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IRRADIATION STUDIES OF FUSED SILICA MATERIALS AND MACHINE LEARNING
TECHNIQUES FOR ATLAS FORWARD DETECTORS IN HEAVY ION COLLISIONS

BY

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DISSERTATION

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ABSTRACT

The Large Hadron Collider (LHC) at CERN is transitioning to the High-Luminosity (HL) LHC configuration, which will be completed by 2028. This upgrade will significantly increase the LHC's collision rate and radiation damage to detector materials and readout electronics in the experiments. The radiation damage leads to the detector performance continuously degrading over time. Because a higher level of radiation damage is expected in the upgrade, the stability of detectors is a challenging issue for the Zero Degree Calorimeters (ZDCs) and the Beam Rate of Neutrals (BRAN) detectors installed in the Target Absorber for Neutrals (TAN) in the ATLAS and CMS experiments. A Joint Zero Degree Calorimeter Project (JZCaP) between ATLAS and CMS was started in 2017 to design and construct a new generation of ZDCs, capable of withstanding the doses expected in the HL-LHC. JZCaP collaborated with the BRAN group to identify a radiation-hard active material suitable for the upgraded ZDC to be constructed for HL-LHC operations. One such material is fused silica to be used as a Cherenkov light radiator material for signal generation. An irradiation campaign of fused silica rods was carried out by the BRAN CERN team, allowing for studies of radiation damage to fused silica and material activation. The irradiated fused silica rods were characterized by different hydroxide (OH) and hydrogen (H₂) doping levels and installed within a BRAN prototype detector in the TAN during LHC Run 2. In this way, the rods were exposed to the same type of radiation that illuminates the ZDC and the BRAN. The accumulated doses and sodium isotope ²²Na activity in the rods were obtained using dedicated FLUKA simulations provided by the CERN FLUKA group. After completion of the irradiation campaign, the rods were shipped to the University of Illinois Urbana-Champaign (UIUC) for measurements of radiation-induced optical losses and ²²Na activation of fused silica.

This dissertation presents studies of FLUKA’s performance in describing the activity profile of ^{22}Na and a multivariate analysis of the fused silica’s optical transmission. In the ^{22}Na activation study, the activity of the rods was measured by two independent experimental setups and compared to the FLUKA simulations. While the simulations reproduce the ^{22}Na activity profile measured along the rods, they underestimate the measured activity by 35%.

In the study of the optical transmission of fused silica, most optical transmission losses were observed in the ultraviolet region and were more severe at lower wavelengths. The impact of the dopant concentration in fused silica on the radiation hardness was examined. With a high H_2 concentration, increasing the concentration of OH improves the radiation hardness of fused silica. With a high OH concentration, raising the H_2 doping level shifts the threshold of the degradation to a higher radiation level. These results informed the material choice of the active material for the ATLAS ZDC Run 3 refurbishment and the upgraded ZDC in HL-LHC. They also motivated additional irradiation studies of Heraeus fused silica samples for Run 3 (2022-2025).

A novel reaction plane detector (RPD) developed and built at UIUC enables the possibility of estimating the event-by-event reaction plane angle (Ψ_1) of heavy-ion (HI) collisions. The RPD is designed to measure the transverse profile of the shower produced by spectator neutrons in the ZDC. With the measured transverse profile, it is possible to estimate the centroid of the shower, directly correlated to Ψ_1 . This dissertation presents a method to estimate Ψ_1 using RPD measurements based on a convolutional neural network. In order to train the network, dedicated Monte Carlo simulations were carried out to generate a data set of mid-central HI collisions. The network shows resolution improvements of up to 55% compared to a conventional “center-of-mass” method for Ψ_1 estimation. These simulation-based results are discussed and compared to previous Ψ_1 measurements.

The results of this dissertation have entered two publications, with the first being accepted for publication in Physical Review Accelerators and Beams, and the second in preparation for submission to Nuclear Instruments and Methods in Physics Research. The work presented in this dissertation was also used as input to a \$2.5 M collaborative proposal to the DOE in support of the construction of the new ZDCs and RPDs for the ATLAS and CMS experiments in view of the HL-LHC era. The participating institutions are the Universities of Illinois and

Maryland, Kansas University, Columbia University, Brookhaven National Laboratory, and Ben Gurion University of the Negev in Israel. Overall leadership, project management, and technical coordination are carried out by UIUC faculty and researchers.

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CHAPTER 1

INTRODUCTION

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the world’s highest-energy particle accelerator. It enables the possibility to test hypotheses of different theories in particle physics. The most significant discovery made at LHC is the Higgs particle [1, 2], observed in data collected by the ATLAS¹ [3] and the CMS² [4] experiments in 2012. The observation of the Higgs particle confirms one of the key predictions of the Standard Model [5], currently the most accurate theory to describe elementary particles and their interactions.

The LHC accelerates two particle beams in opposite directions, colliding them once they reach the desired energy at four interaction points (IPs) located on the LHC ring. Particle detectors were built around the IPs to measure the products of collisions. The LHC can operate in different modes to accelerate and collide a variety of particles such as protons (p) and heavy ions (A), e.g., lead (Pb), xenon (Xe), and oxygen (O). The versatility of the LHC enables collisions between the same particle species ($p+p$ and $A+A$) and also between protons and ions ($p+A$). Each year, approximately one month of the running time is dedicated to collisions that involve heavy ions.

A heavy ion can be modeled as a spherical volume of nucleons with finite dimensions. In a first approximation, a collision between two heavy ions can be considered as the sum of the interactions between nucleons of the two collided nuclei. Protons and neutrons that interact are known as “participants”, while the others are “spectators” [6]. Fig. 1.1 shows an example heavy-ion (HI) collision geometry. These spectators are unstable fragments and later de-excite by emitting particles such as neutrons, protons, and alpha particles.

¹A Toroidal LHC ApparatuS.

²Compact Muon Solenoid.

The relaxation process by particle emission is also known as evaporation. The number of participants and spectators is correlated with the collision's impact parameter (b), defined as the distance between the center of the two approaching nuclei [7].

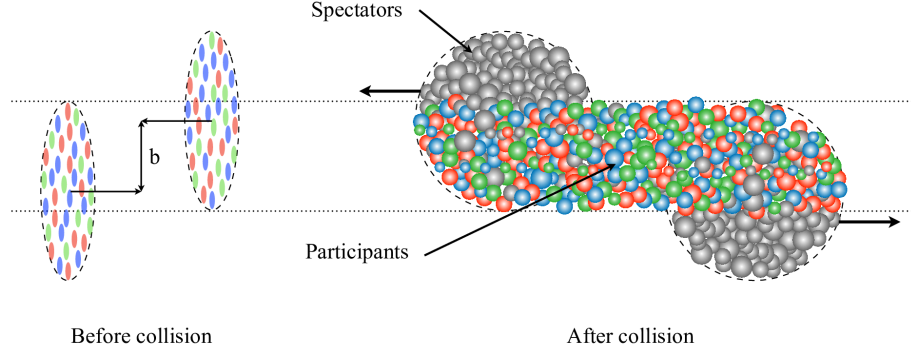


Figure 1.1: An example HI collision geometry. Left: two heavy ions before a collision with an impact parameter b . Right: participants interact in the overlapping area, while spectators are not directly involved in the collision. Figure taken from [8].

HI events are characterized by the relative size of the overlapping region (also known as centrality) between two nuclei, directly correlated to the impact parameter. For example, the most central collisions, corresponding to a small b , have the largest overlapping area, resulting in the highest number of participants. Conversely, in the more peripheral events with a larger b , the number of participants decreases while the number of spectators increases. The impact parameter plays an important role in characterizing the geometry of HI events, but it cannot be directly measured in each collision.

The impact parameter can be inferred by the number of spectator neutrons. After collisions, spectators travel along the collision axis, passing through the experimental hall and reaching the LHC tunnel. Protons and charged fragments are swept away by a series of superconducting magnets in the tunnel, while neutrons move in the same direction. Fig. 1.2 is a schematic drawing to illustrate the charged particles swept by magnets and the neutral particles, such as neutrons and gamma rays, proceeding along the beam axis. Since each neutron is mostly monochromatic, measuring the total deposited energy in a calorimeter

makes it possible to infer the number of the neutrons and, thus, the impact parameter.

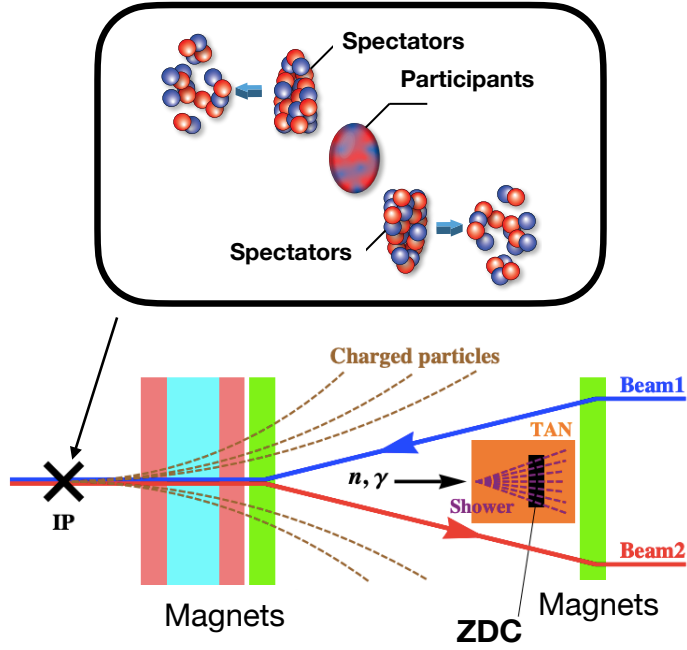


Figure 1.2: A schematic drawing to illustrate the charged particles swept away by magnets and neutral particles proceed along the collision axis. Figure adapted from [9].

The ATLAS experiment primarily uses the Zero Degree Calorimeter (ZDC) [10] installed in opposite arms to estimate the number of spectator neutrons in HI events. “Zero Degree” refers to the approximately zero polar angle of the ZDC location with respect to the IP (see fig. 1.2). During HI runs, the ZDC is installed between the beam pipes in a dedicated slot of the so-called Target Absorber for Neutrals (TAN), copper-steel absorbers used to protect the downstream superconducting magnets from high-energy neutral particles emerging from the IP.

The ZDC is composed of tungsten absorbers and layers of Cherenkov radiators for signal generation. Initial neutrons undergo nuclear interactions in the tungsten plates creating electrically charged particles. With each interaction of high-energy particles, the number of charged particles further increases. The secondary particles produced in this way are referred to as “shower”. The charged particles emit Cherenkov light as they pass through the Cherenkov radiators [11, 12]. The total amount of light is proportional to the energy deposited in the ZDC and, therefore, to the number of neutrons.

Fused quartz rods, sandwiched between the tungsten absorbers, were used as Cherenkov radiators in the ATLAS ZDC from 2011 to 2018 [13]. Due to fused quartz’s refractive index, Cherenkov light can be trapped by total internal reflection and propagated inside of the rods. Light emitted from the top of the rods is redirected by a light guide toward the window of a photomultiplier (PMT), which converts photons to electronic signals. The strength of the signals is correlated to the number of photons produced from the deposited energy of the neutrons. Assuming the ZDC response is the same during data taking, the number of neutrons in each event can be computed. Thus, the stability of the response is crucial for the performance of the ZDC.

The performance stability of the ZDC is limited by the radiation-induced optical transmission degradation of the fused quartz rods. When radiation passes through fused quartz rods, free electrons and electron holes can be created by the breaking of chemical bonds or displacement of atoms. An electron hole is the lack of an electron at a position where one could exist in an atom or atomic lattice. A hole and an electron can recombine and annihilate, but they can also be trapped in point defects, e.g., atomic-sized vacancies and impurity atoms or ions [14]. These point defects become permanent electronic defects, referred to as color centers, that can absorb light at specific wavelengths. Fused quartz produced from natural crystalline silica [15] contains relatively high impurities, at a level of ppm, that facilitate radiation-induced defects, also known as radiation damage. An example of severe radiation damage was observed by measuring the optical transmission of the ZDC rods irradiated in $p+p$ running in 2011. Furthermore, since the damage occurred during ZDC data taking, it resulted in continuously decreasing ZDC performance. This then required additional effort to monitor and compensate for the performance degradation.

As the energy and collision rate involved in LHC collisions continues to be raised, there is an increased risk of radiation damage. An upgrade, known as the High-Luminosity LHC upgrade (HL-LHC), to increase the beam intensity of the LHC was planned in 2011, allowing for more observations of rare events [16, 17]. The raised intensity corresponds to a higher dose rate and, thus, a higher integrated dose compared to that of the current LHC. The expected integrated dose for the ZDC in $p+p$ running after the upgrade is 1 GGy [13], which is 100 times larger than the dose that the ZDC received in 2011. The fused quartz used in

Runs 1 and 2 is not capable of withstanding the expected doses in the HL-LHC upgrade and, therefore, a more robust Cherenkov radiator was needed.

A Joint Zero Degree Calorimeter Project (JZCaP) between ATLAS and CMS was started by the University of Illinois Urbana-Champaign (UIUC) and the University of Kansas, respectively. It is led by UIUC to design and construct a new generation of ZDCs, capable of withstanding the radiation level expected in the upgraded LHC. One of its main goals is to improve the Cherenkov radiator's radiation hardness, the resistance to radiation in terms of optical transmission losses. Starting in 2017, JZCaP collaborated with the CERN FLUKA group and the Beam Rate of Neutrals (BRAN) luminosity detector group. The collaboration aims to analyze the radiation hardness of high-purity silica (silicon dioxide, SiO_2) in amorphous (non-crystalline) form, also known as fused silica. Fused silica rods made by Heraeus were doped with different levels of hydrogen (H_2) and hydroxyl (OH) to study the impact of these dopants on radiation hardness. The rods were irradiated for various periods in the TAN during $p+p$ running between 2016 and 2018. The BRAN group conducted the irradiation experiment, while the accumulated doses within the rods were estimated by the dedicated simulations provided by the CERN FLUKA group.

This dissertation presents two studies carried out on the fused silica rods irradiated by the BRAN in the LHC. The first is an activation study of a sodium isotope (^{22}Na) in the fused silica rods. The isotope activity in the rods was measured by two independent experimental setups at UIUC and Argonne National Laboratory (ANL). The measurement results were compared to the activity estimated by the FLUKA [18] simulations provided by the CERN FLUKA team. The comparisons provide a benchmark for FLUKA's performance in describing activation processes of material in the LHC. The second is a multi-dimensional radiation hardness study of fused silica. The optical transmission along the rods was profiled at different wavelengths. The relation between the radiation damage and the accumulated doses within the rods was analyzed. The transmission study also presents the impact of H_2 and OH levels on the radiation hardness of fused silica. The second study serves to guide the material choice of the Cherenkov radiator of the ZDC for the HL-LHC ZDC upgrade and also motivated another radiation campaign to study chosen fused silica material.

Another physics goal of JZCaP is to measure the event-by-event reaction plane (RP)

angle, which is formed by the beam axis and the impact parameter. RP can be observed by measuring the correlated deflection of spectator neutrons using a position-sensitive detector. One such detector is a reaction plane detector (RPD) proposed by JZCaP. It is composed of fused silica fibers of different lengths to form an array of 4 by 4 tiles, which allows for the extraction of the shift in the shower centroid on the transverse plane. In each event, the spectator neutrons emitted by the nuclear fragments receive a kick resulting in a transverse momentum. If the transverse momentum leads to an azimuthal anisotropy of the neutrons that can be measured, it is then possible to determine the RP.

A machine learning (ML) method for RP angle reconstruction using the ATLAS RPD is presented. Because the fibers in the RPD are routed upward to readout devices, the RPD exhibits non-uniform detector responses in the vertical direction, e.g., columns in the array. To correctly reconstruct RP angles, signals of each channel must be calibrated using the channel's characteristic response. By exploiting the capability of machine learning algorithms, an ML-based model was built to correct the responses and predict event-by-event RP angles based on dedicated Monte Carlo (MC) simulations. The model has shown better performance than a conventional RP reconstruction method regarding angular resolution and RP angle resolution, a metric that makes use of two reaction plane measurements by the RPD in opposite arms.

This dissertation is organized as follows: chap. 2 introduces the LHC, the HL-LHC upgrade, the ATLAS experiment, the ZDC in ATLAS, a brief overview of the RPD, and radiation challenges associated with the HL-LHC upgrade. Chap. 3 describes the fused silica rod irradiation experiment and the corresponding FLUKA simulations. Chap. 4 presents the study of the ^{22}Na isotope in the fused silica samples and discusses the discrepancy between the simulations and the measurements. Chap. 5 covers the study of the radiation hardness of fused silica using optical transmission measurements. Chap. 6 gives a brief overview of HI and flow physics followed by the RPD design, the ML reconstruction method for RP angles, and the performance evaluation of the ML method. Finally, chapter 7 contains the conclusions.

The results presented in chap. 4 have been accepted by the Physical Review Accelerators and Beams (Phys. Rev. Accel.). The study described in chap. 5 is currently in the final

stage of the internal review process and expected to be submitted in Summer 2022 to the Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment. The publications resulting from this dissertation are summarized as follows:

- S. Yang et al., ^{22}Na Activation Level Measurements of Fused Silica Rods in the LHC Target Absorber for Neutrals (TAN) Compared to FLUKA Simulations, available on arXiv [19] and received positive feedback from the reviewers of Phys. Rev. Accel..
- S. Yang et al., Optical Transmission Measurements of Fused Silica Irradiated at the CERN Large Hadron Collider (tentative title), in preparation (2022).

Additionally, the results of chap. 6 contribute to the following HL-LHC note:

- ATLAS Collaboration, A Radiation-Hard Zero Degree Calorimeter for ATLAS and CMS Experiments in the HL-LHC era, 2021 [13].

CHAPTER 2

LARGE HADRON COLLIDER

This chapter presents a concise overview of the experimental facilities associated with the work in this dissertation, namely the LHC and the ATLAS experiment. The LHC and the High-Luminosity LHC upgrade are presented in sec. 2.1 and sec. 2.2, respectively. An overview of the ATLAS detector is given in sec. 2.3 with the sub-detector systems of the ATLAS detector described in 2.3.2. Proceeding outwards from the detector along the beam axis, magnet modules and particle absorbers beyond the ATLAS detector are covered in sec. 2.3.3. The details of the ZDC are given in sec. 2.3.4, while the RPD design is presented in sec. 2.3.5. Radiation damage to the ATLAS ZDC is discussed in sec. 2.4.

2.1 The Large Hadron Collider

The LHC is a circular accelerator with a circumference of 26.7 km on the site of the European Organization for Nuclear Research (CERN) [20]. It is currently the most powerful particle accelerator in the world. The circular shape allows the particles to gain energy by passing accelerating radio-frequency cavities multiple times to reach a much higher center-of-mass energy than fixed target setups [21]. Currently, the LHC can collide same particle species, e.g., protons ($p+p$) at a center-of-mass energy of 14 TeV and Pb+Pb at a 5.5 TeV center-of-mass per nucleon. It also enables collisions between protons and heavy ions such as $p+\text{Pb}$ up to 8.8 TeV per nucleon. Protons and ions are accelerated through different chains starting from different sources, linear accelerators, and synchrotrons. Fig 2.1 shows a schematic of the CERN accelerator complex, including the chains for protons and ions.

Protons are produced by stripping electrons from hydrogen gas. Then, they are accelerated up to 50 MeV by a linear accelerator, LINAC 2. The beam is later injected into the

The CERN accelerator complex *Complexe des accélérateurs du CERN*

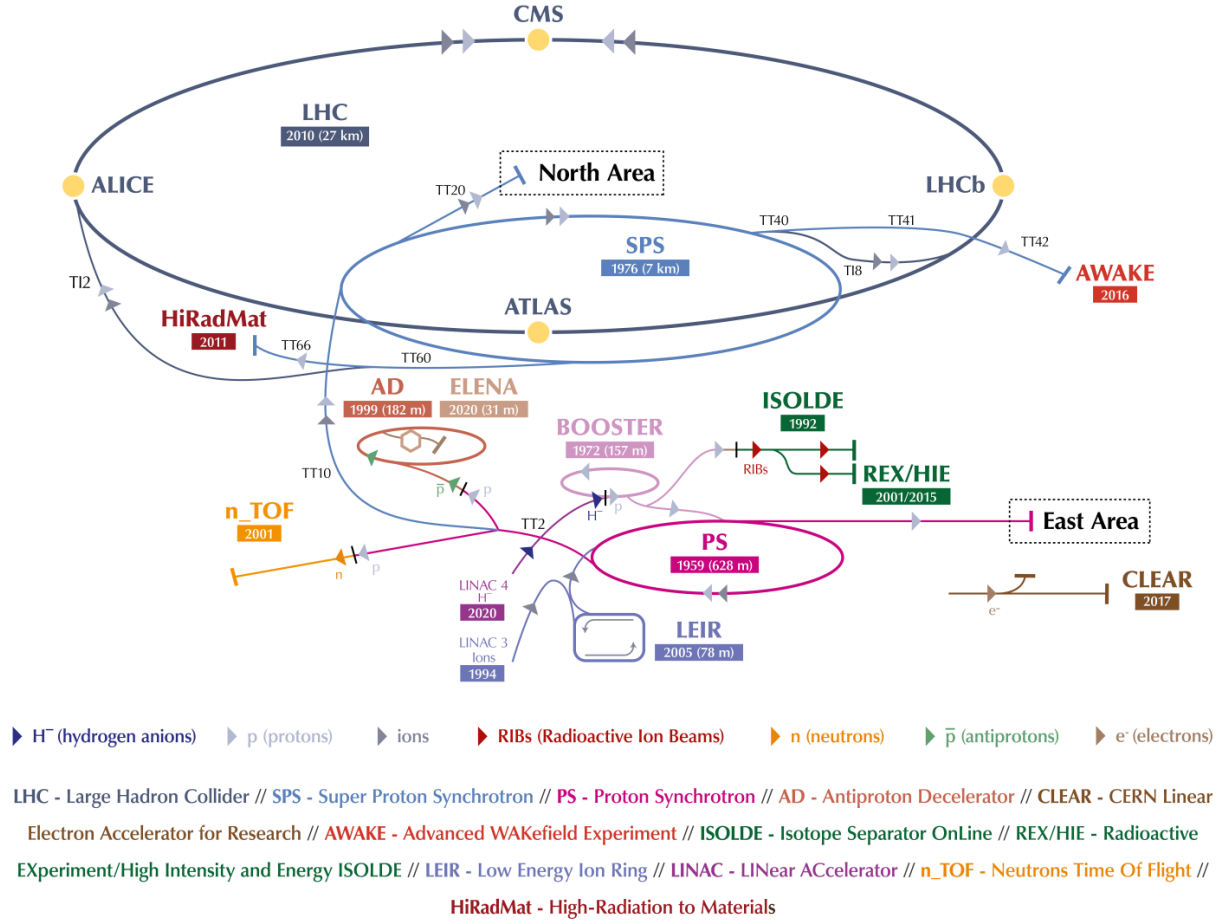


Figure 2.1: CERN accelerator complex [22]. Color arrows represent different accelerator chains for particles.

Proton Synchrotron Booster (PSB), which accelerates the protons to 1.4 GeV before entering the Proton Synchrotron (PS), where they are accelerated to 25 GeV and grouped into particle bunches with equal space, with $\sim 10^{11}$ protons in each bunch. The bunches are then transferred to Super Proton Synchrotron (SPS), where their energy is increased to 450 GeV before entering two separate beam pipes in the LHC ring. The beam in one pipe circulates clockwise while the beam in the other pipe travels counter-clockwise. Finally, the protons are further accelerated to 7 TeV and collide at IPs in the LHC ring. Heavy ions, such as Pb, are extracted from the plasma produced by ionizing the vapor of a heated pure ^{208}Pb

sample. The ions are accelerated to 4.5 MeV per nucleon by a linear accelerator, LINAC 3, before Low Energy Ion Ring (LEIR), where the beam is split into bunches and further accelerated to 72 MeV. After LEIR, the beam is injected into the PS and follows the same route as the proton beam described previously.

As the opposite traveling beams approach the IPs, the particle bunches are focused by a series of superconducting multipole magnets to collide. The bunches collide at an angle, referred to as the “crossing angle”, of a couple hundred microradians to prevent additional collisions away from the IP at the center of the detector. Fig. 2.2 shows a schematic of two beams, composed of particle bunches, colliding at a crossing angle. A small crossing angle increases the overlapping area of bunches, resulting in a higher collision rate. However, the angle must be large enough to mitigate the long-range interactions between the electromagnetic fields generated by the beams.

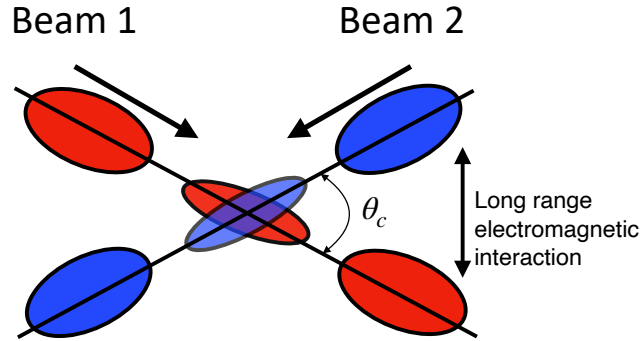


Figure 2.2: Schematic of a crossing angle (θ_c) of two beams traveling in opposite directions in the LHC.

2.2 The High Luminosity Large Hadron Collider

The relative statistical uncertainty (δ_i) of a measurement for a given process i depends on the number of observed events (N_i),

$$\delta_i \propto \frac{1}{\sqrt{N_i}}. \quad (2.1)$$

Increasing the number of events improves the precision of the measurement. In the LHC, the rate of the events (dN_i/dt) is characterized by instantaneous luminosity (L),

$$\frac{dN_i}{dt} = \sigma_i L, \quad (2.2)$$

where σ_i is the cross section of the process i and the unit of L is traditionally expressed in $\text{cm}^{-2}\text{s}^{-1}$ [23]. The total number of events can be computed using the integral of the instantaneous luminosity over time,

$$\int \frac{dN_i}{dt} dt = \sigma_i \int L dt = \sigma_i L_{int} = N_i, \quad (2.3)$$

where L_{int} is integrated luminosity. Note that the unit of cross section is barn (b, 10^{-28} m^2), and it is conventional to describe the LHC integrated luminosity in inverse femtobarns (fb^{-1} , 10^{-15} b^{-1}). Increasing instantaneous luminosity will raise the integrated luminosity, the number of events and, thus, improve the precision of the measurement. Therefore, the LHC has been scheduled to be upgraded every 3-5 years to explore its potential for higher instantaneous luminosity.

The HL-LHC [16, 17] is a major upgrade of the LHC to increase its instantaneous luminosity. The schedule for the LHC and HL-LHC upgrade is shown in fig. 2.3. The goal of the HL-LHC is to deliver an integrated luminosity of 3000 fb^{-1} over ten years, a factor of ten compared to the initial LHC goal by the end of Run 3 [21].

In Run 1, the LHC was successfully commissioned at 7 TeV center-of-mass energy for $p+p$ collisions and reached 8 TeV in 2012. It delivered a total integrated luminosity of 30 fb^{-1} at the end of Run 1. After the first long-shutdown (LS1) for detector upgrades and



Figure 2.3: Schedule for the HL-LHC upgrade, showing the energy of the collisions (upper red line) and instantaneous luminosity (lower red lines). Figure taken from [24]

maintenance, the LHC reached the designed instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with a center-of-mass energy of 13 TeV for proton collisions in 2015.

After the second long-shutdown (LS2), the LHC is planned to operate at a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at 14 TeV center-of-mass energy. At the end of Run 3, the integrated luminosity of the LHC will reach 450 fb^{-1} . However, with the nominal integrated luminosity of the current LHC design, the running time required to halve the statistical uncertainty in measurements would be more than ten years.

The machine will be fully in the HL-LHC configuration after the last stage of the upgrade (LS3). The HL-LHC will enable a peak luminosity reaching $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with leveling, a technique that limits the peak luminosity to meet the constraints imposed by experiments on the number of interactions per bunch crossing. The technique also provides a more stable beam delivery over time and almost the same integrated luminosity compared to the beam without leveling.

2.3 The ATLAS experiment

ATLAS is a general-purpose particle detector built around one of the LHC IPs, IP1. The detector weighs 7000 tonnes, is 44 m long, and 25 m in diameter. It is used to record and track the particles created in collisions. By measuring the energy, momenta, and charge of particles reaching the detector, the physical properties of the particles in the final state of a collision can be reconstructed.

A collection of sub-detector systems is symmetrically constructed around IP1 to measure the particles with a solid angle coverage close to 4π steradian. Proceeding outward from IP1, the sub-detector systems are an inner detector, a calorimeter system, and a muon spectrometer. The inner detector measures the directions and the trajectories of charged particles in a 2 T solenoid field created by a magnet system. The measurements allow for the estimation of particles' charge and momenta. The calorimeters provide the energy information of both charged and neutral particles. The muon spectrometer, the outermost detector, identifies muons and measures their momenta in a toroidal magnetic field with a 4 T strength [25]. More details about the sub-detector systems are provided in sec. 2.3.2.

2.3.1 Coordinate system

A right-handed coordinate system with its origin at the center of the ATLAS detector is defined as follows: x is perpendicular to the beam and points to the center of the LHC ring, y points upward, and z points along the beam line. In polar coordinates, the azimuthal angle ϕ is measured with respect to x in the x - y plane. The polar angle θ is measured with reference to z . The distance r is the radial distance from the beam line. The schematics of ATLAS and its coordinates are shown in fig. 2.4.

To describe collision events in a center-of-mass system independent of Lorentz boosts in z , it is useful to define specific coordinates that are invariant under the boosts [27]. Rapidity is such a Lorentz invariant quantity and is often used instead of the polar angle in a specific

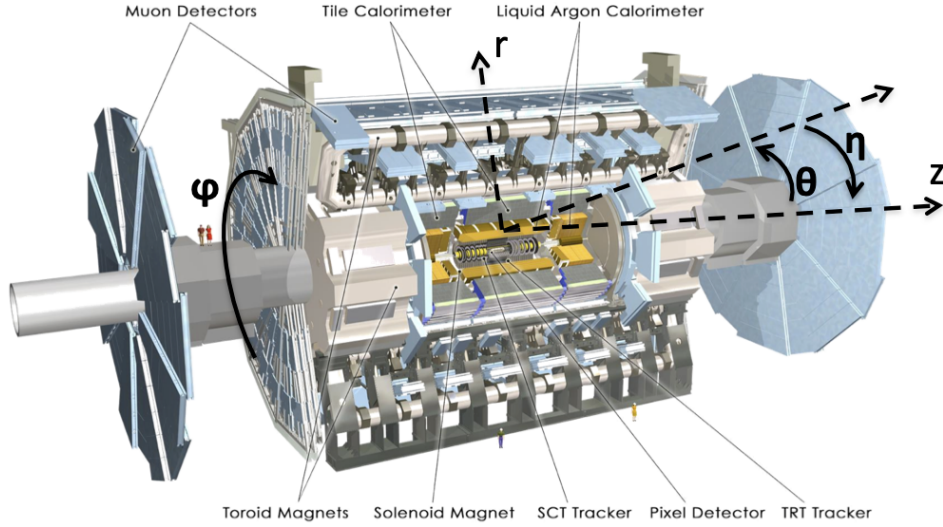


Figure 2.4: Overview of the ATLAS detector in a polar coordinate system. The origin of the system is centered at the IP. Taken from [26].

reference system. The rapidity y is defined as

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.4)$$

where E and p_z are particle's energy and the momentum along z , respectively. For highly relativistic particles, the rapidity can be simplified into pseudorapidity η , frequently used in presenting ATLAS results. It is defined as

$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right) = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (2.5)$$

where $\mathbf{p}$ is the 3-momentum of the particle. Fig 2.5 shows the value of η for various polar angles. When the value of η is 0, it describes the direction perpendicular to the beam line. If η is ∞ , the direction is along the beam line where θ is 0.

Because the primary particles are Lorenz boosted in z , the component of the particles' momenta should be zero in x and y . The momentum of the fragments and particles projected on the transverse (x - y) plane provides meaningful information for event reconstruction. The

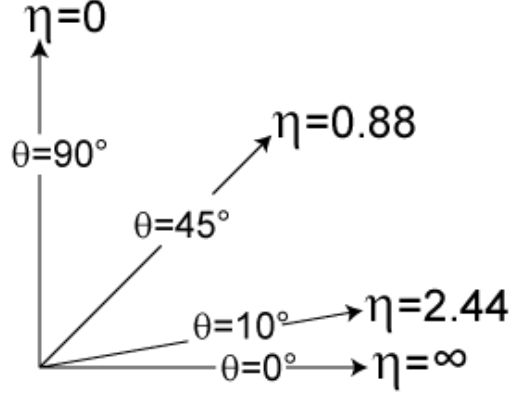


Figure 2.5: Pseudorapidity η and the corresponding polar angle. The ATLAS ZDC and RPD are located in a region with $|\eta| > 8.3$ in Run 1-3 and $|\eta| > 8.5$ in Run 4. Figure taken from [28].

transverse momentum p_T is defined by

$$p_T = \sqrt{p_x^2 + p_y^2}, \quad (2.6)$$

where p_x and p_y are the components of particle momentum in x and y , respectively.

2.3.2 ATLAS sub-detector systems

The sub-detectors near IP1 (known as central detectors) cover the region $|\eta| < 4.9$ [29, 30, 31, 32]. The sub-detectors for particles with relatively small $|\eta|$ are built in the shape of a cylinder's curved surface (known as the barrel region) parallel to the beam pipe. Particles with a relatively large $|\eta|$ are measured by sub-detectors located on the cylinder's bases (known as end-caps) perpendicular to the beam pipe.

The inner detector envelops the IP and is designed to accurately measure the momenta and trajectories of charged particles within $|\eta| < 2.5$. It is a cylindrical shell with a 1 m diameter and a length of 6.2 m with three different sub-detector layers. Each layer has different granularities, mainly for tracking the positions of charged particles in space (see fig. 2.6). The pixel detector is composed of 1744 pixel modules. Each module has 47232 radiation-hard p-n type silicon pixels with a size of $50 \times 400 \mu m^2$. Charged particles pass through the pixels and create electron-hole pairs inside the silicon. The pairs are separated

by an electric field and collected by electrodes of the pixels. The semiconductor tracker (SCT) has 4088 modules, each with 1536 silicon strips, similar to the pixel module design. Each strip is 2.6 cm long and has 80 micro pitch, so the SCT has coarser granularity than the pixel detector. The transition radiation tracker (TRT) consists of 300,000 thin-walled drift tubes of 4 mm in diameter. Each tube filled with Xe and CO₂ uses tungsten wire as its anode and a conductive layer inside the tube as the cathode. When charged particles pass through the tubes, they ionize the gas and produce signals. The sub-detector layers in the barrel region measure the particles with $|\eta| < 1.2$, while the ones on the two end-caps cover $1.2 < |\eta| < 2.5$. From the 3-dimensional maps measured by the sub-detector layers, the path of the charged products after collisions can be reconstructed. Then, information about the original particles in collisions is reconstructed from these paths of the charged products.

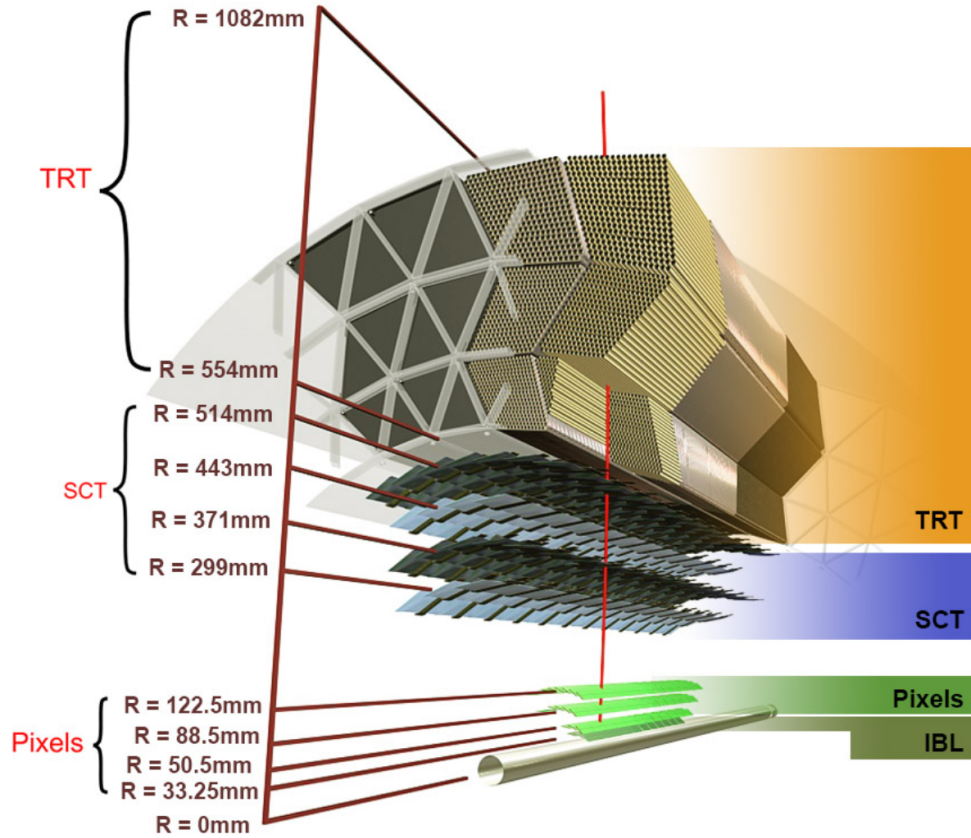


Figure 2.6: Schematic view of the ATLAS inner detector on the barrel region. Figure taken from [33].

one module placed on the end-cap region. The FCal is designed to measure relatively forward particles, so it is only constructed in the end-cap region but close to the beam. It is comprised of three modules; the first module uses copper absorbers dedicated to measuring photons and electrons, while the other modules use tungsten absorbers for measurements of hadron energy.

The muon spectrometer is the outermost sub-detector because muons are the only detectable particle that can penetrate the inner detector and calorimeters. The spectrometer consists of a barrel region and two end-caps, providing precise measurements of the transverse momentum and the charge of muons at $|\eta| < 2.7$. The spectrometer can only measure muons with the transverse momentum above 3 GeV because the lower-momentum muons will never reach the spectrometer due to the energy losses when the muons travel through detector material.

2.3.3 Magnet modules and absorbers beyond the ATLAS detector

Beyond the coverage of the ATLAS central detector, absorbers are built to protect the beam pipe and downstream magnets from the remnants traveling relatively forward to the beam axis. Fig. 2.8 shows a plan view of the absorbers and magnets beyond the IP1, located at ± 140 m from the IP1 in the LHC, in Run 1-3. The forward remnants from collisions pass through a 34 mm cylindrical aperture and encounter the first absorber (TAS), a 1.8 m long copper absorber, 20 m away from the IP. The charged component of the remnants is swept away using a strong quadrupole field generated by a 30 m long string of superconducting magnets (triplets, Q1 - Q3) 55 m from IP1. The charged particles impinge on the triplets in such a way that the deposited power density of charged particles in the triplets and triplets' cables is below a threshold. Followed by the triplets, the two beams are redirected to two separate beam pipes back to the LHC ring by a normal conducting single bore separation dipole (D1) with six 3.4 m long modules, ending 85 m from the IP.

The Target Absorber for Neutrals (TAN) is located between the beam pipes to protect the downstream superconducting magnets from the forward angle neutral component of the collision remnant, e.g., photons and neutrons (see fig. 2.8). The TAN is mainly comprised of

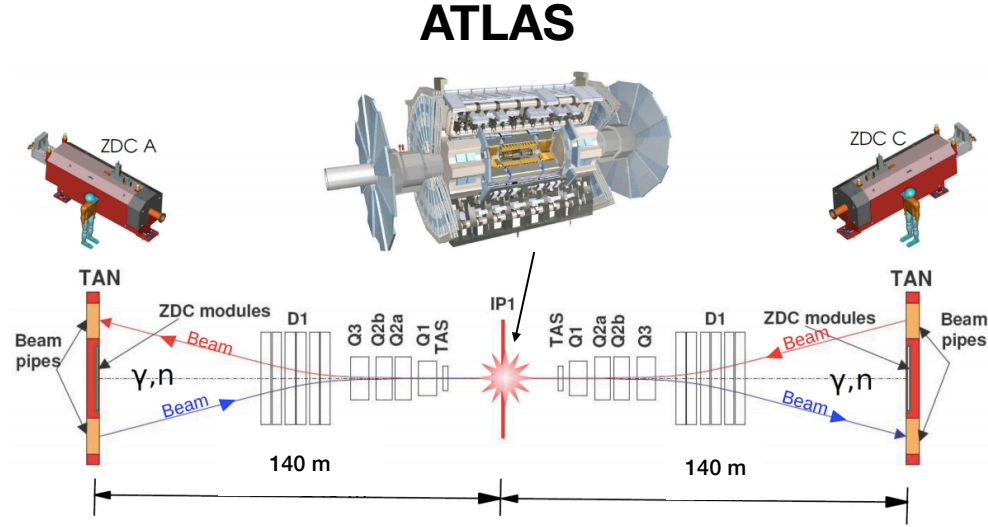


Figure 2.8: The plan view of ATLAS interaction point and the TAN in Run 1-3. Figure adapted from [10].

copper blocks extending over a 3 m length to fully absorb the neural particles. The axis of the particle cone hits in between the two beam apertures. Note that the beam optics in the HL-LHC will be modified; the region where two opposing beams merge will be moved 13 m closer to IP1 and a narrower transverse space between two beam pipes compared to Run 1-3. The current TAN will be replaced by an upgraded TAN (TAXN) designed for the reduced transverse space. This also affects the available space for the detector to be installed in the TAXN, e.g., the ZDC's width will be reduced from 10 to 5 cm.

The TAN serves a special purpose in HI running because neutral particles reaching the TAN contain information about HI collisions, such as the geometry of collisions. Measuring the particles allows for the characterization of HI events in offline analyses. Therefore, the TAN region is exploited by replacing copper blocks with a calorimeter, known as the ATLAS Zero Degree Calorimeter.

2.3.4 Zero degree calorimeter

The ZDC [6, 13] plays an essential role in the ATLAS HI program. It is primarily used to estimate the number of spectator neutrons in HI collisions. The measurement of the

neutrons is used for event triggering and determining the centrality in offline analysis. The ZDC is installed in the TAN (see fig. 2.9) on either side of the IP1. Since upstream magnets have swept out the charged components of the collision debris, with measurements of the central detectors, these neutrons detected in both arms can be used to indicate that the ions have fully broken up.

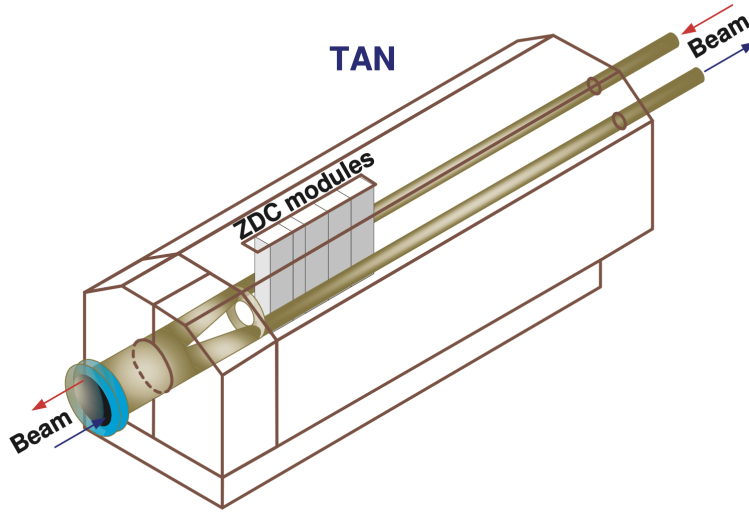


Figure 2.9: Transparent view of the TAN showing the ZDC location and beam pipes. Taken from [6].

The energy deposited in the ZDC is directly correlated with the geometry of the collision and, therefore, the impact parameter. Fig. 2.10 shows a strong correlation between the total energy in both arms of the ZDC and the hadronic energy measured in the central part of the detector by the FCal. For example, high FCal value and low ZDC energy suggest central collisions, while low FCal and high ZDC energy indicate peripheral collisions. Note that low energy in both FCals and ZDCs can indicate non-hadronic collisions.

The ZDC consists of an EM section and a HAD section. Fig. 2.11 shows the side view of the ZDC in the TAN. The EM section is the first module of the ZDC encountered by particles impinging on its front face and is designed to measure EM showers caused by electrons, pions, and photons. The HAD section has three modules installed behind the EM section for hadronic showers. Both sections use tungsten plates as absorbers because tungsten plates can provide the same protection effectiveness with a smaller thickness compared to

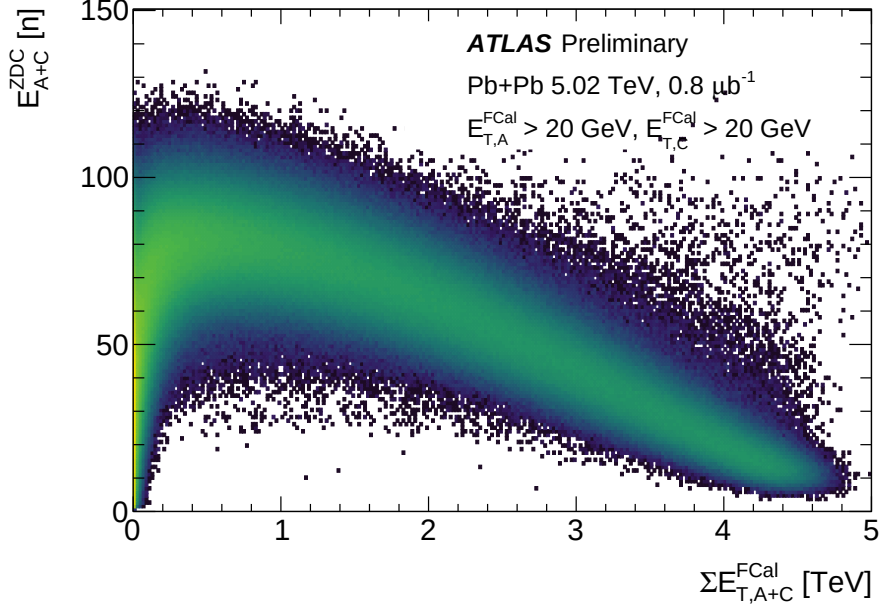


Figure 2.10: Correlation between the total Forward Calorimeter (FCal) transverse energy and the total ATLAS ZDC energy on both arms divided by mean neutron energy. A simultaneous selection was used to suppress electromagnetic events on both FCal sides of > 20 GeV. Figure taken from [13].

the copper blocks installed in the TAN. The usage of tungsten plates provides a space budget and allows for the installation of active material for signal generation.

In Run 1 and Run 2, fused quartz rods were used as Cherenkov radiators in the ZDC. Rows of fused quartz rods were sandwiched by tungsten plates. Fig. 2.12 shows a bottom view of the ZDC detector, where rods sandwiched between tungsten plates can be observed thanks to light shining on them from the other side. Above the plates, light guides were installed to redirect the light emitted from the rods to PMTs. Additionally, a matrix of rods was designed to measure the transverse profile of a shower (see fig. 2.13). The rods were inserted into the holes of the tungsten plates. The side view of the design can be seen in the first two modules in fig. 2.11. At the end of the modules, the rods were bent vertically and routed upward to readout devices¹.

The charged fraction of the shower produced by the neutral particles impinging on the detector can emit Cherenkov light when passing through the rods. The production of Cherenkov light depends on the charged particle's phase velocity with respect to that of

¹These quartz rods turned opaque due to radiation damage early in Run 1, making them non-operational.

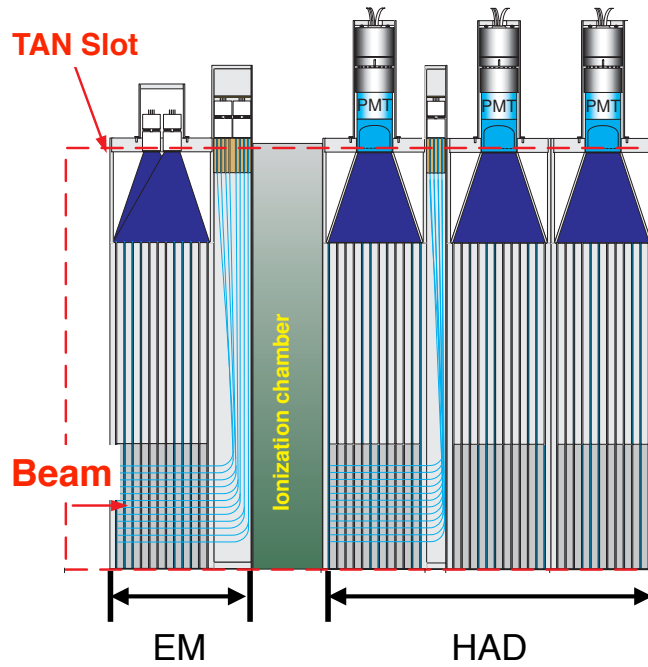


Figure 2.11: Side view of the first ZDC design in one arm. Fused quartz rods are sandwiched between tungsten plates in both EM and HAD sections (see fig. 2.12). The EM and the first HAD module have an additional transverse matrix of fused quartz rods (see fig. 2.13). Note the EM section in the other arm does not have the transverse matrix. Figure adapted from [6].

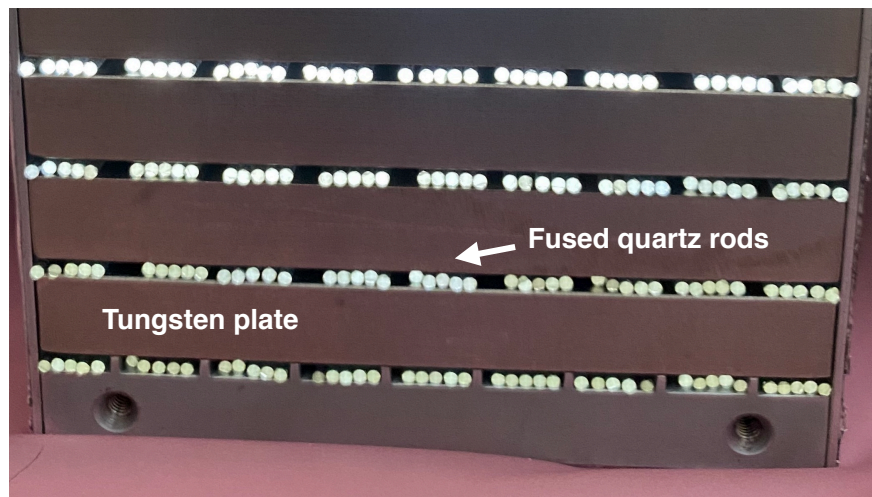


Figure 2.12: Fused quartz rods are sandwiched by tungsten plates. A light source is placed on the other side of the ZDC allowing for the visualization of the rods.

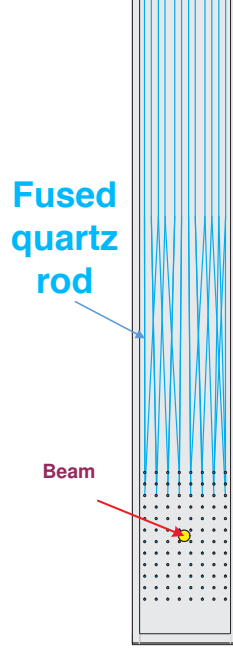


Figure 2.13: A schematic drawing of the transverse matrix of fused quartz rods, viewed from the rear side of the EM section. Figure adapted from [6].

light in a medium. When light at a wavelength (λ) travels in a medium with a refractive index (n), its phase velocity (v_c) is

$$v_c(\lambda) = \frac{c}{n(\lambda)}, \quad (2.7)$$

where c is the phase velocity of light in vacuum. When charged particles travel in a medium with a velocity (v) faster than v_c , they lose their energy through Cherenkov photon emission.

The energy E emitted by a charged particle per unit length x per unit wavelength is

$$\frac{d^2 E}{dx d\lambda} = 2\pi\alpha \frac{1}{\lambda^2} \left(1 - \frac{1}{\beta^2 n(\lambda)^2} \right), \quad (2.8)$$

where α is the fine structure constant and β is the ratio between the speed of the particle and the speed of light [35]:

$$\beta = \frac{v_c}{c}. \quad (2.9)$$

Eq. 2.8 indicates that the spectrum of Cherenkov light is characterized by a dependence on

the wavelength, λ^{-2} . This means that the shorter wavelengths (higher frequencies) correspond to more Cherenkov photons. Thus, most Cherenkov light is ultraviolet (UV).

A consistent fraction of the Cherenkov light is retained within the rods thanks to total internal reflection (TIR). Fig. 2.14 shows a schematic drawing of light traveling from one medium with refractive index n_1 to another medium with refractive index n_2 .

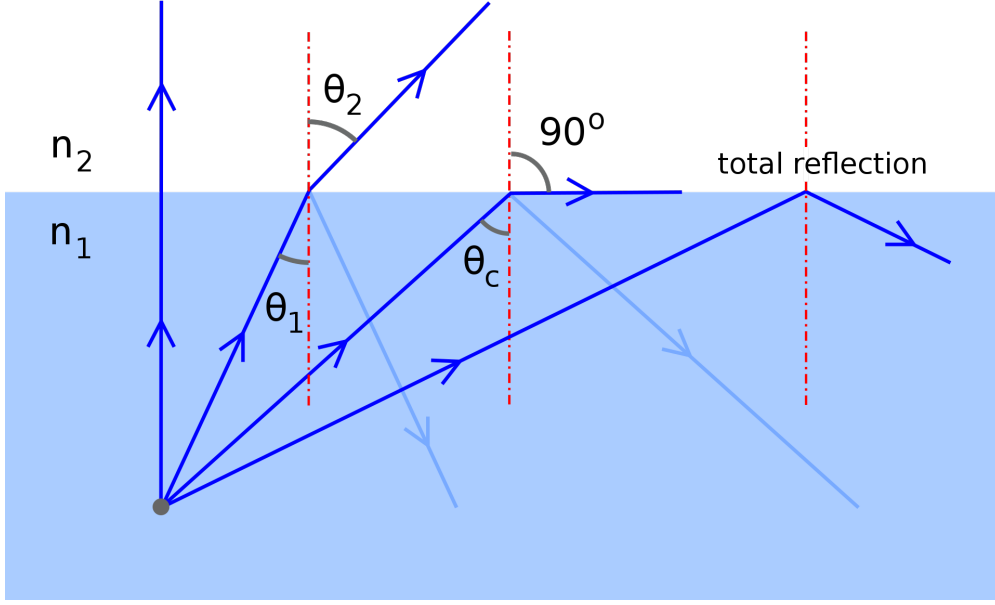


Figure 2.14: Light travels from a medium with refractive index n_1 to a medium with refractive index n_2 . Taken from [36]

TIR is an optical phenomenon in which light arrives at the boundary between two mediums, and light is completely reflected back to the original medium. The phenomenon occurs if the angle of the incident light with respect to the boundary is greater than a critical angle θ_{cri} characterized by

$$\theta_{cri}(\lambda) = \arcsin\left(\frac{n_2(\lambda)}{n_1(\lambda)}\right). \quad (2.10)$$

Note that eq. 2.10 is valid when n_2 is smaller than n_1 . In the case of the ZDC, because the fused quartz's refractive index is higher than the air, Cherenkov light emitted with an angle above θ_{cri} can be trapped in the rods by TIR. For example, the critical angle for 300 nm light is 42.5 degrees for fused quartz². The light above the critical angle is retained within

² n is 1.48 at 20 °C and a pressure of 1 bar [37].

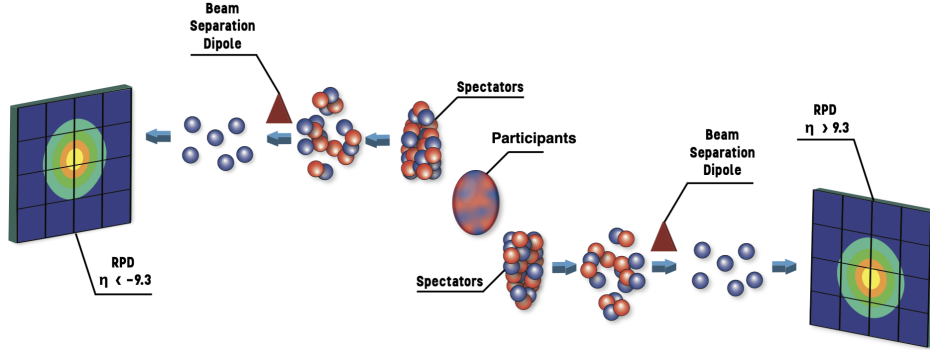


Figure 2.15: Schematic of the spectator’s deflection measurement using the RPD in HI collisions. Blue and red spheres represent neutrons and protons, respectively. Free protons and charged fragments are swept out by the beam optics. Figure adapted from [13]

the rod and bounces until it is absorbed by a color center or exits through one of the two ends of the rod. The light emitted from the top of the rods is collected by means of an air-light guide on the face of a PMT. The PMTs’ signals are used to reconstruct the total energy of incident particles [38].

2.3.5 Reaction plane detector

This section gives a brief overview of the RPD proposed to map the transverse profile of showers produced by spectator neutrons in the ZDC. Such a measurement can be used to estimate the deflection of the spectator neutrons from the beam axis (see fig. 2.15), allowing for reconstructing the so-called reaction plane (RP), a physics observable that is used in particle flow’s analyses (described in chap. 6).

The RPD consists of a 2-dimensional array of fused silica fibers, acting as Cherenkov radiators. Fig. 2.16 shows a visual representation of the fiber pattern in the RPD. Each channel is comprised of fused silica fibers of the same length perpendicular to the LHC beam. For a given channel, 16 fibers are routed upwards and read out by a PMT. The PMTs’ signals can be mapped into an array of 4×4 tiles, allowing for measurements of the transverse shower produced in the ZDC. It is installed in-between the EM and HAD section of the ZDC, where the EM shower generated by spectator neutrons is expected to be maximum. The location maximizes the amount of Cherenkov light that can be collected

in the RPD and, thus, the magnitude of the RPD's signal. Fig. 2.17 shows a finalized RPD for Run 3 and the corresponding technical drawing with fibers from the active area and electronic components.

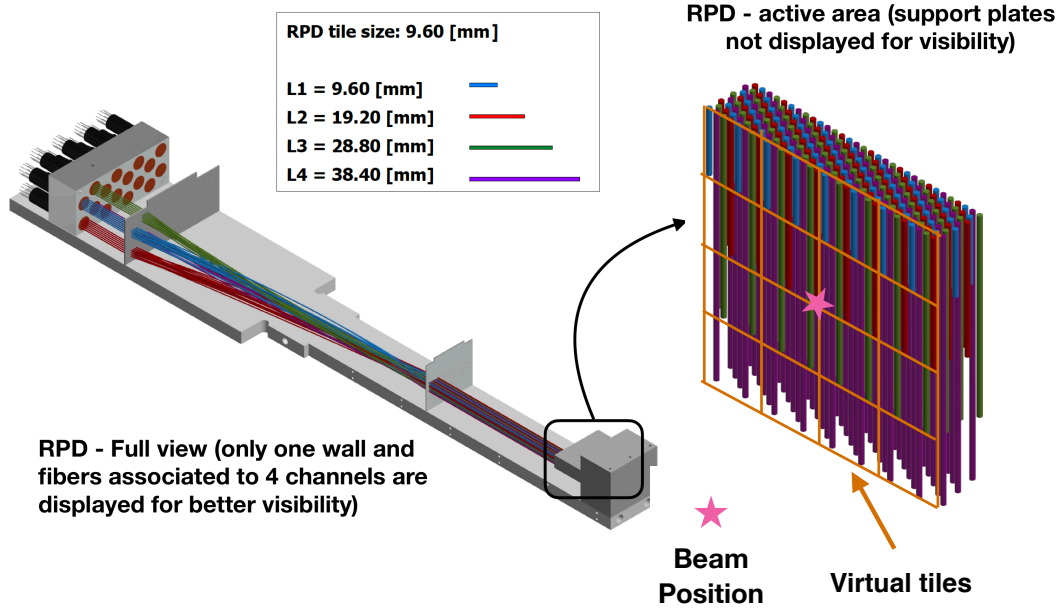


Figure 2.16: The fiber pattern of the RPD. The right side shows the arrangement of the fibers in the RPD. Different fiber colors identify fibers of different lengths. Fibers in a channel are read out by a PMT. The orange line illustrates segments of RPD virtual tiles reconstructed using the PMT signals. The star symbol represents the position of the LHC beam axis.

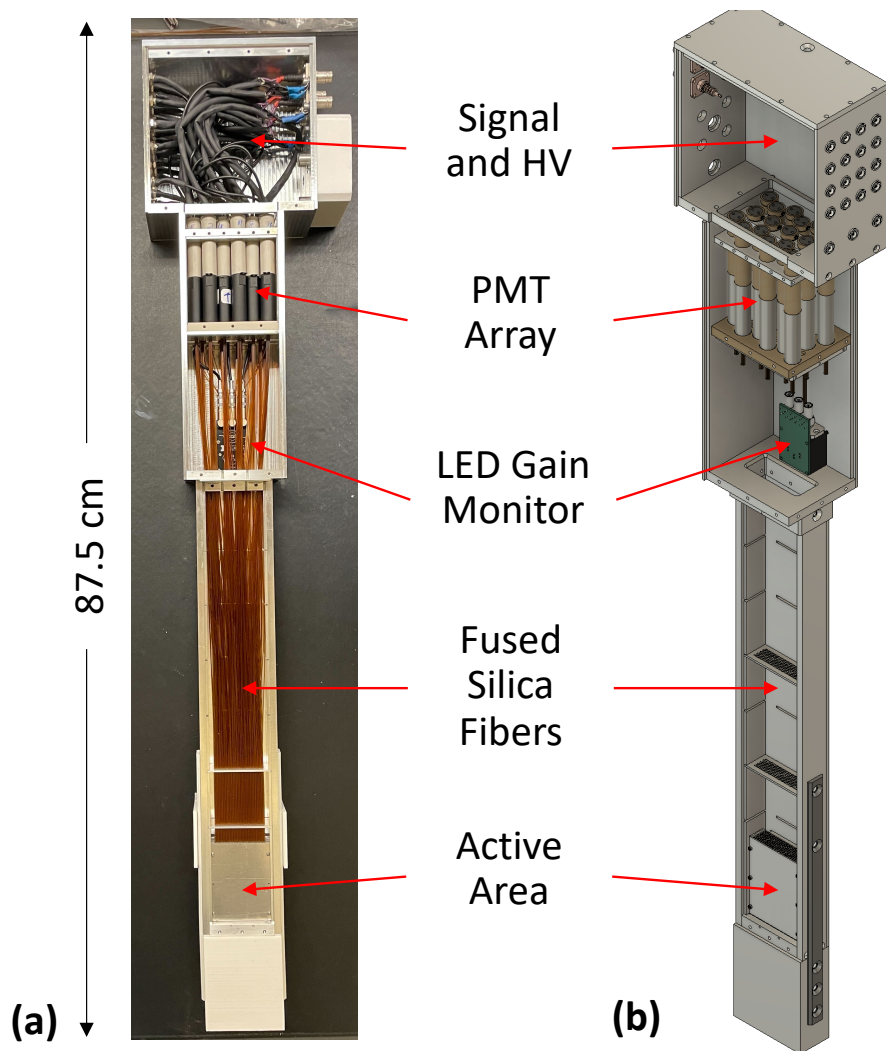


Figure 2.17: Side-by-side diagram of the finalized ATLAS RPD for Run 3 (a) and the corresponding technical drawing (b). Note that the front panel was removed for demonstration. Taken from [39]

2.4 Radiation damage to ATLAS ZDC

Radiation can interact with material through energy transfer to electrons, nuclei, or an atom as a whole. The transfer process can involve different mechanisms such as ionization, electron, nucleus excitation, and hadronic inelastic interaction. The transferred energy can dissipate thermally but can also change the chemical properties of a material. For example, the energy can break chemical bonds between atoms, creating electron-hole pairs. Radiation can also displace an atom, resulting in a permanent vacancy in material structure. Such effects, referred to as radiation damage, are correlated to the amount of energy deposited in a material. The deposited energy is typically quantified by absorbed dose D [40] using

$$D = \frac{E}{m}, \quad (2.11)$$

where E is the energy deposited within a given mass m of material.

Fused quartz is characterized by a relatively high level of impurities, of the order of ppm, which can trap the electrons and holes induced by radiation, resulting in the formation of color centers. Color centers can absorb light at different wavelengths, leading to optical transmission losses. If the absorption wavelengths are in the visible spectrum, a “transparent” material becomes colored or even opaque. During Runs 1 and 2, the ATLAS ZDC used fused quartz (GE214) rods as Cherenkov radiators. Fig. 2.18 shows a comparison between new fused quartz rods and ones exposed to LHC radiation in the ATLAS ZDC during 2011. The rods in the ZDC were irradiated for the whole LHC run, including both $p+p$ and Pb+Pb operations. Due to the radiation-induced color centers, the ZDC rods turn almost completely opaque after the run, corresponding to an integrated dose of approximately 10 MGy.

An optical transmission measurement was carried out to study optical transmission losses of the irradiated rods at different wavelengths. The result is shown in fig. 2.19. Transmission losses are significant and widespread in wavelength for rods irradiated during 1 year of full LHC running ($p+p$ and Pb+Pb), where the dose level reached ~ 10 MGy. The highest damage can be observed in the UV region. Losses in the UV region are detrimental for a



Figure 2.18: Comparison between brand new GE214 [41] fused quartz rods (right) and the same type of rods irradiated in the LHC during Run 1 (~ 10 MGy, left).

Cherenkov radiator, since the emission spectra of Cherenkov light decay with $1/\lambda^2$. The rods irradiated only during Run 2 Pb+Pb data taking also shows considerable deterioration of the transmission. Tab. 2.1 shows the maximum integrated doses in the TAN/TAXN estimated for Runs 2, 3, and 4 using FLUKA simulations provided by the CERN FLUKA team. Based on the doses expected in Runs 3 and 4, a more robust Cherenkov radiator is necessary for the ZDC in the HL era.

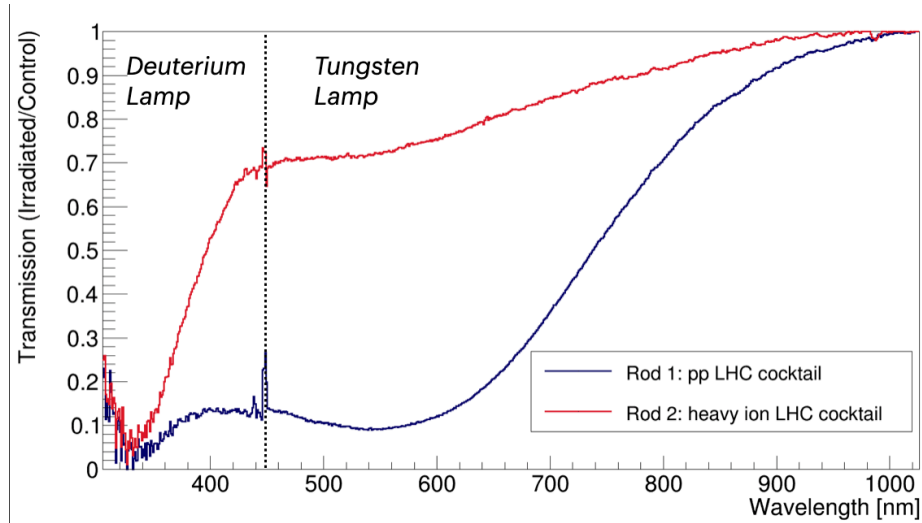


Figure 2.19: Optical transmission of irradiated GE214 fused quartz rods in the ZDC. Rod 1 was exposed to ~ 10 MGy during 1 year of full LHC running ($p+p$ and Pb+Pb) in Run 1, while Rod 2 was exposed only during Pb+Pb running in Run 2.

Table 2.1: Maximum integrated dose expected for different data taking periods in the TAN/TAXN in Runs 2, 3, and 4. The expected doses are based on simulations provided by the CERN FLUKA team. The tag [†] indicates that doses are projected using other simulations by linear re-scaling luminosity and beam energy.

Run		p + p	Low- μ p + p	p+Pb	Pb+Pb
Run 2	CoM energy	13 TeV	5.02 TeV	8.16 TeV	5.02 TeV
	L_{int}	156 fb ⁻¹	272 pb ⁻¹	0.18 pb ⁻¹	2.3 nb ⁻¹
	Dose	250 MGy	60 kGy	170 kGy [†]	92 kGy
Run 3	CoM energy	14 TeV	5.5 - 8.8 TeV	8.8 TeV	5.5 TeV
	L_{int}	270 fb ⁻¹	1.2 + 0.4 fb ⁻¹	0.6 pb ⁻¹	7 nb ⁻¹
	Dose	545 MGy [†]	400 kGy [†]	600 kGy	330 kGy [†]
Run 4	CoM energy	14 TeV	5.5 - 8.8 TeV	8.8 TeV	5.5 TeV
	L_{int}	700 fb ⁻¹	1.2 + 0.4 fb ⁻¹	0.6 pb ⁻¹	7 nb ⁻¹
	Dose	1100 MGy	600 kGy [†]	2.51 MGy	1.4 MGy

The radiation damage to the fused quartz rods leads to two main issues:

- Stability of the ZDC's performance: the accumulated radiation doses during the Pb+Pb operation were enough to reduce the fused quartz rods' optical transmission. The damage occurred during the running, leading to a continuous decrease in ZDC's light yield over time and, thus, unstable detector performance. Therefore, the losses required additional monitoring of the ZDC's detector response and fine-tuning of the PMTs' voltage to compensate for the damage using a higher PMT gain.
- Flexibility of ZDC usage in the LHC run: the dose limit of the fused quartz rods prevents the ZDC from being installed in high luminosity $p+p$ running. Therefore, the ZDC can be installed only during the technical stop of the accelerator preceding the HI run, to be then removed right after. Additionally, the ZDC could not be used for HI runs (i.e. Xe+Xe run in 2017) between $p+p$ running because the total time, including deployment and un-installation of the ZDC, would have been comparable to the HI running time.

To design a generation ZDC able to operate stably at the radiation level expected in HL-LHC, one of the JZCaP's primary goals is to improve the radiation hardness of the

ZDC's Cherenkov radiator. UIUC plays a leading role in JZCaP, with Prof. Matthias Grosse Perdekamp being the project leader and Dr. Riccardo Longo serving as the technical coordinator. JZCaP collaborates with the BRAN group and the FLUKA group at the CERN. The collaboration is dedicated to studying the radiation effects on fused silica, namely the activation and radiation hardness, at the LHC radiation level. The BRAN group carried out an irradiation experiment on fused silica rods doped with various hydrogen (H_2) and hydroxide (OH) levels. The rods were inserted in a BRAN prototype detector installed within the TAN during Run 2 $p+p$ data taking. The light yield of the fused silica rods was read out by PMTs to monitor the radiation damage level as a function of integrated luminosity. The details of the irradiation experiments and the corresponding FLUKA simulations are described in chap. 3.

After completion of the LHC Run 2, the fused silica rods were shipped to UIUC for optical transmission and activation measurements. With support from the FLUKA team at CERN, it was possible to estimate the doses accumulated in the BRAN rods using FLUKA simulations. The simulations were also used to estimate the activation induced by the high-energy hadron cocktail of the showers in the TAN. Therefore, the FLUKA simulations enabled various studies to be carried out on the irradiated BRAN rods. Two such studies are the performance of FLUKA in describing the ^{22}Na activation profile of the BRAN rods, discussed in chap. 4, and a multi-variate analysis of the optical transmission of fused silica in terms of doses, wavelengths, and material compositions, presented in chap. 5.

CHAPTER 3

LHC RADIATION ENVIRONMENT

This chapter presents the details of the irradiation campaign during Run 2, carried out in collaboration with the BRAN team to study the radiation damage to fused silica. The mechanism of radiation damage and the formation of color centers in fused silica are discussed. The details of the FLUKA MC simulation provided by the CERN FLUKA team are reported, along with the estimation of accumulated doses and the isotope activity in the irradiated samples from the campaign. This chapter is structured as follow: sec. 3.1 introduces the motivation to study fused silica’s radiation-hardness with descriptions of fused silica in sec 3.1.1, radiation damage processes in sec. 3.1.2, radiation-induced color centers in sec. 3.1.3, and the details of the Run 2 irradiation campaign in sec. 3.1.4. Sec. 3.2 introduces the FLUKA MC toolkit, providing the details about the simulations setup of the TAN described in sec. 3.2.1, the estimated ^{22}Na activity given in sec. 3.2.3, and the estimated accumulated doses in the TAN presented in sec. 3.2.2.

3.1 Fused silica irradiation campaign

The BRAN detector is a segmented ionization chamber proposed in 1998 [42]. The purpose of the detector is designed to monitor the relative luminosity delivered by the LHC to the experiments (i.e. ATLAS and CMS), allowing for optimizing the performance of the machine during the running time. Four different detectors are installed in the TAN, on both sides of the LHC interaction points, IP1 (ATLAS) and IP5 (CMS), to measure neutral particles resulting from $p+p$, $p+\text{Pb}$, and $\text{Pb}+\text{Pb}$ collisions [9, 43]. However, the BRAN design was optimized for the beam configurations in Run 1, e.g., 7 TeV center-of-mass energy and $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity [44]. Severe radiation damage to the BRAN detector was observed at

the beginning of Run 2 due to higher luminosity and beam energy compared to Run 1. A new detector design, based on the use of radiation-hard fused silica as Cherenkov radiator material, was proposed in view of the HL-LHC upgrade. A detector prototype based on this idea was installed in one of the TAN around IP1 during $p+p$ running in Run 2.

3.1.1 Fused silica

Fused silica consists of pure silica (silicon dioxide, SiO_2) in amorphous (non-crystalline) form produced through chemical deposition, which makes its purity higher compared to fused quartz made from natural minerals [45, 46]. Fused silica has an excellent optical transmission ranging from UV to infrared wavelengths among all glassy materials, along with its mechanical and chemical durability, making it preferable for low-loss optical communication applications [47]. The concentration of impurities in fused silica is relatively low, e.g., smaller than 0.015 ppm in the fused silica rods used in the BRAN prototype detector [48]. Since impurities facilitate radiation-induced optical transmission losses in general, fused silica has excellent radiation hardness compared to other glassy materials due to its high purity [49, 50, 51, 52]. Such characteristic is reported in ref. [53]; the study presents the optical transmission of three types of fused silica after receiving up to 100 kGy delivered by a 150 MeV proton beam. All the materials involved in the analysis did not show significant optical transmission losses. Ref. [54, 55] presents optical transmission studies for fused silica irradiated by an ^{16}O ion beam at 100 MeV/c, with a dose rate of 6 MGy/h. Up to an accumulated dose of 200 MGy, the optical transmission between 400 and 700 nm shows negligible losses. However, since radiation-induced damage depends on the nature and energy of the radiation, the BRAN group decided to install a prototype detector in the TAN during Run 2 to study the radiation hardness of fused silica in the LHC radiation environment.

3.1.2 Radiation damage processes

The structure of fused silica can be modeled as a random continuous network (RCN), characterized by the distribution of n -membered $(\text{Si-O})_n$ rings connected by a shared (“bridging”)

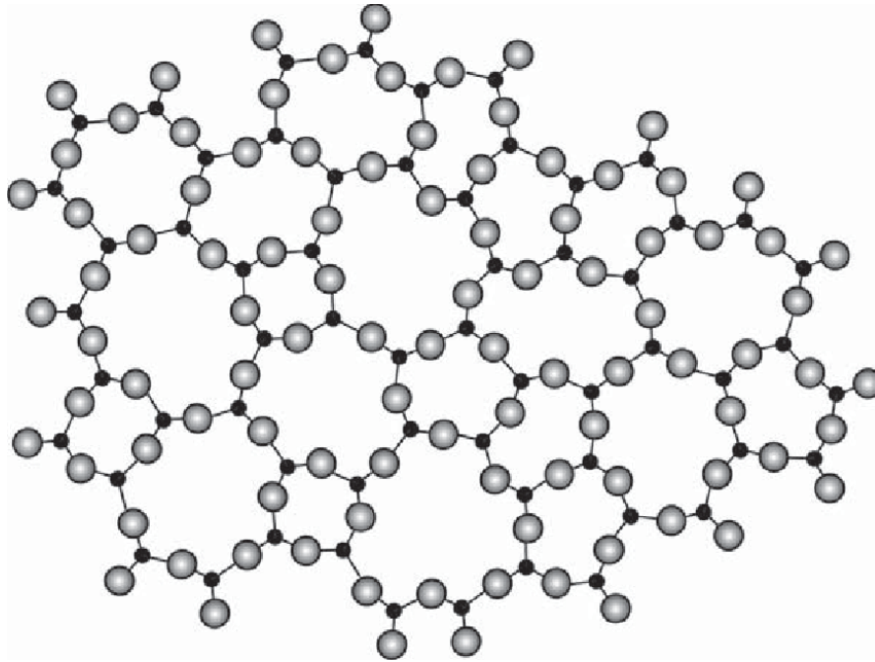


Figure 3.1: An example random continuous network of fused silica in 2D. Dark circles are Si atoms and light circles are O atoms. The network is fully connected by sharing O atoms. Rings with different size can be observed. Picture taken from ref. [56]

oxygen atom (see fig. 3.1). Deviations from the ideal RCN are described as point defects, e.g., impurities in the network or missing chemical bonds between atoms. The former is known as impurity defects, while the latter is referred to as intrinsic defects. The concentration of impurities in fused silica is relatively low, so most defects are intrinsic [47].

These defects can be induced by the energy transferred from radiation to electrons or atoms. Fig. 3.2 shows how defects in glass material are generated by various types of radiation. In general, there are three processes causing radiation damage: radiolysis, displacement damage, and electron rearrangement. These three processes are not mutually exclusive and can happen concurrently [57].

Radiolytic processes are atomic rearrangements due to the energy provided by the recombination process of electrons and holes. In principle, any radiation capable of exciting electrons to create electron-hole pairs can induce radiolytic processes. When an electron and a hole recombine, the excited energy will be released. The energy is transferred into nuclear motions, e.g., breaking of chemical bonds, when the energy can not be emitted through photons and is only channeled to a single atom. In that case, it is likely to create a defect.

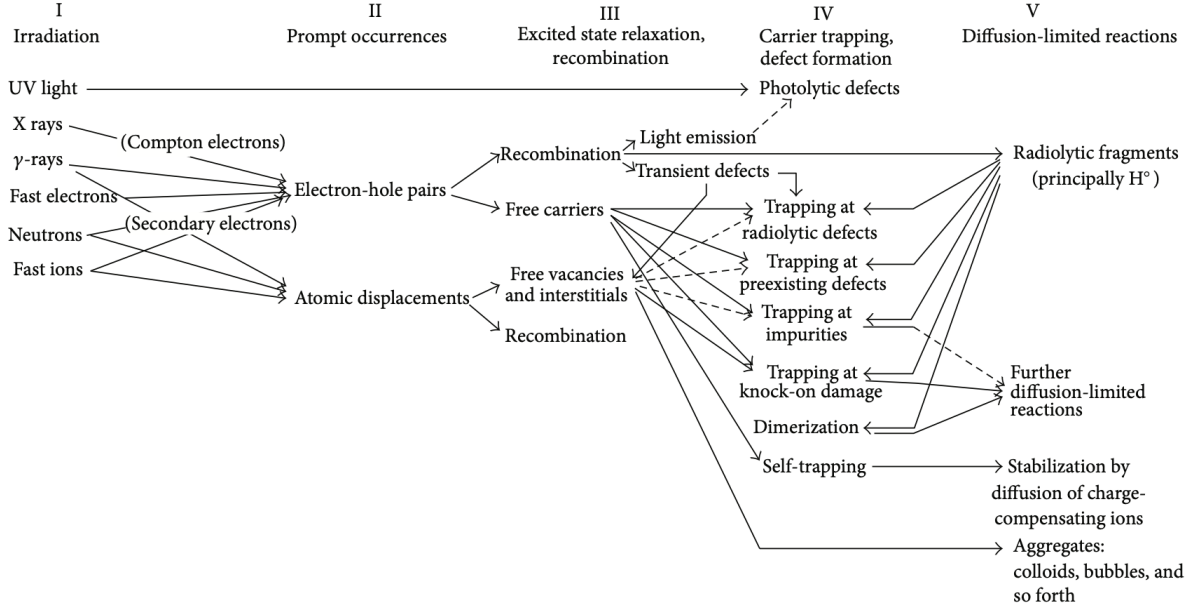


Figure 3.2: Radiation damage processes in glasses subjected to various type of ionizing radiation and particles. In the LHC radiation environment, charged hadrons, similarly to fast electrons, are abundant and can create electron-hole pairs during interactions. Diagram taken from [57, 58].

Displacement damage is caused by direct energy transfer from the incident particle to an atom in the network. If the transferred energy is sufficient to break the bonds, the struck atom can be displaced into an interstitial position in the RCN. The amount of energy that causes the displacement should be the same order as the broken bonds, typically 4-25 eV [57]. However, if incident particles are charged particles, the contribution of displacement to the damage is less prominent because charged particles typically transfer more energy through ionization processes.

Electron rearrangement can only happen when other types of defects present, such as vacancies or impurities, serve as pre-existing traps (precursors) for electrons and holes. The precursors can also be created from the damage in radiolytic processes and displacement damage. A precursor can immobilize an electron or a hole, prevent recombination with other carriers of opposite charge, and form a color center.

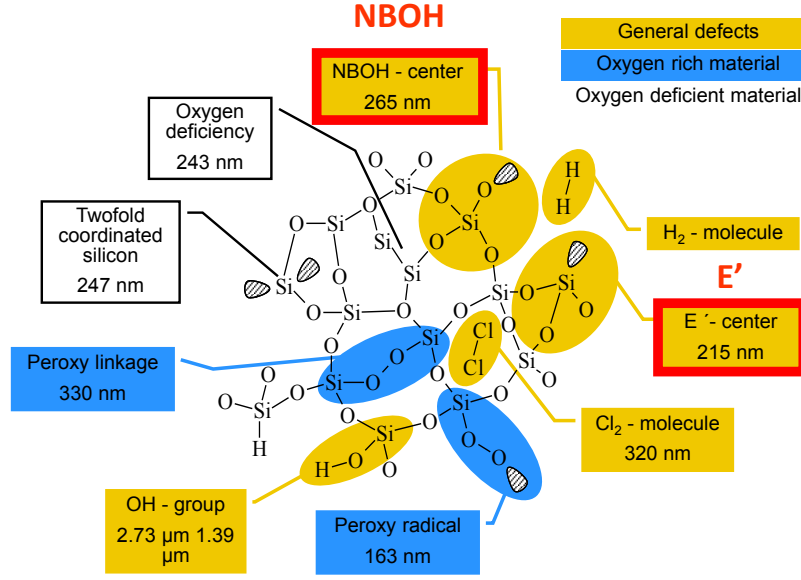
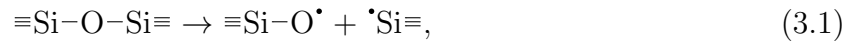


Figure 3.3: Defect centers with the corresponding center wavelengths of absorption in fused silica. Picture is taken from [59].

3.1.3 Color centers

Fig. 3.3 shows the color centers causing optical transmission losses in fused silica. Most centers lead to transmission losses in the UV region. The optical transmission losses are mainly caused by dangling bond type centers, immobilized atoms with unpaired electrons. Two common centers are dangling silicon bonds, known as E'-center, and non-bridging oxygen hole centers, NBOH. The former feature an unpaired electron in the silicon orbital ($\equiv\text{Si}^\bullet$)¹ while the latter ($\equiv\text{Si}-\text{O}^\bullet$) are created by breaking the strained (Si-O) bond



or, more often, by breaking network-bound hydroxyl (silanol, $\equiv\text{Si}-\text{O}-\text{H}$)



Decreasing the amount of dangling-bond defects in fused silica can increase the radiation

¹The dot in $\equiv\text{Si}^\bullet$ indicates a unpaired electron, while the bars represent chemical bonds (paired electrons).

hardness in the UV region [47, 59]. A technique to achieve that is solving H_2 into fused silica during the production process, to combine with the dangling bonds. For example, NBOH centers can break H_2 at room temperature so eq. 3.2 can be reversed as follow:

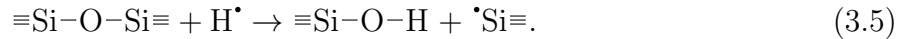


Because the end products do not absorb light, the optical transmission can be maintained. In addition, the number of the E' center can also be reduced:



Note that Si-H is not stable compared to Si-O-H. Thus, Si-H can be broken again and generate transient absorption phenomena. This phenomena, known as rapid damage process “RDP”, leads to optical transmission losses in UV.

Loading a high amount of H_2 into fused silica does not work for all applications in general. Heavy H_2 loading can lead to an abundant amount of Si-H, resulting in RDPs at the beginning of the irradiation. Additionally, the H_2 loading can shift the reaction equilibrium in fused silica to the creation of E' as a combination of eq. 3.1 and 3.3



As a result, the concentration of E' in the fused silica with higher H_2 content is more than that of the fused silica with a lower H_2 level [60], leading to more optical transmission losses in UV.

3.1.4 Irradiation experimental setup

The information presented above was mostly obtained by irradiating fused silica with UV laser beams. For LHC applications, where the irradiation occurs by means of a high energy particle cocktail, these data provide limited information. The best way to study the behavior of fused silica under in this radiation environment is to carry out dedicated experiments in

the accelerator complex itself. For this reason, a BRAN prototype detector, equipped with fused silica rods, was installed in the TAN at IP1 during Run 2 [61]. Fig. 3.4 shows the detector before installation, while fig. 3.5 provides details about the configuration of the TAN slot and of the rods in the prototype. The detector can accommodate up to 8 fused silica rods sandwiched between three copper plates parallel to the beam direction. The fused silica rods were doped with different levels of OH and H₂ to study the impact of the dopants in improving fused silica's radiation hardness. Tab. 3.1 lists the different fused silica materials tested in the BRAN prototype detector.

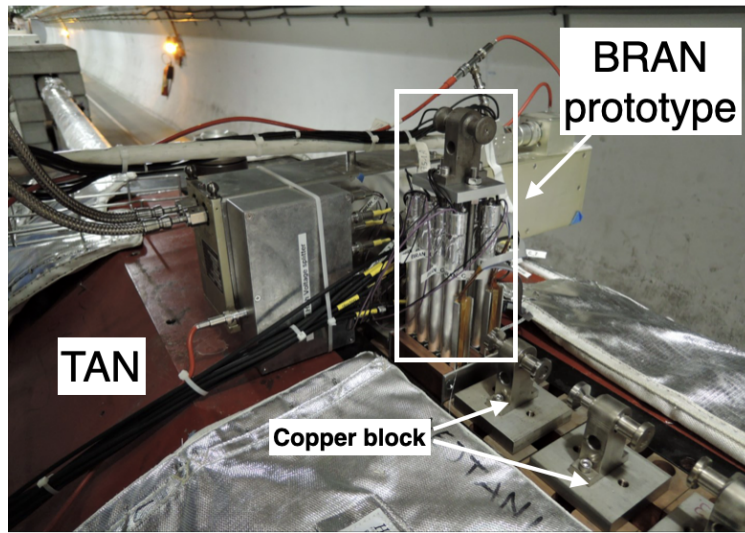


Figure 3.4: BRAN prototype partially inserted in the TAN at IP1 before installation. Figure adapted from [19]

The rods, manufactured by Heraeus Quarzglas in Germany, were cylinders with a length of 40 cm and a diameter equal to 1 cm. The rods were inserted into slots 1 to 6, while positions 7 and 8 were left empty to study Cherenkov light yield in air (results not discussed in this dissertation). On top of each rod, a Hamamatsu R3878P PMT was placed to convert Cherenkov light generated by the charged component of showers into an electrical signal (see fig. 3.6). By monitoring the change in the magnitude of the signals over time, the radiation damage to the rods can be studied as a function of the luminosity delivered by the accelerator.

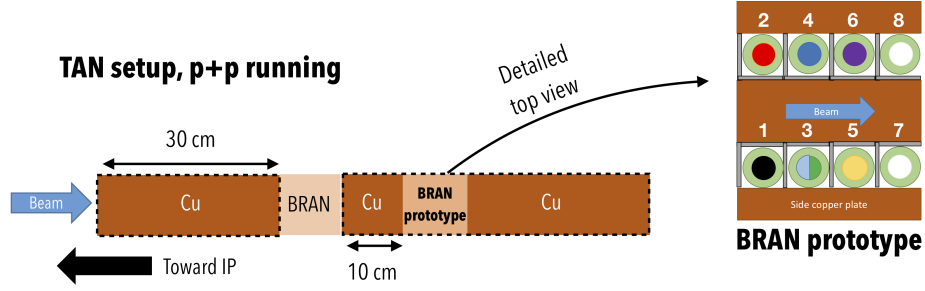


Figure 3.5: TAN setup during $p+p$ running in LHC Run 2 (2016-2018). The dashed lines identify the slot used to install the ZDC during the heavy-ion runs. The right side shows a detailed top view of the BRAN prototype. The numbers identify the position of the fused silica rods. Detailed information on the materials of the rods and maximum irradiation reached for each of them are reported in tab. 3.1.

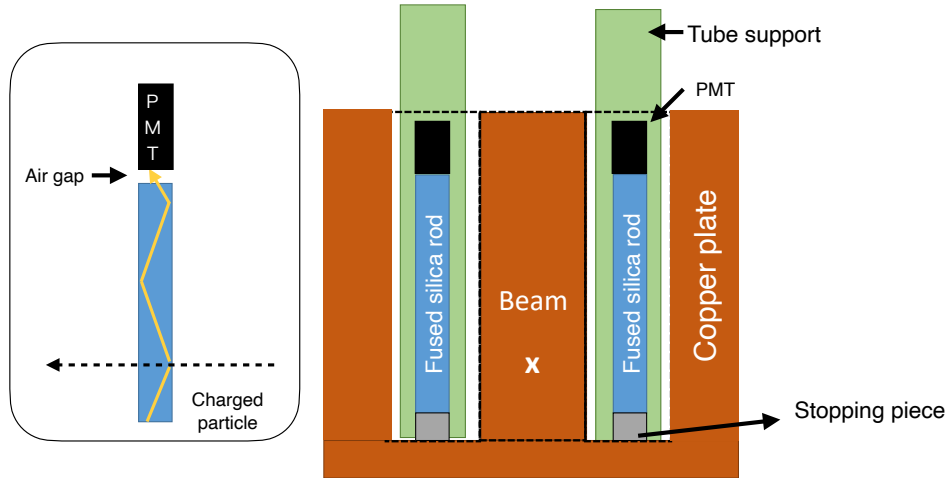


Figure 3.6: Front view of the BRAN prototype. The left insert shows an enlarged view inside the tube support where the PMT read out Cherenkov light when a charged particle passes through the fused silica rod.

Table 3.1: Specifications of fused silica rods in the BRAN prototype. The number assigned to each rod corresponds to a given position in the detector, as shown in fig. 3.5. Rods 3a and 3b occupied the same slot, but at different times.

BRAN Position	Irradiation Period	Max. Exposure [MGy]	Material	H₂ [mol/cm³]	OH [ppm]
1	04/2016 - 12/2018	18	Spectrosil 2000 (High OH, Mid H ₂)	7.20e17	1120
2	04/2016 - 12/2017	10	Spectrosil 2000 (High OH, Mid H ₂)	7.20e17	1120
3a	04/2016 - 12/2016	5	Spectrosil 2000 (High OH, High H ₂)	2.80e18	1000
3b	04/2017 - 12/2018	16	Spectrosil 2000 (High OH, Mid H ₂)	7.20e17	1120
4	04/2016 - 12/2017	9	Spectrosil 2000 (High OH, H ₂ free)	0	1011
5	04/2016 - 12/2017	8	Suprasil 3301 (Low OH, High H ₂)	3.00e18	15
6	04/2016 - 12/2018	17	Suprasil 3301 (Low OH, H ₂ free)	0	14

Fig. 3.7 shows the change of the PMT signal charge for Rod 1 during LHC runs 2016 and 2017. The data are presented as a function of integrated luminosity delivered to ATLAS. The charge measured by the PMT is divided by the number of bunches delivered by the LHC and then normalized using the initial value. A decrease of about 40% in the PMT signal charge is observed during the delivery of the first 20 fb^{-1} . After that, the measured charge is found to be stable for the rest of the irradiation period. The interpretation of the observed losses in light yield requires additional information. For instance, the readout signal represents a convolution between the wavelength dependent PMT quantum efficiency and the wavelength spectrum of Cherenkov light. Therefore, it is essential to conduct optical transmission measurements of the rods to further understand the radiation damage at different wavelengths. These optical transmission measurements were carried out as part of this dissertation at the Frederick Seitz Material Research Laboratory.

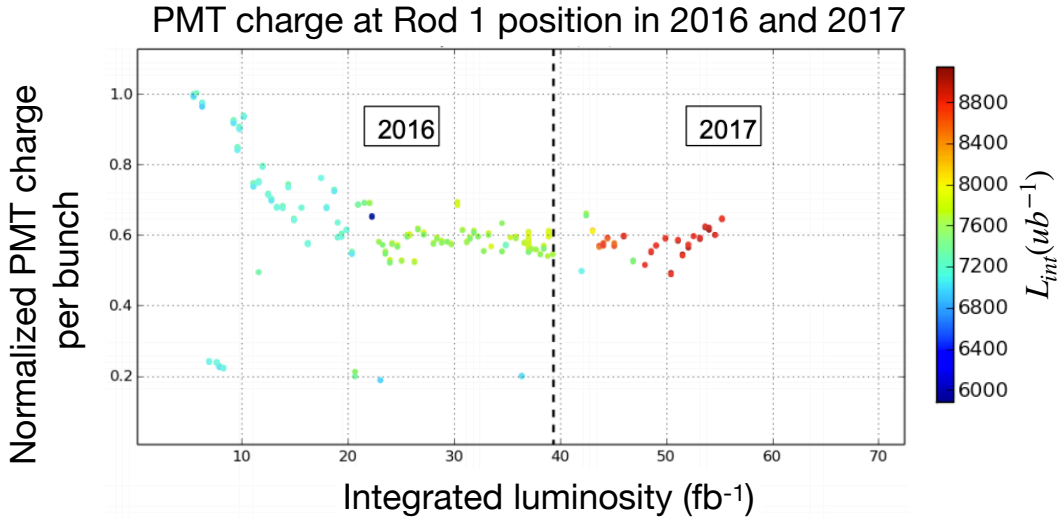


Figure 3.7: The normalized PMT charge in Rod 1 in BRAN prototype from 2016 to 2017. The charge is divided by the bunches of the beam and, then, normalized by the initial divided charge value. Color bar represents the integrated luminosity of each data taking. Figure adapted from [61].

3.2 FLUKA simulations of the TAN

FLUKA [18] is a fully integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei in matter. It has been used in a wide variety of LHC applications, including energy deposition studies associated with LHC detectors, material degradation, and residual nuclei estimation. There are extensive benchmarking studies presenting excellent agreement between simulated and measured values in the complex radiation environment of the LHC [62, 63, 64, 65, 66].

The detailed implementation of particle interaction and transport in the software, together with the accurate description of the LHC accelerator complex, are key elements to obtain this agreement. The former depends on the incorporation of complementary physics models covering a wide range of particle types and energies, while the latter relies on detailed material composition and beam optics description, including detailed magnetic field maps for the whole accelerator complex. A benchmark of the FLUKA simulations for the Long Straight Sections (LSS) around IP1, where the TAN is located, is provided by Beam Loss Monitor (BLM) measurements [67, 68]. The LHC BLM is a gas ionization chamber that measures energy deposited by beam losses, e.g., collision products, with multiple time resolutions. It serves as an online dose monitor used to trigger beam abortion when the deposited energy exceeds a pre-defined threshold. There are a few thousand BLMs installed along the 27 km beam line. Fig. 3.8 shows a comparison between the dose per luminosity unit accumulated in the BLM estimated by FLUKA simulations of the LSS and the measurement of dose recorded by the BLM itself. The FLUKA simulations take into account the beam optics and the model of the entire geometry of the LSS, allowing for a direct comparison between data and simulations. The FLUKA-based estimate is computed from the energy deposited in the gas region of the BLMs by charged particles. These charged particles can either be generated in the IP or by interactions of collision products with matter present in the tunnel. Both the simulation and real data correspond to the environment presented for the 2018 Run. The agreement between FLUKA and BLM data is excellent, in particular in the TAN region (approximately 135 - 145 m in the figure).

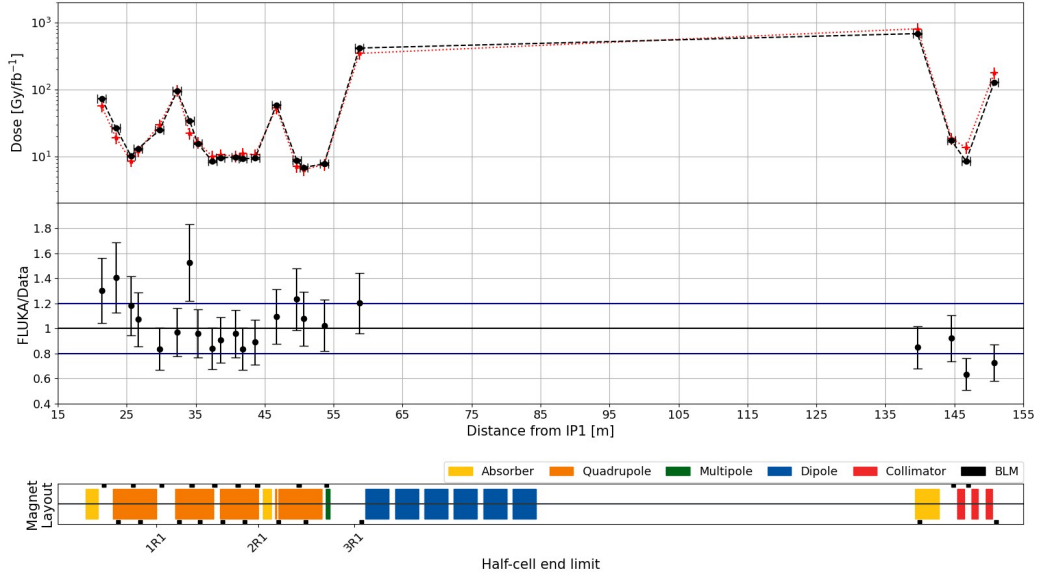


Figure 3.8: Top panel: dose comparison between simulations (black circles) and measurements (red crosses) of BLM in the LSS on arm 8-1 of IP1 in 2018. The TAN is located approximately 135 - 145 m from IP1. The data correspond to 20.3 fb⁻¹ of $p+p$ collisions with a center-of-mass energy of 13 TeV. Mid panel: ratios between simulation values and data. The errors on the ratios are driven ($\sim 20\%$) by data. Bottom panel: machine layout. Figure taken from [19].

3.2.1 Simulation setup

Dedicated FLUKA simulations of the TAN during Run 2, including the BRAN prototype detector in the setup, were provided by Dr. Marta Sabate Gilarte and Dr. Francesco Cerutti in the CERN FLUKA team. The coordinates used in the simulations follow the coordinates defined by ATLAS described in sec. 2.3.1. The main radiation source in the simulations are products of the $p+p$ collisions taking place in IP1 and propagated through the accelerator lattice. The absorber and beam optics in the LSS used in the simulation are described in sec. 2.3.3. During the irradiation, the TAN slot upstream of the prototype was filled with three copper blocks, the BRAN detector, and another copper block from front to rear. Fig. 3.9 shows a schematic drawing of each component in the BRAN prototype. Note that impurities and dopants in the rods were not simulated because, due to their relatively low

concentration, they are expected to have a negligible impact on the activation and dose estimation.

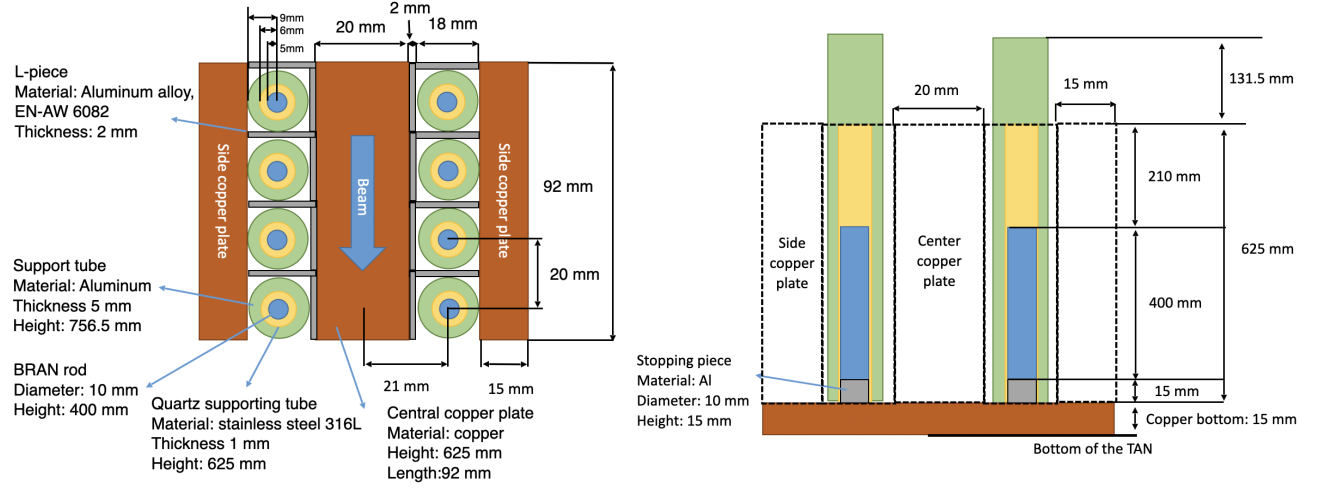


Figure 3.9: Top (left) and front (right) view of the BRAN prototype, including dimensions and materials for each component.

The BRAN prototype experienced different proton beam configurations during irradiation. One of the key parameters to describe the interaction of beams in the LHC IPs is the crossing angle (see fig. 2.2), which directly affects the distribution of neutral products of the collision that reaches the TAN. A change in polarity and magnitude of the crossing angles at IP1 was implemented in Run 2 between 2016 and 2017, to optimize the performance of the machine in the two high luminosity interaction regions. In order to account for the different crossing angles characterizing 2016 and 2017, two dedicated FLUKA simulations of the TAN region were produced with the following settings:

1. $p+p$ - 2016 optics ($-180 \mu\text{rad}$ crossing angle) and integrated luminosity (38.5 fb^{-1}).
2. $p+p$ - 2017 optics ($+140 \mu\text{rad}$ crossing angle) and integrated luminosity (50 fb^{-1}).

The angle sign reflects the colliding beams pointing direction, e.g., the positive sign corresponds to the upward direction of the beam while the negative to downward. Each simulation was characterized by different beam crossing angles and irradiation times, depending on the year of LHC data taking. During 2016 and 2017 LHC runs, the rods were irradiated for 198 and 173 days, respectively [69, 70].

Note that, since the 2017 and 2018 runs were characterized by the same beam configurations [71], it was possible to use the 2017 simulation to estimate the dose received by the rods during the 2018 Run. This step was accomplished by re-scaling the 2017 simulation results using a ratio of the integrated luminosity delivered to ATLAS between 2017 and 2018.

3.2.2 Dose estimation

When incident particles interact with the TAN absorber, secondary and higher generation particles are produced by nuclear and electromagnetic reactions. The electromagnetic component of the shower dominates the energy deposition processes. Fig. 3.10 shows the x - z profile of the dose in the TAN during the $p + p$ collision running in both 2016 and 2017. The doses are averaged over a 3 mm interval in the y coordinate where the maximum dose is in the TAN. The TAN slot where the BRAN prototype was installed is 10 cm wide, and centered between the two beam pipes. The white box indicates the location of the original BRAN detector behind three copper blocks, while the black box highlights the location of the BRAN prototype detector. Eight rod slots can be seen in the simulation geometry. Fig. 3.11 presents a y - z dose distribution inside the prototype in 2016 and 2017. The dose values correspond to the averages in a range of $1.8 < x < 2.7$ cm. The impact of different crossing angles can be observed from the comparison of dose profile along y .

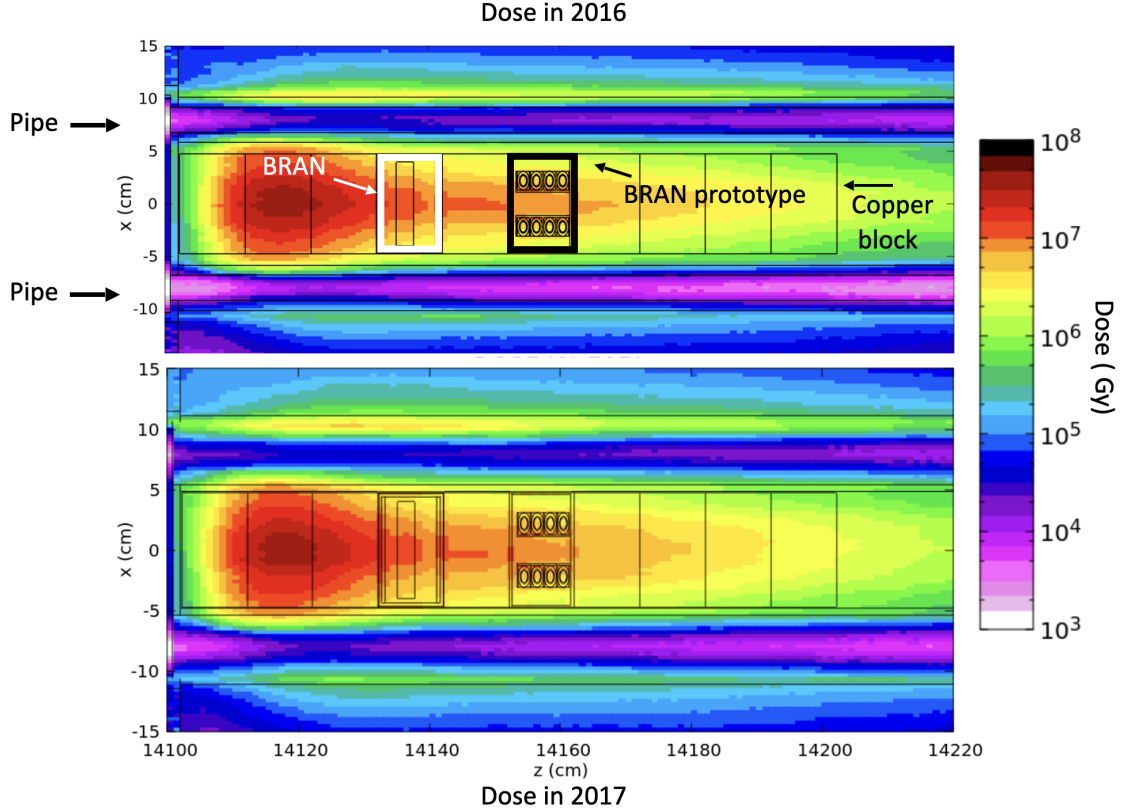


Figure 3.10: x - z profile of the dose accumulated in the TAN during 2016 (upper) and 2017 (lower) $p+p$ runs, respectively. Dose values were averaged over a 3 mm interval in y . The y coordinate corresponding to the maximum dose in the TAN was used to produce the plot. The modules highlighted by the white and black boxes indicates the BRAN and the BRAN prototype, respectively. The black lines indicate the copper bars. The luminosity delivered by the LHC was 38.5 and 50 fb^{-1} in 2016 and 2017, respectively.

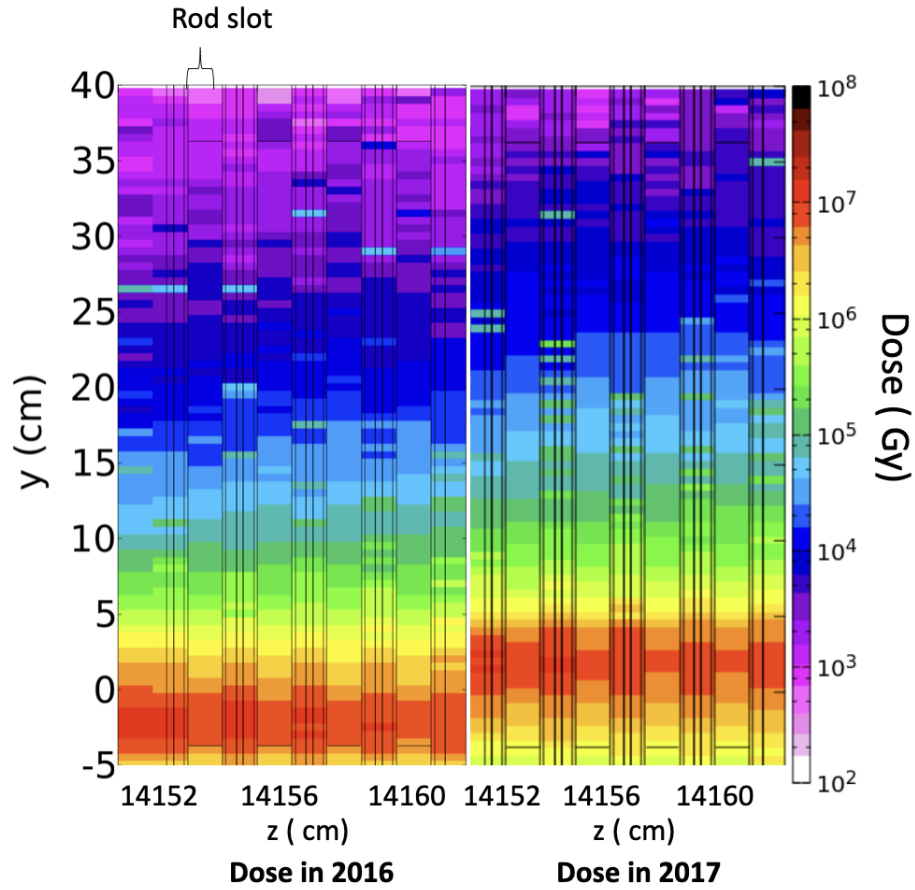


Figure 3.11: y - z profile of the dose accumulated in the BRAN prototype for 2016 (right) and 2017 (left) $p+p$ runs, respectively. The crossing angle in each year has been included in the simulation, as is evident from the vertical shift in the maximum exposure position. The luminosity delivered by the LHC in 2016 and 2017 was 38.5 and 50 fb^{-1} , respectively.

FLUKA also allows for the scoring of particle fluxes depositing energy in the materials. Fig. 3.12, 3.13, 3.14, and 3.15 shows the spectrum of neutrons, protons, negative pions, and positive pions in Rod 1 in 2016 and 2017. For each given particle, three different spectrum are reported. Those correspond to three different vertical segments of Rod 1. Each of them is 5 cm along y . Comparing the 2016 results to the 2017 results, the energy of the particles in the middle section becomes higher due to the change in crossing angle.

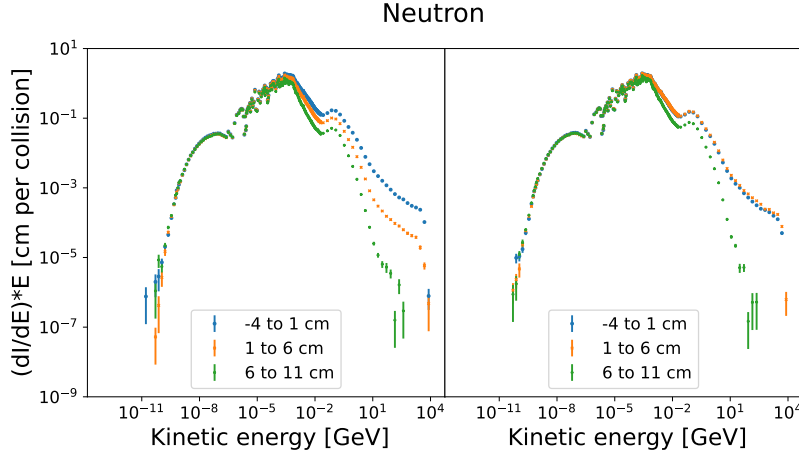


Figure 3.12: Kinetic energy spectrum of neutrons depositing energy in Rod 1 for 2016 (left) and 2017 (right). The energy spectrum is shown for three different segments (5 cm each) along y .

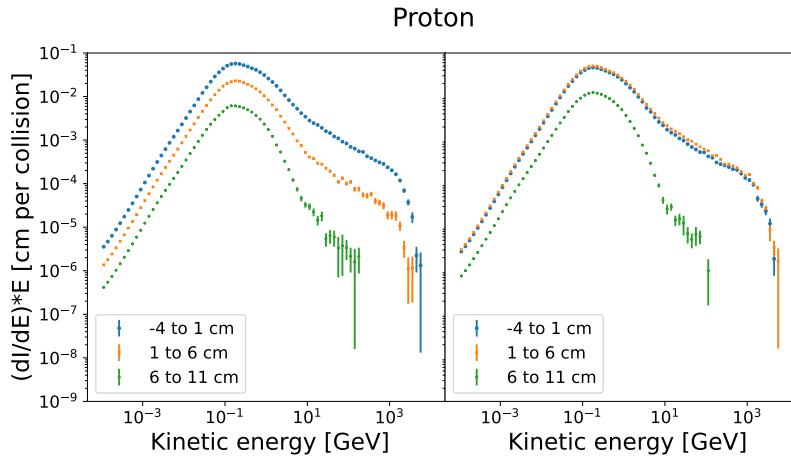


Figure 3.13: Kinetic energy spectrum of protons depositing energy in Rod 1 for 2016 (left) and 2017 (right). The energy spectrum is shown for three different segments (5 cm each) along y .

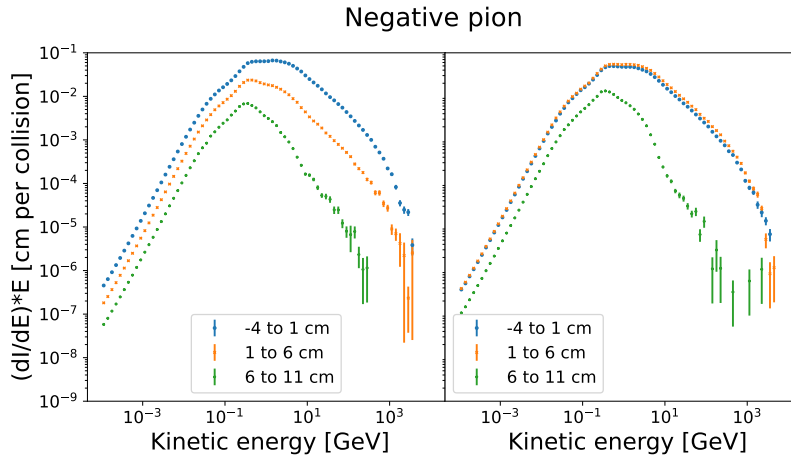


Figure 3.14: Kinetic energy spectrum of negative pions depositing energy in Rod 1 for 2016 (left) and 2017 (right). The energy spectrum is shown for three different segments (5 cm each) along y .

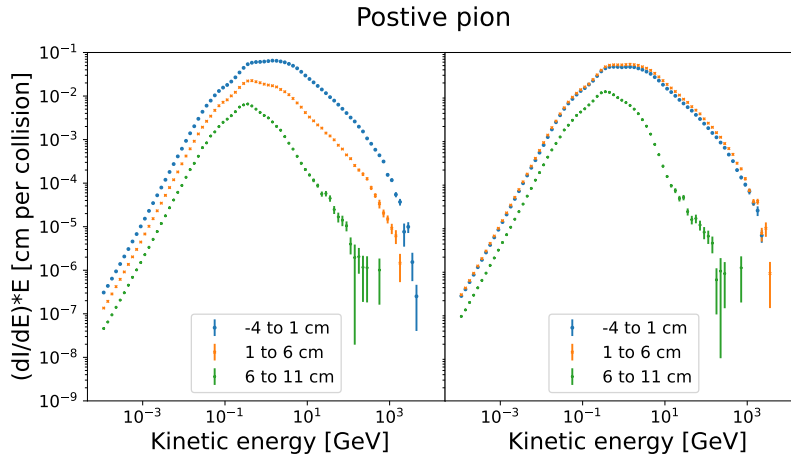


Figure 3.15: Kinetic energy spectrum of positive pions depositing energy in Rod 1 for 2016 (left) and 2017 (right). The energy spectrum is shown for three different segments (5 cm each) along y .

3.2.3 Activation estimation

To describe in detail activation of materials under irradiation in FLUKA, nuclear breakup models for nuclear reactions occurring in different material are necessary. These models describe the transformation of the target nucleus into radioactive residue after de-excitation. These processes include evaporation in competition with fission, gamma de-excitation, and/or the Fermi breakup process. Residual nuclei production is calculated from tabulated cross sections for low-energy ($E < 19.6$ MeV) neutron interactions where data libraries are used [72]. For nuclear interactions above 19.6 MeV, a cascade-preequilibrium model, PEANUT [73, 74], is used to simulate nuclear interactions up to 20 TeV.

In the scope of this dissertation, the targeted isotope, ^{22}Na , is generated from silicon in the rods activated by different particle species. For example, figs. 3.16 and 3.17 show the cross section of ^{22}Na production induced by protons and neutrons, respectively. The data cover a wide energy range. The curves in the figures show the cross section obtained from the FLUKA models, while the points represents the experimental results. As the particle energies increase, the data become less available and have higher uncertainty.

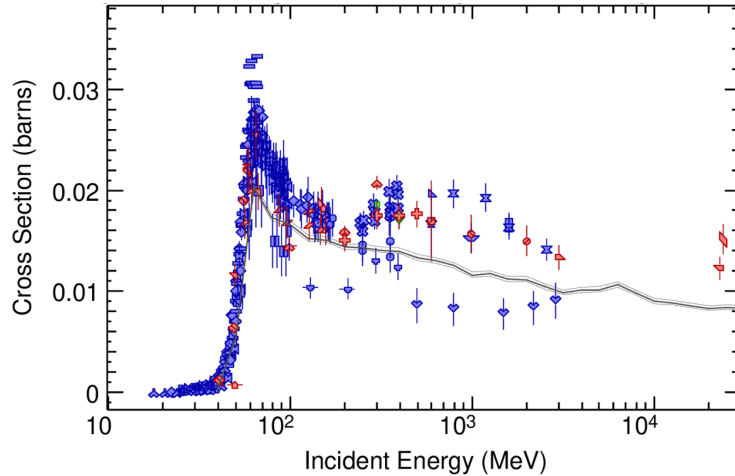


Figure 3.16: $^{nat}\text{Si}(p,*)^{22}\text{Na}$ cross section. Symbols are experimental data from EXFOR [75]. The grey curve results from the FLUKA interaction model.

In FLUKA simulations, the delivered luminosity per day throughout an irradiation period is constant. However, the delivered luminosity during LHC running time varies daily due to the intermittent operation of the LHC, such as (but not only) technical stops for standard

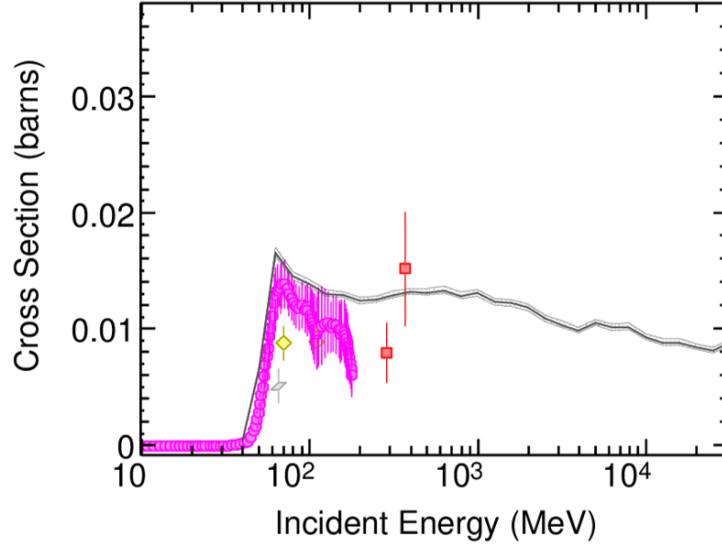


Figure 3.17: $^{nat}\text{Si}(n,*)^{22}\text{Na}$ cross section. Symbols are experimental data from EXFOR [75]. The grey curve results from the FLUKA interaction model.

maintenance operations and unexpected critical equipment failures [76]. Fig. 3.18 shows the integrated luminosity per day delivered by the LHC and recorded by ATLAS in 2016.

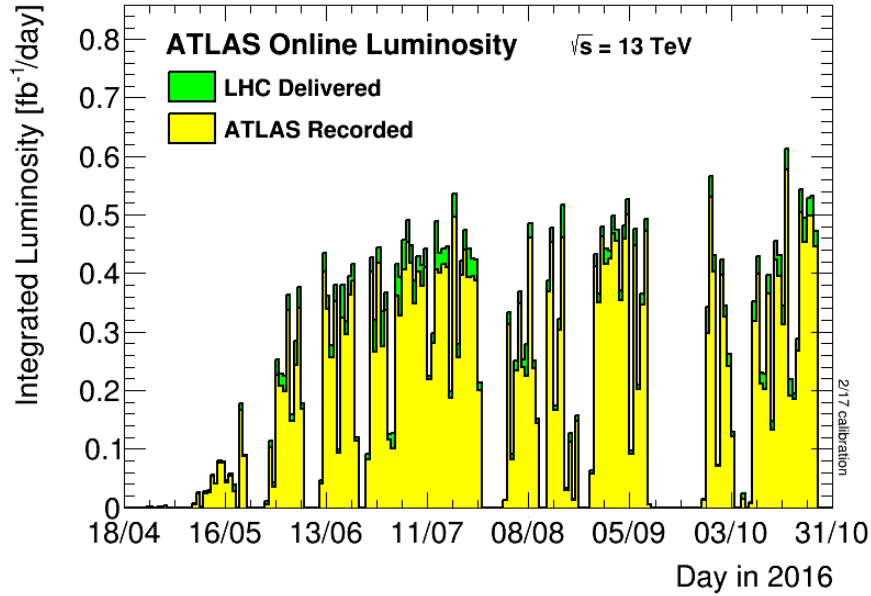


Figure 3.18: Daily integrated luminosity of $p+p$ collisions in the ATLAS in 2016. The luminosity recorded by the ATLAS is in green while and the luminosity delivers by the LHC is in yellow. All the details about the time profile of luminosity delivered to ATLAS in 2016, 2017, and 2018 runs can be found in [77].

A correction for the scored activity in the simulations with a constant luminosity was studied. The correction was found to be negligible because the half-life (2.6 yrs) of ^{22}Na [78] is much longer than the irradiation periods (i.e., 198 days in 2016). The derivation of the correction is provided in the following paragraphs.

In a given LHC year, the yield $N(t)$ of ^{22}Na on t^{th} day is assumed to be dependent on the delivered luminosity $\mathcal{L}(t)$ on the same day. The activity $A(t)$ of the isotope can be calculated as

$$A(t) = \lambda N(t), \quad (3.6)$$

where λ represents the decay constant of ^{22}Na . Thus, $A(t)$ is proportional to $\mathcal{L}(t)$. To include the decay factor of ^{22}Na , one can define an equivalent luminosity $L(t)$ as

$$L(t) = \mathcal{L}(t) \cdot e^{-\lambda(t_1-t)} \propto A(t) \cdot e^{-\lambda(t_1-t)}, \quad (3.7)$$

where t_1 is the last day of the irradiation period in that year. The total activity deriving from the profile of luminosity delivered by the LHC in that year is proportional to the superposition of the equivalent luminosity $L(t)$ characterizing every day of running, that can be expressed as

$$L = \sum_{t=t_0}^{t_1} \mathcal{L}(t) \cdot e^{-\lambda(t_1-t)}, \quad (3.8)$$

where t_0 is the the first day of irradiation in the same year. For a constant luminosity, eq 3.8 can be simplified to

$$L_c = \bar{\mathcal{L}} \sum_{t=t_0}^{t_1} e^{-\lambda(t-t_1)}, \quad (3.9)$$

where $\bar{\mathcal{L}}$ is the average luminosity of the irradiation period and L_c denotes the sum of the equivalent luminosity obtained from a constant luminosity.

By exploiting the equivalent luminosity, the relation between the activity derived from a time-dependent luminosity profile A_t and from a constant luminosity A_c can be expressed as

$$A_t = A_c \cdot C, \quad (3.10)$$

where

$$C = \frac{L_c}{L}. \quad (3.11)$$

Based on the luminosity profiles and the total luminosity in Run 2, obtained from [77], the correction factor C is 1.02, 0.99, and 0.99 for 2016, 2017, and 2018, respectively.

CHAPTER 4

IRRADIATED FUSED SILICA STUDIES: ACTIVATION MEASUREMENT

This chapter presents the ^{22}Na activation study of the irradiated BRAN fused silica rods¹. Sec. 4.1 introduces procedures for preparing the BRAN samples for measurements. Two experimental setups for activation measurements at UIUC and ANL and a ^{22}Na source used for calibration in the experiments are described in sec. 4.2. The data analysis carried out on the results of the activation measurement is presented in sec. 4.3. In sec. 4.4, the measured ^{22}Na activity is compared to the FLUKA estimates, and the discrepancy is discussed.

4.1 Sample preparations

The BRAN rods were cut into smaller samples to measure the activation profile along the rods. In addition, the maximum sample length was constrained by the available space in a spectrophotometer, Cary 5000 [79], used for optical transmission measurements. Thus, a sample length of 10 mm was chosen to meet both requirements. Specifications for the cutting equipment used to produce the BRAN rod samples are given in tab. 4.1. All BRAN rod cutting was performed using a wet cut, where the bottom edge of the saw blade was constantly submerged in a mixture of water and coolant. This technique was used to avoid annealing of color centers at high temperatures, affecting the results of subsequent optical transmission measurements.

The rod holder assembly consists of a Nylon-12 3D-printed block with a 10 mm wide channel machined into its surface that houses the BRAN rod to be cut. Along the length on either side of the channel are pairs of screw holes that allow the rod to be fastened into

¹The content of this chapter is an extended version of ref. [19], for which the author of this dissertation served as co-lead author.

Table 4.1: Specifications for BRAN Rod Cutting Apparatus

Model number	UKAM Smart Cut 6001
RPM	3,400
Blade Material	Resin Bond, Diamond
Blade Thickness	0.015"

the holder.

At each iteration of the sample cutting, the weights of both the cut sample and the remaining uncut rod were recorded to account for the material losses. A caliper was used to measure the maximum length (t_i^{max}) and minimum length (t_i^{min}) of the i^{th} sample. The measurement was performed by rotating the sample 360° within the calipers. The cut length for the i^{th} sample, t_i , was then computed by

$$t_i^s = \left(\frac{t_i^{max} + t_i^{min}}{2} \right). \quad (4.1)$$

In order to properly map the activity results in the FLUKA simulation, the center of the samples within the BRAN rod prior to cutting was calculated as

$$P_i = t_{rem,i} + t_{loss} + 0.5 \cdot t_i^s, \quad (4.2)$$

where P_i is the center of the i^{th} sample in the uncut rod, $t_{rem,i}$ is the length of the remaining uncut rod after the i^{th} cut and t_i is the length of the i^{th} sample, calculated using eq. 4.1. The amount of rod lost due to cutting, t_{loss} , is assumed to be equal to the width of the saw blade, 0.38 mm. Note that, for the first and the last cuts of the rod, t_{loss} is assumed to be 0.19 mm since those samples were obtained with only one cut.

4.2 Experimental measurements of ^{22}Na activity

Two independent activation measurements led by the author were carried out at UIUC and ANL, using a high purity germanium, HPGe, radiation detector, and a thallium-activated

sodium iodide, NaI(Tl), well-type detector, respectively. The HPGe detector was provided by Prof. Angela Di Fulvio in the Nuclear, Plasma, Radiological Engineering (NPRe) department at UIUC. The measurements at ANL were carried out by one of the graduate students, Nicolas Santiago, in our group using the well-type detector in Dr. Michael D. Kaminski's lab. In both cases, the activity of the ^{22}Na isotope in each rod sample was measured.

4.2.1 Calibrated volumetric source

To calibrate both detectors, a customized ^{22}Na cylindrical source was purchased from Eckert & Ziegler. The relevant specifications are listed in tab. 4.2. The dimensions of the source were chosen in order to match those of rod samples produced by cutting the irradiated BRAN rods, as described in sec. 4.1. The activity of the ^{22}Na isotope was $0.1 \mu\text{Ci} \pm 3.3\%$ on 10/15/2019 and was uniformly distributed throughout the source volume. The activity and its uncertainty are certified by the National Institute of Standards and Technology.

Table 4.2: Specifications for ^{22}Na volume source

Diameter	10 mm
Length	10 mm
Material	Solid plastic matrix
Density	$1.17 \text{ g/cm}^3 \pm 3\%$
Isotope	^{22}Na
Activity	$0.1 \mu \text{ Ci} \pm 3.3\%$

4.2.2 Activation measurement using HPGe detector at UIUC

The relative efficiency and energy resolution (FWHM) of the HPGe detector used in this experiment are 19% and 1.68 keV for the 1.332 MeV peak of a cobalt isotope, ^{60}Co , respectively. A full list of specifications for the HPGe detector is given in tab. 4.3. During the measurement, the detector was shielded using tungsten plates to reduce the contribution from background radiation. A sketch of the experimental setup at UIUC is shown in fig. 4.1. Each sample was measured for 15 minutes to achieve a 2% statistical error for the 1.274 MeV characteristic line of ^{22}Na . For the ^{22}Na calibration source, the measurement time was

14 hours, corresponding to a statistical error of 0.1%. The background was measured for 24 hours and then subtracted from all the measurements obtained with the HPGe in this study.

Table 4.3: Specifications for the HPGe detector

Model number	Ortec GEM-10-P4
Energy resolution	1.68 keV @ 1.33 MeV, ^{60}Co
Detector diameter	49.9 mm
Detector length	54.6 mm
Relative efficiency	19% @ 1.33 MeV, ^{60}Co

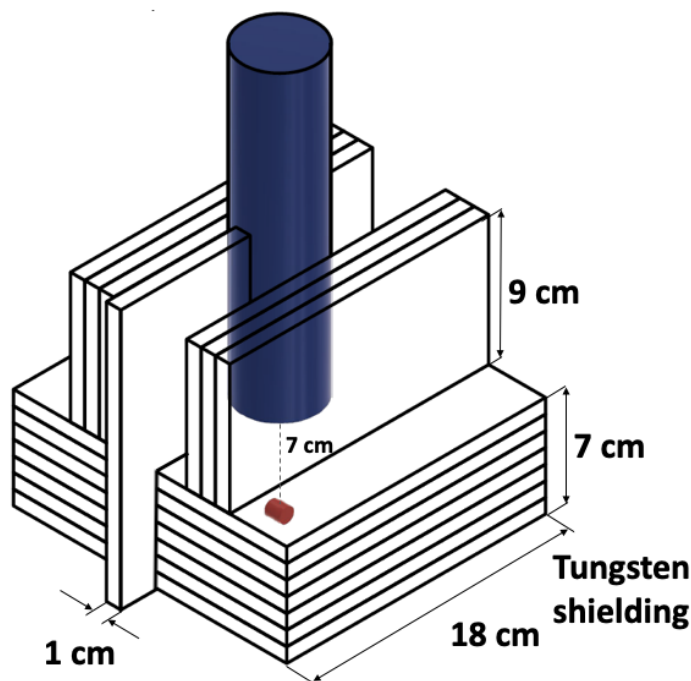


Figure 4.1: Experimental setup of HPGe detector used at UIUC. The transparent plates represent the tungsten shielding. The blue cylinder depicts the HPGe detector, and the red cylinder indicates the location of the sample during measurements.

4.2.3 Activation measurement using well-type detector at ANL

At the ANL, a well-type detector [80] with energy resolution $<10\%$ for a caesium isotope, ^{137}Cs , was used to measure the ^{22}Na activity. Its specifications are reported in tab. 4.4. The activity of each sample was obtained from the built-in analysis software, including the uncertainty on the gamma count rate. Each sample was measured for a time sufficient to

reach a statistical error less than 1% for the 1.274 MeV characteristic peak of ^{22}Na . The volumetric ^{22}Na calibration source was measured for 1 hour, achieving 0.39% statistical error.

Table 4.4: Specifications of the well-type detector at ANL

Model number	2480 Wizard gamma counters
Material	Na(Tl) crystal
Energy resolution	$< 10\%$ for ^{137}Cs
Crystal diameter	75 mm
Crystal height	80 mm
Relative efficiency	47% for ^{137}Cs

4.3 Data analysis

The details of the gamma count rate analysis for the UIUC measurements are presented in sec. 4.3.1. The activity analysis techniques, material losses, and cooling corrections applied to the measurements at UIUC and ANL are described in sec. 4.3.2, 4.3.3, and 4.3.4, respectively.

4.3.1 Estimation of count rate for HPGe detector

The gamma count rate was estimated from the spectrum measured using the HPGe detector. Fig 4.2 shows the decay scheme of ^{22}Na . There are two decay paths. In the first, ^{22}Na decays directly to neon-22, ^{22}Ne , by β^+ decay with a probability of 0.1 %. The positron from the decay collides with an electron resulting in the annihilation of both particles and the generation of two 0.511 MeV gammas. In the second path, ^{22}Na decays to an excited state of ^{22}Ne via β^+ decay (90.4%) and internal electron capture (9.5%). Next, the excited ^{22}Ne de-excites to the ground state by emitting a 1.274 MeV gamma. Overall, each ^{22}Na decay has a probability of 99.9% to emit a 1.274 MeV gamma via the second path. Therefore, the count rate of the 1.274 MeV gamma closely represents the activity of ^{22}Na . For this reason, the 1.274 MeV gamma was targeted in the measurements using the HPGe detector.

Fig. 4.3 shows the gamma spectrum of the ^{22}Na calibration source and the background measured using the HPGe detector. In the spectrum, one can see two dominant photon

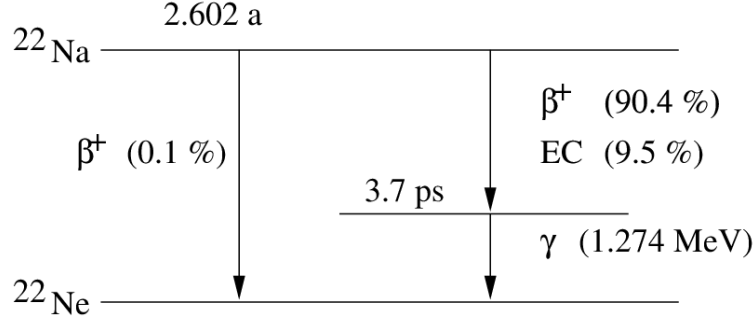


Figure 4.2: Decay scheme of ^{22}Na . β^+ represents the positron emission process, EC is the electron capture process, and γ is a gamma emission decay. The percentage is the probability of each decay process. Figure taken from [81].

peaks at 0.511 and 1.274 MeV, respectively. The 0.511 MeV peak is caused by the gamma from the annihilation process.

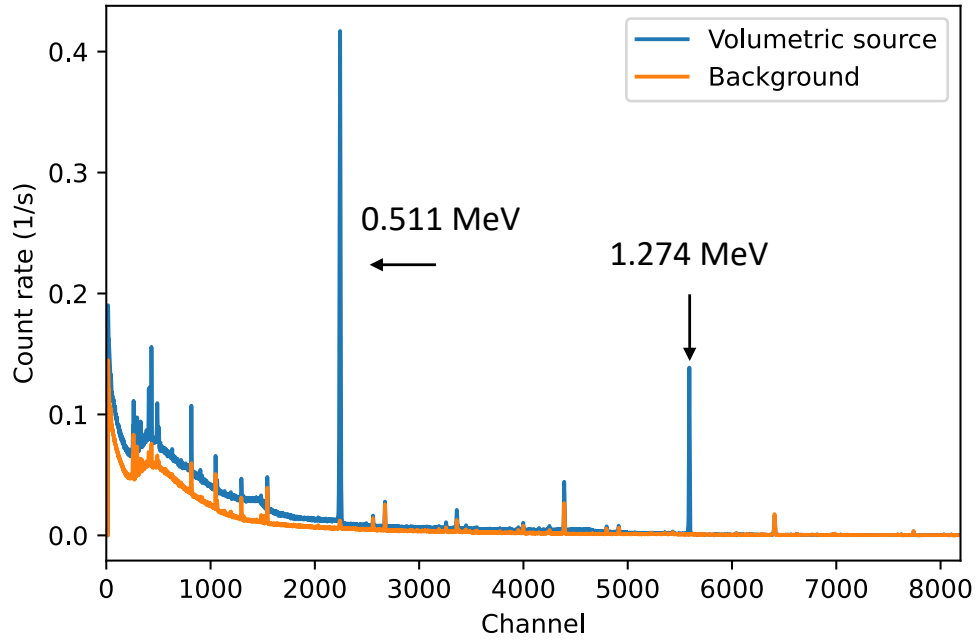


Figure 4.3: Count rate of ^{22}Na calibration source and background measured using the HPGe detector.

After subtracting the background and the baseline from the targeted peak, a Gaussian fit was applied to estimate the count rate, defined as the area within the full width tenth maximum (FWTM) of the fit. Fig 4.4 shows the 1.274 MeV peak from fig. 4.2 fitted with a

Gaussian function after subtracting background and baseline.

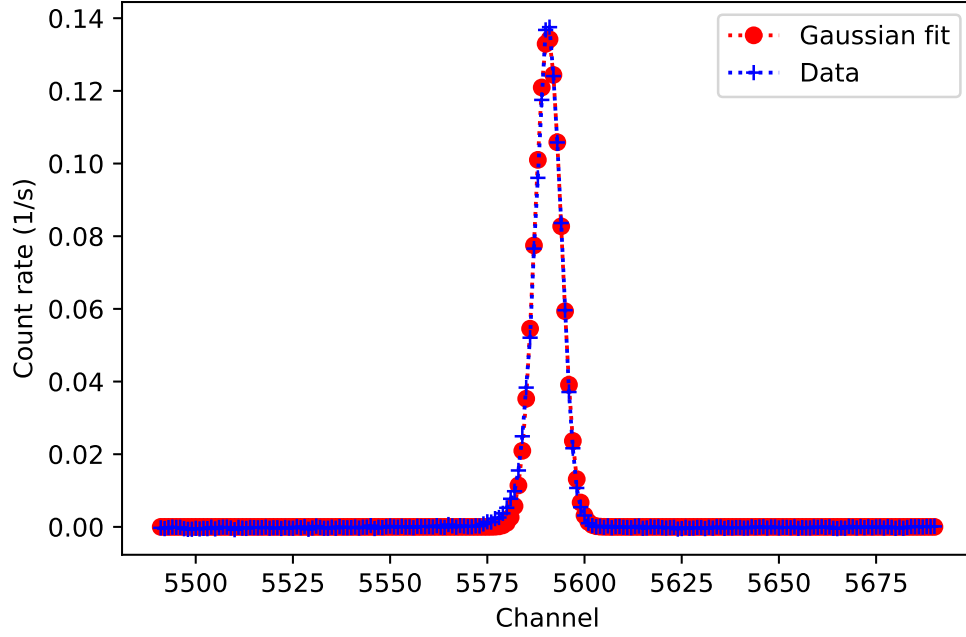


Figure 4.4: 1.274 MeV peak from fig. 4.2 fitted with a Gaussian function after subtracting background and baseline.

4.3.2 Estimation of ^{22}Na activity

The acceptance of the experimental setup must be taken into account when estimating the activity of a volumetric isotope sample. Two types of acceptance effects are relevant for the measurement presented in this dissertation. The first is introduced by differences between the geometry of the calibration source and the samples. To account for this effect, the volumetric source described in sec. 4.2.1 was used to calibrate the setup. Because the geometry of the calibrated source and the BRAN samples are consistent with one another, as well as the positioning of samples within the experimental setup, the acceptance was taken to be equivalent. This conclusion relies on the assumption that the activity of both the samples and the calibrated source is homogeneous. The second effect, introduced by the intrinsic acceptance of the experimental setup for a single photon measurement, can be canceled out by taking the ratio of the count rates recorded for the sample and calibration source.

The activity of the i^{th} sample is calculated as

$$A_i = \frac{I_i}{I_{CS}} \cdot A_{CS}, \quad (4.3)$$

where I_i and I_{CS} are the measured count rate of the i^{th} sample and the volumetric calibration source, respectively, while A_{CS} is the known activity of the calibration source. The relative uncertainty on A_i , R_{A_i} , was obtained from the error propagation of each component in eq. 4.3 and is given as

$$R_{A_i} = \sqrt{R_{I_i}^2 + R_{I_{CS}}^2 + R_{A_{CS}}^2}, \quad (4.4)$$

where $R_X, X \in \{I_i, I_{CS}, A_{CS}\}$ represents the relative error of the variables entering eq. 4.3.

4.3.3 Material loss correction

A correction was applied to account for the decrease in intensity of each sample due to material losses during the cutting process. The correction coefficient, C_i , is based on the weight of lost material per sample:

$$C_i = \frac{W_0}{W_i}, \quad (4.5)$$

where W_0 is the weight of a precisely 10 mm long sample of BRAN rod and W_i is the measured weight of the i^{th} sample. W_0 is derived from the volume of a cylinder with 1 cm length and the density of the rod. The density of Rod 1, 3b, and 6 is 1.74 g/cm^3 . The corrected activity of each sample A_i^* was computed as

$$A_i^* = C_i \cdot A_i. \quad (4.6)$$

The correction is applied under the assumption that the activity is homogeneous within the sample.

4.3.4 Cooling correction

The isotope activity for each sample was estimated making use of UIUC and ANL measurements separately. To allow for a comparison of estimates carried out for a given sample, as well as a comparison between the measurements and the FLUKA simulations, the activity for all samples was normalized to the same reference date (12/14/2019).

The Beer–Lambert law [40] was used to extrapolate the activity to the reference date:

$$A_t = A_0 e^{-\lambda t}, \quad (4.7)$$

where A_t is the activity on the reference date, A_0 is the activity on the measurement date, t is the time between the measurement and reference date, and λ is the decay constant of the isotope being measured. For the ^{22}Na isotope considered in this study, the decay constant is 0.2664 yr^{-1} [78].

4.4 Results and discussions

The comparisons between the ^{22}Na activity measurements done at UIUC (HPGe) and ANL (well-type detector) for Rods 1, 3b and 6 are shown in Figs. 4.5, 4.6, and 4.7, respectively. Note that the horizontal axes presented in this section are consistent with y defined in fig. 3.11, allowing for a comparison between the radiation profiles and the activity distributions along the rods. The origin ($y = 0$) is referenced to the LHC beam pipes, and the bottom of the rods is at $y = -3.7 \text{ cm}$. At this stage, both the results are not corrected for material losses, since the effect equally affects both the measurements. The blue and red curves represent the activity of each sample measured with the HPGe and well-type detector, respectively. Due to the crossing angle in 2017 and 2018, when the majority of the luminosity was delivered, the peak of the activity centers approximately $y = 1.5$. The lower portion of the figures shows the ratio between the two measurements, with a unit constant to demonstrate the consistency between the two curves. Since the results between the HPGe detector and the well-type detector are consistent, only the well-type results are used in the following discussions for simplicity.

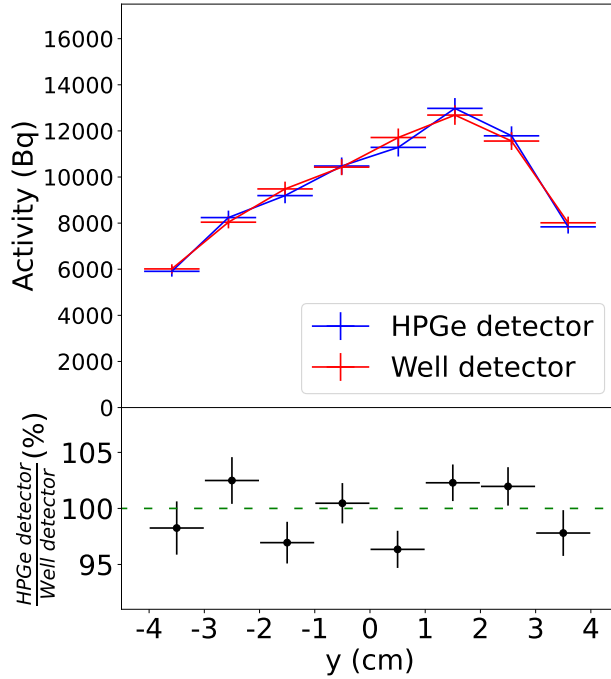


Figure 4.5: Comparison of Rod 1 activity measurements performed at UIUC, using a HPGe detector (sec. 4.2.2), and ANL, using a well-type detector (sec. 4.2.3). The errors on the abscissa represent the half-length of the samples. The bottom panel shows the ratio between the two measurements. A dashed green line that corresponds to unity is drawn for direct comparison. The horizontal axis follows y defined in fig. 3.11 for a comparison and the origin ($y = 0$) is referenced to the position of the beam pipe. Please note that there is an additional 3.3% correlated uncertainty on the calibration source activity that is not included in the ratio uncertainties. Results have been normalized to a reference date of 12/14/2019.

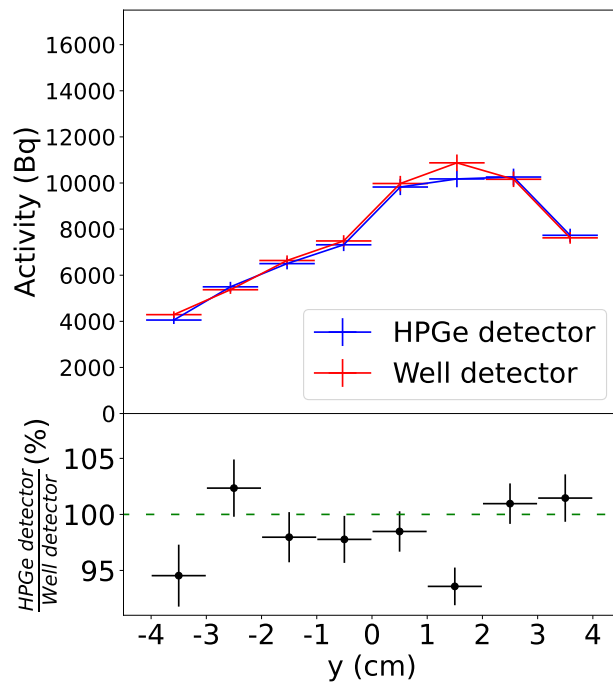


Figure 4.6: Comparison of Rod 3b activity measurements using a HPGe detector and a well-type detector. Refer to the caption of fig. 4.5 for details related to the plotting.

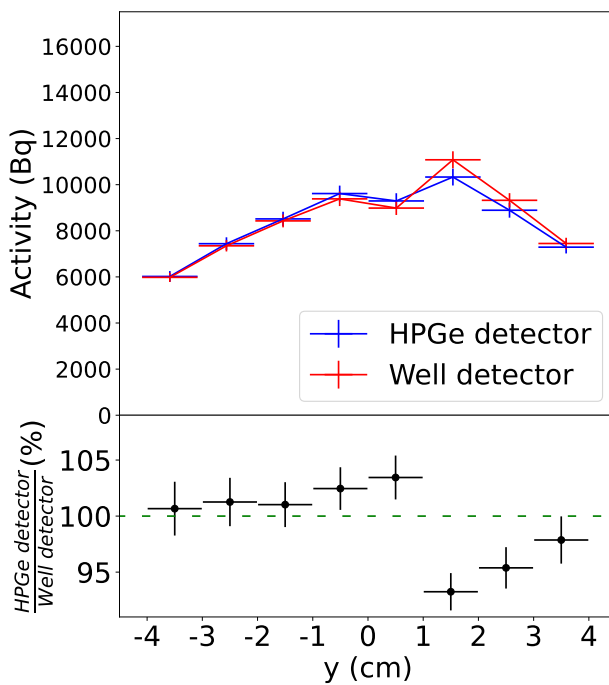


Figure 4.7: Comparison of Rod 6 activity measurements using a HPGe detector and a well-type detector. Refer to the caption of fig. 4.5 for details related to the plotting.

Fig 4.8, 4.9, and 4.10 shows the comparison of the activity profile of Rod 1, 3b, 5, and 6, respectively, before and after applying the loss coefficient C_i to correct the activity. The profile of the rod becomes smoother after the loss correction.

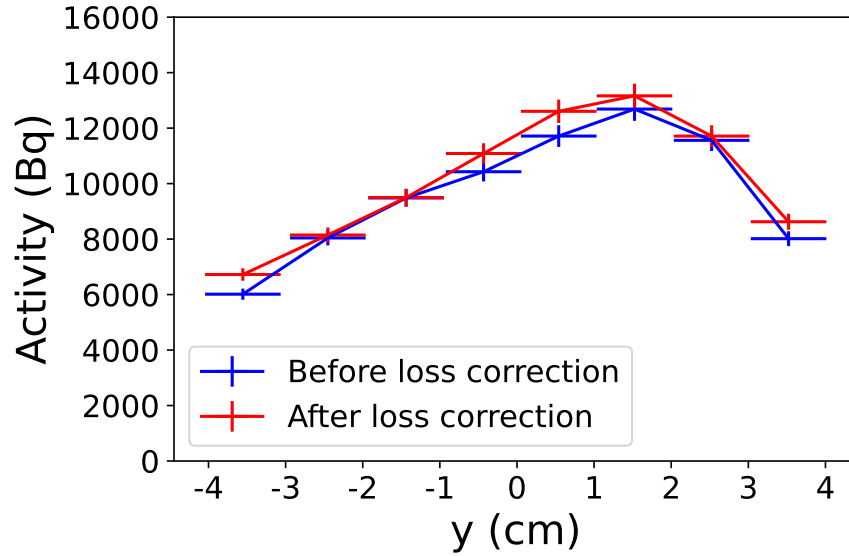


Figure 4.8: Comparison of the Rod 1 activity profile before and after material loss correction.

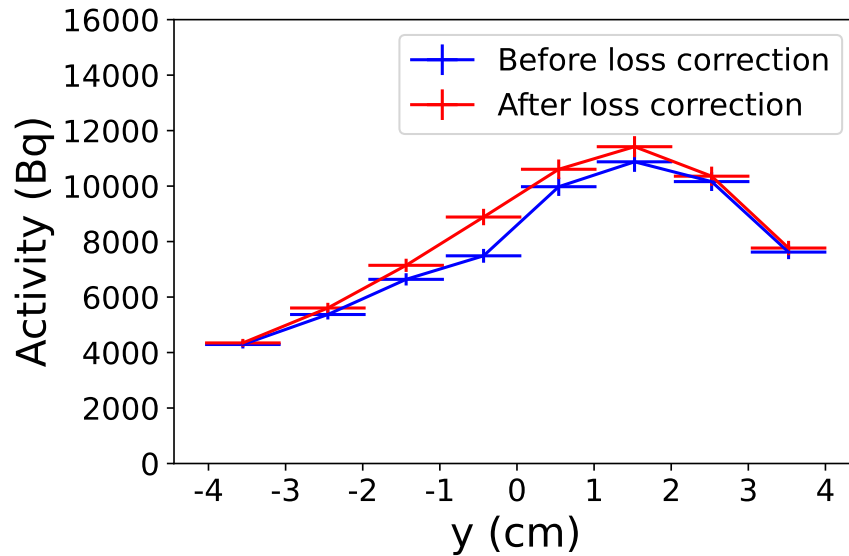


Figure 4.9: Comparison of the Rod 3b activity profile before and after material loss correction.

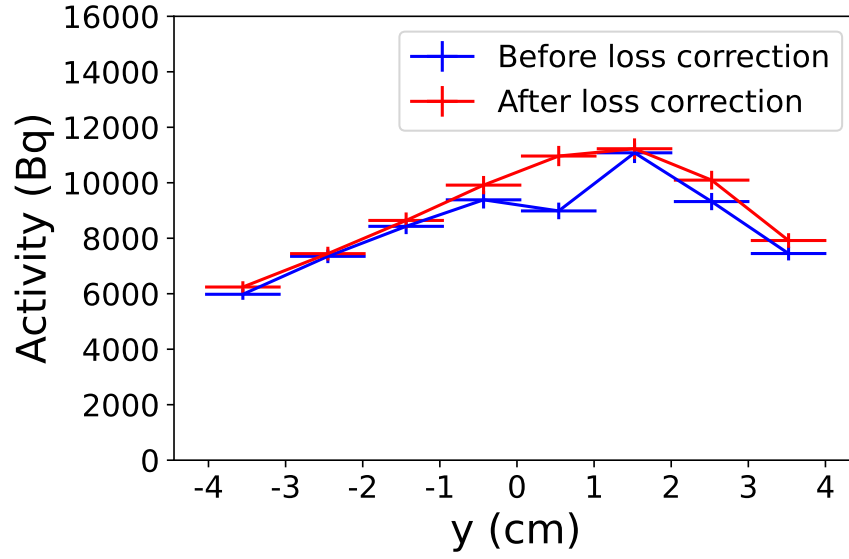


Figure 4.10: Comparison of the Rod 6 activity profile before and after material loss correction.

4.4.1 Comparisons between experimental results and FLUKA simulations

Fig. 4.11 shows the activity component from each year in Rod 1 in the FLUKA simulations. The activity was normalized to 12/14/19 using eq. 4.7. The total activity is the sum of each

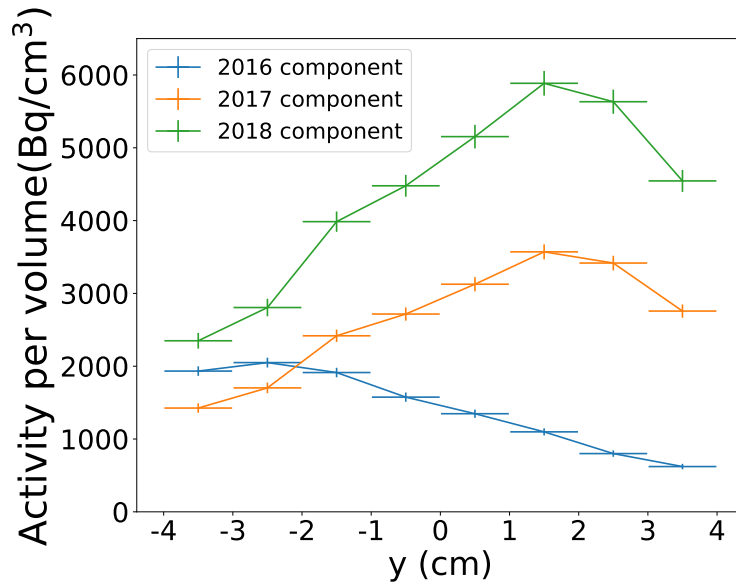


Figure 4.11: Activity component of each year in Rod 1 in the FLUKA simulations. Each component has been normalized to 12/14/19.

component corresponding to the irradiated period of the rod. The impact of the crossing angle in 2016 and 2017 can be observed by looking at the different location of the activity peak in the two years. In 2016, when the crossing angle was pointing downwards, the peak is located approximately $y = -2.5$ cm, while 2017, characterized by an upwards crossing angle, shows the peak located at $y = 1.5$ cm.

To be consistent with the simulation results in the following discussions, the corrected activity of the samples is translated into the activity per volume. Fig. 4.12, 4.13, and 4.14 show the activity per volume comparison between the measurement and simulation for Rods 1, 3b, and 6, respectively.

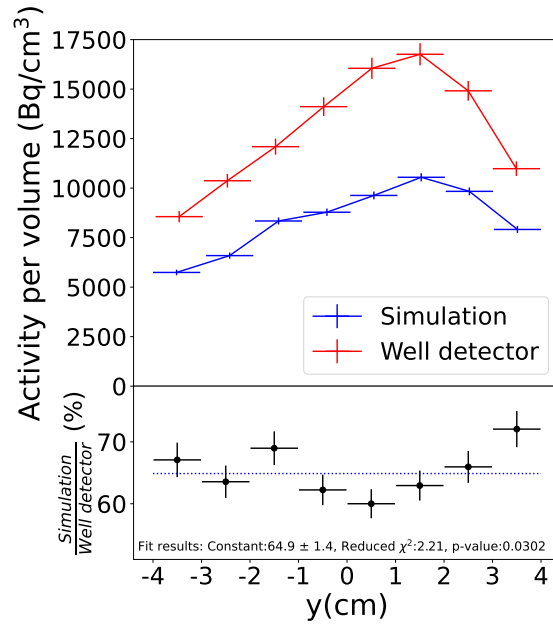


Figure 4.12: Comparison of activity measurements at ANL, using a well-type detector, and FLUKA simulations for Rod 1. Results have been normalized to a reference date of 12/14/2019. The dotted line represents the fit of the ratio between data and simulations.

The experimental results are corrected for material losses (sec. 4.3.3). Both experimental and simulation results are normalized to the same reference date, as described in sec. 4.3.4. The relative statistical uncertainty for simulation and experimental results is 3% and 4%, respectively. The simulation reproduces the peak of activity observed in the experimental measurements approximately $y = 1.5$ cm. However, it underestimates the activity of ^{22}Na by 30-35 % compared to the experimental results. The comparisons provide a benchmark for the

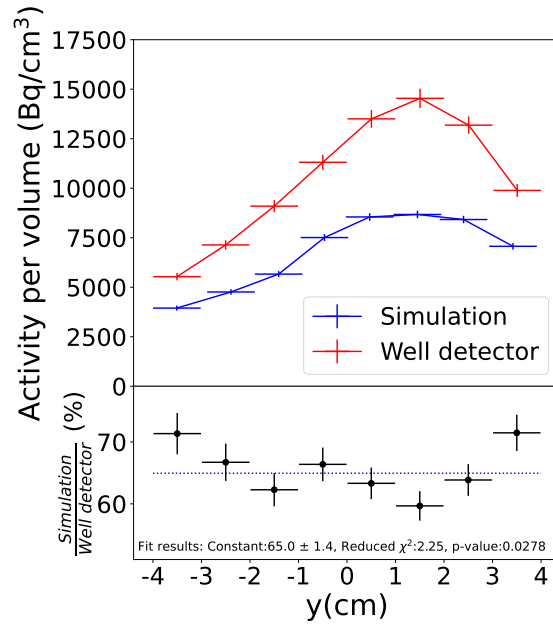


Figure 4.13: Comparison of activity measurements and FLUKA simulations for Rod 3b. Refer to the caption of fig. 4.12 for details related to the plotting.

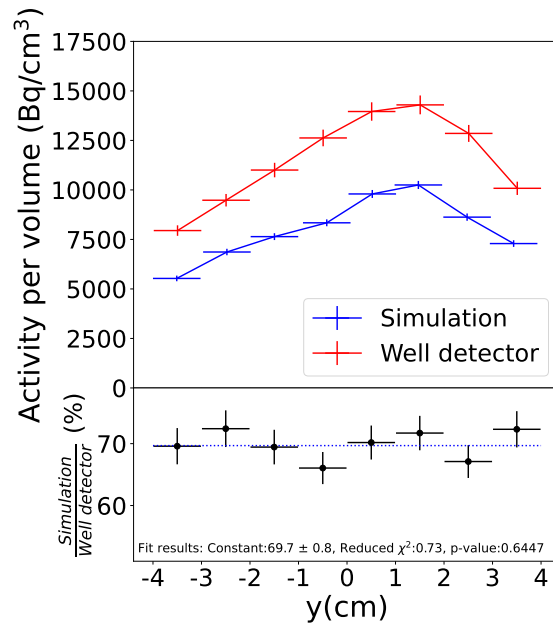


Figure 4.14: Comparison of activity measurements and FLUKA simulations for Rod 6. Refer to the caption of fig. 4.12 for details related to the plotting.

performance of the FLUKA simulations in describing nuclear breakup reactions for silicon material in the TAN. Fused silica rods will be used as Cherenkov radiators in the detectors, such as the ZDCs, installed in the TAN. After the irradiation, these fused silica rods will be activated. Before removing these activated rods from the detectors after running, the rods must be cooled down till their activity is below a certain level for radiation safety of working staff. The benchmark presented in this study may play an important role in estimating the cooling time for these rods and received doses for the staff using FLUKA.

CHAPTER 5

IRRADIATED FUSED SILICA STUDIES: OPTICAL TRANSMISSION MEASUREMENT

This chapter presents the study of the radiation hardness to fused silica at different wavelengths and doses. Sec. 5.1 illustrates the experimental setup used for the optical transmission measurements. The data analysis procedures are presented in sec. 5.2 with the corrections and the uncertainty estimation for the measurements described in sec. 5.2.1 and 5.2.2, respectively. Results are presented and discussed in sec. 5.3. The impact of the beam configuration in different years on the transmittance profile of the rods is discussed in sec. 5.3.1. The wavelength dependence of the optical losses due to radiation is reported in sec. 5.3.2, while the impact of the dopants on fused silica's radiation hardness is analyzed in sec. 5.3.3.

5.1 Experimental setup of the optical transmission measurement

During the cutting processes in the sample preparation (sec. 4.1), the contact between the blade and the samples created a rough surface diffusing incident light. An example of a rough surface cut is shown in fig. 5.1. The surfaces of the sample directly affect the transparency of the sample along the longitudinal direction. To reduce the effect of the surface on the optical transmission measurements, a refractive index matching liquid was used. The chosen liquid was Series AA from Cargille Laboratories, which has a refractive index value of 1.456 at 589.3 nm at 25.0°C [82]. Fig. 5.2 shows a close match between the chosen liquid and fused silica in the refractive index. In order to immerse the samples in the liquid during the measurements, a cuvette made of fused silica, Suprasil 3001 [48], was used (see fig. 5.3). One can observe that the diffusive effect of the surfaces is significantly reduced, allowing for optical transmission measurements along the longitudinal direction of the samples.

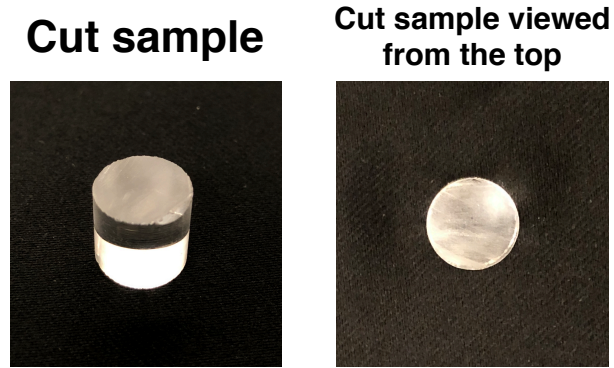


Figure 5.1: Left: picture of a cut sample. Right: top view of the sample. The diffusive effect of the surface is so strong that one can barely see through the sample.

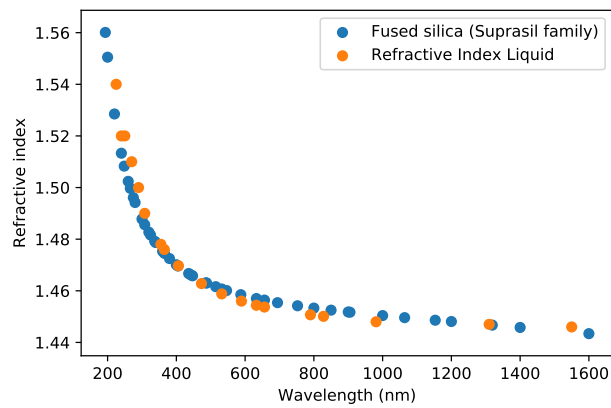


Figure 5.2: Refractive index comparison between fused silica (Suprasil family) and the chosen Series AA refractive index matching liquid at different wavelengths.

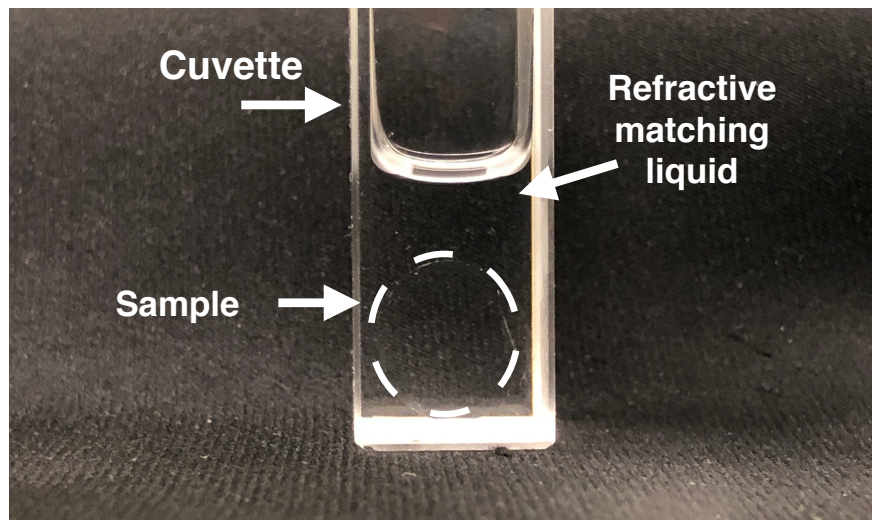


Figure 5.3: A sample immersed in the refractive index matching liquid within the fused silica cuvette.

The optical transmission of the samples was measured using a Varian Cary 5000 [79] available in the Frederick Seitz Materials Research Laboratory at UIUC. The instrument allowed for measurements in a wide range of wavelengths, ranging from 240 to 1500 nm. The sampling interval was 1 nm, the average measurement time was 0.1 second, and the spectral bandwidth was 2 nm. Air was used as a reference to calibrate the instrument for the fused silica samples. For each measurement, the sample was immersed in the refractive index matching liquid in the cuvette placed in the Cary's built-in cuvette holder. The sample was centered with respect to the optical beam with 1 cm diameter. A sketch of the experimental setup is shown in fig. 5.4. To compare the radiation-induced optical losses of the irradiated samples, a sample was cut from an un-irradiated fused silica rod, manufactured by Heraeus. The sample, referred to as the control sample, was obtained by the procedures described in sec. 4.1. It is a cylinder with a length of 1 cm and a diameter of 1 cm. The relevant specifications of the control sample are listed in tab. 5.1. The measurement of its optical transmission was used as a reference for the irradiated samples.

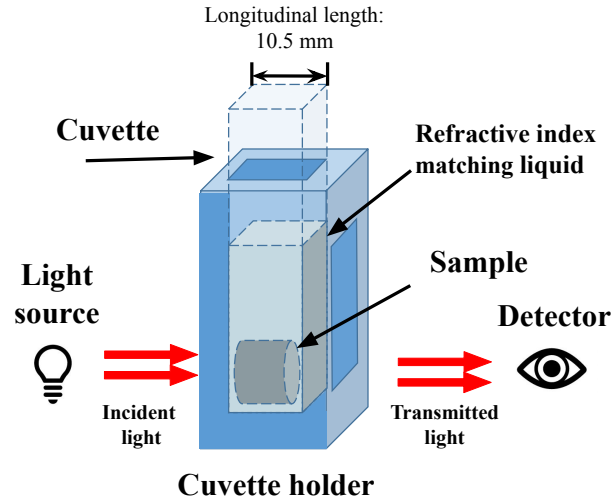


Figure 5.4: Schematic drawing of the optical transmission measurement setup.

Table 5.1: Specifications for the un-irradiated control sample.

Material	Spectrosil 2000
Length (cm)	1 ± 0.001
Diameter (cm)	1 ± 0.001
H ₂ doping level (mol/cm ³)	7.20e17
OH doping level (ppm)	1020

5.2 Data analysis

5.2.1 Attenuation correction of refractive index matching liquid

In order to account for the optical absorption caused by the liquid during the measurements, a correction was applied to the measurement results using the liquid's attenuation coefficient. The Beer-Lambert's law has been widely used to model the attenuation of light in a slab of an absorber with parallel faces (see fig. 5.5) [83]. The absorber's attenuation coefficient α can be calculated as

$$\alpha = \frac{-1}{t} \ln(I), \quad (5.1)$$

where I is the intensity (expressed in fraction) of the transmitted light and t is the thickness of the absorber.

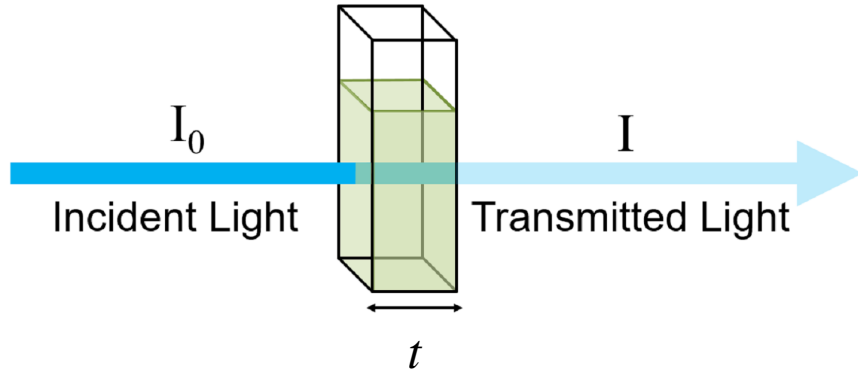


Figure 5.5: An example drawing of light transmitting in a absorber. I_0 is identical to 1. Figure adapted from [84].

As the cuvette is filled with the refractive index matching liquid, similar to the geometry

shown in fig. 5.5, the attenuation coefficient α_l of the liquid can be calculated by

$$\alpha_l = \frac{-1}{t_c} \ln(I_l), \quad (5.2)$$

where t_c is the longitudinal length of the cuvette and I_l is the average intensity of 10 measurements carried out with only liquid in the cuvette. In this case, because no sample is placed in the cuvette, the longitudinal length of the liquid is equal to that of the cuvette. In this study, the longitudinal length t_c of the cuvette is 1.05 cm.

In a given sample measurement, the given sample was inserted into the cuvette and, thus, the longitudinal length of the liquid t_l was computed as

$$t_l = t_c - t_s, \quad (5.3)$$

where t_s is the length of the sample:

$$t_s = \left(\frac{t^{max} + t^{min}}{2} \right), \quad (5.4)$$

where t^{max} and t^{min} are the maximum length and minimum length of the sample, respectively. The correction applied to the measured intensity I of the sample immersed in the liquid can be expressed as

$$\hat{I} = I e^{\alpha_l t_l}, \quad (5.5)$$

where $\hat{I}$ indicates the corrected intensity.

The transmittance T of the sample compared to the control sample was calculated as [85]

$$T = \frac{\hat{I}}{\hat{I}_u}, \quad (5.6)$$

where $\hat{I}_u$ is the corrected intensity of the control sample, obtained by the same procedure (eqs. 5.3 - 5.5) using the measurements of the control sample.

To allow for a comparison between different samples, the transmittance of the sample should be normalized to transmittance per unit length. For this reason, the attenuation

coefficient α_s of the sample was used for the normalization and computed as

$$\alpha_s = \frac{-1}{t_s} \ln(T). \quad (5.7)$$

By making use of α_s , the transmittance per unit length $\bar{T}$ can be estimated:

$$\bar{T} = TC, \quad (5.8)$$

where C is a correction factor computed as

$$C = e^{-\alpha_s(t_n - t_s)}, \quad (5.9)$$

where t_n is the arbitrary unit length chosen. Because the typical length of the samples used in the transmission measurements is 1 cm, t_n is set to be 1 cm in this study.

5.2.2 Uncertainty estimation

Two primary sources of uncertainty were identified in this study, one introduced by the attenuation correction described in sec. 5.2.1, and the other related to the systematic error associated to the variation in positioning the samples in each measurement.

The uncertainty on attenuation coefficient of the liquid σ_{α_l} in eq. 5.2 was calculated as

$$\sigma_{\alpha_l} = \sqrt{\sigma_{I_l}^2 \left(\frac{-1}{I_l t_c} \right)^2 + \sigma_{t_c}^2 \left(\frac{\ln I_l}{t_c^2} \right)^2}, \quad (5.10)$$

where σ_{I_l} is the standard deviation of the 10 measurements with only liquid in the cuvette and σ_{t_c} is the uncertainty (0.05 mm) on the length of the cuvette specified by the manufacturer. The uncertainty on the corrected intensity $\sigma_{\hat{I}}$ in eq. 5.5 can be derived using error proportion:

$$\sigma_{\hat{I}} = \hat{I} \sqrt{(\alpha_l t_l)^2 \left[\left(\frac{\sigma_{\alpha_l}}{\alpha_l} \right)^2 + \left(\frac{\sigma_{t_l}}{t_l} \right)^2 \right] + \left(\frac{\sigma_I}{I} \right)^2}, \quad (5.11)$$

where σ_I is the uncertainty on the sample's intensity measurement and σ_{t_l} is the uncertainty

on the longitudinal length of the liquid in the measurement. The attenuation caused by the liquid is affected by the uncertainty on the liquid thickness, σ_{t_l} , that was assumed to be equal to

$$\sigma_{t_l} = t^{max} - t^{min}. \quad (5.12)$$

This assumption provides a conservative uncertainty on the corrected intensity. Note that the Cary 5000 spectrophotometer does not provide the uncertainty on measurements so σ_I was not available and assumed to be zero. However, the main sources of this uncertainty are the variations between each measurement, such as the sample positioning and fluctuations of the spectrophotometer performance. The reproducibility of the transmittance result was estimated using an overall systematic error that will be described later in this section.

The uncertainty on the transmittance σ_T of the sample can be expressed as

$$\sigma_T = T \sqrt{\left(\frac{\sigma_{\hat{I}}}{\hat{I}}\right)^2 + \left(\frac{\sigma_{\hat{I}_u}}{\hat{I}_u}\right)^2}, \quad (5.13)$$

where $\sigma_{\hat{I}}$ and $\sigma_{\hat{I}_u}$ are the uncertainty on the corrected intensity of the sample and the control sample computed by eq. 5.11, respectively. The uncertainty σ_{α_s} on the sample's attenuation coefficient was computed as

$$\sigma_{\alpha_s} = \sqrt{\sigma_T^2 \left(\frac{-1}{T t_s}\right)^2 + \sigma_{t_s}^2 \left(\frac{\ln T}{t_s^2}\right)^2}, \quad (5.14)$$

where σ_{t_s} is the uncertainty on the sample's length and was assumed to be the same as σ_{t_l} . Finally, the uncertainty $\sigma_{\bar{T}}$ on the transmittance per unit length was calculated as

$$\sigma_{\bar{T}} = \sqrt{\sigma_T^2 C + \sigma_{t_s}^2 T C(t_s - t_n) + \sigma_{\alpha_s}^2 T \alpha_s C}. \quad (5.15)$$

The systematic error resulting from variations introduced by sample positioning in each measurement due, for instance, to different rotations of the samples in the cuvette or thickness of liquid upstream/downstream of the sample, was also evaluated. A set of representative samples were selected based on their lengths and positions in the rod, using the procedure described in the following. The 40 samples obtained from each rod were first

grouped in batches of 10 consecutive samples each. The samples characterized by the maximum and minimum lengths were selected within each of these groups, resulting in 8 samples for each 40 cm long rod. The control and each selected sample were measured ten times. In every iteration, the sample was rotated and flipped randomly to maximize the variations in each measurement.

Every measurement of the selected sample was paired with ten control measurements to calculate the corresponding transmittance per unit length. As a result, a distribution was formed at each wavelength using the 100 transmittance results for each given sample in order to evaluate the corresponding standard deviation. For each rod, at every wavelength, the maximum standard deviation among the 8 samples was then taken as the systematic error.

5.3 Results and discussion

Using FLUKA simulations, it was possible to correlate the transmittance with the dose received by each rod segment. In the simulations, the whole geometry was divided into cells (see fig. 3.11). In each cell, the deposited energy and the corresponding error were computed by FLUKA. To calculate the dose of each rod segment, the dose of all the cells within the segment was averaged. The error associated with the average was also propagated from the cells.

It should be noted that rods irradiated in 2016 and 2017 experienced different beam configurations, which directly impact the dose profiles in the rods. In order to accurately describe the dose distribution of these rods, the two different beam configurations described in sec. 3.2.1 and the positioning of the rods with respect to the beam must be considered.

5.3.1 Impact of crossing angles

For simplicity, the “transmittance” mentioned in the following sections refers to the transmittance per unit length ($\bar{T}$). Fig. 5.6 shows the impact of the crossing angles on the transmittance profile and the dose distribution of Rod 3a and 3b at two different wavelengths. The minimum transmittance along Rods 3a and 3b can be observed approximately

at $y = -2.5$ and 1.5 cm, respectively. The positions of the minimum transmittance in the two rods are characterized by two different crossing angles in 2016 and 2017-18¹. As another piece of evidence, the location of the minimum transmittance observed in Rod 3b is also consistent with the peak of Rod 3b's ^{22}Na activity profile shown in fig. 4.13. The correlation between transmittance and doses can be observed by looking at dose distribution and the transmittance profile: as expected, the position of the minimum transmittance along the rod is where the maximum accumulated dose is.

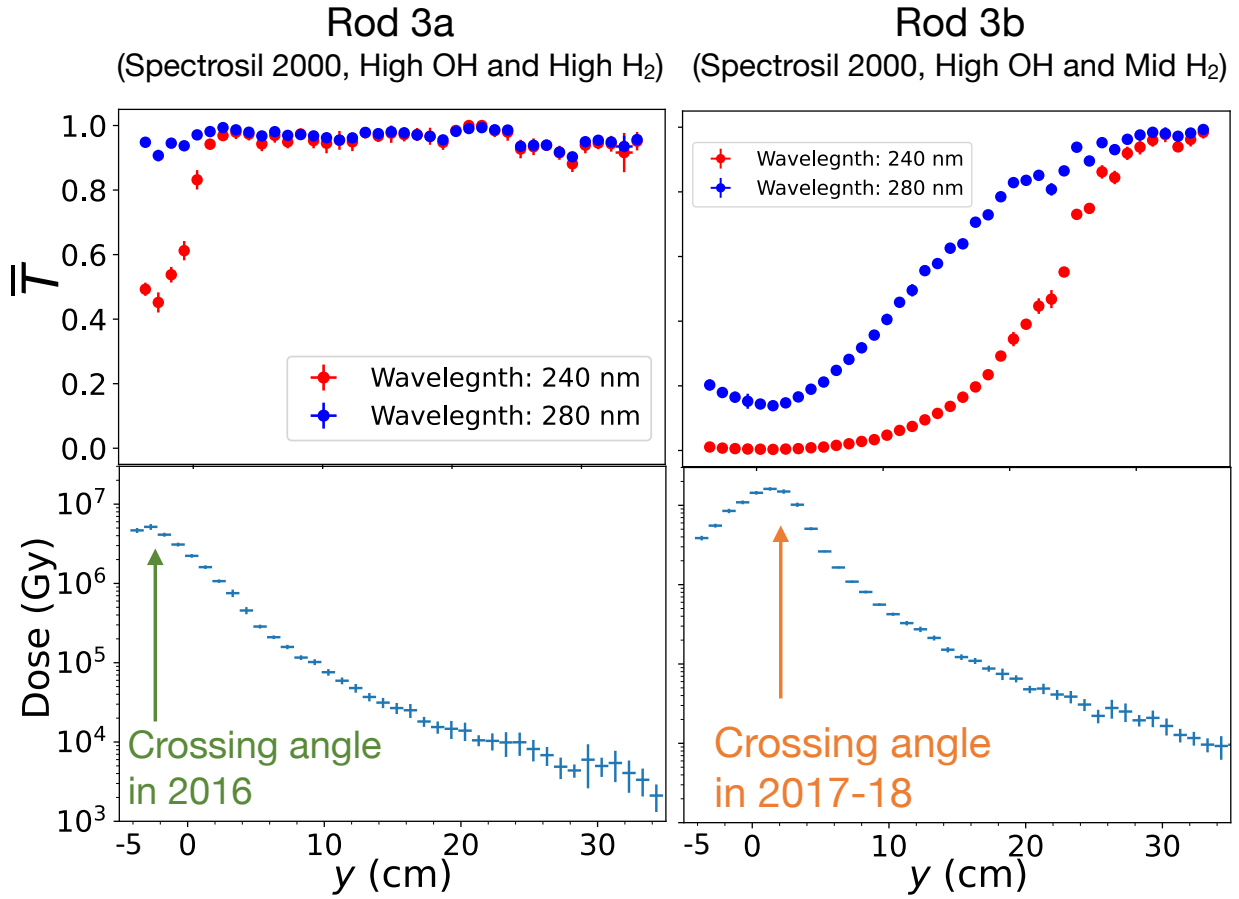


Figure 5.6: Transmittance profile at 240 and 280 nm and dose distribution of Rod 3a (2016 crossing angle) and Rod 3b (2017-18 crossing angle). The top row shows the transmittance profile of the rod, while the bottom row represents the dose profile.

However, a different correlation between doses and transmittance results was observed in Rod 4 (see fig. 5.7), characterized by two different crossing angles. From the transmittance

¹The beam configuration in 2018 is the same as that in 2017.

profile of Rod 4, the minimum transmittance is approximately at $y = -2.5$ and 6 cm. This observation does not match the location ($y = 2.5$ cm) of the maximum dose in Rod 4. The reason causing this misalignment is still under investigation with our collaborators, the BRAN team and the FLUKA group. The results from Rod 4 are not included in the discussion in the following sections.

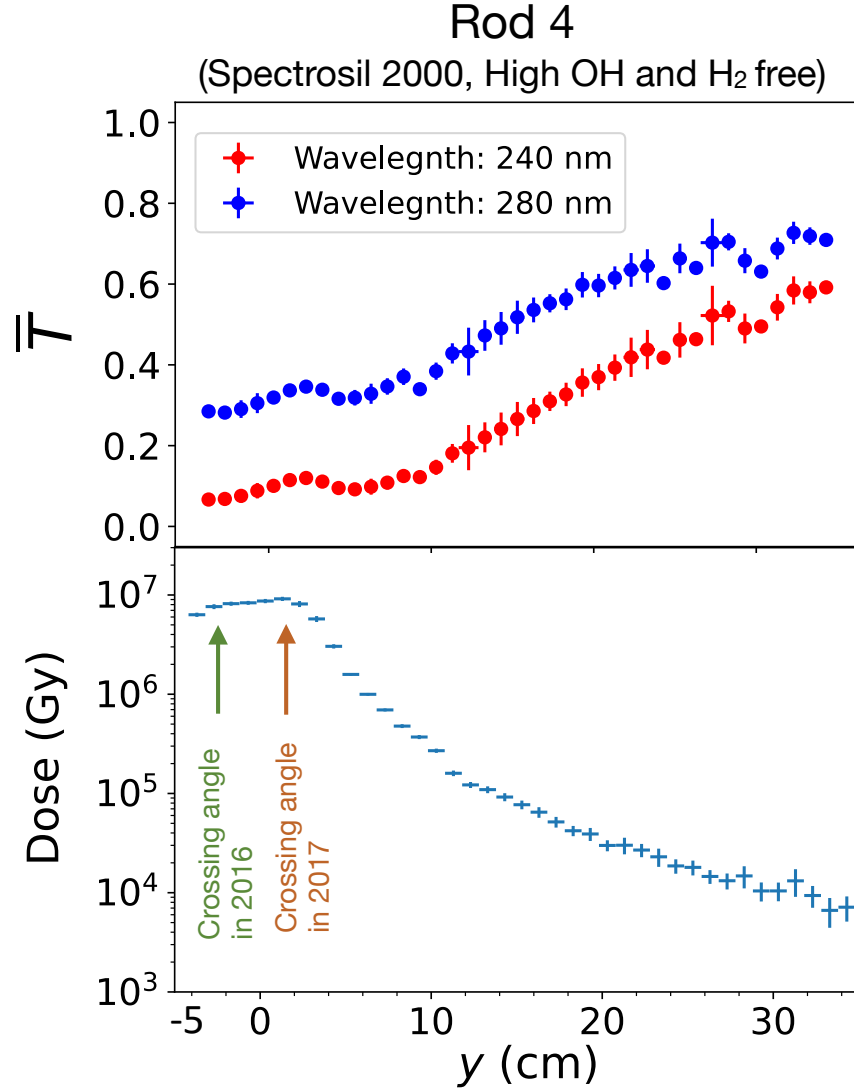


Figure 5.7: Transmittance profile at 240, 280, and 320 nm and dose distribution of Rod 4 (Spectrosil 2000, High OH, H₂ free), which experienced two crossing angles in 2016 and 2017. The top shows the transmittance profile of the rod, while the bottom panel represents the dose distribution taken into account for two crossing angles in 2016 and 2017.

5.3.2 Correlations between wavelengths, transmission losses, and doses

Fig. 5.8 shows transmittance for Rods 3a, 3b, 5, and 6 as a function of received dose and wavelength. To have a meaningful comparison, the results in the figure are presented only in the dose range experienced by all rods, e.g., 1.5×10^4 to 5×10^6 Gy. Among Spectrosil rods with an intermediate level of H_2 dopants, Rod 3b was chosen for the analysis because its position is consistent with that of Rod 3a. Although the wavelength of the measurement is up to 1500 nm, no significant degradation in transmittance was observed above 350 nm. Thus, the vertical axis was restricted to a region of interest for typical PMT applications [86].

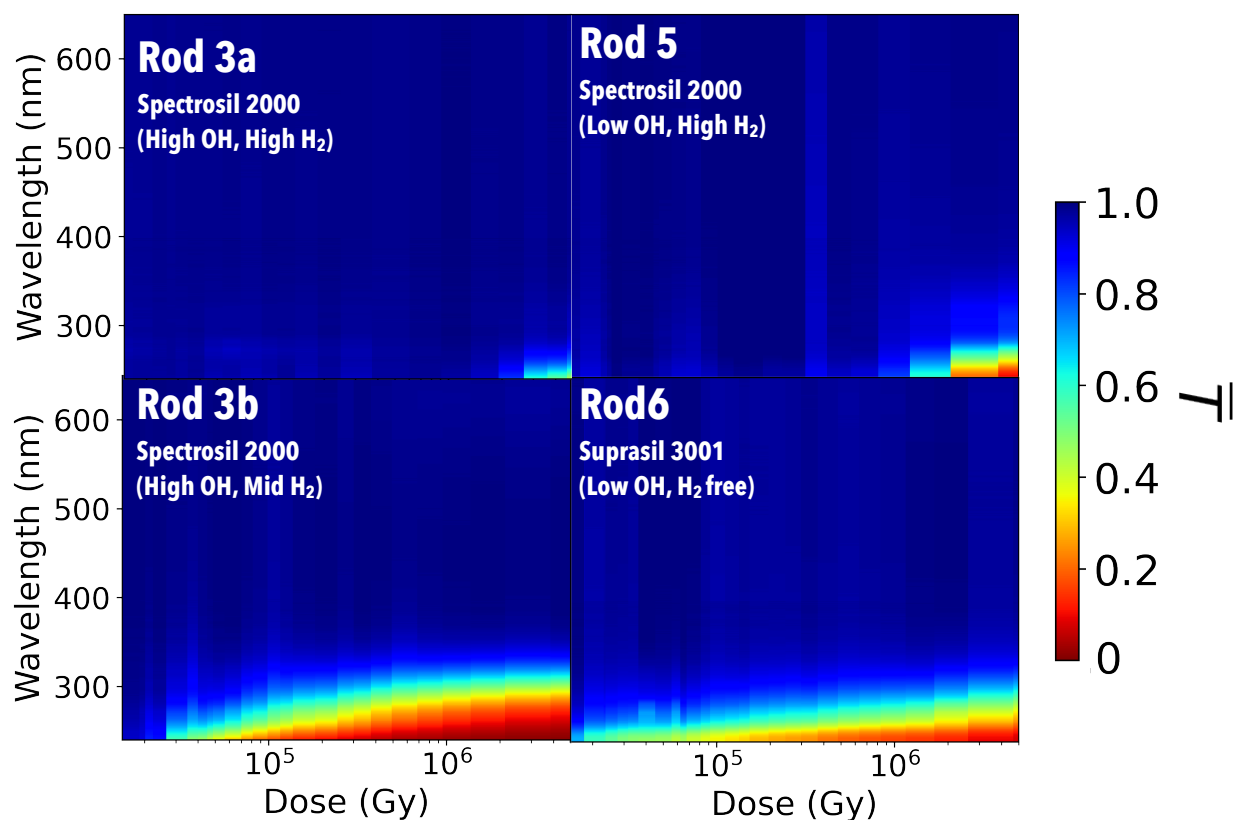


Figure 5.8: Transmittance versus received dose and wavelength for Rods 3a, 3b, 5, and 6. The vertical axis represents the wavelength of the transmittance measurement. The horizontal axis displays the dose received by each sample. Note that the horizontal axis was limited to the dose range experienced by all rods, 1.5×10^4 to 5×10^6 Gy, and the vertical was restricted between 240 and 650 nm, the maximum wavelength of the sensitivity of a typical PMT.

Fig. 5.9 presents the transmittance as a function of dose in the UV region. The trans-

mittance of each rod was plotted as a function of dose for five different wavelengths, in increments of 40 nm from 240 to 400 nm. At a given dose level, the lower the wavelength, the higher the optical losses were observed. Among all the rods, Rod 3a shows the lowest transmittance degradation in the UV region.

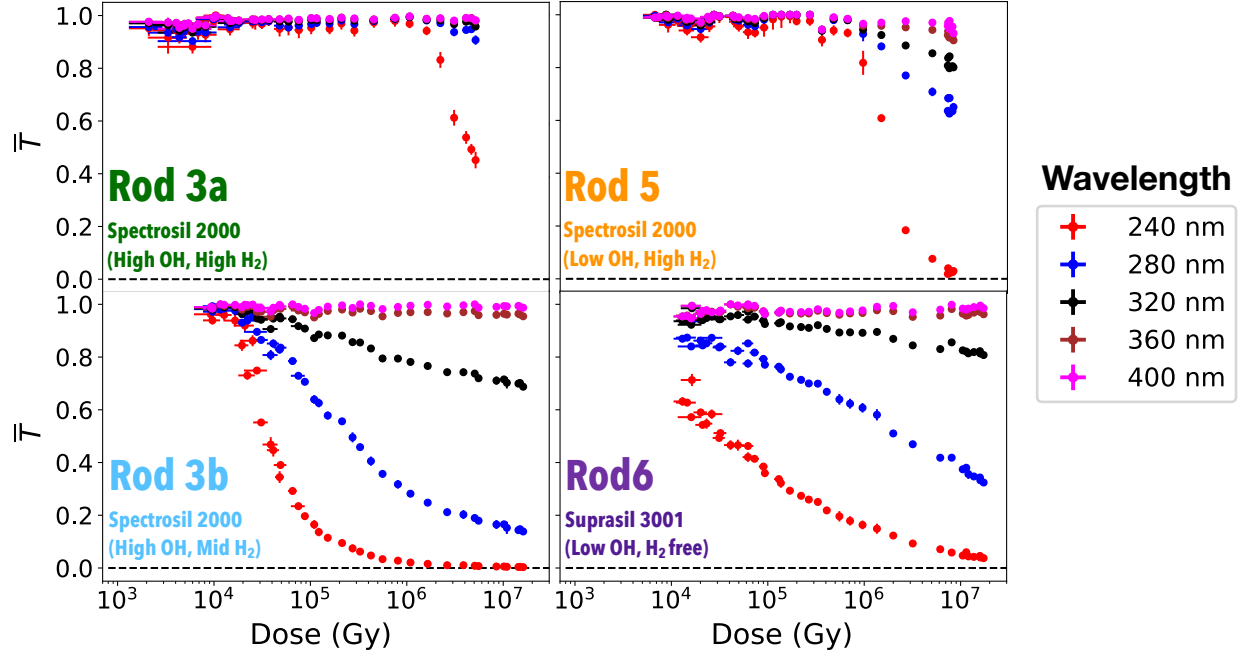


Figure 5.9: Transmittance as a function of dose in the UV region for Rods 3a, 3b, 5, and 6. The vertical axis represents transmittance. The horizontal axis displays the dose received by each sample. Statistical uncertainties are contained within the markers.

5.3.3 Impact of the dopant level on the transmittance degradation

In this section, the impact of dopant levels (OH and H₂) on the transmittance degradation is discussed. The lower limit of the wavelength spectra, 240 nm, shows the highest level of degradation for all materials studied. For this reason, the results at 240 nm were chosen to discuss the effect of the dopants on the radiation hardness.

Different subsets of rods were selected to investigate the effects of specific dopants. For instance, in fig. 5.10, one can see a comparison of the transmittance between Rods 5 (Low OH) and 3a (High OH) as a function of dose. Those two rods are characterized by comparable levels of H₂, but different concentrations of OH. For the highest doses received, dose >1 MGy, it is apparent that Rod 3a experienced less degradation than Rod 5. This trend indicates that a high concentration of OH can slow down the degradation when the fused silica is doped with a high concentration of H₂.

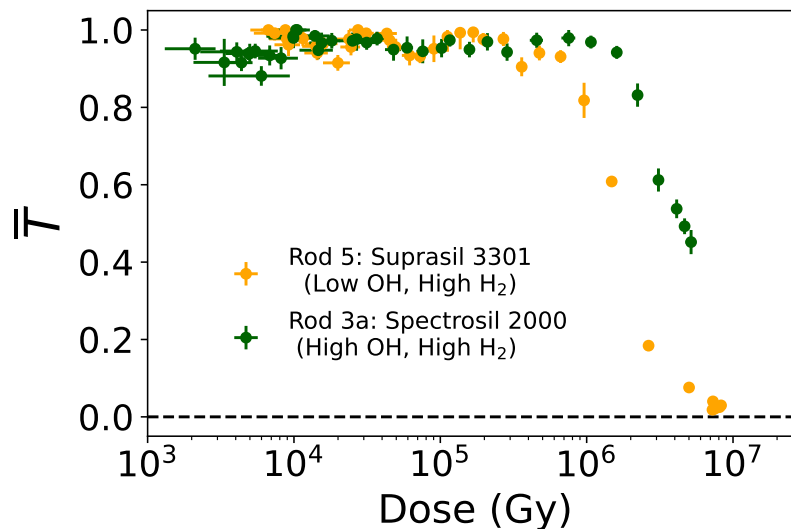


Figure 5.10: Comparison of the transmittance at 240 nm between Rod 5 (Suprasil 3301, Low OH and High H₂) and Rod 3a (Spectrosil 2000, High OH and High H₂) at different dose levels. A dashed line that corresponds to zero transmittance is drawn for reference. Statistical uncertainties are contained within the markers.

By comparing the results obtained for Rods 5 (High H₂) and 6 (H₂ free) in fig. 5.11, one can observe that, after 10 MGy of irradiation, the optical transmission of 240 nm light is reduced to a few % for both materials. However, it is interesting to note how the transmittance degradation occurs with substantially different dependence on doses. Rod 6 exhibits

a gradual loss starting already from the kGy scale, while Rod 5 shows little losses up to 500 kGy. Beyond that dose level, the transmittance of the H₂ doped rod rapidly declines and reaches values close to zero, while the H₂ free rod tends to maintain a few % transmittance even after 20 MGy of irradiation.

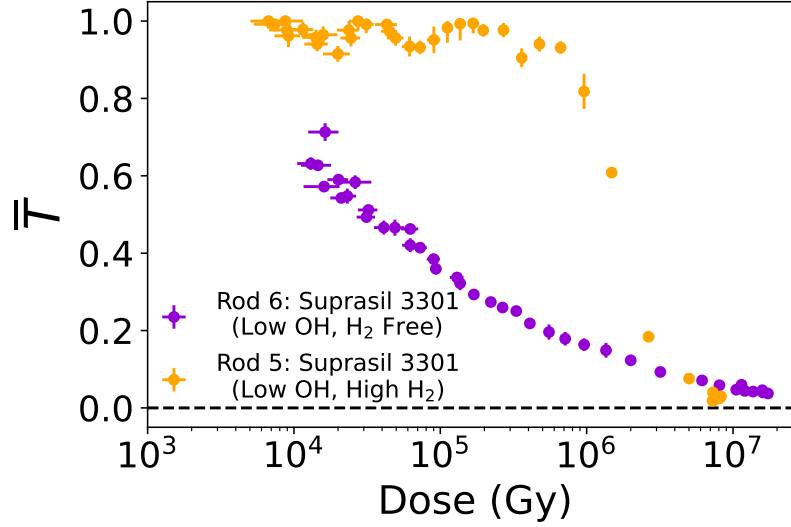


Figure 5.11: Comparison of the transmittance at 240 nm between Rod 6 (Suprasil 3301, Low OH level and H₂ free) and Rod 5 (Suprasil 3301, Low OH and High H₂) at different dose levels. A dashed line that corresponds to zero transmittance is drawn for reference. Statistical uncertainties are contained within the markers.

Fig. 5.12 shows the impact of H₂ concentration on the radiation hardness of high OH fused silica. Comparing Rod 3a (High H₂) to Rod 3b (Mid H₂), it appears that the H₂ doping level defers the threshold for the transmittance degradation to a higher radiation level. In the interval between 0.1 and 1 MGy, the fused silica samples with a high H₂ level undergo minimal transparency losses, while the optical transmittance of mid-H₂ fused silica sample already decays below 0.2. This indicates that if the concentration of H₂ is increased by a factor of 4, the dose threshold for the turn-on of transmittance degradation increases by 2 orders of magnitude.

In summary of the observations, the impact of the dopant concentration on the radiation hardness was examined. With a high H₂ concentration, increasing the concentration of OH can increase the radiation hardness. With a high OH concentration, increasing the H₂ doping level can effectively defer the transmittance degradation to a higher radiation

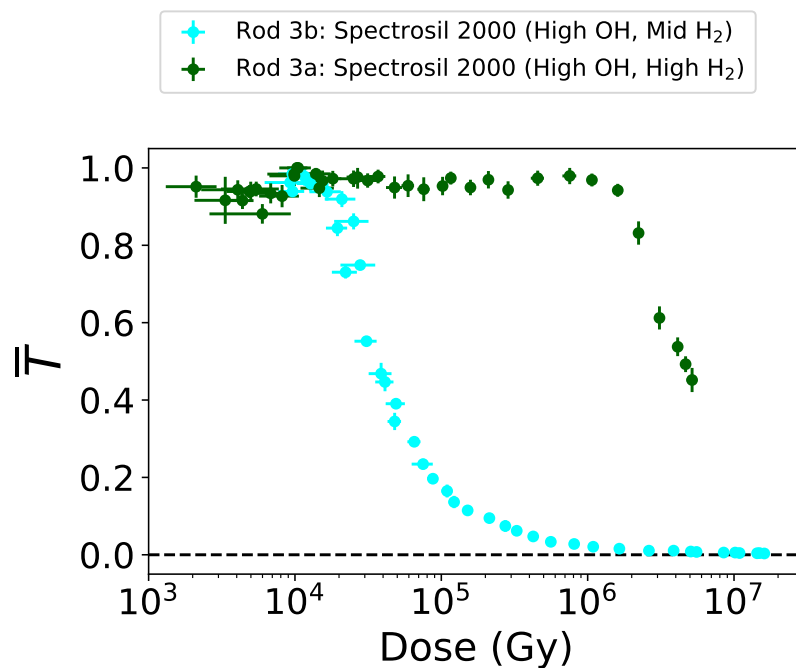


Figure 5.12: Comparison of the transmittance at 240 nm between Rod 3b (Spectrosil 2000, High OH and Mid H_2) and Rod 3a (Spectrosil 2000, High OH and High H_2) at different dose levels. A dashed line that corresponds to zero transmittance is drawn for reference. Statistical uncertainties are contained within the markers.

level. To further study the radiation hardness of fused silica, further irradiation studies of Heraeus fused silica samples for Run 3 (2022-2025) were prepared and set up in the TAN. The delivered doses in the future irradiation study will be at least one order of magnitude higher than that of the samples in this chapter, closer to the doses expected in the HL-LHC. The fused silica samples are 1 cm long cylinders and polished on both ends by Heraeus, which avoids the cutting process described in sec. 4.1 for future optical transmission measurements and thus further reduces surface effects on the optical transmission.

CHAPTER 6

REACTION PLANE RECONSTRUCTION WITH THE REACTION PLANE DETECTOR

This chapter presents a new reaction plane detector (RPD) for ATLAS and CMS and a novel machine-learning-based method for the RPD data analysis. First, flow physics of heavy-ion (HI) collisions is introduced, along with analyses to study the physics principles of HI collision dynamics. To perform such analyses taking into account for the geometry between two colliding ions, these analyses rely on the reconstruction of a reference plane. This reference plane, known as the reaction plane, allows for characterizing the azimuthal anisotropy of particle emission in HI collisions. The RP can be estimated by measurements using the reaction plane detector (RPD) in the upgraded Zero Degree Calorimeter (ZDC) proposed by the Joint Zero Degree Calorimeter Project (JZCaP) (described in chap. 2). The detector design and its characteristic response are discussed in this chapter. In order to reconstruct the RP using RPD measurements, a machine-learning (ML) method was developed, and the performance of the method was evaluated and compared to previous experimental RP measurements. This chapter is organized as follows: sec. 6.1 gives a brief overview of the flow physics of HI collisions. The conceptual design of the RPD and its characteristic detector response are covered in sec. 6.2. The ML-based method is discussed in sec. 6.3. This starts with an approach to generate RPD data using dedicated simulations to optimize the ML model given in sec. 6.3.1. The description of the ML model is presented in sec. 6.3.2 and the performance evaluation of the model is discussed in sec. 6.3.3.

6.1 Flow physics of heavy-ion collisions

In HI collision physics, a collision can be characterized by the size of the overlap region between two interacting ions. The size of the region and its geometry are important parameters

used in the analyses of HI collisions, allowing for the understanding of the physics driving HI collision dynamics. A collision with a relatively large size is referred to as a “central” collision. In a non-central collision, characterized by a relatively small or medium overlap size, the geometry of the overlapping region will be of an almond shape (see fig. 6.1 for an illustration). Note that the coordinates used in this chapter follow the definition given in sec. 2.3.1. The colliding nucleons heat the volume of overlap in the nuclear collision and create a hot dense medium of nuclear matter. The medium expands rapidly, cools, and transitions to a large number of energetic hadrons emitted in all directions. A pattern of hydrodynamical flow can be observed during the expansion. The expansion is modeled as fluid flowing along pressure gradients [87]. In collisions characterized by a geometry similar to fig. 6.1, the azimuthal distribution of the gradients’ magnitudes is anisotropic with respect to the RP, formed by the impact parameter vector and the beam axis. The magnitudes of the pressure gradients along the RP are larger compared to gradients pointing out of the plane. In the final state of the expansion, particles are emitted from the medium. Since the medium expands following the pressure gradients, the particles emitted near the RP inherit more momenta, on average, from the medium. Therefore, the momentum distribution of the particles at azimuthal angles is also anisotropic with respect to the RP.

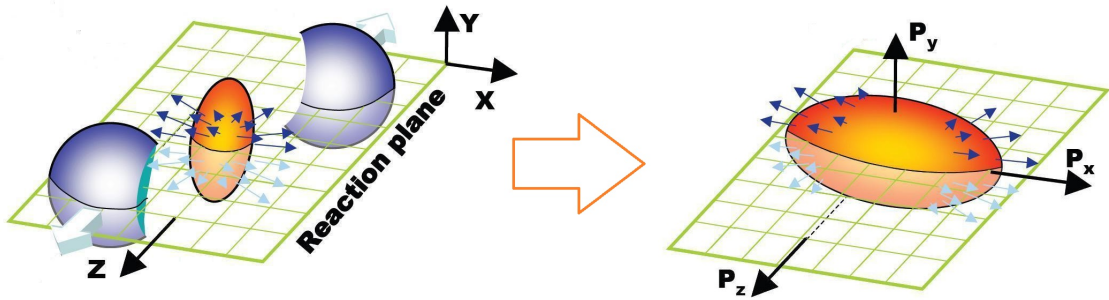


Figure 6.1: An example of anisotropic expansion in a non-central collision. Left: the blue spherical fractions represent clusters of spectator nucleons, while the orange almond-shaped area indicates the hot and dense medium produced by participants (nucleons in the overlap region). The arrows on the surface of the medium illustrate pressure gradients. The gradients are larger along the RP direction. Right: the medium expands anisotropically due to the pressure gradients. Figure taken from [88].

The particle distribution at different azimuthal angles can be described by Fourier-series expansion [89, 90]:

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)] \right), \quad (6.1)$$

where ϕ is the azimuthal angle, E is the particle energy, p is the particle momentum, p_T is the transverse (x - y) component of p , y is rapidity, v_n is the n -th harmonic Fourier coefficient, and Ψ_n is the n -th harmonic RP angle.

The coefficient v_1 , better known as directed flow [90, 91] provides a measurement of the asymmetry in the number of particles emitted along the RP direction. In other words, a non-zero directed flow indicates the presence of a preferential direction for particle emission during the collision. A key ingredient to determine v_1 is the measurement of the RP angle Ψ_1 , making use of the spectators of the collision (described in chap. 1). In a given event, the RP angle, Ψ_1 , of the directed flow can be inferred by the positions of spectators. Fig. 6.2 shows two colliding nuclei and spectators in the x - y plane. In a conventional method to

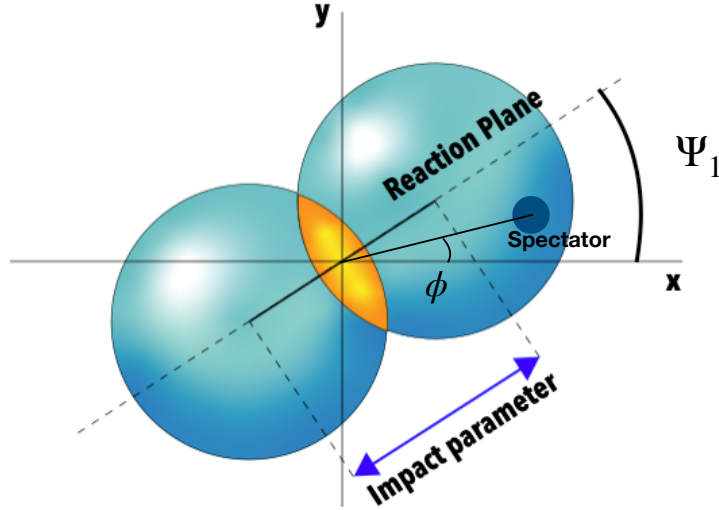


Figure 6.2: Collision geometry in the x - y plane. Ψ_1 is the RP angle for the directed flow. ϕ is defined by the transverse position of the spectators and the beam axis.

reconstruct Ψ_1 , the angle is determined from a flow vector $\vec{Q}$ [89]. The x and y components of the vector (Q_x and Q_y) are

$$\begin{aligned} Q_x &= Q \cos \Psi_1 = \sum_i w_i \cos \phi_i, \\ Q_y &= Q \sin \Psi_1 = \sum_i w_i \sin \phi_i, \end{aligned} \tag{6.2}$$

where the sum is over all the spectators in a given event, ϕ_i is the azimuthal angle characterizing the i^{th} spectator, and w_i is the corresponding weight. It is customary to optimize w_i to produce the best possible RP resolution. Q_x and Q_y provide access to the overall deflection of the neutrons, while the azimuthal angle of the flow vector is directly associated with the spectator RP, Ψ_1 . The RPD presented in this dissertation allows for the reconstruction of the flow vector using its measurements and, thus, the estimation of Ψ_1 .

Event-by-event fluctuations play an important role in the measurement of the RP using spectator neutrons. Fig. 6.3 shows an illustration of the difference between the true RP and one that can be defined using spectators that reach the ZDC. The true RP differs from the RP reconstructed using the positions of spectators.

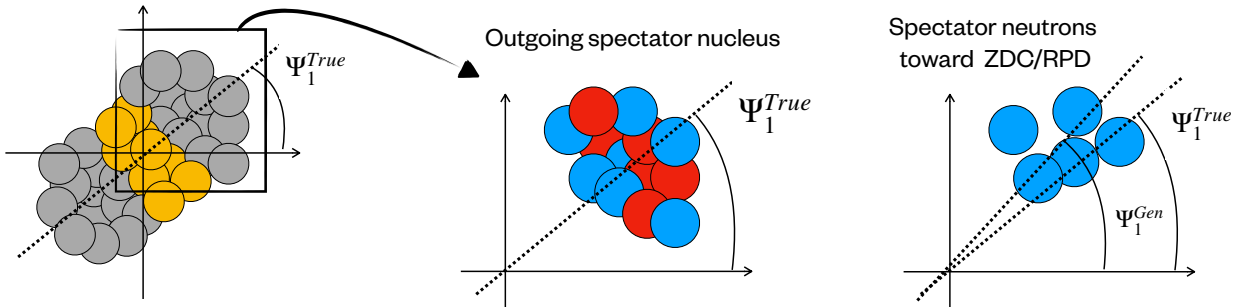


Figure 6.3: Drawing of the true RP angle (Ψ_1^{True}) and the RP angle (Ψ_1^{Gen}) formed by the spectators impinging on the ZDC/RPD.

6.2 RPD design

Two of the most important factors that were considered when designing the RPD were:

- Radiation hardness of the RPD: the RPD is integrated with the ATLAS ZDC installed in the TAN, allowing for measurements of spectator neutrons in the HI collisions runs. The expected radiation levels in the TA(X)N¹ in Runs 3 and 4 were presented in chap. 3. The harsh radiation environment imposes a requirement on the radiation-hardness of the active material to be used for the RPD.
- Detector accessibility: the detector is placed at the bottom of the TA(X)N absorber but can only be accessed in the y direction due to the space limited by the beam pipes (as shown in fig. 3.10). However, the RPD readout devices need to be placed far from the detector in y to protect them from radiation damage. One has to note that the radiation levels in the TAN decrease steeply with the distance from the beam axis. For example, in fig. 3.11, the dose level decreases by four orders of magnitude from $y = 0$ to 40 cm. As a result, any signals detected in the RPD must be routed upward to the sensitive electronic devices above.

Given the constraints listed above, the RPD design relies on fused silica fibers [13]. Each fiber has a fused silica core that acts as a Cherenkov radiator. The core is cladded and buffered, making the fiber flexible, allowing for fibers to be routed directly to readout devices. Therefore, Cherenkov light produced and trapped by total internal reflection (TIR) in the fibers is transported to the PMTs. Fig. 6.4 shows the conceptual design of the RPD active area. The RPD has 16 channels, each composed of 16 fibers that are routed upward and interfaced with a PMT. Each RPD signal is reconstructed as an array of 4×4 tiles. Each tile is a square with a 9.6 mm side defined by the position of the fibers. Fig. 6.5 shows a schematic drawing of the ZDC design for Run 4. The RPD is installed in-between the electromagnetic (EM) and hadronic (HAD) section of the ZDC, where the EM component of the shower generated by spectator neutrons is expected to be at maximum.

¹The existing Target Absorber for Neutrals is known as TAN. After Run 3, the absorber will be upgraded to accommodate the new lattice of the accelerator. The upgraded version of the TAN will be used for the first time in Run 4 and is referred to as TAXN.

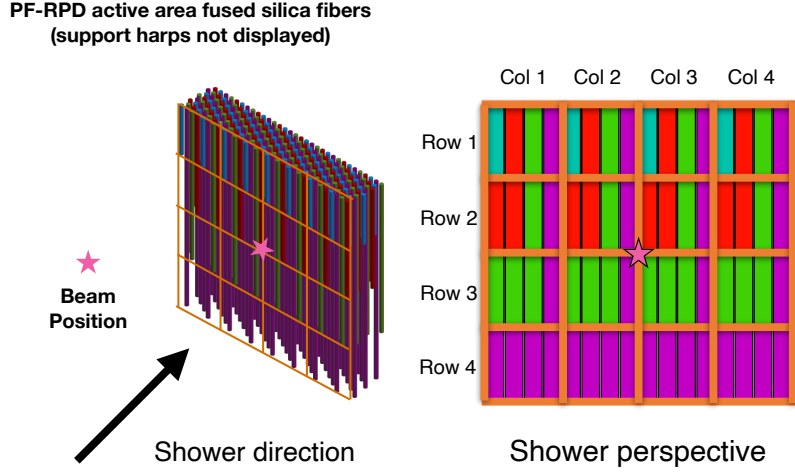


Figure 6.4: Left: fiber arrangement in the RPD active area. Individual fibers with the same length are characterized by the same color. The orange mesh represents an array of RPD virtual tiles that can be reconstructed using PMTs' readout values. Right: shower perspective of the fibers in the RPD. The index of the rows and the columns are labeled on the left side and the top of the array, respectively.

The RPD exhibits non-uniform responses in the vertical direction due to the fiber arrangement. For example, in the left side of fig. 6.6, Cherenkov light produced within the D' segment is carried by the purple fiber. Since the purple fiber is routed upward through the active area, particles above the D' segment can also create light in the purple fiber. As a result, the purple fiber also contains signals from other segments. One should also note that the RPD fibers are not limited to what is defined as the active area but extend from the active region to the PMTs (see fig. 2.16). Therefore, the signal distribution of RPD tiles in a column does not directly reflect the profile of the shower in y .

A subtraction scheme was proposed to unfold the signal of each row in a given column. A depiction of the subtraction scheme is given in the left hand side of fig. 6.6. The signal value read out by the green fiber (C) is subtracted from that of the purple fiber (D). In this way, the signal only belonging to the D' segment can be extracted. A similar procedure can be applied to the signals in other rows. As a result, the signal of each row in the same column can be recovered.

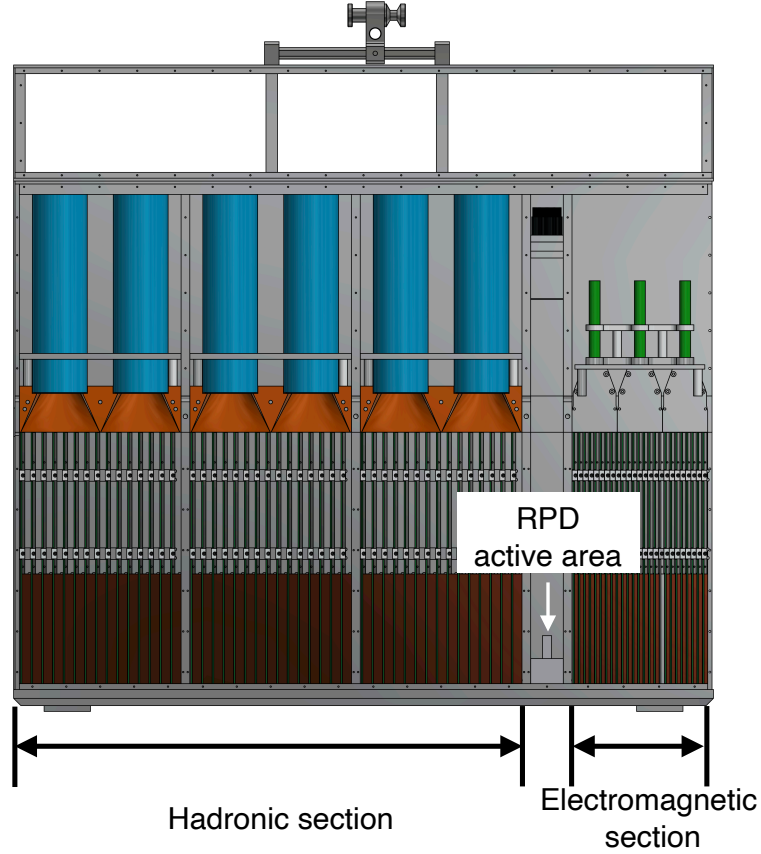


Figure 6.5: Side view of the current ZDC design for Run 4. Three sections can be identified: the EM, the RPD, and the HAD section. Refer to ref. [13] for more details about the ZDC geometry.

In order to use the subtraction scheme, the number of different fiber lengths in a given column must be the same. Fig. 6.7 shows a top view of the mixed fiber pattern in the RPD. The signal of a RPD channel is carried by 16 fibers, which are spaced out across eight layers. Within each layer, a pattern of the four fiber colors is repeated twice. Every other layer is offset by half a fiber pitch.

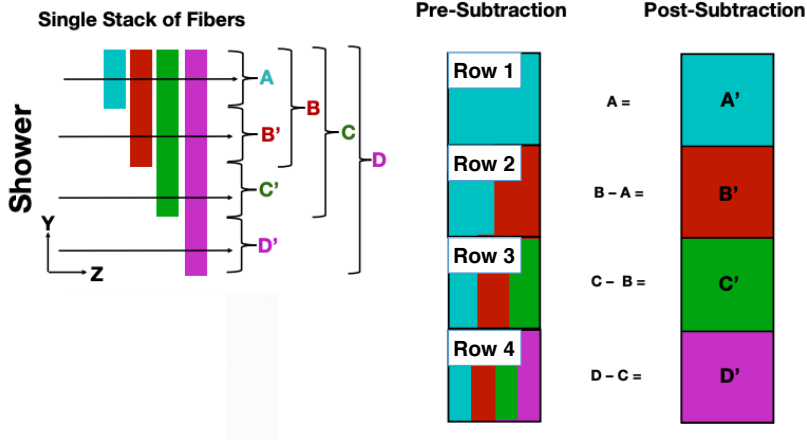


Figure 6.6: Subtraction scheme to correct signal strengths in a given column of the RPD. Left: particles at different y can generate signals in the same fiber, resulting in a mixed signal in the readout. Colors indicate fibers with different lengths. The letters represent the total signal read out by the corresponding fibers. The letters with prime (') indicate the signals only belonging to a single segment within the column. Right: colors in the pre-subtraction column represent the contribution from the particles above. Post-subtraction shows that the signals of each row are recovered.

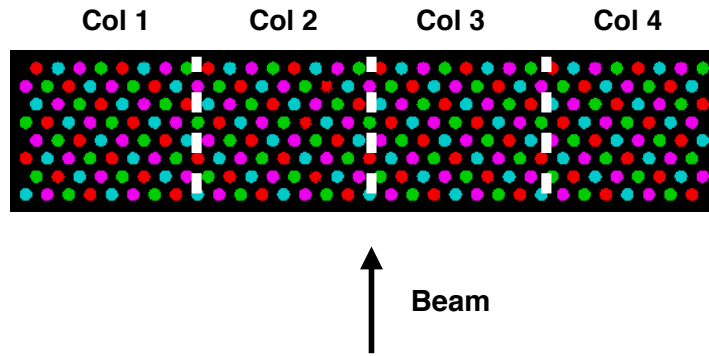


Figure 6.7: RPD fiber mixing pattern, viewed from the top. Colors represent fibers of the same length, while the dashed lines indicate the division of the columns.

Signal distributions of the RPD before and after applying the subtraction scheme were studied using a dedicated simulation of a 2.76 TeV neutron beam in GEANT4 [92, 93]. The neutron beam was aligned to the center of the RPD. The results are shown in fig. 6.8. The left-hand side shows the average simulated RPD signal without the subtraction correction. A non-uniform response is observed from the two center columns, where one would expect equal signals due to the beam being centered. The RPD signals corrected using the subtraction scheme are shown on the right-hand side. The distribution of the corrected signals still shows asymmetry with respect to the center of the RPD. The asymmetry can be attributed mainly to fluctuations and to a vertical bias in the light acceptance in the fibers with total internal reflection.

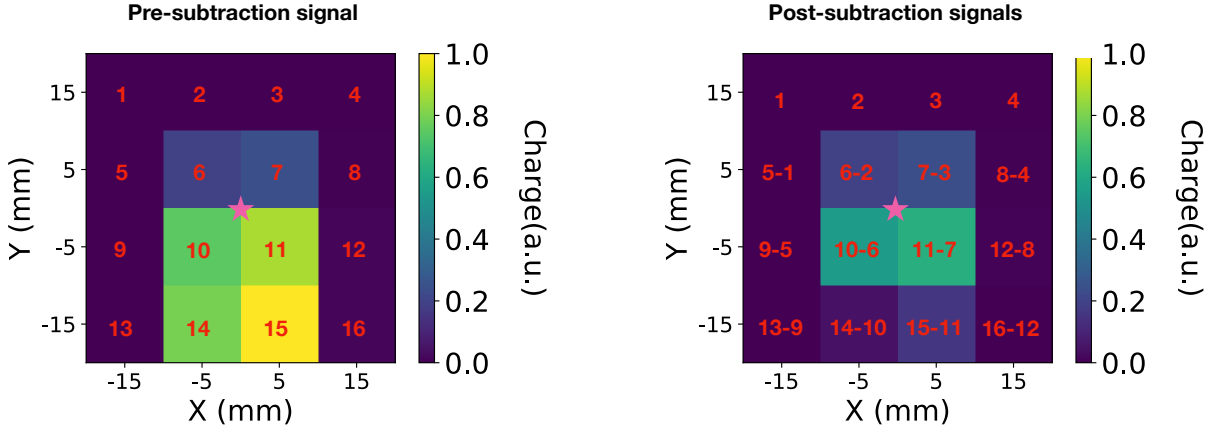


Figure 6.8: Left: the average simulated RPD signal of all the single-neutron events. The star indicates the x - y position of incident neutrons on the EM module before the RPD. Signals were normalized by the maximum values among all the tiles. The number corresponds to a given RPD channel. Right: the RPD signal after the subtraction scheme was applied. Each tile shows the subtraction operation using the signals from the corresponding channels on the left figure.

A conventional “Center-of-mass” (CoM) method can be used to compute the flow vector [89] using the corrected RPD signal. The x and y components of the vector (Q_x and Q_y) can be expressed as:

$$Q_x = \sum_{i=0}^N \frac{E_i \cos \phi_i}{E}, \quad Q_y = \sum_{i=0}^N \frac{E_i \sin \phi_i}{E}, \quad (6.3)$$

where N is the number of tiles in the RPD, E_i is the signal strength of the i^{th} tile, E is the sum over all the 16 signals registered by each tile, and ϕ_i is the azimuthal angle corresponding to the center of the i^{th} tile. The reconstructed vector (0.1, -0.5) points downward rather than at the center where the beam is. This indicates that the subtraction scheme does not entirely describe the underlying mechanism of the RPD response.

6.3 Reaction plane reconstruction using machine learning

To better calibrate the RPD response for the flow vector estimation, a method based on ML algorithms was proposed. Machine learning are algorithms that optimize a given model for a given objective using provided data. This data-driven characteristic allows the model, without explicit instructions, to learn correlations that can not be interpreted directly, such as relations between pixels in an image. Therefore, it is possible for a model to calibrate the hidden correlations between RPD tiles automatically when optimizing the model to estimate the RP angle.

A supervised learning algorithm was chosen to optimize a model for RP angle predictions. In supervised learning, data are provided as examples. Each example is an input and desired output pair. A model takes the input and makes a prediction. In each iteration, the algorithm updates the parameters of the model such that the model's prediction is closer to the desired output. The optimization process is also known as “training”, and the provided examples are usually referred to as a “training set”. In an ideal case, a well-trained model can correctly map unseen examples. In the RP reconstruction case, the inputs are the RPD signals in 2D, while the desired outputs are the RP angles.

The supervised learning algorithm requires output values, e.g., RP angles, to be known (labeled) for training. There are two possible ways to obtain labeled examples.

1. Experimental data: it is best to train a model on the HI event data collected by detectors in the real application scenario. However, as mentioned in chap. 1, because of event-by-event fluctuations, the true RP angle cannot be measured directly in HI collisions. This excludes the possibility of generating labeled examples using the data

collected during the HI Run.

2. Realistic simulation: given the limitation mentioned above, the approach proposed in this dissertation is to generate examples through dedicated simulations. In Monte Carlo (MC) simulations, details of each particle can be recorded and analyzed afterward, allowing for accessing the RP angle characterizing each generated HI collision. The limitation of this approach is the ability of the simulation to realistically model the physics being simulated. If the simulations accurately reflect HI collision events recorded during the data taking, the model trained on the simulations should be representative.

The proposed method aims to train a model on simulated data and use the model to predict the RP in the HI collisions.

The RPDs built by UIUC for Run 3 were first tested at the EHN1 test beam facility at the CERN North Area in July 2022. The beam extracted from the SPS and delivered to EHN1 can be configured to be composed of different charged particles, including protons or electrons. The beam position can be measured, providing labeled examples for the ML model. The test beam is lower energy charged particle beam compared to high-energy neutrons in HI running, and the setup in the test beam differs from the TAN. The model should be trained on the simulations describing the test beam condition. The data collected at the test beam can be used to test the accuracy of the model. For example, the model can predict the test beam position event-by-event using the collected data. The performance of the model, such as the accuracy of the predicted beam position, can play an essential role in validating the ML method and the simulation description.

6.3.1 Simulation for spectator neutron in HI events

Simulated examples were generated through the official MC simulation package for JZCaP. The Joint Zerodegree Calorimeter Prototype Analysis (JZCaPA) package [94], developed and maintained by the UIUC ZDC group, provides a comprehensive framework for simulation and data analysis within JZCaP. The part of the package responsible for the simulations is

built upon the GEANT4 MC toolkit, widely used in particle physics applications. GEANT4 provides detailed physics models of a full range of particle types and energies. Experimental benchmarks were carried out to validate GEANT4 performance. Good agreement was found between GEANT4 predictions and experimental data collected at the LHC [95, 96, 97]. JZCaPA includes a detailed description of materials and geometry of the existing and upgraded ZDCs and RPDs, as well as libraries written for ZDC and RPD data processing and analyses. JZCaPA has been used to produce the simulation results of the ZDC and RPD compiled in ref. [13] and analyses of the ZDC data collected during test beam campaigns [98].

An event generator was used to simulate Pb+Pb collisions at an energy of 2.76 TeV per nucleon. The event generator includes the kinematics of spectator neutrons, a correlated deflection of the spectators due to directed flow originating in the Pb+Pb collision. A dedicated generation mechanism was implemented to introduce directed flow effects in the distribution of the generated neutrons. Event-by-event fluctuations in the number of neutrons, due to the fragmentation of the spectator nuclei, were included by sampling a Poisson distribution with $\lambda = 30$ to determine the number of neutrons. This value was chosen to emulate the typical neutron multiplicity characterizing mid-central HI collisions. To simulate the Fermi motion of neutrons in a nucleus, the initial momenta (p_x , p_y , p_z) of each neutron were sampled between 0 and 265 MeV [99] and assigned independently. Then, the neutrons were boosted along the longitudinal (z) direction into a collider frame. After generating the momenta of the neutrons in the collider frame, the directed flow was introduced as an additional transverse momentum kick (applied to each neutron momentum vector) along the direction of the RP, p_T^{spec} . For the studies presented in this manuscript, the magnitude of the kick was uniformly distributed between 10 MeV and 50 MeV. This range was constructed around a reference measurement performed by ALICE at 2.76 TeV, 16 (22) MeV/nucleon for 5-10% (30-40%) centrality [100].

The generated spectator neutrons were injected into a dedicated GEANT4 simulation established within JZCaPA. The simulated ZDC and RPD geometries, as well as the distance of the detectors from an interaction point (IP), reproduces the Run 4 scenario (see fig. 6.5 for the Run 4 detector setup). The neutrons were initially placed at the IP, 127 m from each of the two ZDC arms, symmetrically installed on the two sides of the IP. The neutrons

were then propagated towards both the ZDCs, hereafter referred to as ZDC-A and ZDC-C. Fig. 6.9 shows, for one Pb+Pb event which includes effects of the directed flow, the spatial distribution of spectators at the front of the ZDC. The high-energy charged component of the shower generated by the neutrons incident on the ZDC emits Cherenkov light in the RPD's fused silica fibers. The information about the Cherenkov light that is trapped by TIR and reaches the top of the fibers is recorded on an event basis. Since in the RPD each group of 16 fibers characterized by the same length is routed to a PMT, in the MC the photons generated in fibers belonging to the same readout unit are summed up to build the per-channel light yield.

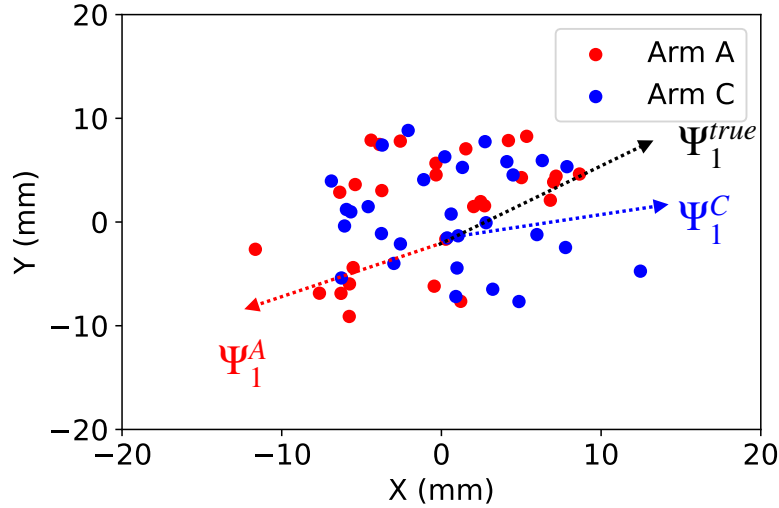


Figure 6.9: Spatial distribution of spectator neutrons at the front of the ZDC-A and ZDC-C, respectively. Red and blue dots indicate the positions of the neutrons. The kinematics of the neutrons in the IP, used to propagate them to the ZDC, includes effects due to directed flow. The black arrow represents the true RP Ψ_1 at the time of the collision. The red and blue arrows show RPs constructed using the spectators information directly from the generator, e.g., without experimental effects.

It is worth noting that data collected by the RPD in HI collisions are waveforms from PMTs, read out by waveform digitizers. Instead of photon counts, features of the digitized waveforms, e.g., the amplitude or the integral of pulses within the registered waveforms, are extracted to characterize the RPD signals. To make the simulation represent the experimental data, digitization procedures that convert Cherenkov light into digitized waveforms are

being developed and bench-marked by the UIUC ZDC group.

6.3.2 ML-model description and reconstruction method

A convolutional neural network (CNN) algorithm [101] was chosen to capture the correlation between tiles. This extraction is accomplished by applying a convolution between a 2D input and a kernel, which slides across the input and multiplies with input values. Fig. 6.10 demonstrates the convolutional operation of a kernel on a 2D array. The relatively high output value indicates that the corresponding region in the input is more similar to the pattern of the kernel. By making use of the convolutional operation, local correlations between pixels can be extracted.

A group of kernels seeing the same input is known as a convolutional layer used to learn different correlations between pixels. Each learned kernel can be used to detect a specific pattern in an image to perform tasks. Fig. 6.11 shows an example of the learned kernels in the first layer of the AlexNet model [102] used to perform image classification tasks. The kernels show patterns like lines and edges in different orientations, allowing for extracting similar features of input images through convolution. By exploiting the characteristic of convolutional layers, the vertical bias (similar to the left-hand side of fig. 6.8) in the RPD response should be extracted. The extracted bias can be calibrated by the rest of the network while optimizing the network for RP predictions.

Input		Kernel		Output																													
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37	43	16																															
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Figure 6.10: Visualization of the kernel operation. The higher value in the output indicates the corresponding region in the input is more similar to the pattern of the kernel.

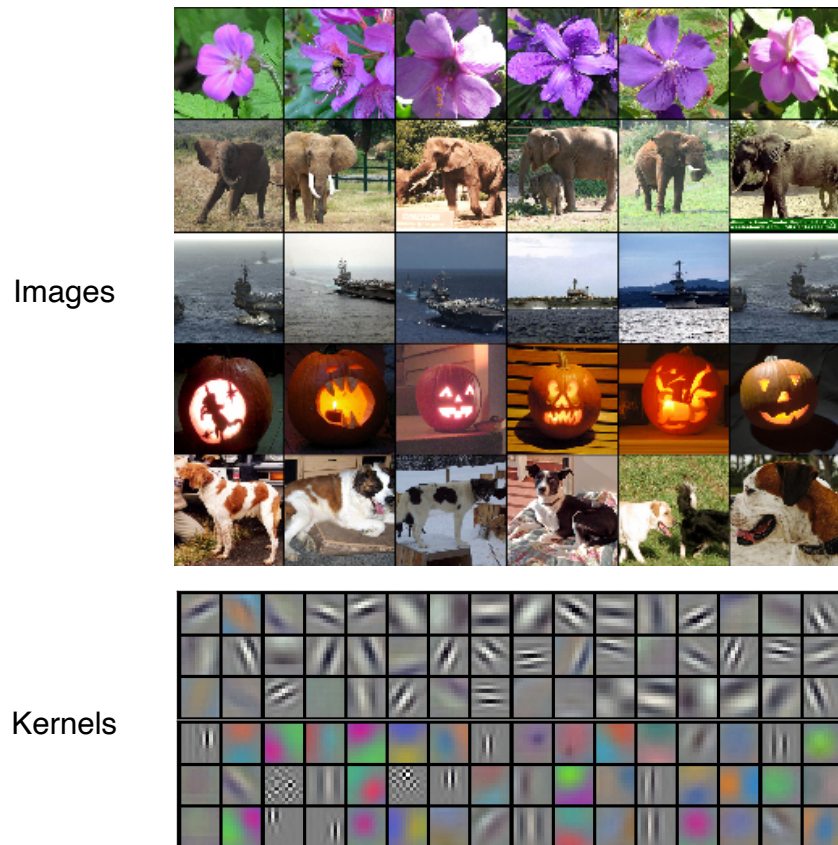


Figure 6.11: Upper: image examples. Lower: visualization of 96 convolutional kernels with $11 \times 11 \times 3$ in the first layer of AlexNet. Each kernel shows a specific pattern, such as edges or circles. These kernels can serve as a pattern detector to extract similar patterns in input images. Figure adapted from [102].

The structure of the model to perform RP reconstruction is shown in fig. 6.12. The inputs of the model are 4×4 RPD signals padded with zeros, resulting in 6×6 inputs. The zero-padding technique is an empirical method to capture information at the boundaries [103]. The first convolutional layer serves to up-sample the input with 64 1×1 kernels. The second convolutional layer performs pattern extraction to generate a 2D map. The map later is flattened into a 1D vector and fed into a series of fully connected layers [101], acting to process the output values from the second convolutional and perform a prediction. At the end of the network, the dimension is reduced to 2 to estimate Q_x and Q_y .

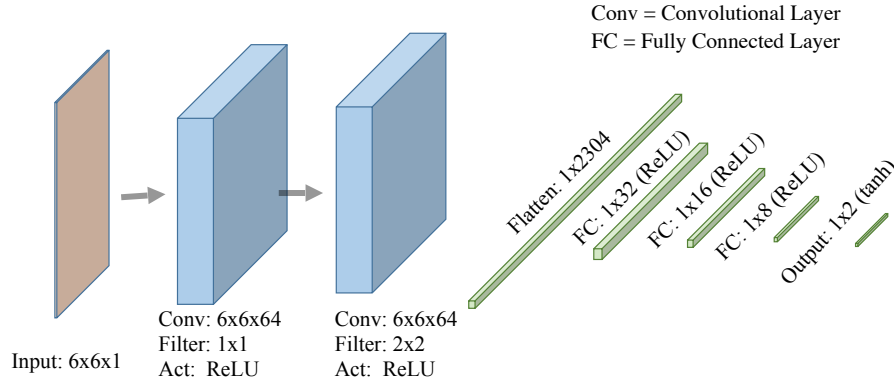


Figure 6.12: Visualization of the ML model for RP angle reconstruction.

Here we define the computing methods of RP angles for model training and performance evaluation in this study:

1. Truth - the true RP angle characterizing the Pb+Pb collision in the event generation process. When generating the spectators' momenta, the direction of the transverse momentum kick, p_T^{spec} , is chosen to match the one of this RP.
2. Gen - the RP angle computed from the average positions of injected spectators in the MC simulations. This value is computed from a subset of the neutrons remaining in unstable spectator nuclei after Pb ions collide. These nuclei emit charged fragments, free protons, and neutrons (see fig.1.2). Only the neutrons make it to the ZDC. Therefore, this value of RP is affected by event-by-event fluctuations.
3. Rec - the RP angle reconstructed starting from the signals detected in the RPD.

The model was built and trained using the Keras package [104] on an NVIDIA V100 GPU provided by the HAL cluster at UIUC. For model training, the target of the ML model was a unit vector (Q^{Gen}), computed from Ψ_{Gen} . The optimization algorithm for the parameters of the model was Adam [105] with default arguments in Keras. The mean absolute error function was used to evaluate the difference between targets (Q^{Gen}) and the flow vector (Q^{Rec}) predicted by the model. 0.8 and 0.2 million events, including information from each arm of the detector (ZDC A and C), were used for the training and test sets, respectively. The test set was used for the model performance evaluation.

6.3.3 Performance evaluation

In this study, the CoM reconstruction method (eq. 6.3) was used as a baseline model for performance comparison. The vectors reconstructed by the ML method and the CoM method can be translated into the RP angle Ψ_1 [106]:

$$\Psi_1 = \arctan \frac{Q_y}{Q_x}. \quad (6.4)$$

A function, encoded as “arctan2”, in Python programming language was used to perform the computation and map the inverse tangent of (y/x) in $-\pi$ and π [107].

For a single-arm RPD (e.g. ZDC-A), the performance of a reconstruction method was evaluated by looking at the standard deviation σ_r of a Gaussian fit of two residual distributions, i.e., $\Psi_1^{Gen} - \Psi_1^{Rec}$ and $\Psi_1^{Truth} - \Psi_1^{Rec}$. The fit was performed in a range defined as $\pm$ one standard deviation of the distribution around the mean. Fig. 6.13 compares the angular residual distributions between the CoM and ML methods. The quantity ($\sigma_r^{Gen-Rec}$) provides an estimate of the reconstruction performance in terms of the RP resulting from the distribution of spectators reaching the detector. The standard deviation ($\sigma_r^{Gen-Rec}$) for the CoM and the ML methods are 1.42 and 0.63, respectively. By using the ML method, one can achieve an improvement of 55%. Comparing $\sigma_r^{Truth-Gen}$ between the two reconstruction methods, the angular performance of the ML method still shows a 46% improvement compared to the CoM method. Note that $\sigma_r^{Truth-Gen}$ is intrinsically limited by physics due to various sources

of fluctuations in HI collisions, e.g., variations in the magnitude and direction of intrinsic Fermi momentum of the neutrons.

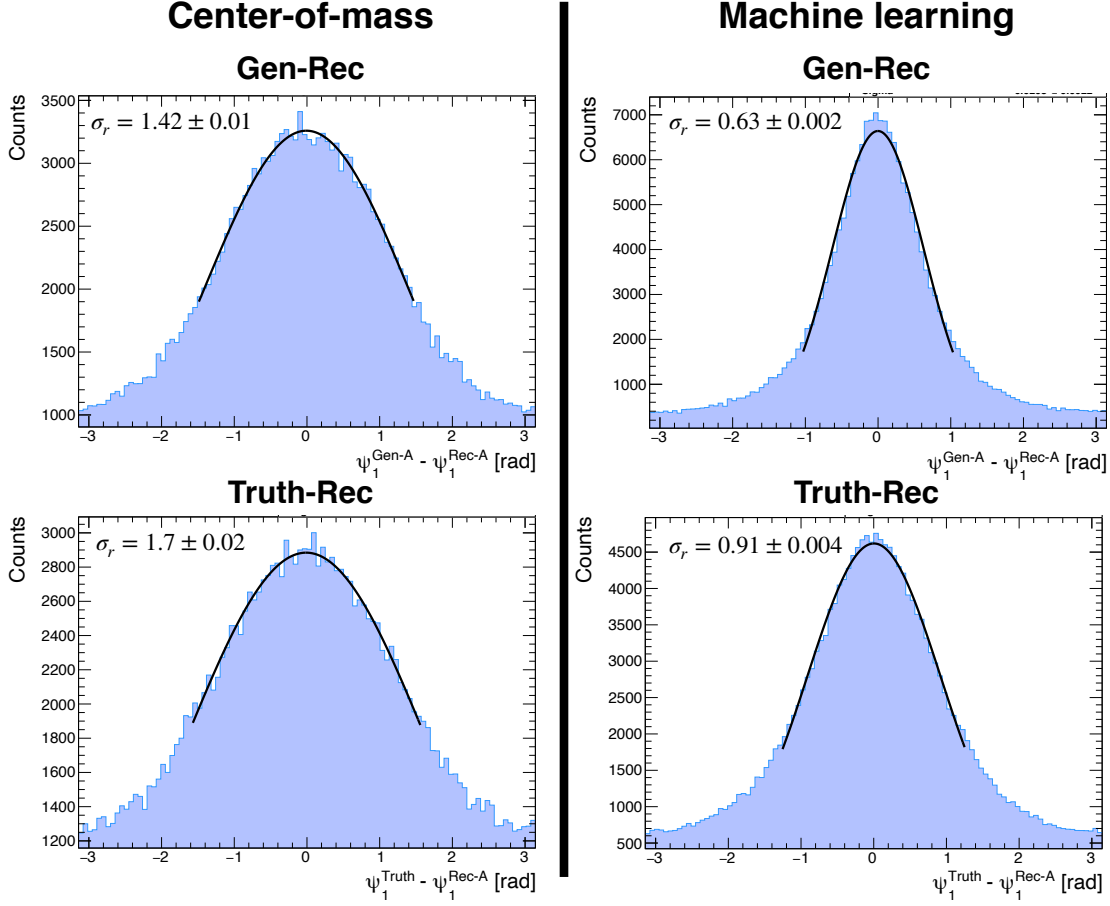


Figure 6.13: Comparison of angular residual distributions between the CoM method (left column) and the ML method proposed in this dissertation (right column) in ZDC-A. The top row shows the distributions between the particle level RP angle and the reconstructed RP angle using the RPD signals, while the bottom presents the difference between the true RP angle and the reconstructed RP.

When analyzing the measured directed flow v_1 in the experiments, a correction, known as reaction plane resolution (R), has to be applied to the observed v_1 to account for the detector coverage, detector resolution, and fluctuations in events [89, 108]. To compute the correction, a well-established technique [91] is to split a RP into two independent sub-reaction planes of equal size. The RP resolution for the true RP is

$$R = \langle \cos(\Psi_1^{Sub} - \Psi_1^{Truth}) \rangle, \quad (6.5)$$

where Ψ_1^{Sub} is one of the sub-RP angles. In the specific case of the ZDCs, the correlation between the RP resolution and the two sub-RPs measured by two arms of the ZDC can be expressed as

$$\langle \cos(\Psi_1^A - \Psi_1^C) \rangle = \langle \cos(\Psi_1^A - \Psi_1^{Truth}) \rangle \cdot \langle \cos(\Psi_1^C - \Psi_1^{Truth}) \rangle, \quad (6.6)$$

where Ψ_1^A and Ψ_1^C are the sub-RP angles measured by ZDC-A and ZDC-C, respectively. Under the reasonable assumption that the two sub-RP have the same resolution, the RP resolution can be re-written as

$$R = \langle \cos(\Psi_1^{Sub} - \Psi_1^{Truth}) \rangle = \sqrt{\langle \cos(\Psi_1^A - \Psi_1^C) \rangle}, \quad Sub = \{A, C\}. \quad (6.7)$$

Note eq. 6.7 indicates that the RP resolution equaling 1.0 would denote a perfect resolution. The RP resolution of the ML method is 0.45. Due to the poor performance of the CoM method, the mean of the cosine values is -0.6, and thus, the RP resolution cannot be computed.

As mentioned above, the simulation used to extract the presented results is characterized by a uniform distribution in p_T^{spec} ranging from 10 to 50 MeV. One can try to further analyze what would be the effect of the physics on the RP resolution by binning the results in different intervals of p_T^{spec} characterizing the MC generation. Another aspect to be taken into account is the multiplicity of neutrons in mid-central HI collisions, which may significantly affect the nature of the signal detected in the RPD. Fig. 6.14 shows the RP resolution of the ML method binned into different neutron multiplicity and the transverse momentum selections. The overall resolution, integrating over the number of neutrons, are given in the figure for $p_T^{spec} = 10-20, 20-30, 30-40, 40-50$ MeV, respectively. The RP resolution of the RPD depends on the number of neutrons and p_T^{spec} . As expected, a larger p_T^{spec} leads to the centroid of spectators away from the origin; thus, it is easier to resolve a RP, while the centroid close to the origin is more subject to fluctuation when estimating the RP angle. Increasing the number of neutrons improves the RP resolution for events with a p_T^{spec} greater than 20 MeV while, for lower- p_T^{spec} events, more neutrons can deteriorate the resolution.

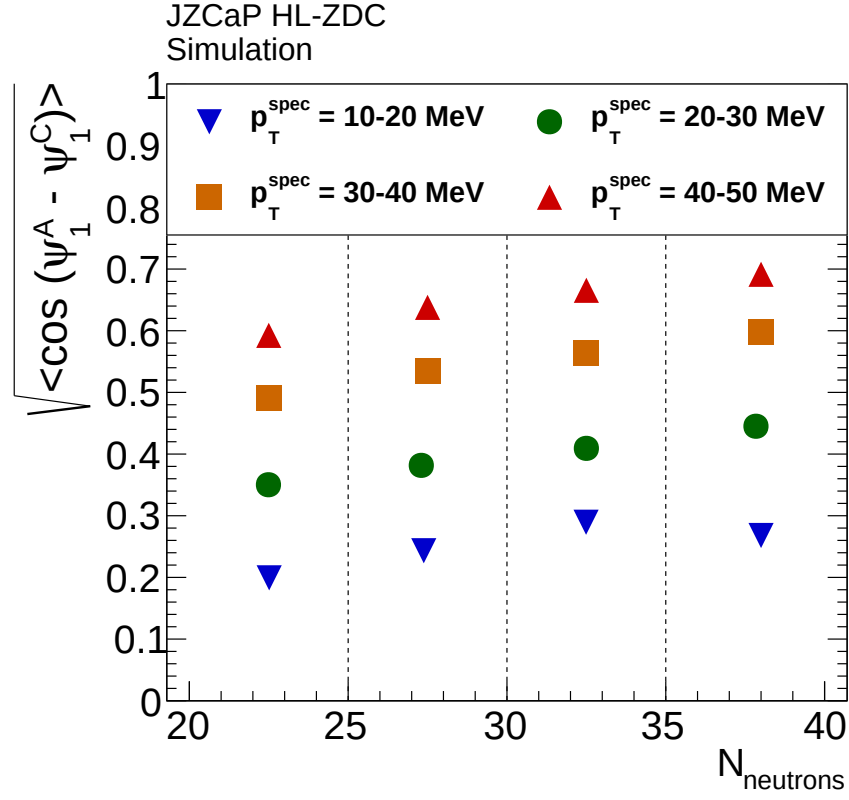


Figure 6.14: Reaction plane resolution estimated using the two sub-reaction planes measured by the two arms of the ZDC [89]. The results are presented for four different simulations where the transverse momentum kick along the direction of the RP, p_T^{spec} , was varied in well-defined intervals. The vertical dashed lines correspond to the limits of the four bins in neutron multiplicity where the resolution was evaluated. Error bars are contained within the markers.

The RP resolution results can be compared to similar measurements performed by previous experiments, for instance, the STAR collaboration. Tab. 6.1 shows the RP resolution of the directed flow reported by the STAR experiment [109] for various particle species and energies. Looking at the resolution achieved by STAR², it can be seen that RPD is expected to have similar or better performance compared to the STAR Shower Max Detector (SMD). A more quantitative statement cannot be produced until p_T^{spec} has been measured at LHC Run 3 energies. However, the resolution values expected from the studies presented in this dissertation are always competitive with the STAR's SMD ones. If confirmed, such a result would be remarkable, considering the wider space available at the Relativistic Heavy Ion Collider to implement the SMD and the milder radiation environment compared to that of the TAN.

In summary, the RPD developed at UIUC enables the possibility of estimating the RP angle in HI collisions using spectator neutrons. Such estimation provides opportunities to perform a variety of new flow-related physics analyses. To reconstruct the RP angle, the characteristic response of the RPD must be taken into account. Thanks to the optimization mechanism of machine-learning algorithms, it is possible for a model to calibrate the RPD responses during training. The ML method presented in this chapter provides a way to reconstruct the RP directly using the RPD signals without applying any corrections. The performance of the model shows very promising results compared to the traditional reconstruction method (CoM) and previous experimental measurements reported by the STAR. Since the ML method relies on the simulated data for training, it is essential to make the simulations closer to the experimental measurements of HI collisions, such as converting Cherenkov light in simulation into digitized waveforms. The UIUC ZDC group is dedicated to developing digitization procedures. Also, the physics model to generate spectator neutrons can be improved by incorporating DPMJET III [110], an event generator including a consistent description of the spectator nuclei produced in HI collisions. Finally, the model to perform the RP reconstruction may be further optimized using different training hyper-parameters or model structures.

²The 20-40 neutrons used in the simulation is equivalent to a range of centrality between 8 and 35%.

Table 6.1: Reaction plane resolution reported by the STAR experiment. The 20-40 neutron used in the simulation is equivalent to a range of centrality between 8 and 35%. Table taken from [111].

Centrality (%)	200 GeV Au+Au	62.4 GeV Au+Au	200 GeV Cu+Cu	62.4 GeV Cu+Cu
70–80	0.296 ± 0.003	0.179 ± 0.005		
60–70	0.348 ± 0.003	0.185 ± 0.004		
50–60	0.382 ± 0.002	0.176 ± 0.005	0.140 ± 0.003	0.039 ± 0.011
40–50	0.397 ± 0.002	0.167 ± 0.005	0.144 ± 0.003	0.043 ± 0.011
30–40	0.390 ± 0.002	0.138 ± 0.006	0.147 ± 0.003	0.032 ± 0.015
20–30	0.365 ± 0.002	0.110 ± 0.008	0.121 ± 0.004	
10–20	0.309 ± 0.003	0.081 ± 0.010	0.095 ± 0.005	
5–10	0.220 ± 0.006		0.059 ± 0.008	
0–5	0.120 ± 0.002		0.059 ± 0.008	

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

The HL-LHC upgrade opens new frontiers for more precise, as well as novel, physics measurements. On the other hand, it poses new challenges regarding the radiation hardness of detectors to be deployed during high luminosity running. For instance, forward detectors installed around ATLAS and CMS interaction points, like the ZDC and the BRAN, will have to withstand an unprecedented level of radiation during Run 4 and beyond. JZCaP, a project led by the UIUC ZDC group, has made research efforts to design and build a new generation of ZDCs for ATLAS and CMS, capable of withstanding the harsh radiation environment expected in the HL-LHC TAXN. The similar challenges to be faced for Run 4 and beyond have catalyzed a collaboration between JZCaP and the CERN BRAN group, to study the radiation hardness of Cherenkov radiator candidates, in particular fused silica. A batch of fused silica rods, doped with different OH and H₂ levels, was irradiated in the TAN by the BRAN group during Run 2. In this dissertation, the optical transmission and the ²²Na activity measurements of the fused silica rods carried out at UIUC were presented. A multi-variant analysis was performed to study fused silica's optical radiation hardness. In particular, thanks to the simulations provided by the CERN FLUKA team, it was possible to correlate optical transmission as a function of wavelength and dose deposited in different rod segments. Thanks to dedicated simulations, the performance of FLUKA in describing the ²²Na activation within fused silica in a complex radiation environment was evaluated.

The optical transmission study presented in this dissertation provides a key input to the material choice for ATLAS ZDC Run 3 refurbishment (Spectrosil 2000 with a high H₂ level) and the upgraded ZDC in Run 4. It also allows for projecting out the expected stability of the detector during the HL running time. Preliminary results of the analysis were used in the JZCaP proposal to the LHC Committee (see ref. [13]). Final results were also

included in a \$2.5 M proposal submitted by JZCaP to the Department of Energy on July 8th 2022, to support the construction of the new radiation-hard ZDCs for ATLAS and CMS. A publication of the transmission results for irradiated fused silica materials in collaboration with CERN BRAN and FLUKA teams is currently being drafted. It is supposed to be submitted for publication in the month next to the defense of this dissertation.

The activity study provides a new benchmark for the accuracy of the nuclear breakup models in FLUKA. The results have been drafted in a joint publication with CERN BRAN and FLUKA teams and recently accepted by the Physical Review Accelerators and Beams.

The results achieved using the BRAN rods irradiated in Run 2, and presented in this manuscript, have motivated a radiation experiment of fused silica during LHC Run 3, to further study the radiation hardness of fused silica samples at unprecedented radiation levels. The irradiation setup relies on dedicated grooves carved out in the new BRAN-D design that was installed in the TAN at IP1 and IP5 in January 2022. The expected accumulated dose in the samples will surpass the one presented in this dissertation by at least one order of magnitude. This irradiation experiment enables studies that will bring the understanding of the radiation hardness of fused silica to completely new levels. The experience with sample preparation acquired while carrying out the work described in this manuscript has also provided crucial inputs to the preparation of samples for new irradiation studies.

The RPD developed by the UIUC ZDC group will enable the possibility of measuring the RP in HI collisions using spectator neutrons in both ATLAS and CMS, providing the opportunity for a wide range of new flow-related physics analyses. Thanks to radiation-hard fused silica fibers, the detector design can meet the requirements, such as the limited space in the TAN slot and only access to the detector in the vertical direction. The RPD design, allowing for measurements of the transverse profile of the showers, was presented in this dissertation, together with simulations carried out to study the expected detector response.

To perform reaction plane reconstruction with the RPD, a machine-learning-based approach was developed and studied in this dissertation. The performance of the method shows improvements of up to 55% compared to a traditional reconstruction (CoM) method. Compared to the STAR experiment's results, the projections of the RPD performance are very competitive. An RPD based on the design presented in this thesis will be installed

in ATLAS in November 2022 and used during the heavy-ion running in November and December 2022. This will be the first opportunity to test the RPD design and the novel machine-learning-based analysis technique for the reaction plane reconstruction under the conditions of the high radiation environment in the LHC.

REFERENCES

- [1] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. A. Khalek, A. A. Abdelalim, R. Aben, B. Abi, M. Abolins, O. AbouZeid *et al.*, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” *Physics Letters B*, vol. 716, no. 1, pp. 1–29, 2012.
- [2] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan *et al.*, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Physics Letters B*, vol. 716, no. 1, pp. 30–61, 2012.
- [3] G. Aad, M. Ackers, F. Alberti, M. Aleppo, G. Alimonti, J. Alonso, E. Anderssen, A. Andreani, A. Andreazza, J. Arguin *et al.*, “ATLAS pixel detector electronics and sensors,” *Journal of Instrumentation*, vol. 3, no. 07, p. P07007, 2008.
- [4] S. Chatrchyan, G. Hmayakyan, V. Khachatryan, C. Collaboration *et al.*, “The CMS experiment at the CERN LHC,” *Journal of instrumentation*, vol. 3, no. 8, p. S08004, 2008.
- [5] C. Burgess and G. Moore, *The standard model: A primer*. Cambridge University Press, 2007.
- [6] P. Jenni, M. Nessi, and M. Nordberg, “Zero degree calorimeters for ATLAS,” CM-P00072881, Tech. Rep., 2007.
- [7] C. A. Salgado, “Lectures on high-energy heavy-ion collisions at the LHC,” *arXiv preprint arXiv:0907.1219*, 2009.
- [8] R. Aaij, C. A. Beteta, T. Ackernley, B. Adeva, M. Adinolfi, H. Afsharnia, C. A. Aidala, S. Aiola, Z. Ajaltouni, S. Akar *et al.*, “Centrality determination in heavy-ion collisions with the LHCb detector,” *Journal of Instrumentation*, vol. 17, no. 05, p. P05009, 2022.
- [9] H. S. Matis, M. Placidi, A. Ratti, W. C. Turner, E. Bravin, and R. Miyamoto, “The BRAN luminosity detectors for the LHC,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 848, pp. 114–126, 2017.
- [10] M. A. Leite, “Performance of the ATLAS zero degree calorimeter,” in *2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC)*. IEEE, 2013, pp. 1–5.

- [11] J. V. Jelley, “Cerenkov radiation and its applications,” *British Journal of Applied Physics*, vol. 6, no. 7, p. 227, 1955.
- [12] G. F. Knoll, *Radiation detection and measurement*. John Wiley & Sons, 2010.
- [13] “A radiation-hard zero degree calorimeter for ATLAS in the HL-LHC era,” ATLAS Collaboration, Tech. Rep., 2021.
- [14] A. Silins, “Defects in glasses,” *Radiation effects and defects in solids*, vol. 134, no. 1-4, pp. 7–10, 1995.
- [15] R. K. Sharma, S. Sharma, and K. Vvas, “Analysis of different types of core materials in photonic crystal fiber,” in *2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*. IEEE, 2018, pp. 1–6.
- [16] G. Apollinari, O. Brüning, T. Nakamoto, and L. Rossi, “High luminosity large hadron collider HL-LHC,” *arXiv preprint arXiv:1705.08830*, 2017.
- [17] “The HL-LHC project: High luminosity large hadron collider.” [Online]. Available: <https://hilumilhc.web.cern.ch/>
- [18] G. Battistoni, F. Cerutti, A. Fasso, A. Ferrari, S. Muraro, J. Ranft, S. Roesler, and P. Sala, “The FLUKA code: Description and benchmarking,” in *AIP Conference proceedings*, vol. 896, no. 1. American Institute of Physics, 2007, pp. 31–49.
- [19] S. Yang *et al.*, “ ^{22}Na activation level measurements of fused silica rods in the LHC target absorber for neutrals (TAN) compared to FLUKA simulations,” *Physical Review Accelerators and Beams*, in preparation (2022).
- [20] “CERN.” [Online]. Available: <https://home.cern/>
- [21] L. Evans and P. Bryant, “LHC machine,” *Journal of instrumentation*, vol. 3, no. 08, p. S08001, 2008.
- [22] J. Haffner, “The CERN accelerator complex,” Tech. Rep., 2013.
- [23] W. Herr and B. Muratori, “Concept of luminosity,” 2006.
- [24] “The HL-LHC project schedule.” [Online]. Available: <https://project-hl-lhc-industry.web.cern.ch/content/project-schedule>
- [25] H. Ten Kate, “Superconducting magnet system for the ATLAS detector at CERN,” *IEEE transactions on applied superconductivity*, vol. 9, no. 2, pp. 841–846, 1999.
- [26] R. H. M. Taibah, “Upgrade of the ATLAS tracking detector in preparation for the High-Luminosity phase of the LHC: Planar pixel module characterisation and calibration for the current and future ATLAS inner tracker,” Ph.D. dissertation, Centre National de la Recherche Scientifique (FR), 2021.

- [27] E. Daw, “Lecture 7-rapidity and pseudorapidity,” *The University of Sheffield*, 2012.
- [28] W. Commons, “File:pseudorapidity2.png — wikimedia commons, the free media repository,” 2020, [Online; accessed 8-April-2022]. [Online]. Available: <https://commons.wikimedia.org/w/index.php?title=File:Pseudorapidity2.png&oldid=460055103>
- [29] ATLAS Collaboration, “Technical design report for the atlas inner tracker pixel detector,” *CERN-LHCC-2017-021. ATLASTDR-030*, 2017.
- [30] A. Artamonov, D. Bailey, G. Belanger, M. Cadabeschi, T.-Y. Chen, V. Epshteyn, P. Gorbounov, K. Joo, M. Khakzad, V. Khovanskiy *et al.*, “The ATLAS forward calorimeter,” *Journal of Instrumentation*, vol. 3, no. 02, p. P02010, 2008.
- [31] F. Bauer, U. Bratzler, H. Dietl, H. Kroha, T. Lagouri, A. Manz, A. Ostapchuk, R. Richter, S. Schael, S. Chouridou *et al.*, “Construction and test of MDT chambers for the ATLAS muon spectrometer,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 461, no. 1-3, pp. 17–20, 2001.
- [32] ATLAS Collaboration, “ATLAS muon spectrometer: Technical design report,” *CERN/LHCC*, vol. 97, p. 22, 1997.
- [33] —, “Keeping the ATLAS inner detector in perfect alignment,” 2020. [Online]. Available: <https://atlas.cern/updates/experiment-briefing/inner-detector-alignment>
- [34] W. Commons, “File:schematic of a particle shower.svg — wikimedia commons, the free media repository,” 2020, [Online; accessed 19-May-2022]. [Online]. Available: https://commons.wikimedia.org/w/index.php?title=File:Schematic_of_a_particle_shower.svg&oldid=498944280
- [35] H. Alaeian, “An introduction to cherenkov radiation,” *Recuperado el*, vol. 26, 2014.
- [36] W. Commons, “File:reflexiontotal.svg — wikimedia commons, the free media repository,” 2020, [Online; accessed 17-June-2022]. [Online]. Available: <https://commons.wikimedia.org/w/index.php?title=File:ReflexionTotal.svg&oldid=444546178>
- [37] I. H. Malitson, “Interspecimen comparison of the refractive index of fused silica,” *Josa*, vol. 55, no. 10, pp. 1205–1209, 1965.
- [38] J. D. Jackson, “Classical electrodynamics,” 1999.
- [39] F. Mohammed Rafee *et al.*, “A new reaction plane detector for ATLAS heavy ion physics program in Run 3,” in *APS Division of Nuclear Physics Meeting Abstracts*, vol. 2021. ATLAS collaboration, JZCaP, 2021, pp. GA–002.
- [40] J. R. Lamarsh and A. J. Baratta, *Introduction to nuclear engineering*. Prentice hall Upper Saddle River, NJ, 2001, vol. 3.

- [41] “Wale Apparatus.” [Online]. Available: <https://www.waleapparatus.com/category/quartz-rod-tubing>
- [42] W. C. Turner, “Instrumentation for the absorbers in the low Beta* insertions of the LHC,” Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), Tech. Rep., 1998.
- [43] A. Ratti, J. Beche, J. Byrd, K. Chow, P. Denes, L. Doolittle, W. Ghiorso, P. Manfredi, H. Matis, M. Monroy *et al.*, “The luminosity monitoring system for the LHC: modeling and test results,” in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*. IEEE, 2010, pp. 286–289.
- [44] “AB BI PM Home page,” BE-BI-PM. [Online]. Available: <https://ab-dep-bi-pm.web.cern.ch/?n=Activities.BRAN>
- [45] M. Tomozawa, D.-L. Kim, and V. Lou, “Preparation of high purity, low water content fused silica glass,” *Journal of non-crystalline solids*, vol. 296, no. 1-2, pp. 102–106, 2001.
- [46] N. Akchurin and R. Wigmans, “Quartz fibers as active elements in detectors for particle physics,” *Review of scientific instruments*, vol. 74, no. 6, pp. 2955–2972, 2003.
- [47] L. Skuja, M. Hirano, H. Hosono, and K. Kajihara, “Defects in oxide glasses,” *physica status solidi (c)*, vol. 2, no. 1, pp. 15–24, 2005.
- [48] “Data and properties optics fused silica,” Heraeus. [Online]. Available: https://www.heraeus.com/media/media/hca/doc_hca/products_and_solutions_8/optics/Data_and_Properties_Optics_fused_silica_EN.pdf
- [49] C. D. Marshall, J. A. Speth, and S. A. Payne, “Induced optical absorption in gamma, neutron and ultraviolet irradiated fused quartz and silica,” *Journal of non-crystalline solids*, vol. 212, no. 1, pp. 59–73, 1997.
- [50] R. Weeks and C. Nelson, “Trapped electrons in irradiated quartz and silica: II, electron spin resonance,” *Journal of the American Ceramic Society*, vol. 43, no. 8, pp. 399–404, 1960.
- [51] D. L. Griscom, “Optical properties and structure of defects in silica glass,” *Journal of the Ceramic Society of Japan*, vol. 99, no. 1154, pp. 923–942, 1991.
- [52] D. Griscom, “ γ and fission-reactor radiation effects on the visible-range transparency of aluminum-jacketed, all-silica optical fibers,” *Journal of applied physics*, vol. 80, no. 4, pp. 2142–2155, 1996.
- [53] M. Hoek, E. Bennet, D. Branford, E. Cowie, M. Düren, K. Föhl, D. Glazier, R. Kaiser, A. Lehmann, S. Lu *et al.*, “Radiation hardness study on fused silica,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 595, no. 1, pp. 190–193, 2008.

- [54] B. Grosdidier, “Etude d’un nouveau type de calorimetre hadronique extremement rapide et resistant a des dizaines de gigarads pour l’experience NA38 du CERN,” Ph.D. dissertation, Université Louis Pasteur-Strasbourg I, 1992.
- [55] P. Gorodetzky, B. Grosdidier, and D. Lazic, “Very hard radiation resistant and ultra-fast calorimetry,” *Radiation Physics and Chemistry*, vol. 41, no. 1-2, pp. 253–261, 1993.
- [56] G. S. Henderson, “The structure of silicate melts: A glass perspective,” *The Canadian Mineralogist*, vol. 43, no. 6, pp. 1921–1958, 2005.
- [57] D. L. Griscom, “Nature of defects and defect generation in optical glasses,” in *Radiation Effects on Optical Materials*, vol. 541. International Society for Optics and Photonics, 1985, pp. 38–59.
- [58] —, “A minireview of the natures of radiation-induced point defects in pure and doped silica glasses and their visible/near-IR absorption bands, with emphasis on self-trapped holes and how they can be controlled,” *Physics Research International*, vol. 2013, 2013.
- [59] F. Nürnberg, B. Kühn, A. Langner, M. Altwein, G. Schötz, R. Takke, S. Thomas, and J. Vydra, “Bulk damage and absorption in fused silica due to high-power laser applications,” in *Laser-Induced Damage in Optical Materials: 2015*, vol. 9632. International Society for Optics and Photonics, 2015, p. 96321R.
- [60] B. Kühn, E. Arnold, H. Witzke, F. Schilling, M. Stamminger, and B. Uebbing, “Boundary conditions for the saturation and amplitude of induced absorption in synthetic fused silica,” in *8th Symposium” SiO₂, Advanced Dielectrics and Related Devices”*, Varenna, Italy, 2010.
- [61] M. Palm, “Update on luminosity monitoring for HL-LHC,” BE-BI-PM, 2018. [Online]. Available: https://indico.cern.ch/event/755408/contributions/3153780/attachments/1725682/2787563/2018_HL-LHC_BRAN_MPalm_v0.1.pdf
- [62] A. Lechner, B. Auchmann, T. Baer, C. B. Castro, R. Bruce, F. Cerutti, L. Esposito, A. Ferrari, J. Jowett, A. Mereghetti *et al.*, “Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider,” *Physical Review Accelerators and Beams*, vol. 22, no. 7, p. 071003, 2019.
- [63] R. G. Alía, M. Brugger, F. Cerutti, S. Danzeca, A. Ferrari, S. Gilardoni, Y. Kadi, M. Kastriotou, A. Lechner, C. Martinella *et al.*, “LHC and HL-LHC: Present and future radiation environment in the high-luminosity collision points and RHA implications,” *IEEE Transactions on Nuclear Science*, vol. 65, no. 1, pp. 448–456, 2017.
- [64] T. Böhlen, F. Cerutti, M. Chin, A. Fassò, A. Ferrari, P. Ortega, A. Mairani, P. Sala, G. Smirnov, and V. Vlachoudis, “The FLUKA code: Developments and challenges for high energy and medical applications,” *Nuclear Data Sheets*, vol. 120, pp. 211

- 214, 2014. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0090375214005018>
- [65] G. Battistoni, F. Broggi, and V. Boccone, “FLUKA capabilities and CERN applications for the study of radiation damage to electronics at high-energy hadron accelerators,” *Progress in Nuclear Science and Technology*, vol. 2, pp. 948–954, 2011.
 - [66] R. Rata, R. Barlow, and S. Lee, “FLUKA simulations for radiation protection at 3 different facilities,” in *7th Int. Particle Accelerator Conf.(IPAC’16), Busan, Korea, May 8-13, 2016*. JACOW, Geneva, Switzerland, 2016, pp. 1940–1942.
 - [67] C. Zamantzas, B. Dehning, E. Effinger, J. Emery, and G. Ferioli, “An FPGA based implementation for real-time processing of the LHC Beam Loss Monitoring system’s data,” in *2006 IEEE Nuclear Science Symposium Conference Record*, vol. 2. IEEE, 2006, pp. 950–954.
 - [68] B. Dehning, E. Effinger, J. Emery, G. Ferioli, G. Guaglio, E. Holzer, D. Kramer, L. Ponce, V. Prieto, M. Stockner *et al.*, “The LHC beam loss measurement system,” in *2007 IEEE Particle Accelerator Conference (PAC)*. IEEE, 2007, pp. 4192–4194.
 - [69] “LHC schedule 2016,” 2016. [Online]. Available: https://indico.cern.ch/category/6175/attachments/1235571/2198015/LHC_Schedule_2016_version2.2.pdf
 - [70] M. Lamont *et al.*, “LHC schedule 2017.”
 - [71] “Luminosity results for Run-2 (2016-2018).” [Online]. Available: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>
 - [72] M. Brugger, A. Ferrari, S. Roesler, and P. Sala, “Calculation of radionuclide production cross sections with FLUKA and their application in high energy hadron collider studies,” in *International Conference on Nuclear Data for Science and Technology*. EDP Sciences, 2007, pp. 1193–1196.
 - [73] A. Ferrari and P. Sala, “A new model for hadronic interactions at intermediate energies for the FLUKA code,” in *MC93 Int. Conf. on Monte-Carlo Simulation in High-Energy and Nuclear Physics*, 1993.
 - [74] A. Ferrari and P. R. Sala, “The physics of high energy reactions,” CERN-ATL-PHYS-97-113, Tech. Rep., 1997.
 - [75] V. Zerkov and B. Pritychenko, “The experimental nuclear reaction data (EXFOR): Extended computer database and web retrieval system,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 888, pp. 31–43, 2018.
 - [76] V. Kain, R. Schmidt, and R. Assmann, “Equipment failure and beam losses in the LHC,” *EPAC ’02, Paris, June*, 2002.

- [77] “Luminosity public results Run 2,” <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>, accessed: 2020-12-23.
- [78] M. S. Basunia, “Nuclear Data Sheets for $A = 22$,” *Nucl. Data Sheets*, vol. 127, pp. 69–190, 2015.
- [79] “Agilent Cary 4000/5000/6000i series UV-VIS-NIR spectrophotometers.” [Online]. Available: https://www.agilent.com/cs/library/brochures/5990-7786EN_Cary-4000-5000-6000i-UV-Vis-NIR_Brochure.pdf
- [80] “Specifications of 2480 Wizard2 - IVD automatic gamma counters,” Perkin Elmer. [Online]. Available: https://www.perkinelmer.com/lab-solutions/resources/docs/SPC_2480-WizardSpecSheetIVD_F.pdf
- [81] P. E. Adamson, “A general quantum mechanical method to predict positron spectroscopy,” 2007.
- [82] “Data sheet of refractive index liquid series AA,” 2018. [Online]. Available: <https://cargille.com/wp-content/uploads/2018/10/Refractive-Index-Liquid-Series-AA-n-1.4560-at-589.3-nm-and-25%C2%AFC.pdf>
- [83] D. F. Swinehart, “The Beer-Lambert law,” *Journal of chemical education*, vol. 39, no. 7, p. 333, 1962.
- [84] “Blog:the beer-lambert law.” [Online]. Available: <https://www.edinst.com/blog/the-beer-lambert-law/>
- [85] A. Höpe, “Diffuse reflectance and transmittance,” in *Experimental Methods in the Physical Sciences*. Elsevier, 2014, vol. 46, pp. 179–219.
- [86] Hamamatsu Photonics, “Photomultiplier tubes and assemblies for scintillation counting & high energy physics,” *Web (accessed date September 14 2020): R8055 R7250 Datasheet*, 2017.
- [87] S. Voloshin and Y. Zhang, “Flow study in relativistic nuclear collisions by fourier expansion of azimuthal particle distributions,” *Zeitschrift für Physik C Particles and Fields*, vol. 70, no. 4, pp. 665–671, 1996.
- [88] M. Mårtenson and D. Silvermyr, “Elliptic flow of π , k, p and φ in Pb-Pb collisions at the Large Hadron Collider,” 2015.
- [89] A. M. Poskanzer and S. A. Voloshin, “Methods for analyzing anisotropic flow in relativistic nuclear collisions,” *Physical Review C*, vol. 58, no. 3, p. 1671, 1998.
- [90] W. Reisdorf and H. Ritter, “Collective flow in heavy-ion collisions,” *Annual Review of Nuclear and Particle Science*, vol. 47, no. 1, pp. 663–709, 1997.
- [91] N. Herrmann, J. P. Wessels, and T. Wienold, “Collective flow in heavy-ion collisions,” *Annual Review of Nuclear and Particle Science*, vol. 49, no. 1, pp. 581–632, 1999.

- [92] S. Agostinelli, J. Allison, K. a. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. . Barrand *et al.*, “GEANT4—a simulation toolkit,” *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, 2003.
- [93] J. Allison, K. Amako, J. Apostolakis, P. Arce, M. Asai, T. Aso, E. Bagli, A. Bagulya, S. Banerjee, G. Barrand *et al.*, “Recent developments in GEANT4,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 835, pp. 186–225, 2016.
- [94] Joint ZDC Calorimeter Collaboration, “Joint ZDC calorimeter project analysis,” 2019. [Online]. Available: <https://gitlab.engr.illinois.edu/rlongo/JZCaPA>
- [95] A. Ribon, J. Apostolakis, A. Dotti, G. Folger, V. Ivanchenko, M. Kosov, V. Uzhinsky, and D. Wright, “Status of GEANT4 hadronic physics for the simulation of LHC experiments at the start of LHC physics program,” *CERN-LCGAPP*, vol. 2, p. 2010, 2010.
- [96] J. Allison, J. Apostolakis, A. Bagulya, C. Champion, S. Elles, F. Garay, V. Grichine, A. Howard, S. Incerti, V. Ivanchenko *et al.*, “GEANT4 electromagnetic physics for high statistic simulation of LHC experiments,” in *Journal of Physics: Conference Series*, vol. 396, no. 2. IOP Publishing, 2012, p. 022013.
- [97] A. Bagulya, J. Brown, H. Burkhardt, V. Grichine, S. Guatelli, S. Incerti, V. N. Ivanchenko, O. Kadri, M. Karamitros, M. Maire *et al.*, “Recent progress of GEANT4 electromagnetic physics for LHC and other applications,” in *Journal of Physics: Conference Series*, vol. 898, no. 4. IOP Publishing, 2017, p. 042032.
- [98] S. Shenkar, “The electromagnetic module for an LHC Run-4 zero degree calorimeter,” ATL-COM-PHYS-2022-196, Tech. Rep., 2022.
- [99] E. J. Moniz, I. Sick, R. Whitney, J. Ficenec, R. D. Kephart, and W. Trower, “Nuclear fermi momenta from quasielastic electron scattering,” *Physical Review Letters*, vol. 26, no. 8, p. 445, 1971.
- [100] ALICE Collaboration, “Directed flow of charged particles at mid-rapidity relative to the spectator plane in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV,” *arXiv preprint arXiv:1306.4145*, 2013.
- [101] Y. LeCun, Y. Bengio, and G. Hinton, “Deep learning,” *nature*, vol. 521, no. 7553, pp. 436–444, 2015.
- [102] A. Krizhevsky, I. Sutskever, and G. E. Hinton, “Imagenet classification with deep convolutional neural networks,” *Advances in neural information processing systems*, vol. 25, 2012.
- [103] A. Karpathy, “CS231n convolutional neural networks for visual recognition,” 2016.

- [104] F. Chollet *et al.*, “Keras,” <https://github.com/fchollet/keras>, 2015.
- [105] D. P. Kingma and J. Ba, “Adam: A method for stochastic optimization,” *arXiv preprint arXiv:1412.6980*, 2014.
- [106] S. A. Voloshin, A. M. Poskanzer, and R. Snellings, “Collective phenomena in non-central nuclear collisions,” *arXiv preprint arXiv:0809.2949*, 2008.
- [107] “Manual of numpy.” [Online]. Available: <https://numpy.org/doc/stable/reference/generated/numpy.arctan2.html>
- [108] P. Danielewicz and G. Odyniec, “Transverse momentum analysis of collective motion in relativistic nuclear collisions,” *Physics Letters B*, vol. 157, no. 2-3, pp. 146–150, 1985.
- [109] B. Abelev, M. Aggarwal, Z. Ahammed, B. Anderson, D. Arkhipkin, G. Averichev, Y. Bai, J. Balewski, O. Barannikova, L. Barnby *et al.*, “System-size independence of directed flow measured at the BNL relativistic heavy-ion collider,” *Physical Review Letters*, vol. 101, no. 25, p. 252301, 2008.
- [110] S. Roesler, R. Engel, and J. Ranft, “The monte carlo event generator DPMJET-III, in proceedings of the international conference on advanced monte carlo for radiation physics, particle transport simulation and applications (mc 2000), lisbon, portugal, 23–26 october 2000,” 2000.
- [111] G. Wang, S. Collaboration *et al.*, “Incident-energy and system-size dependence of directed flow,” *Journal of Physics G: Nuclear and Particle Physics*, vol. 34, no. 8, p. S1093, 2007.