}{I} - \beta^2 \right),
\]

where \( m \) is the electron mass, \( z \) is the charge of the particle, \( \rho \) is the density of the medium, \( Z \) is its atomic number and \( A \) is its atomic mass, and the constant \( K \) is given by:

\[ K = \frac{4\pi e^2 (hc)^2}{m^2 c^2} N A (10^3 \text{ kg}) = 30.7 \text{ keV m}^2 \text{ kg}^{-1} \]
potential. It has a major contribution to the radiation dose that influences the performance of some detectors and destroys non radiation-hard electronics elements. The formula \(2.1\) is limited to the energy interval higher than the speed of the atomic electrons. If the particle is below that threshold, a fraction of the energy is lost to the excitation of atomic and molecular levels. On the other hand, in really high energies (a few hundreds of GeV for muons and pions, much more for protons) the ionization is dominated by Bremsstrahlung losses in the nuclear Coulomb fields. The formula fails to describe that process, hence it has an upper energy boundary as well. The last described phenomenon concerns the electron at much lower energies due to its small mass, therefore its energy loss cannot be described by the Bethe-Bloch formula \[5\]. An example of the mass stopping power curve for positive muons in copper is shown in figure 2.1. The interval described by the formula \(2.1\) is indicated with the vertical bands.

\[
\frac{dE}{dx} = \text{Mass stopping power [MeV cm}^2/\text{g]}
\]

\[
\beta \gamma = \frac{p}{M_c}
\]

![Mass stopping power curve for positive muons in copper](image)

Figure 2.1: Mass stopping power \((-dE/dx)\) for positive muons in copper as a function of \(\beta \gamma = \frac{p}{M_c}\). Solid curves indicate the total stopping power. Vertical bands indicate boundaries between different approximations \[27\].

### 2.2 CMS radiation environment

As stated in the previous chapter (sec. 1.3), the CMS experiment has a very complex structure. As a result, a unique radiation environment is generated by the primary proton-proton collisions. A thorough understanding of the radiation environment is required to design proper shielding.
This insight is also vital to guarantee reliable operation and a sufficient life span of the detectors. The radiation background in the sub-systems of CMS has to be reduced to a tolerable level. CMS comprises of many silicon-based delicate detectors which are exposed to the displacement damage that causes their degradation. On the other hand, there are sub-systems including heavy elements that produce intense albedo (e.g. ECAL). The activation of their materials can lead to a decrease in the overall performance. The highlights mentioned earlier do not exhaust the abundance of aspects that need to be considered [16].

In reality, during the operation of such a complex system, it is inevitable to suffer from proton beam energy losses. As a consequence, radionuclides are created in hadronic interactions as well as spallation and low-energy neutron reactions. Their half-lives can range from fractions of seconds to years. Hence, it is important to include the buildup resulting from long collision periods in the induced activity studies.

The access to the experimental site during operation is forbidden due to high dose equivalent rates, in the order of $10 \text{ mSv/h}$ in outer cavern areas and much more closer to the beamline. Due to additional shielding, radiation levels are reduced from extreme values ($\sim 1 \text{ Sv/h}$). The most influential is the forward shielding covering elements between the last CMS endcaps and the cavern wall. It comprises of: shielding around the HF, the Rotating Shielding (RS) along the beam-pipe (15 – 22 m from IP) and the blockhouse that seals the tunnel entry leading to the LHC. These elements are made of effective shielding materials such as steel, concrete, and borated polyethylene. The thick part of the RS was carefully developed as it covers the passive absorbers (TAS), which are by far the most intense source of background radiation. What is more, the beam-pipe shape was optimized for the reduction of the radiation background [15].

Radiation shielding is an important issue however CMS performance has always the priority. As a result, there are some elements exposed to extremely hostile radiation such as the collimator and the vacuum equipment close to the experiment. The maintenance of some calorimeters is limited due to their activation. The CMS experimental area is enclosed by concrete walls a few meters thick, allowing for access during operation to adjacent service rooms if necessary. As for the entire LHC complex, there is an additional shielding of 100 m of rocks and soil that minimise the influence on the outside environment.

2.3 Relevant Radiation Protection aspects

The previously described demanding radiation environment has to be supervised to ensure personnel safety. CERN’s radiation protection policy stipulates that the exposure of persons to radiation and the radiological impact on the environment should be as low as reasonably achievable (in accordance with the ALARA principle) [13]. Additionally, any exposure of the personnel to the ionizing radiation has to be justified and personal doses have to be kept below legal limits. The Radiation Protection (RP) group was formed to supervise the compliance of
the safety code. However, the challenges they must face are not only related to the operation and monitoring, their work already starts during the design phase.

There is no access to the experimental sites during operation, due to high levels of stray radiation. Only remote actions are allowed. Radiation background is present also during beam-off periods. It needs to be monitored and reduced to reasonable levels either by a cool down time or additional shielding. The RP sweep is performed after each cool down before admitting the personnel into experimental sites.

Protection quantities such as effective dose or dose equivalent are used to express the general limits. At CERN, a standard classification is adopted:

- Non-designated area - 1 mSv/year
- Supervised area - 6 mSv/year
- Controlled area - 20 mSv/year

These protection limits are easily calculated, although cannot be directly measured. For area monitoring, point quantities are needed to provide a conservative estimate or upper limit, the effective dose is not the appropriate quantifier. $H^*(10)$ is an operational quantity, dose equivalent which would be generated in the associated oriented and expanded radiation field at a depth of 10 mm in soft tissue. It is supposed to be a good estimate for the dose a person would receive if they would be at that place.

The health effects of ionizing radiation are divided into two types: stochastic and deterministic. The former relates to effects which occurring probability is a function of dose without any threshold. It includes malignant diseases and inheritable degenerations in offspring. The latter concerns effects resulting from exceeding an absorbed dose threshold. The consequences involve temporary or permanent injury of cells. These effects can cause acute radiation syndrome, which in harsh cases can lead to the demise. The severity of reactions increases with the dose level.

### 2.4 FLUKA simulation package

To have a better insight into the radiation environment around the experiment it is desirable to have a tool capable of simulating it. Within the CMS group, FLUKA is the principle simulation tool, this is a Monte Carlo simulation package dedicated to particle physics. Proton beams can be defined with details and collided. The latest FLUKA uses DPMJET-III (Dual Parton Model and JETs) heavy ion event generator which includes a precise description of high energy hadronic interactions. By modeling the CMS sub-parts and their surroundings—the experimental cavern, FLUKA can estimate the radiation effects. All the elements can be described accurately through the mathematical combinations of elementary shapes. As
a result, even very complicated forms can be created. However, a more detailed geometry model requires a more details description which can lead to longer CPU times when simulating and increased manpower requirements for maintenance. It is of high importance to assign appropriate materials with accurate densities and composition to the geometry volumes. Trace elements might be crucial in the activation studies.

FLUKA predictions are useful to test shielding effectiveness as well as to assess radiation damage and detector performance in the specific radiation environment. The FLUKA output format is specified using so-called ‘scorings’—predefined cards that estimate desired information during a simulation. The output can be a particle flux map over a particular region (USRBIN) or particle energy spectra estimated in a volume (USRTRACK) or at a boundary of two adjacent regions (USRBDX). The user can specify the particle type or the group of particles (e.g., charged/neutral hadrons) to be included in the scoring. There are also more practical output forms available—flux converted into a special unit of measure (e.g., 1 MeV equivalent neutron fluence in Silicon) and dose-like types (e.g., energy deposition, dose). Typical physical quantities generally used in the FLUKA output are fluence and current. The former can be estimated using tracklength or boundary crossing scoring. All regional estimates (e.g., USRBIN) use the tracklength. It is calculated by adding paths \( dt = \cos \theta \) of particles crossing the infinitesimal thickness \( dt \) of the boundary with an angle \( \theta \) with respect to the normal to that surface and then dividing it by the boundary volume \( S \cdot dt \):

\[
\Phi = \lim_{dt \to 0} \sum_{i} \frac{dt_i}{S dt \cos \theta_i}.
\]  

(2.2)

In case of boundary crossing fluence estimation number of particle \( dN \) crossing an element of surface \( da \) perpendicular to the particle direction is scored:

\[
\Phi = \frac{dN}{da}.
\]  

(2.3)

The current is a boundary crossing estimator. It is defined as the number of particles crossing the surface divided by the area of that surface:

\[
J = \frac{dN}{dS}.
\]  

(2.4)

Fluence is independent of the area of the surface, hence it is different from current across a given surface. For more advanced FLUKA users it is possible to define more sophisticated and focused scorings. One can implement any desired logic and set the information list to be saved in the output [4, 11].

As the simulation is finished, the results are always averaged and normalized per primary event, regardless of the number of primary particles set in the input. They can be scaled to the desired luminosity by applying:

\[
\text{FLUX} \left[ \frac{1}{\text{cm}^2 \cdot \text{s}} \right] = \text{FLUKA result} \left[ \frac{1}{\text{cm}^2 \cdot \text{primary}} \right] \times \text{Luminosity} \left[ \frac{1}{\text{mb} \cdot \text{s}} \right] \times \sigma \text{[mb]},
\]
where $\sigma = 80$ mb—inelastic cross section used for the beam energy of 7 TeV. The normalization can also include the integrated luminosity to provide the accumulated estimation.

FLUKA has applications far beyond high energy experimental physics studies, it is used for detector and telescope design, cosmic ray studies, medical physics, and radiobiology.

### 2.4.1 The CMS geometry model

The CMS FLUKA model is constantly evolving, various versions are maintained for estimates with past (benchmark), current and future (upgrade) detector configurations. The example Run II geometry is presented in figure 2.2. It is important for further considerations that the axes labels are fixed. The $z$ axis is parallel to the beamline, pointing from the negative to the positive end of the cavern. The $y$ axis points from the cavern floor to its ceiling and the $x$ axis points from so-called ‘far’ to ‘near’ side of the cavern, which refer to towards or away from the centre of the LHC ring. The CMS geometry model is mostly symmetric in $\phi$ and $z$ (with respect to the interaction point). The main exceptions are the vertical access shaft and the CASTOR detector, being present only on the negative end of the cavern. The symmetry in $z$ is implemented using the ‘lattice’ FLUKA card—it is visible in figure 2.2 as the blurred area on the left side of the picture. All the symmetric elements in the negative end of the cavern are the mirror image of the positive end.

![Figure 2.2: The CMS geometry modeled in FLUKA (y – z cut)](image)

There are some amenities present, especially when it comes to outside detector geometry. Cavern elements geometries are simplified, for example, HF risers, balconies, floor. There are
some components of lower importance with an abundance of parts made of various materials not relevant to implement in detail. If it is certain that they do not have much impact on the radiation environment, an averaged material is assigned to include simulation of backscatter into the detectors. This approach is applied for example to the electronics racks.

FLUKA code transports all the particles until they reach the cutoff limits. The information about the influence of the solenoid on the particles is included in the magnetic field map.

2.5 RAMSES monitors

RAMSES (The RAdiation Monitoring System for the Environment and Safety) is a system consisting of hundreds of monitors installed all around CERN, in the underground areas as well as on the surface. Its main task is to monitor the ambient dose equivalent rates ($H^*(10)$) described in section 2.3 in experimental areas. It provides continuous and real-time measurements of induced radioactivity as well as prompt radiation, helping to keep all exposed staff safe. RAMSES can generate local radiation warnings and alarms which are transmitted to the control rooms [24].

RAMSES monitors are of various types, however, the main interest in this thesis is focused on one of them. They are generally called Induced Activity Monitors (IAM), and the specific type that is used inside CERN has a product name ‘PMI’. These are simply gas-filled ionization chambers, which have been used for decades (described below in section 2.5.1). They can be installed in strongly irradiated areas because the DAI4 measurement electronics are remote from the sensor at distances maximum of 750 meters thanks to the SPA6 cable. The DAI4 can measure the current over a dynamic range of 9 decades without dead time. It establishes the measurement on 0.1 s steps ranging between 1 second and one hour and dates it. The monitors are calibrated periodically with a 662 keV photon source by the RP group. They are meant to detect photons in the energy range from 50 keV to 7 MeV. The dose rate measurement range is constraint by the current measurement limits—from 5 $\mu$Sv/h ($1.4 \times 10^{-13}$ A) to 500 mSv/h ($1.4 \times 10^{-8}$ A). They operate at 1000 V of polarization voltage applied to the 3 liters of air at atmospheric pressure. The air is surrounded by 4 mm of PE graphite coated wall ($0.95 \text{ g/cm}^3$), forming a cylindrical shape presented in fig. 2.3. In figure 2.4 a picture of a monitor in the CMS cavern is shown.

There are 10 PMI monitors distributed around the CMS experimental hall. The layout is presented in figure 2.5. Most of the monitors are located close to the cavern walls, on various levels. Two monitors were installed slightly later, after the beginning of the LHC operation, in more central locations—on the balconies over the HF.
Figure 2.3: Scheme of a cross-section through the PMI chamber [31]

Figure 2.4: Picture of one of the PMIs in the CMS cavern

Figure 2.5: The layout of RAMSES monitors in the CMS cavern
2.5.1 Ionization chamber

The ionization chamber detects the charge created by a crossing ionizing particle inside its active volume. The crucial information is the number of electron-ion pairs induced along the track of the incoming particle. To collect all pairs produced in a gas-filled detector, an electric field must be applied. It has to be strong enough to make recombination negligible and in this way efficiently collect all the charges without any loss. As neutrons are neutral particles and do not ionize directly, an additional process is required. Typically, they are detected indirectly through elastic scattering reactions—a conversion material is used.

2.6 The Medipix-based neutron camera

Over the last few years, novel Medipix-based cameras were investigated to be used inside the CMS experimental cavern for the neutron flux measurement. They use the Medipix3RX front-end ASIC bump-bonded with the silicon sensor. It is designed to mitigate the charge sharing effect, thus overcome the effects of fluorescence and charge diffusion. The detector is covered with a conversion layer to allow for neutron detection by producing charged particles in nuclear reactions.

Medipix3RX is a CMOS pixel detector readout chip (130 nm). It consists of $256 \times 256$ matrix of individual analog to digital circuits with counters, each occupies $55 \ \mu m$ space of the chip surface. Four adjacent pixels form a cluster to implement a charge summing operation mode which mitigates the charge sharing effect. Each pixel circuit includes a channel comprising of a preamplifier, a shaper, two threshold discriminators and two 24-bit counters. The output voltage generated by an incoming particle is compared to two threshold levels set by two 10-bit digital to analog converters (DACs). Provided that the amplitude is in a range set by the thresholds, a single pulse is generated at the output. Before the detector can be used for measurement, an equalization procedure is required \[23\]. It assures the compensation for the mismatch between individual pixel’s noise and baseline levels \[3\, 21\].

The cameras installed around CMS consist of two such detectors. They were prepared in three configurations:

1. Silicon layer covered with 6 mm of polypropylene (PP)—designed for medium and high energy neutrons measurement ($E_n \geq 1 \ MeV$). An incoming neutron reacts with a hydrogen atom, transferring its energy at elastic scattering and causing emission of a recoiled proton: $n + ^1\text{H} \rightarrow n' + p$. The proton can be seen by the detector as a group of exited pixels forming a distinguishing track.

2. Silicon covered with thin Lithium Fluoride layer—low energy neutrons have a very high cross section for a nuclear reaction with Lithium-6: $n + ^6\text{Li} \rightarrow ^3\text{H} + \alpha$. The emitted charged $\alpha$ particle is detected in silicon.
3. Bare silicon layer—expected to show the rate of particles without conversion, mostly other than neutrons. The only contribution from neutrons are the low-probability neutron nuclear reactions in silicon $^{28}\text{Si}(n,p)^{28}\text{Al}$ and $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$. The signal from such detector is used in the data analysis as the background rate.

The detectors forming a camera and the front-end electronics are enclosed in an aluminum box, with a thicker aluminium layer below the detectors that additionally works as a heat sink. A picture of the camera setup is presented in figure 2.6, it has an upper cover removed to show the arrangement of the detectors. Four out of seven intended cameras were installed in the CMS cavern and fully commissioned in September 2018. Their locations with description are listed below, the labels are used in the following chapters to refer to the specific camera:

- HFTOP—on the handrails of the balcony just above the Hadron Forward Calorimeter
- HFX3—the same distance from IP as the previous one, but closer to the beamline, just outside the HF
- X3IP—between the electronics racks, close to the wall, on the height of the beamline and IP
- X3FORWARD—on the handrails of the X3 level balcony, further from the IP than the other cameras

In figure 2.7, two of these locations are indicated. All of the cameras are located on the positive end of the cavern. Operating cameras recorded data in the final period of Run II collisions.
Figure 2.6: A camera assembly consists of two Medipix-based detectors fixed on the aluminum heat sinks installed on the longer sides of the box. The detector on the right-hand side has the PP conversion layer (long greyish block). This configuration corresponds to the camera installed in the HFX3 location.

Figure 2.7: A picture from the CMS experimental cavern showing locations of two cameras.
Chapter 3

Radiation levels studies

3.1 Benchmark of the residual radiation in the CMS Cavern

Introduction

At the time of writing, FLUKA version v.2011, (with various sub-versions) is commonly used in radiation protection studies at CERN facilities. In general, FLUKA has been very well benchmarked for induced activity at high energy facilities [6]. However, the current release version has a simplified model for isomer where equal branching ratios are applied to the production of isomeric states production. This is not an issue for the majority of very short-lived isomers but can be for specific longer lived isomers as described in the following section. A FLUKA version under development will include extensive libraries for isomer production, but in general, can not be used for publishable results. In addition to limitations of the released version of the FLUKA code, material modelling is especially important for activation studies as a small amount of impurity can account for a large part of the induced activity.

The purpose of this benchmark was to validate estimates of the residual radiation field as predicted with released FLUKA v2011 version and with a simple fix to account for a specific isomer production problem. This will likely be the technique used until the next major FLUKA release.

In this section, measurements and simulations for the inner part of the CMS model are presented. The investigated region is the so-called ‘Tracker Bulkhead’ region shown in the illuminated part of the picture in figure [3.2]. It is a region where extensive work is performed in shutdowns. The picture was taken during the Year End Technical Shutdown (YETS17/18) when all detachable end caps are moved away. The YETS is a unique time each year during Runs for such measurements. For most shorter accesses, and always during collisions, the experiment is in a closed configuration and the area is not accessible. There are various materials present in these inside layers of CMS as well as cabling and mechanical structures. It is well known from
various studies (CMS and other) that the presence of silver often causes overestimation with FLUKA predictions. To visualize, the ambient dose equivalent rate estimations in the Tracker Bulkhead region are presented in figures 3.1. They were prepared for the previous YETS 16/17. The first plot shows estimates calculated with standard FLUKA, whereas for the second plot (figure 3.1b), FLUKA with SESAME, which allows a manual fix to be implemented to isomer production cross-sections, was used. The radiation levels are notably higher in (a) than (b), particularly in tracker regions approximately 100 cm from the beamline. In the air regions close to the tracker bulkhead ($z \sim 300$ cm; $R \sim 100$ cm), results in figure (a) were found to be substantially higher than a few recorded measurements and (b) was found to be in better agreement.

The problem originates from the fact that silver is present in various cable regions in recent FLUKA modelling. The proportion of silver represented is thought to be accurate. However, silver $^{110}$ has two metastable isomeric states, one of which is long-lived metastable (279 days—compatible with LHC shut down periods). With a standard FLUKA v2011 set up, a branching ratio of 50% is applied. However, the production cross-sections in such a region are typically much smaller. The manual fix is thus referred to as a ‘silver fix’ in this thesis where the production cross-sections for specific isomers in the SESAME set up are adjusted to a single more realistic value based on simulations of the prompt radiation field in these particular regions.
The branching ratios in standard FLUKA are defined by the number of atoms decaying by the given decay mode to the total number of decaying:

$$BR_i = \frac{k_i}{k} = \frac{k_i}{k_1 + \ldots + k_i + \ldots},$$

where $k_i$ is the ‘partial’ decay constant, resulting from the half-life of the particular mode of decay. It is important that BRIL compares simulations with data at several shut down and cool down periods. The following describes in more detail the measurements taken in YETS 17/18 and the corresponding simulation process (using FLUKA 2011 SESAME tool with ‘Silver fix’).

**Measurements**

Measurements of the residual ambient dose equivalent rate $H^\ast(10)$ (defined in sec. 2.3) were taken with a simple Geiger-Muller counter (AD6 device, presented in figure 3.3). It is a small and light device with sensitivity cut-off below 60 keV and above 1.3 MeV. It has a measuring range from 0.1 $\mu$Sv/h to 10 mSv/h. The measurements were taken during YETS17/18 on a temporarily added balcony that facilitated access to the most inner parts of CMS layers. Results are presented in figure 3.4 on a sketch of the bulkhead region. There are three measurements taken along the Tracker and ECAL layers (positions 3, 4, 5) and two more along the beam pipe, just outside the Fishing Rod Structure (positions 1, 2). The uncertainty of these measurements
is a systematic error of the AD6 device. It was not given explicitly as it is negligible when compared to the simulation model uncertainty.

Figure 3.2: A picture of the CMS in the open configuration. The measurement area is in the enlightened centre of the picture.

Figure 3.3: AD6 detector used for the ambient dose equivalent measurements.

Figure 3.4: The scheme of the measurement area with exact positions marked and corresponding $H^*(10)$ values. [10]

Measurements with AD6 25 Jan 2018 Evangelina Dimovasili, Sophie Mallows, Joanna Wanczyk
Simulation

The simulation is performed in two separate steps:

- **Prompt Step** which describes the phase of active collisions inside the CMS—radiation is instantaneously transported through the full CMS geometry.

- **Decay Step** includes the residual radiation as a result of the prior step, which is transported through the modified geometry, that corresponds the CMS open configuration at the time of taking measurements.

To apply this two-step strategy the BRIL-developed SESAME tool is used [25]. It allows for a better geometry modification in between steps (standard FLUKA options are limited), as well as a manipulation of the relative abundances of radio-nuclides produced. In this way, the production of the long-lived Silver 110m2 isomer is suppressed to 5%, as recommended by the RP for the typical neutron field in that region.

In the study, the latest CMS geometry description (v.3.29.00) for Run II is used. It includes a detailed implementation of the Tracker Bulkhead region. What is more, there was an intensive crosscheck of ECAL material composition and extensive cable crosscheck performed since the corresponding study from YETS16/17. The geometry structure for the Prompt Step is the standard CMS model as explained in the previous section (figure 2.2). The Decay Step geometry was created by removing all CMS end caps to represent the open configuration. The freed space is filled with air. It is assumed, that in practice the removed parts are moved away far enough so that they do not contribute to the radiation field in the measurement region. This customized model is presented in figure 3.5.

![Figure 3.5: The modified CMS geometry to describe the open configuration. The presented view includes z range 0–10 m from IP. The vertical axis covers 0–5 m from IP in y axis, showing the cross-section of the CMS up to the first Iron Yoke layer.](image-url)
In the first step of the simulation, the FLUKA physical parameters are set as for the activation study. The activation of heavy ion transport, coalescence, and evaporation ensure the correct nuclide production. Additional cards are added to provide the creation of isotopes and to export all the activation information after this step is finished. Before the second step can be simulated, the geometry transformation is performed together with the nuclides present in the manipulated components.

In the Decay Step, the created nuclides have to be loaded from the output files of the Prompt Step. The radiation source has to be set to these isotopes, no additional primary particles are added. It is crucial, to include the profile describing the beam intensities for given irradiation time intervals. In the study, the entire LHC operating period was included. For the Run I (2009–2013) and the first part of the Run II (2015, 2016), the relevant collision periods are merged into intervals by year. The latest period until September 2017 is described in the beam intensity month by month. The last two months before the YETS are divided into week-long periods to improve the estimation of the generated radionuclides in that period. This approach grants a better evaluation of the radionuclides with a half-decay time in order of weeks or a few months. In the ideal situation, intervals should correspond to the lumisections (LS), as they are used for luminosity measurement in the experiment. However, in the case of the activation study, the assumed resolution is sufficient. It was selected to be appropriate for the cooldown times corresponding to the moment of taking measurements. The final segment of the profile is presented in the table 3.1 with a cross-check of the total 2017 CMS delivered luminosity.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Days</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>YETS16/17</td>
<td>26.10 – 24.04</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>24.04 – 31.05</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>01.06 – 30.06</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>01.07 – 31.07</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>01.08 – 31.08</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>01.09 – 30.09</td>
<td>30</td>
</tr>
<tr>
<td>October</td>
<td>1.10 – 7.10</td>
<td>7</td>
</tr>
<tr>
<td>and</td>
<td>8.10 – 14.10</td>
<td>7</td>
</tr>
<tr>
<td>November</td>
<td>15.10 – 21.10</td>
<td>7</td>
</tr>
<tr>
<td>chopped</td>
<td>22.10 – 28.10</td>
<td>7</td>
</tr>
<tr>
<td>into weeks:</td>
<td>29.10 – 04.11</td>
<td>7</td>
</tr>
<tr>
<td>weeks:</td>
<td>5.11 – 11.11</td>
<td>7</td>
</tr>
<tr>
<td>Total delivered [fb^{-1}]</td>
<td>51.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: The final part of the irradiation profile used to describe the collision rate before YETS17/18 that generated the residual radiation present in the beam-off period
Heavy ion runs, machine development periods and other low luminosity periods are considered as cooling time in calculations for the profile. All the corresponding dates were checked with the official LHC Schedule 2017 [18]. In this way, the build-up and decay processes of radionuclides are covered. The integrated luminosity presented in the table was extracted from the database using brilcalc. The CMS delivered luminosity was used, labelled as the best. This data set includes a combination of the best measurements from several luminometers. It was used to calculate the collision rate included in the simulation according to the formula:

\[ \text{PP collision rate} = \frac{\text{delivered luminosity}}{\text{time interval}}. \]

Results

The simulation results for the above-described setup are presented in figure 3.6. The grey marks indicate the measurement positions. The exact values are summarized in the table 3.2. Overall, reasonable agreement was found between the simulation and measurements.

Figure 3.6: Benchmark of FLUKA2011.2x with the measurements in the CMS cavern from YETS17/18

The first position close to the beam pipe has the closest estimation. It is a reassuring finding as it is an area of high dose gradient close to the hotspot which is caused by higher mass of material in regions of pipe joints that include the bellows and flange. Positions 2 and 3 are the closest to the cabling regions where the long-lived Ag isomer is produced. In this case, there
is a slight discrepancy between measurements and FLUKA results. Position 4 is further away from the problematic region hence its influence is decreased.

The ‘silver fix’ is still an approximation as the cross-section would vary from region to region depending on the energy or particles in the prompt field. The next major FLUKA release currently under development would account for this and of course include libraries for branching ratios for all isomers, not just Ag-110. It has been used once with a successful benchmark, but requires special permission for the publication of each result—thus is not a practical option.

This benchmark has shown that the released FLUKA v2011 with a single silver fix can be used for predictions with the current CMS geometry. The statistical uncertainty estimated by FLUKA varies in the investigated region from 1 to 3%. The systematic uncertainties are much bigger. They result from the location determination—finding the exact measurement position is not trivial. To elaborate, the high dose gradient, especially close to the highly activated beam pipe, can cause major differences for near locations. Another thing is the error emerging from the geometry model and material description precision which has the biggest impact. It can vary for different positions.

<table>
<thead>
<tr>
<th></th>
<th>Position 1</th>
<th>Position 2</th>
<th>Position 3</th>
<th>Position 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement</strong> $\mu$Sv/h</td>
<td>27.2</td>
<td>14.3</td>
<td>10.0</td>
<td>8.7</td>
</tr>
<tr>
<td><strong>FLUKA</strong> $\mu$Sv/h</td>
<td>29</td>
<td>23</td>
<td>18</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3.2: Comparison of the exact values extracted from figure 3.6 with the measurements
3.2 Benchmark of the prompt radiation background in the CMS Cavern with RAMSES measurements

It is desirable to understand the ability of CMS FLUKA simulations to predict the prompt radiation in the outer cavern regions and validate its use for shielding studies. Thus part of thesis work includes a comparison of the RAMSES monitor data with the most up-to-date FLUKA model, a comparison that has not been performed since 2012 [30].

In the CMS cavern, there are 10 RAMSES monitors present, however, one of them had to be excluded from the study due to low and rare measurements. It is the PMI5502 which is installed below the CMS structure, on the X0 level. This area is shielded by all CMS layers and the floor from all other sides which results in very low dose levels.

Simulation

For the simulation, the monitors were not inserted in the CMS geometry model. Their volumes were separated from the air that fills the cavern around the CMS and particle spectra were scored around them. It is the special routine provided by the RP group, that identifies the region with the RAMSES monitor response. It includes energy dependent factors for the conversion of fluence to charge created in the monitor in an arbitrary mixed radiation field. The particle spectra are folded with the PMI response functions per particle type. These functions are presented in figure 3.7. The results are obtained in pC×cm². An additional production
threshold for gammas is applied to the PMI regions so that all gammas in the sensitivity range of the detector are included. It is lowered from the standard setting to 80 keV, thus improving the final energy deposition inside the PMI chamber.

As previously described, the CMS model comprises a countless number of elements and is very complex. FLUKA estimations in the remote regions from the IP requires significant computing time, hence a lot of resources are needed to obtain a small statistical error of the results, especially for rarely occurring particles. The simulation comprised of 875400 primaries and the latest available Run II CMS geometry was used. The statistical error obtained for all particle fluence is of an order of ~ 1% close to the cavern walls, even lower in the CMS regions. FLUKA results are always given per primary particle. To compare them with real data they need to be normalized. In the study, the number of events in 2017 (49.79 fb⁻¹) is used to compare with the integrated dose measured by the RAMSES monitors in the cavern for that year. The results for each monitor are presented in table 3.3, total and per particle type contributions are displayed.

There are two pairs of the RAMSES monitors which are located in the symmetric locations at the opposite ends of the cavern. In the FLUKA CMS model, these positions would refer to exactly the same regions due to the 'lattice' FLUKA option as explained in section 2.4.1. It implies that for the paired monitors PMI11, PMI13 and PMI14, PMI15, the results will be completely the same, averaged on the two ends of the cavern. Nonetheless, this approach is beneficial for increasing the statistical precision of the simulated fluxes.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PMI01</td>
<td>49.79 ± 3.7%</td>
<td>10.29 ± 21.7%</td>
<td>12.71 ± 47.4%</td>
<td>8.19 ± 3.4%</td>
<td>1.57 ± 62.4%</td>
<td>0.0 ± 0.0%</td>
<td>82.55 ± 8.2%</td>
</tr>
<tr>
<td>PMI11</td>
<td>42.49 ± 4.0%</td>
<td>5.28 ± 28.8%</td>
<td>13.99 ± 50.4%</td>
<td>6.43 ± 3.9%</td>
<td>1.67 ± 59.2%</td>
<td>0.64 ± 0.6%</td>
<td>70.5 ± 10.6%</td>
</tr>
<tr>
<td>PMI12</td>
<td>37.84 ± 4.1%</td>
<td>8.37 ± 24.1%</td>
<td>13.03 ± 63.4%</td>
<td>6.72 ± 3.8%</td>
<td>0.87 ± 58.6%</td>
<td>0.53 ± 99.0%</td>
<td>67.35 ± 12.9%</td>
</tr>
<tr>
<td>PMI13</td>
<td>42.49 ± 4.0%</td>
<td>5.28 ± 28.8%</td>
<td>13.99 ± 50.4%</td>
<td>6.43 ± 3.9%</td>
<td>1.67 ± 59.2%</td>
<td>0.64 ± 0.6%</td>
<td>70.5 ± 10.6%</td>
</tr>
<tr>
<td>PMI14</td>
<td>206.83 ± 2.1%</td>
<td>12.42 ± 21.0%</td>
<td>45.92 ± 28.0%</td>
<td>27.34 ± 1.9%</td>
<td>8.85 ± 37.5%</td>
<td>8.79 ± 36.1%</td>
<td>310.15 ± 4.7%</td>
</tr>
<tr>
<td>PMI15</td>
<td>206.83 ± 2.1%</td>
<td>12.42 ± 21.0%</td>
<td>45.92 ± 28.0%</td>
<td>27.34 ± 1.9%</td>
<td>8.85 ± 37.5%</td>
<td>8.79 ± 36.1%</td>
<td>310.15 ± 4.7%</td>
</tr>
<tr>
<td>PMI21</td>
<td>43.41 ± 4.2%</td>
<td>7.89 ± 28.3%</td>
<td>10.66 ± 46.1%</td>
<td>6.69 ± 3.9%</td>
<td>3.87 ± 34.4%</td>
<td>2.42 ± 42.1%</td>
<td>74.88 ± 7.9%</td>
</tr>
<tr>
<td>PMI22</td>
<td>40.48 ± 4.3%</td>
<td>4.78 ± 27.4%</td>
<td>8.87 ± 57.3%</td>
<td>6.7 ± 3.9%</td>
<td>6.86 ± 26.8%</td>
<td>1.19 ± 99.0%</td>
<td>68.88 ± 8.6%</td>
</tr>
<tr>
<td>PMI31</td>
<td>7.51 ± 7.3%</td>
<td>1.73 ± 46.1%</td>
<td>0.0 ± 31.0%</td>
<td>2.58 ± 6.0%</td>
<td>0.0 ± 0.0%</td>
<td>0.0 ± 0.0%</td>
<td>11.83 ± 8.3%</td>
</tr>
</tbody>
</table>

Table 3.3: RAMSES simulated integrated charge for 2017, per particle type and their sum in the last column.

In order to interpret the above-presented results, the radiation field composition for the PMI locations needs to be understood well. In figures 3.8–3.13, the ratios of the simulated fluences per particle type to all particles fluence are presented. In this way, the huge neutron contribution can be explained. In the RAMSES locations, about 60% of all particles are neutrons. However, low the response of RAMSES to neutrons is when compared to charged particles, the abundance of low energy neutrons close to the cavern walls generates most of the charge inside most of the monitors. The neutron contribution is the most prominent for the PMI14 and PMI15. These
are the monitors located on the balcony over HF, closer to the centre of the cavern. In these areas, higher energy neutrons are expected to escape from HF. The response of the monitors in this energy range is an order of magnitude higher than for low energy neutrons. The second most common particle type in the RAMSES locations is a photon, it constitutes about 40% of all particles. However, the PMI response to photons is several times lower than to neutrons, hence the contribution is less significant. Electrons and positrons amount to about 1% of all particles in the monitors’ locations. Their contribution as well as for all other charged particles is essential, despite the low number of these particles. Protons, Pions, and Muons constitute only fractions of a percent of all particles. Their rare occurrence results in a high statistical error for the simulated charge generated by these particles.

**Real data**

To perform the benchmark, the measured dose rates in 2017 were obtained from the ERGO database. They are saved in the units of Sv/h since their main aim is to measure the ambient dose equivalent rate in photon fields (in the beam off periods). However, they also provide a good indication about Gy deposited in air in mixed radiation fields for the beam on periods. The conversion from coulombs collected in the chamber to the dose is linear as stated in the technical note describing RAMSES monitors [14]. The summed charge values for the entire 2017 are presented in table 3.4. The systematic uncertainty for these values is problematic to define due to the logarithmic sensitivity range of the monitors. What is more, it depends on the calibration and electronics drift. Taking into account previous tests and benchmarks it is expected to be of an order of a few percent in case of dose rates which are far from the sensitivity thresholds. To conclude, the error is assumed to be much lower than errors for the simulation results, hence they would have a minor contribution to the final error.

<table>
<thead>
<tr>
<th>Real data [μC]</th>
<th>PMI01</th>
<th>PMI11</th>
<th>PMI12</th>
<th>PMI13</th>
<th>PMI14</th>
<th>PMI15</th>
<th>PMI21</th>
<th>PMI22</th>
<th>PMI31</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.90</td>
<td>58.01</td>
<td>54.65</td>
<td>50.59</td>
<td>281.27</td>
<td>202.79</td>
<td>47.35</td>
<td>37.15</td>
<td>3.54</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Charge generated in all RAMSES PMI monitors in 2017

The data from the CMS cavern indicates similar dose levels for all monitors located close to the cavern walls installed at the IP level (X3) and lower (PMI01, PMI11, PMI12, PMI13). Monitors PMI14 and PMI15 read much bigger rates as they are located closer to the IP and they are exposed to higher energy particles and higher possibility of charged hadrons detection. Monitors PMI21 and PMI22 have lower exposition as they are located at the very ends of the cavern on the last floor (X5). The last monitor PMI31 has the smallest amount of charge generated over the year. It is due to its location among the electronics racks additionally shielded by the muon chamber layers.

The readings are always higher on the positive end of the cavern when the symmetrically located monitors are compared (PMI14 to PMI15, PMI21 to PMI22, PMI11 to PMI12 or
PMI13). It means that the radiation field, that the PMI chambers are exposed to in the experimental site is not fully symmetric. It is a known dependency, having a source in the cavern asymmetries, especially the shaft which is located only on the $-z$ end.

**Benchmark**

To assess the results, the ratio of the simulated values to the measured charge is calculated. It is presented in table 3.5 per each monitor.

<table>
<thead>
<tr>
<th>Ratio sim/meas</th>
<th>PMI01</th>
<th>PMI11</th>
<th>PMI12</th>
<th>PMI13</th>
<th>PMI14</th>
<th>PMI15</th>
<th>PMI21</th>
<th>PMI22</th>
<th>PMI31</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.40</td>
<td>1.22</td>
<td>1.23</td>
<td>1.39</td>
<td>1.10</td>
<td>1.53</td>
<td>1.58</td>
<td>1.85</td>
<td>3.34</td>
</tr>
</tbody>
</table>

Table 3.5: The ratio of simulated to measured charge for RAMSES monitors

In general, the results validate the reliability of the FLUKA estimations with the CMS model, as most of the ratios are close to 1. It is important to note that this order of precision was rather unexpected as the monitors are located in the outer cavern. These areas are normally neglected as most simulations focus on the impact on CMS subsystems. What is more, the conversion factor from charge to the dose rate is based on a calibration with Cs–137 gamma source, hence it is not meant to be applied for prompt radiation. The ratio for PMI31 deviates the most. It can indicate the material description imperfections. The PMI31 is the only monitor located between the electronics racks which are one of the most simplified elements in the CMS model. Moreover, it is a low dose area, the readings of this monitor are much lower than for the rest of the monitors. There is a significant difference between the charge accumulated in the chambers PMI14 and PMI15. Consequently, the ratio with simulated values which are averaged on both ends is lowered for PMI14 and overvalued for PMI15.

![Figure 3.8: Ratio of neutrons to all particles](image-url)

Figure 3.8: Ratio of neutrons to all particles
Figure 3.9: Ratio of photons to all particles

Figure 3.10: Ratio of electrons and positrons to all particles

Figure 3.11: Ratio of protons to all particles
Figure 3.12: Ratio of pions to all particles

Figure 3.13: Ratio of muons to all particles
3.3 Background in Muon Chamber ME4/2—investigation with FLUKA

Motivation

In this section, an example of specially designed FLUKA simulation for the background radiation investigations in the CMS cavern is presented. It aims to show that the well benchmarked CMS model can be used not only for general estimations but also for more specific problems associated with the experiment operation. The problem that this part focuses on arose from incomprehensible signals reported in one of the sections of the Muon Chambers system. In one layer of the CSC (sec. 1.3) a clearly increased and $\phi$-asymmetric trigger rate was spotted in 2015. The concerned region is generally called ‘ME4/2’ disc as it is the fourth (and the last) layer of the Muon Endcap. The ‘/2’ in the name refers to the section of the disc which is further from the beamline. It is the only directly exposed endcap of the muon system as all other profit from the shielding provided by the massive iron yoke.

In the study, a strategy to understand the problem using the Monte Carlo event generator is introduced. The objective is to collect a wide range of information for each particle entering the disc. It would approve a thorough analysis with a possibility for a deep insight into particle groups, split by their characteristics. The advantage is that the data simulated once can be filtered and scrutinized in various ways. It is important to note that the presented results are preliminary and do not give an exhaustive explanation to the problem, as it extends beyond the content of this thesis. Further analysis of the simulated data is ongoing to fully understand the issue.

Simulation

To give an overview of the previously described region, its FLUKA model is presented in figures 3.14 and 3.15. The former shows the $x-y$ cross-section of the CMS model at $z = 1025$ cm. The interesting region was marked with red lines. In the latter figure, there is the $x-z$ cut. In this view, the thickness of the disc is visible, also marked in red. Beyond the discussed area, along the $z$ axis, there is only YE4 (green rectangle)—the last Yoke Endcap. The geometry model included in the study is the nominal version for the CMS configuration in the Run II. The latest available FLUKA version was used (FLUKA2011.2x) to simulate 4 million proton-proton events in the Run II conditions. Energy per proton was set to 6.5 TeV and the crossing angle at which the beams collide to 285 $\mu$rad.

The default FLUKA scorings have limited options and always give an averaged results per primary particle. They cannot be used to obtain detailed information on each particle crossing the ME4/2 boundaries. It is necessary to create an event interface with a customized output. FLUKA offers several user routines that can be used to achieve that \[11\]. The implementation
of those templates is in FORTRAN format and can be modified by the user. In this way, external packages can be used. Furthermore, the insertion of further calls to user-defined routines is possible. A special command in the standard input file is required for the routines to be activated.

In the study, the MGDRAW subroutine is used. It records a list of all selected transport events depending on the entry used. In this case, BXDRAW entry is used which is called at boundary crossing as the particles entering ME4/2 are of interest. There are many other entries available called at event end or allowing for trajectory drawing, energy depositions recording, etc. There is no default output, hence the argument list to be recorded is supplied. It includes attributes as follows:

- number of the primary proton-proton collision that the particle originates from
- type of particle by particle code
- kinetic energy of the particle (total energy - rest mass, units [GeV])
- location of the particle crossing the boundary, saved as coordinates \((x, y, z)\) in [cm]
- momentum of the particle (units [GeV/c])
- weight of the particle, in the study, always equals one, as no biasing is applied
- age of the particle (units [s])
- total curved path
- direction cosines of the current particle for all coordinate axes \((\cos \theta_x, \cos \theta_y, \cos \theta_z)\)

The one-way boundary crossing estimator is applied. It means that only particles crossing from outside air to inside of the CSC regions are registered. The involved boundaries have to be indicated inside the routine. The user can also apply a filter already in this step. As was
presented in the previous section (3.2), neutrons constitute most of the radiation field in the CMS cavern. Exploring in more detail the ME4/2 areas in figures 3.8–3.9 gives a possibility to foresee that the simulation output will mostly comprise of neutrons and photons. However, the CSCs are multi-wire proportional chambers with very low sensitivity to these particles. For neutrons, the sensitivity is lower than $\epsilon_n < 10^{-4}$, due to small gas volume and lack of hydrogen in the operating gas. For photons it is $\epsilon_\gamma \sim 1\%$ for $E_\gamma = 1$ MeV \[2\]. Given these circumstances, an additional filter was included inside the MGDRAW routine to save only electrons, positrons, and charged hadrons. This approach is also beneficial for the processing time and the amount of allocated memory. It is crucial, as according to the plan four million events were simulated. This enormous number is necessary to observe the rare particles in the ME4/2 region and have enough data for further analysis. The output was carefully checked against the standard FLUKA scorings in the first step.

**Results**

To visually show the asymmetries described in the motivation, the output data is presented in figures 3.16 and 3.17 in the form of particle densities on both sides of the ME4/2 (the flat parts of its toroidal shape). Both sides are labelled with their $z$ distance from the IP and correspond to IP ($z = 1010$ cm) and YE4 ($z = 1027$ cm) side with intention of a better understanding where the particles come from. These labels are used with the same meaning in the following figures in this section.

![Figure 3.16: Electron and positron densities on the outside flat surfaces of the ME4/2](image)

(a) $z = 1010$cm
(b) $z = 1027$cm

Figure 3.16: Electron and positron densities on the outside flat surfaces of the ME4/2

The first striking feature in the figures for the YE4 side is the lower density in the bottom part of the disc. This asymmetry was also spotted in the CSC rates and it is easily explainable. It is a result of the mechanical design of the subsystem located just after the Muon end caps—the HF. Its dimensions are much smaller than ME and it is supported by raisers from the
Figure 3.17: Charge hadrons densities on the outside flat surfaces of the ME4/2

ground. To illustrate, the HF raisers model is included in the CMS geometry and it is visible in figure 2.2 about 11 m in z from the centre in dark-brown colour, labelled as ‘HFRise1’. The albedo created at the end wall of the experimental hall by the punch-through particles is reduced by the HF raisers material. The density reduction is less, but still visible for electrons and positrons coming from the IP side. The origin is the same as these particles are very light and they scatter much more than hadrons. Returning to the problematic asymmetry—it comes from the upper part of the ME4/2. A trace of it is visible in figure 3.17b at y ~ 600 cm.

The analysis focuses mainly on the timing information. The output is in the form of a recording tape which allows for the application of feasible, script-based filtering on any available variable. An example is shown in figure 3.18 where two groups of particles are separated and a comparison of arrival time for particles entering ME4/2 from different sides is presented.

Figure 3.18: The comparison of arrival time on both sides of ME4/2 per particle group

There are many more particles coming from the YE4 side because outside YE4 is the open
cavern and the secondary particles can travel freely. The timing distribution for $e^{+)/-}$ actually starts about 35 ns after the collision. It is the time needed for a particle travelling with (almost) the speed of light to cover the distance from IP to the first surface of ME4/2 (10.1 m). The charged hadrons distribution starts slightly later, about 50 ns after the collision. In figure 3.18a, the particle count increases up to a characteristic peak at $t = 95$ ns. This cannot be related to the albedo coming from the cavern wall as 90 ns is the minimum time needed for a particle to reach the cavern wall in a straight line, without taking into account coming back. However, there is one more bulky, thus active element located closer that can play a crucial role. The TAS (its absorbers) which is installed at $z \sim 20$ m. It is well shielded, however, there are a few inevitable gaps, through which some particles can escape to the outer cavern. The minimum time needed for a particle to be scattered from TAS (at a narrow-angle) is about 95 ns, which matches the time when $e^{+)/-}$ arrive at ME4/2 at the highest count.

The distributions change in the same way with time for both sides. However, on the YE4 side, the particle count is almost twofold the IP side count as of the peak. After the peak, particle count decreases with time as the particles lose their energy. The corresponding distributions for charged hadrons are completely different (figure 3.18b). On the IP side, the maximum occurs just after the primary collision at $t \approx 70$ ns. Whereas for the YE4 side, the rate is also high in the beginning, however, it still rises until $t = 130$ ns.

As was mentioned before, the interesting asymmetry is located in the upper part of the ME4/2 segment. To compare the upper and lower halves, the previously presented distributions are separated by y coordinate—below and above the beamline. The results are presented in figures 3.19 and 3.20.

![Figure 3.19: Arrival time for upper and lower halves of ME4/2 per side for $e^{+)/-}$](image)

Distributions for $e^{+)/-}$ in figures 3.19 exhibit a generally lower particle count in areas below the beamline. It is a result of the cavern asymmetries which was confirmed in the additional study (described briefly in the next subsection 3.3.1). Results for charged hadrons in figures
Figure 3.20: Arrival time for upper and lower halves of ME4/2 per side for charged hadrons verify there is no difference in the case of particles coming from the IP side. On the YE4 side, a significant discrepancy is evident. The high particle rate in the upper half of ME4/2 appears at $t \approx 125 \text{ ns}$.

To narrow down the area of the investigated segment of ME4/2, a cut on $x$ coordinate was added. The included area is marked by a red frame in the geometry view in figure 3.21. The high occupancy area is assumed to be constrained by $|x| < 100$ cm.

Figure 3.21: $x - y$ view of the ME4/2 with the cut on $x$ marked in red frame

The resulting timing distributions are presented in figures 3.22 and 3.23. A clean peak emerges in figure 3.23b. Additionally, the $\cos \theta_z$ distributions were prepared for the small ME4/2 region. The results are presented in figure 3.24. The most common value for $e^{+/–}$ at both halves is $\cos \theta_z = -1.0$. It corresponds to a particle travelling along the $z$ axis but in
the opposite direction, hence arriving perpendicularly to the ME4/2 plane. The smaller the angle between particle direction and $z$ axis the lower the particle count. The maximal value $\cos \theta_z = 0.0$ means the parallel direction of the particle to the ME4/2 flat surface. On the other hand, the distribution for charged hadrons varies for both halves. In the upper part, the count follows the same behaviour but it is steeper than for $e^{+/−}$. That means the ratio of particles arriving at a high angle, up to $140^\circ$ is higher, while in the lower half the distribution is rather uniform. The direction of all charged particles is influenced by the magnetic field of the CMS solenoid. It makes the identification of the primary direction and thus the source of these particles ambiguous.

Figure 3.22: Arrival time for upper and lower halves of ME4/2 per side for $e^{+/−}$

Figure 3.23: Arrival time for upper and lower halves of ME4/2 per side for charged hadrons
3.3.1 Cavern asymmetries impact cross-check

To verify the assumption that the difference of $e^+/-$ entering ME4/2 in the lower and upper halves stems from the cavern asymmetries, a side study was conducted. The CMS geometry used in the previous section was modified. The floor was removed and at its place, the same shape as the ceiling was implemented. In case of some asymmetric elements in the cavern (e.g., electronics racks and HF raisers) the assigned material was simply changed to air. The resulting geometry is presented in figure 3.25.

Figure 3.25: The modified CMS geometry—all outer cavern asymmetries removed
In this way, the impact of the asymmetric cavern elements on the results can be assessed. As it is just a crosscheck, the simulation comprised of many fewer primary events, to be precise half a million proton-proton collisions. The other simulation settings were adapted from the main study. The results are presented in figures [3.26]. Only a slight difference between upper and lower halves remains for the $e^{+/-}$ entering on the IP side. It is presumably a cause of a few small asymmetric geometry elements left unchanged: blockhouse, an ion pump, gaps, regions around TAS (including the two gaps at the top). Nevertheless, it can be already concluded that the cause of lower $e^{+/-}$ number for $y < 0$ is the multiple scattering on asymmetric parts. They are located mostly far in $z$ direction, whereas the difference we try to understand is visible for particles coming from closer $z$.

![Figures 3.26](image.png)

(a) IP side  
(b) YE4 side

Figure 3.26: Arrival time for upper and lower halves of ME4/2 per side for electrons
3.4 Radiation level changes with RAMSES measurements

Introduction

As it was verified in section 3.2 the RAMSES radiation protection monitors can be used to benchmark simulations. The purpose of this section was to observe if the RAMSES data could be used to observe changes as minor modifications were made to the shielding structures in CMS during LHC Run II. At the time of writing, the additional structures are not included in the CMS geometry model (such modification require significant manpower) and will likely be added in one step for a comparison study to be performed in the future. However, observations of the measurements alone provide crucial feedback to the efficiency of shielding arrangements that will continue to be developed in the lead up to the HL-LHC era.

To give an idea of the typical RAMSES readings for conditions where luminosity is close to the peak luminosity, a map of registered values on 25.08.2018 at 5:40 is shown in figure 3.27. It was measured during a fill with the peak luminosity of $1.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

![Figure 3.27: The map of the RAMSES measurements during a high luminosity fill](image)

The values are lower in the outer than in the inner part of the cavern. It can be easily noticed that when two monitors in the symmetrical locations (to the IP) are compared, the values are always higher on the positive end of the cavern (the left side of the figure). They can also vary depending on the floor they are installed. The balconies in the experimental hall have six floors and are marked from X0 to X5. The first one denotes the level below the CMS
structure and the last one is almost on the same height as the top of the Muon Chambers. The vertical location of all monitors is collected in table 3.6.

<table>
<thead>
<tr>
<th>Monitor</th>
<th>PMIL5502</th>
<th>PMIL5501</th>
<th>PMIL5511/12/13</th>
<th>PMIL5514/15/31</th>
<th>PMIL5521/22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>X0</td>
<td>X1</td>
<td>X3</td>
<td>X4</td>
<td>X5</td>
</tr>
</tbody>
</table>

Table 3.6: Vertical locations of the RAMSES monitors

The performance of the monitors was also tested against the instantaneous luminosity during a fill. The comparison of one of the monitors—PMIL5511 is presented in figure 3.28. The luminosity values are the measurements provided by the HF (HFET). The same fill is used as in the previous figure.

Figure 3.28: The comparison of the RAMSES measurements (PMIL5511) with instantaneous luminosity (HFET) during a high luminosity fill. The dose rate is plotted in blue and the luminosity in red.

There is no saturation visible, the monitors’ measurements are stable and they follow the luminosity slope evidently. Any electronic drift is negligible. As expected, some differences are visible in quick luminosity changes: in the beginning, luminosity levelling and the beam dump. The reason is that the two compared devices have different averaging times for measurement.

Results

The study includes RAMSES data from the entire Run II period. Technical stops are targeted for investigations. Modifications in the cavern are possible only in these periods as there is
no beam and the area is accessible. Mainly, the maintenance work is performed on the sub-detectors but also the shielding around them. In order to address radiation leaks, additional shielding is adjoined. Commonly the most complex shielding area is addressed—the Rotating Shielding (RS) which surrounds the part of the beam pipe between the cavern wall and the CMS. In the following part, the main modifications are explained along with their impact on the radiation field in the cavern observed by the RAMSES monitors.

To begin with, the YETS15/16 was considered. There were two main modifications to the RS and HF area performed in that period. The first one concerned only $+z$ end of the cavern. The issue was a gap in the Thin Section of the RS. The shielding consisted of three plates installed inside upper and lower halves of the RS. They were positioned on both sides of the RS so that they overlap in the closed alignment, as presented in figure 3.29. The grey plate is made of steel and has dimensions $25 \times 100 \times 2240$ mm, the green ones are made of borated polyethylene (5%) and have dimensions $22.5 \times 200 \times 2600$ mm. The second modification concerned the area of the RS surrounding HF. The shielding was added at both $z$ ends of the cavern. It consisted of three segments: two steel plates on far and near sections with dimensions $10 \times 150 \times 3466$ mm, on the top of them there was one steel bar with dimensions $50 \times 50 \times 3460$ mm, surmounted by two layers of high density borated polyethylene with dimensions $45 \times 500 \times 3200$ mm. The visualization of the shielding is presented in figure 3.30. The entire section concerned for additional shielding is marked in the red frame on the HF-RS top view in figure 3.31.

![Figure 3.29: The first modification in the RS during YETS15/16—green and grey plates filled the gap in the Thin Sections on $+z$](image)

To identify the impact of the previously described changes on the radiation levels, the RAMSES detected absorbed dose per fb$^{-1}$ was investigated. The dose rates were summed over all the stable fills in 2015 and 2016 and normalized to the total integrated luminosity defined
for the physics analyses:

\[ L_{2015} = 2.93 \text{ fb}^{-1} \ (\pm 2.3\%), \quad L_{2016} = 39.28 \text{ fb}^{-1} \ (\pm 2.5\%). \]

The outcome is presented in figure 3.32 on the layout of the RAMSES monitors in the CMS cavern. The number next to the monitor label corresponds to the ratio of the total absorbed dose per fb\(^{-1}\) from 2016 to 2015. The uncertainty is 3.7\% assuming 1\% error for each RAMSES sum.

The ratio for PMIL5502 is not included as it is the low rate monitor with not reliable sum. Its measurements were hardly above the monitor’s sensitivity threshold. Firstly, it is observed that the monitors located over HF and its newly added shielding (PMIL5514 and PMIL5515) feel the relative drop of the escaped radiation by 10 – 16\%. Secondly, all other monitors located on the +z, apart from PMIL5511, indicate about 10 – 11\% reduction, while the ones located on –z, apart from PMIL5512, show only 2 – 3\%. The shielding effect of borated polyethylene and steel is visible mostly on +z, as expected. The two omitted monitors are problematic as they have belittled values for 2015. It is suspected that they might have been moved in that time, however, it is difficult to verify. What is more, there is much less data for that year than for the following years as it was only the beginning of the Run II period. The LHC was advancing the performance, thus there not many fills with stable beams declared.
During the next YETS, at the turn of 2017, the symmetric gap in the Thin Section of the RS was filled on the negative end ($-z$). The same materials and dimensions were used and the installation was done in the same manner. Both ends were eventually in the same configuration. The ratios were calculated in an analogical way as for previous YETS, using the same 2016 total integrated luminosity and for 2017, according to the Luminosity Physics Object Group:

$$L_{2017} = 49.79 \text{ fb}^{-1} (\pm 2.3\%).$$

The results are presented again on the CMS layout in figure 3.33.

Similarly, as in the case of the same shielding at the other end, there is a drop of $7 - 11\%$ for all of the monitors on the negative end. The total uncertainty of each ratio is $3.7\%$. The ratio of the monitors located on the $+z$ is very close to 1 apart from monitor PMIL5514. It is most certainly the effect of the gaps in the shielding around HF, very close to that monitor. Moreover, this element is frequently open for maintenance during Technical Stops. It is quite a complicated mechanical structure, therefore the alignment of the gaps can differ at each closing. This can result in the observed anomaly.
During the last YETS of Run II, at the turn of 2018, the previously inserted plates into the gaps in the Thin Section of RS were exchanged. The ones made of borated polyethylene were substituted with steel on both ends of the cavern. The concerned RS section is coloured in blue in figure 3.34.
The ratios of the normalized dose for the year following that modification to the previous one are presented in figure [3.35]. The overall decrease in radiation levels is noticeable. Excluding the monitor PMIL5502 located in the low dose areas, the reduction of dose ranges from 5 to 17%. The uncertainty per each monitor amounted to 5.7%. The normalization for 2018 is the total integrated luminosity until the 9th September (the time of calculation):

\[ L_{2018} = 55.32\text{fb}^{-1} (\pm 5\%). \]

Figure 3.35: Ratio 2018/2017 of total absorbed dose per fb\(^{-1}\) for all RAMSES monitors
3.5 Neutron flux measurement with the Medipix3RX-based cameras

Introduction

The main aim of this part of the thesis was to obtain the intermediate and high energy neutron flux measurement using recently installed Medipix3RX neutron cameras in the CMS cavern. The network of cameras and their locations are described in the introduction (section 2.6). It is the first attempt to analyse the data collected at the end of Run II. It was performed to check the usability of the acquired data as well as to study the detector performance. The presented approach is only an initial step in the process of commissioning the cameras for the online neutron flux measurement.

The dataset consists of seven LHC fills collected in a configuration for higher energy neutron measurement. This configuration includes short exposure times ranging from 10 to 60 s combined with DAC thresholds varying in the range of 60–130. The thresholds are changed in steps of 10, corresponding in the High Gain Mode to the change of 1 nA or 29 e⁻. Examples of frames are presented in figure 3.36

Figure 3.36: Example frames registered on all working chips during Run II, fill no. 7328. Settings: DAC = 100, shutter time = 10 s, inst. luminosity: 17.419 [10^{33}/cm²/s]
At first glance, the dependency of the multiplicity of tracks on location is clear. It is similar for HFX3 and X3FORWARD locations, which are close to each other, separated mainly in the horizontal distance from the beamline. A much denser signal is registered on the sensors in the HFTOP location. Both cameras installed close to the HF are affected by high energy particles escaping through the gaps in the HF shielding. In the case of the last detector in the X3IP location, the frame is practically empty. It was foreseen as this is the lithium covered sensor built for the low energy neutron detection. There are very low particle rates in this location, the camera is hidden among the electronics racks. What is more, the exposure and DAC threshold settings would have to be optimized for the low energy neutron measurement. Therefore, it is excluded from further considerations in this section.

Data processing and reconstruction

To recognize and count traces, a Blob Finder algorithm was implemented. It was based on the MAFalda framework [19], though built in Python as it includes all necessary modules to read the format of the acquired data files. Moreover, the Anaconda Python distribution facilitates data analysis and allows for quick development. The program analyses the dataset provided in the input, frame by frame. It uses multiprocessing, hence shortens the execution time by taking advantage of all CPU cores. A blob is defined as a cluster of pixels in an image including the signal. The algorithm searches a frame for signal positions, row by row. The signal position denotes indexes (row, column) of the signal occurring in the frame. At each of those positions, a spiral is built from all adjacent pixels. Then, the spiral is checked if it includes the minimum number of pixels with the signal to be a blob (adjusted by the user). If the condition is met, the blob is followed until all neighbouring pixels are included. Additionally, the parameter of discontinuity can be set. It provides the inclusion of close but not adjacent pixels, within a distance depending on its value.

Multiple tests were performed to optimize the settings mentioned above. The length of the spiral was set to 9 to include the first order of adjacent pixels. It is expected that the higher the number of pixels in the blob, the lower the blob count as the small blobs are effectively excluded. The recoiled protons coming from PP layer are expected to excite at least four pixels, forming a square as presented in figure 3.37a. However, setting the minimum number of pixels for a blob to be 4 leads to the inclusion of additional patterns, examples are presented in figure 3.37b. The first one shown on the left-hand side is an example resembling rather an electron than proton trace. The inclusion of such traces can slightly inflate the blob count. On the other hand, the blob count can be slightly deflated by the disability of the algorithm to separate overlapping traces. The other example, on the right-hand side, is an ambiguous trace. It could be left by a proton as well as other particles.

All things considered, the discussed problems should not have a serious impact on the final result as most of the protons are expected to excite more than four pixels. To suppress the
false track count, the minimal number of pixels in a blob was eventually set to 5.

Secondly, the discontinuity parameter was investigated. It was understood that some traces are not continuous, especially the long ones. The parameter was set to the distance of 1 pixel. As a result, the blob count boosted, up to twofold. Further increase of the parameter might cause the merging of close tracks. To illustrate the performance of the program, a data frame and the corresponding reconstruction of blobs are presented in figure 3.38. Colours were used to indicate pixels belonging to the same blob.

All the Run II data frames were processed in the same way. The results were normalized per lumisection (approximately 24 s) for the comparison. In the program, a very tolerant maximal occupancy threshold is set, frames are analysed provided their occupancy is below 50%. For this reason, many frames from the HFTOP location were skipped. An example fill is shown in figure 3.39.

The number of reconstructed blobs per lumisection is plotted in different colours for each DAC threshold. In black, the CMS measured instantaneous luminosity is shown for comparison—its values are marked on the vertical axis on the right-hand side. During a fill, data is collected...
Figure 3.39: Reconstructed blob rate and corresponding luminosity values in the same period. The axis on the left shows the amount of the reconstructed blobs per lumisection. Each DAC threshold used in that fill is plotted with a different colour. The right-hand side axis shows the instantaneous luminosity values, which are plotted with black points in a sequence of changing shutter times and DAC thresholds. If all of the frames would be analysed by the program, the number of points should be similar per each configuration. However, it is observed that the lower the DAC threshold, the more points are missing. What is more, for the set including data with the highest threshold an evident branching is present. It is believed to be an indication of the reconstruction efficiency loss caused by the high concentration of tracks. The problems persist for all frames acquired in the HFTOP location, hence the data seems unusable with the applied algorithm.

To determine the occupancy level for the branching effect, the percentage occupancy per each frame was tested. The HFX3 location data was used with two different DAC thresholds. The reconstructed data is presented in figures 3.40 with separated shutter time settings and the corresponding occupancy levels are presented below in figures 3.41.

In figure 3.40a the branching occurs at occupancy level of approximately 10 – 15%—the values were read from the corresponding figure 3.41a. To validate that range, the results for higher DAC threshold are presented in figure 3.40b which does not exhibit any reconstruction efficiency loss. The corresponding occupancy levels are always below 11%, as shown in figure 3.41b. The conclusion was made to rely only on the low occupancy frames in the further flux calculation.
Figure 3.40: The number of reconstructed blobs per lumisection detected in the HFX3 location during fill no. 7314. Different DAC thresholds are plotted separately and each of them includes three sets of shutter time settings plotted with different colours.

Figure 3.41: Occupancy of the PP-covered chip in the HFX3 location at the time of measurements presented previously in figures 3.40.

As the blob count is highly dependent on the DAC threshold value, two separate approaches were planned. In the case of the low threshold (60–100) the subtraction of background from the uncovered detector is applied. However, due to the above-described saturation problem, the frames have to be carefully selected. The data with a high threshold (110–130) was treated as a
pure signal. This procedure is essential for the detector in the X3FORWARD location, as there is no working uncovered sensor. Unfortunately, the energy values corresponding to the applied DAC threshold are unknown due to the unstable reference voltage. The issue arises from the hardware implementation stage and needs to be addressed before the Run III operation.

During the data processing, it was quickly discovered that the difference between the covered and uncovered detectors in one setup is smaller than expected. The detectors are aligned parallel to the beamline and separated by 5 cm distance in the case of the camera installed in the HFX3 location. Taking into account the proton stopping power in the air, one can conclude that protons recoiled by a neutron in the PP layer can actually traverse the distance between the two sensors. For the HFX3 camera setup, their energy has to be above $\sim 1.5$ MeV. The impact on the uncovered sensor was studied during the calibration with the high energy neutron source and is described in the next paragraph. Nevertheless, it was established that the second approach with the high DAC threshold is more accurate for the flux calculation.

**Calibration**

To convert the obtained blob count into the flux, the calibration coefficient needs to be defined. It was obtained during the calibration at the CERN’s facility with an Americium-241/Beryllium (Am-241/Be) neutron source with an activity of 888 GBq. Most of the decaying neutrons have energy in range $0.1 - 10$ MeV with the most probable value of $4.2$ MeV. The cameras were tested at 70 cm distance from the source providing the flux of $100$ n/s $\times$ cm$^2$. The DAC threshold was adjusted to remove the gamma-rays contribution. For all experiments, frames were acquired with a fixed shutter time of 15 s.

The first test was aimed at measuring the contribution of the low-probability neutron nuclear reactions in silicon $^{28}$Si($n,p)^{28}$Al and $^{28}$Si($n,\alpha)^{25}$Mg. The uncovered sensor was used, giving the most common value of one blob per frame. However, the deviation was quite high from 0 to 3 blobs. For further calibrations, it is planned to acquire more frames and obtain better reliability of the results. On average, the contribution of the silicon layer to the neutron signal is estimated to be $1.5 \pm 1.1$ blobs per frame.

The second test was performed with the PP covered sensor. From this setup, the calibration coefficient was obtained. The average blob count was $9.8 \pm 3.2$ per frame.

The acquired data had to be normalized to the flux units. The blob count was divided by the shutter time and the area of the chip ($\sim 1.98$ cm$^2$). To calculate the calibration coefficient, a simple equation was applied:

$$\text{Calibration coefficient} = \frac{\text{Flux}}{\text{Blobs}} \left[ \frac{1}{\text{s} \times \text{cm}^2} \right],$$

and the resulting calibration coefficient was $C_{\text{coeff}} = 302.3 \pm 100.4$ (33%).

The PP covered detector was designed so that the conversion layer does not touch the fragile surface of the sensor. It is fixed at approximately 1.5 mm in distance. The following test was
performed to investigate the influence of the PP layer moved 10 cm away. The average blob count was equal $4.1 \pm 1.9$. It is about 42% of the total signal in the PP covered detector. This experiment explains the previously mentioned problem with the low difference in blob count for two detectors forming a camera. In the case of the camera located in HFX3 position the distance between detectors is twice smaller (5 cm), hence one can expect a much higher impact on the uncovered detector as extra protons with slightly lower energies can cover that distance.

**Flux results and comparison**

As the data frames acquired in the HFTOP and HFX3 locations are either saturated or suffer from the reconstruction efficiency loss, a reliable flux measurement can be obtained only from the camera in the X3FORWARD location.

The following results concern only one of the acquired fills (no. 7334), as an example. Firstly, the combined blob count from two exposure times (30 s and 50 s) was plotted along with the instantaneous luminosity. The comparison is presented in figure 3.42. It is observed, that the blob rate follows the luminosity slope. The sudden luminosity changes, for example, luminosity levelling by LHC operators and emittance scans, last too short for the cameras to observe with precision.

![Figure 3.42: The reconstructed blob rate compared with the instantaneous luminosity along the fill no. 7334](image-url)

Figure 3.42: The reconstructed blob rate compared with the instantaneous luminosity along the fill no. 7334
To evaluate the spread of the constant of proportionality of the blob rate to the luminosity, the figure of merit was used. It is presented for the two used shutter times in figures 3.43.

![Figure 3.43: Figures of Merit for the proportionality of the blob rate to the instantaneous luminosity](image)

It is apparent, that the longer the exposure, the smaller the spread. The data acquired in that fill with the shortest exposure time (10 s) was rejected due to a much wider spread of the scaling factor. The presented assessment was defined as a technique to optimize the settings for future data acquisition.

The previously assessed dataset was used to obtain neutron flux values. The blob rate was converted into flux by applying the calculated calibration coefficient from the calibration with the neutron source. The result is presented in figure 3.44, compared with the neutron flux estimated for that region with FLUKA. The simulation result is scaled along the fill to examine the correlation for all measurement points. To begin with, the compared sets include neutrons within different energy ranges. The simulation covers all possible neutrons from thermal up to the order of the beam energy, whereas the measurement is designed to include neutron with energy above 1 MeV. The response as a function of energy was not well characterized for the covered detector. What is more, the measured energy range cannot be determined due to the floating reference voltage. This is a complex problem as the analog circuit of a pixel has many configuration inputs and some of them might have not been tuned properly. The voltage regulator power budget may also be a reason of the floating behaviour. However, as it was mentioned in the previous sections, the outer cavern is not well modelled, hence the correct order of magnitude is an encouraging agreement.
Figure 3.44: The comparison of measured and simulated flux values in the X3FORWARD location, for fill no. 7334
Summary and Outlook

The thesis comprises of five separate parts that form the radiation level investigations. Both real measurements and simulated estimations are included.

In the two initial sections, the FLUKA benchmarks were performed in the CMS environment. They concerned both residual radiation during the beam off period and stray radiation during the beam on period. For the former, measurements were taken with a simple dosimeter during a Technical Stop in the open areas of the Tracker Bulkhead. The simulation was divided into two steps so that it could describe accurately the reality. An additional patch was applied to reduce the production of the problematic isomer. For the second FLUKA benchmark—against the stray radiation, readings from the RAMSES monitors were used. The simulation included a specialized routine with the detector’s response function. It folded the spectra of all crossing particles in the monitors’ locations giving the estimation of generated charge per area unit. A satisfactory agreement of the simulated data to the measured quantities was found. It can be concluded that the CMS FLUKA model is a reliable representation of the real structure for the quantities of interest in this thesis, thus giving good predictions of the generated radiation field. Such studies are vital in order to establish trust in the FLUKA-based forecasting as well as testing in the design phase.

In the next part, the previously benchmarked model was used to investigate the composition of the background radiation in one of the Muon Chambers segments. The aim was to determine the source of the asymmetrical background visible in the initial bunch crossings. Therefore, the emphasis was put on the timing information. Thanks to the specialized simulation setup it was possible to select the most harmful background components. Charged hadrons arriving from the outer cavern to the upper part of ME4/2 were found in excessive amounts. Their arrival time, picking at $t = 130$ ns indicates the TAS absorbers as the most probable source. This study has gone some way towards enhancing our understanding of the problematic asymmetry, however, it cannot provide a definite conclusion. Additionally, the impact of the elements that are different on each end of the CMS experimental hall on the background field composition was examined. The timing distributions of electrons and positrons obtained on each side of ME4/2 were approximately the same below and above the beamline.

In the following section, the existing monitoring was used to investigate the effect of additional shielding installed during Technical Stops. The spread of RAMES monitors around the
CMS hall gives an opportunity for multiple observations at the same time. It was shown, by year-to-year comparisons that radiation levels are constantly evolving. Moreover, the efforts put in the design of shielding modifications proved to be effective in decreasing the amount of escaping particles, thus reducing their contribution to the total dose per $1 \text{ fb}^{-1}$ of delivered luminosity. The study proves that the network of monitors can be used as a feedback of the modifications around CMS.

In the final section, an evaluation of a specially designed equipment for the neutron flux measurement is presented. Such appliances are necessary in order to understand the major and most damaging ingredient of the outside-detector radiation field. It is of high importance especially in preparation for the forthcoming Phase II harsh conditions.

The Medipix-based neutron cameras were successfully installed for the final weeks of the Run II period (at the end of 2018). The acquired data were used to test the performance in each location as well as to conclude the best camera settings. The reconstruction algorithm was built and calibration was performed with a neutron source in order to calculate neutron flux from the raw signal. Figures of Merit showed good performance of the cameras, as the signal changes proportionally to the instantaneous luminosity. The final results were compared with simulation, however, the range of included neutrons differs in both curves. Precise comparison requires further investigations of the cameras’ sensitivity. In particular, the conversion layer has to be tested and detection efficiency referring to the specific material has to be well established. What is more, the next implementation of the cameras has to be checked carefully to prevent the errors causing the problems with the reference voltage. Given the experience gained so far with the installed cameras, the system could be improved significantly for further operation. It is planned to upgrade the cameras in forthcoming production with more rigid, thus durable transition boards.
Appendices
Appendix A

FLUKA input settings

The primary proton beams are described by the SPECSOUR card which invokes DPMJET-III event generator. The beam parameters for the LHC Run 2 running conditions are listed below:

<table>
<thead>
<tr>
<th>Unit</th>
<th>p-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>TeV/n</td>
</tr>
<tr>
<td>(\sqrt{s_{\text{nn}}})</td>
<td>TeV</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>(\mu\text{rad})</td>
</tr>
<tr>
<td>Vertex spread (along (z))</td>
<td>cm</td>
</tr>
</tbody>
</table>

DEFAULTS card is used with the PRECISIOn option to define the default physics options for precision simulation. The setting includes many important parameters, for example, particle production energy thresholds. Some of them had to be explicitly adjusted to include the energies relevant for the CMS radiation studies. The full list per particle type is included below:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadrons</td>
<td>(\text{keV})</td>
</tr>
<tr>
<td>Muons</td>
<td>(\text{keV})</td>
</tr>
<tr>
<td>Neutrons</td>
<td>(\text{meV})</td>
</tr>
<tr>
<td>Photons</td>
<td>(\text{keV})</td>
</tr>
<tr>
<td>Electrons</td>
<td>(\text{keV})</td>
</tr>
</tbody>
</table>

However, in some regions with high-density material they are changed to higher values to avoid too high CPU load.
Appendix B

RAMSES measured locations

In order to perform simulations concerning the RAMSES monitors, their locations had to be measured. In the table below, all monitors present in the CMS cavern are listed with FLUKA coordinates and a short description of each location.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>x [m]</th>
<th>y [m]</th>
<th>z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMIL5501</td>
<td>near side, positive end, X1 level, next to UPS55</td>
<td>10,6</td>
<td>-5,7</td>
<td>22</td>
</tr>
<tr>
<td>PMIL5502</td>
<td>near side, negative end, below CMS, X0 level</td>
<td>1</td>
<td>-10,2</td>
<td>-3</td>
</tr>
<tr>
<td>PMIL5511</td>
<td>near side, positive end, X3 level, next to RS on the cavern wall</td>
<td>9,9</td>
<td>1</td>
<td>26,5</td>
</tr>
<tr>
<td>PMIL5512</td>
<td>far side, negative end, X3 level, on the cavern wall</td>
<td>-9,3</td>
<td>0,7</td>
<td>-26,5</td>
</tr>
<tr>
<td>PMIL5513</td>
<td>near side, negative end, next to UPX56, X3 level (~IP height), on the side of the rotating shielding next to the visitors platform</td>
<td>9,8</td>
<td>0,6</td>
<td>-26,5</td>
</tr>
<tr>
<td>PMIL5514</td>
<td>far side, positive end, X3 level, HF balcony, just over RS</td>
<td>-1,6</td>
<td>2,5</td>
<td>14,5</td>
</tr>
<tr>
<td>PMIL5515</td>
<td>far side, negative end, X4 level, on the fence of HF balcony, just above RS</td>
<td>-1,7</td>
<td>2,5</td>
<td>-14,5</td>
</tr>
<tr>
<td>PMIL5521</td>
<td>near side, positive end, X5 level, on the cavern wall, higher than X4 but lower than the small balcony on the end wall</td>
<td>0,8</td>
<td>4,6</td>
<td>26,5</td>
</tr>
<tr>
<td>PMIL5522</td>
<td>on the blockhouse wall, negative end, hidden behind the big red pipe of the foam system, over the green cupboard near the middle in x</td>
<td>-0,5</td>
<td>5,1</td>
<td>-26,5</td>
</tr>
<tr>
<td>PMIL5531</td>
<td>near side, positive end, X4 level, along z next to YB+1</td>
<td>10,8</td>
<td>4,4</td>
<td>4</td>
</tr>
</tbody>
</table>
Bibliography


[9] *Courtesy of Domenico Dattola*.

[10] *Courtesy of Sophie Mallows*.

