

RPC MAINTENANCE AND UPGRADE STUDIES OF THE ATLAS MUON SPECTROMETER AND A MUON TOMOGRAPHY DESIGN USING LARGE AREA PARTICLE DETECTORS

A Thesis

by

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Submitted to the
Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Physics

Özyeğin University
December 2023

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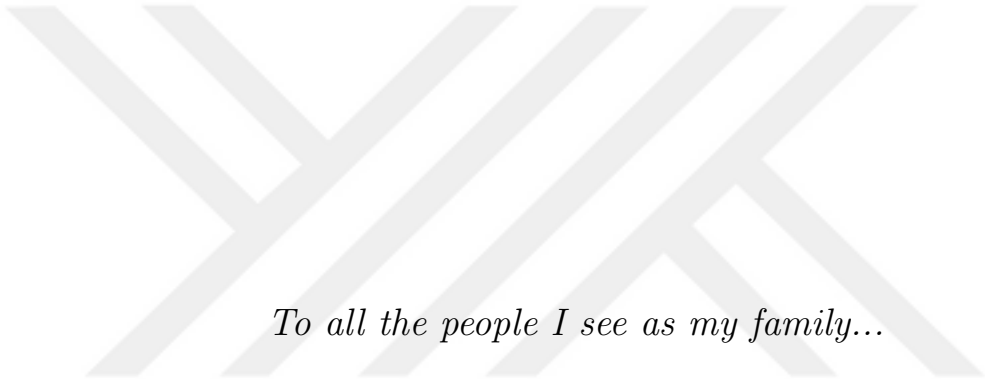
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To all the people I see as my family...

ABSTRACT

This thesis describes the spacing studies of BM/BR chambers to be installed on the ATLAS Detector at Long Shutdown 3 (LS3), the development of a new repair technique, and its implementation in the ATLAS Detector to repair and prevent gas leaks that cause critical problems in many aspects in ATLAS RPC System, and the crude design of a Muon Tomography with Large Area Particle Detectors.



ÖZETÇE

Bu tez, LS3'te ATLAS Dedektörüne kurulacak BM/BR odacıklarının yerleştirme çalışmalarını, ATLAS RPC Sistemi'nde oluşan ve birçok açıdan kritik sorunlara neden olan gaz sızıntılarını onarmak, önlemek için geliştirilen tekniğin tüm gelişim sürecini ve ATLAS Dedektöründe uygulanmasını, Büyük Hacimli Parçacık Dedektörleri kullanarak bir Müon Tomografinin kaba tasarımını anlatmaktadır.



ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my esteemed advisors, Taylan Akdoğan, Serkant Ali Çetin, and Bora Işıldak, for their invaluable guidance and support throughout my thesis work.

I am deeply grateful to the Turkish Energy, Nuclear and Mineral Research Agency for providing the necessary budget for the studies at CERN, which constitute a significant part of my thesis. I would also like to extend my heartfelt appreciation to Boğaziçi University KAHBELab and İstinye University High Energy and Particle Physics Group for hosting the project in their laboratories, enabling local RD studies to be carried out.

Furthermore, I would like to express my profound appreciation to Sinem Şimşek, Giulio Aielli, Davide Boscherini, Aydın Özbey, and Enrico Pastori in the ATLAS RPC Team for their exceptional expertise, understanding, and patience, which significantly contributed to my research experience. Without their generosity with their time and knowledge, it would not have been possible to bring the studies on the Foam Technique to this point. I am also grateful to Rinaldo Sontonic, who has supported the Foam Technique from the beginning and advocated its development on every platform.

I wish to express my sincere gratitude to my esteemed colleagues at İstinye University for their insightful discussions and the stimulating environment they provide. The support and inspiration from BİLSEV, an association committed to developing new educational systems and a better culture for science and art, have been invaluable in my academic journey.

I would like to thank my beloved wife, whose love, understanding, and encouragement have been my greatest source of strength throughout this endeavor. She has consistently supported and believed in my work, providing me with constant

motivation and comfort.

I must also acknowledge my dear family and friends for their unwavering support and encouragement throughout my study. This accomplishment would not have been possible without their unwavering support.

Finally, I express my gratitude to the wider scientific community for their invaluable insights and contributions to the fields of high-energy physics and mechanical engineering. Their work has been a constant source of inspiration and a benchmark for my efforts.



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CHAPTER I

INTRODUCTION

Throughout the course of history, humanity has devoted significant effort to understanding the natural world. Initially, the effort to understand nature started with the pure abstract thoughts of philosophers. In the 5th century BC, Democritus put forward the idea that everything we see around us consists of a fundamental, indivisible particle, which is taken from the Ancient Greek word *átomon*, "indivisible thing".

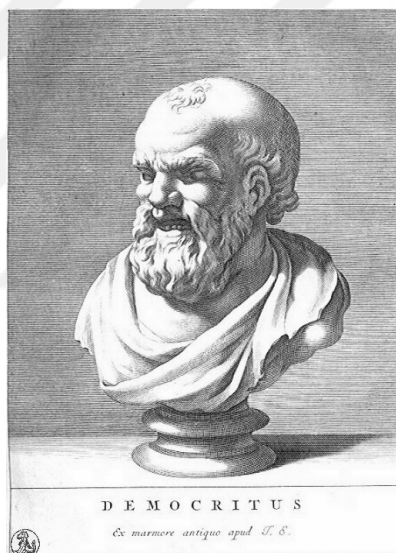


Figure 1: Portre of Democritus

Another theory that became popular in BC is Aristotle's Theory of the 4 Elements, which many of us have heard. Aristotle taught that all substances are made up of Fire, Air, Earth, and Water, as well as their combinations.

Throughout history, people have proposed theories and written books to explain the laws of nature in various regions of the world.

To better understand the next period, it is necessary to understand the cultural accumulation of humanity in the field of science and the outputs of this

accumulation. Until the 18th century, this discipline, which tried to understand nature, was called Natural Philosophy. Of course, when the 19th century started, "Physics" was now considered a "Natural Science", but it stood at a different point from both philosophy and other sciences.

Physics has come a long way in systematic experimentation and observation in this period. Since the 16th century, with both experimental culture and theories being based on mathematics, human beings who want to understand nature have started to clarify many complex issues clearly. From this point on, many theories based on experiments and observations have been put forward, forming the basis of current physics to understand nature.

1.1 The History of Chasing an Answer to Biggest Question

In the effort to understand all of nature, one question did not change when we came to the 19th century. What basic building block makes up the matter we see around us?



Figure 2: John Dalton

In the early 19th century, scientists conducted experiments to improve their understanding of atoms. Dalton conducted his first experiment to prove that matter is composed of atoms. After his experiments, he was able to likened the atom to a cake with grapes on it.

Subsequently, Thompson, Rutherford, and Bohr developed experiments on this subject, and a more accurate definition of the atom emerged with time. It was explained that the atom consists of an atomic nucleus formed by neutrons and protons at the center and electrons rotating around it by condensing at certain energy levels and forming orbits.

At the end of the 19th century, the atom was no longer the most fundamental particle for physicists but a structure made up of protons, neutrons, and electrons.

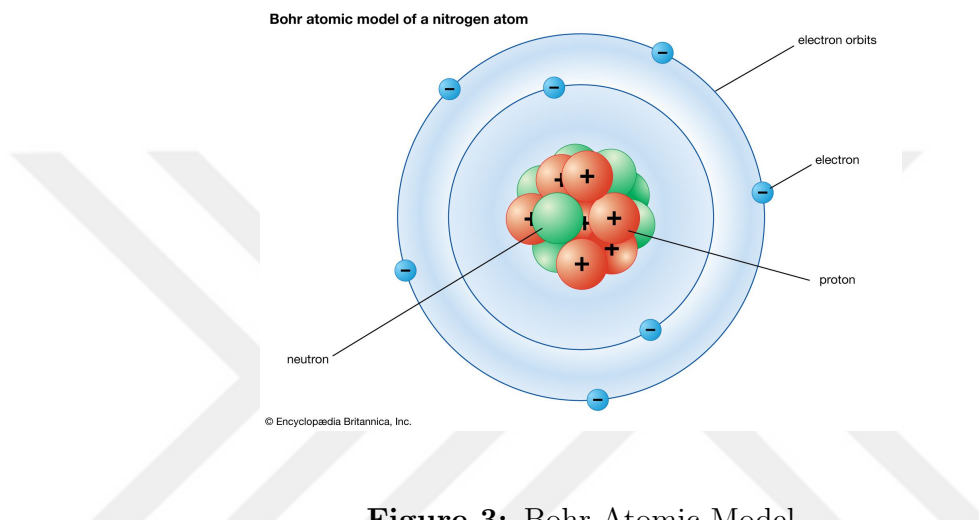


Figure 3: Bohr Atomic Model

In addition to all these studies on the structure of the atom, studies on radiation brought a new question to the minds of scientists: Did atoms have such great energy that we could not realize yet?

With this question, another door was opened for researchers to explain atoms with a deeper understanding. In the first half of the 20th century, those who entered this door did very important work in the fields of Nuclear Physics and Quantum Mechanics. With the discovery of Nuclear Fission and Nuclear Fusion in 1939, the energy possessed by atoms became identifiable. This situation especially attracted the attention of all stakeholders in the policy. With the start of World War II, this energy was used to make nuclear weapons. These Nuclear weapons used in World War II created one of the greatest disasters in human history.

1.2 Brief Overview of CERN and ATLAS Experiment

Trying to heal its wounds with the end of the 2nd World War, Europe gained significant experience. They understood that a beautiful future for Europe was only possible by succeeding in working together peacefully. In 1948, with the coming together of 11 European countries, the European Nuclear Research Council was established to carry out Nuclear Research in Europe under a common roof.



Figure 4: Cern Council in 1952.

This council continued its work near the Franco-Swiss Border in Geneva, under the name of the European Center for Nuclear Research (CERN) in 1954. After 2nd World War, not only in Europe, the Particle Physics Communities in many developed countries succeeded in establishing large international laboratories worldwide due to the high technological potential and the high potential for scientific success it promised to countries and people. Some significant laboratories around the world are

- 1947: Brookhaven National Laboratory, Long Island, USA
- 1954: European Nuclear Research Center (CERN)
- 1956: Joint Institute for Nuclear Research (JINR), Dubna, Russia

- 1959: DESY, Hamburg, Germany
- 1967: Fermilab, Chicago, USA.



Figure 5: FermiLab, Chicago, USA.

When we look at the establishment dates of the laboratories listed above, we see that they were established from the Second World War to 1970. In fact, in this period of time, with the establishment of these laboratories, many more particles have been found than physicists expected until 1980. That's why this time period is sometimes called "Particle Zoo".

CERN has managed to become the largest of these laboratories over the years. Since its establishment in 1954, it has been the most productive research center in the world in terms of infrastructure, number of collaborations, and scientific/technological inventions.

CERN is an independent body managed by member states and organizations.

The Large Hadron Collider Project has significantly increased CERN's popularity. This design studies of the project started in 1983 and its construction in 1998 after 15 years of preliminary work.

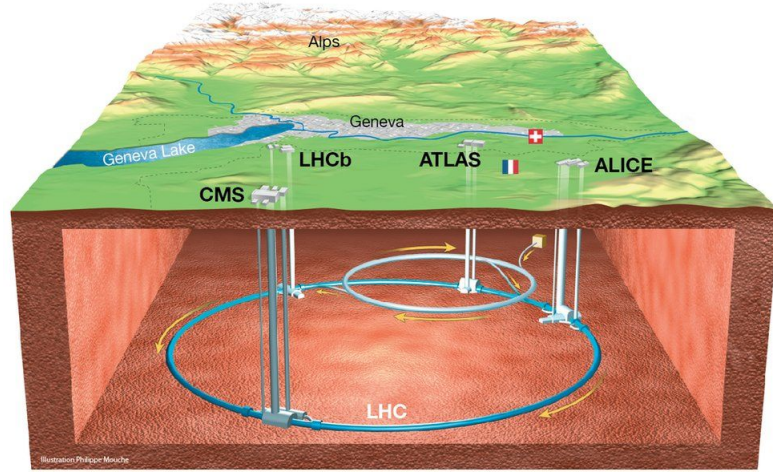


Figure 6: Large Hadron Collider at CERN.

The Large Hadron Collider is a circular accelerator/collider with a circumference of 27 km. The main goal of the Large Hadron Collider is to accelerate the particles to a certain energy to create the extreme conditions that occurred in the first few moments of the universe. Protons that are accelerated brought face to face at the LHC to cause them to collide head-on at points. In these points, 4 large Particle Detectors are placed to detect the particles emerged from collisions. These detectors are ATLAS, CMS, ALICE and LHCb.

The ATLAS Experiment is one of the 4 major experiments on the LHC. The experiment began to receive its first data in 2012. Its popularity reached its peak with the discovery of the Higgs Boson and receiving the 2014 Nobel Prize in Physics 60 years after the theory was put forward with the data they received together with the CMS, which are the verification experiments of each other. ATLAS will continue its activities until 2042.

1.3 Objectives and Outlines The Thesis

As the name suggests, this thesis consists of two main studies.

Chapter 2 summarizes key information on CERN and the ATLAS Experiment necessary to enter the mentioned studies.

Chapter 3 explains the work done on ATLAS RPCs, the first of my thesis



Figure 7: ATLAS Experiment.

studies. It covers the large gas system of the ATLAS RPCs and the operation and repair of this system in detail.

Chapter 4 explains the use of Large-Area Muon Detectors in Muon Tomography simulations and presents results. The detectors were utilized to measure the muon in the ATLAS Muon Spectrometer. At the end of the chapter, a simulation was conducted with different detectors' spatial resolution parameters. A preliminary study was performed to determine which detectors could perform Muon Tomography.

CHAPTER II

CERN AND ATLAS EXPERIMENT

Trying to heal its wounds with the end of the 2nd World War, Europe gained significant experience. They understood that a beautiful future for Europe was only possible by succeeding in working together peacefully. At this point, many scientists in Europe working in this field, especially Raoul Dautry, Pierre Auger, Lew Kowarski, Edoardo Amaldi, and Niels Bohr, began to share the same dream: an international atomic physics laboratory that would gather all European scientists in this field.

Louis de Broglie formally presented this idea for the first time at the European Cultural Conference held in Lausanne on December 9, 1949. At the Intergovernmental Meeting of UNESCO, the first proposal was made for the European Council for Nuclear Research. The council was established at the end of the last two months with an agreement signed by 11 countries and chose CERN as the abbreviation of its name in French.

The council started to work rapidly after its establishment, and chose Geneva, Switzerland, as the city where this center would be established in its third session in 1952. In addition, during the construction of the center to be established, it was decided to continue the theoretical studies in Copenhagen under the leadership of Niels Bohr.

At the 6th CERN Council Session, which took place on July 1, 1953, the international convention was signed by the 11 countries included in the council and the United Kingdom in addition to and was officially established on September 29, 1954, as the European Organization for Nuclear Research. Although the name of the council has changed CERN, which was used as the abbreviation of the council, continued to be used as the abbreviation of the organisation.

2.1 The Largest Accelerator of the Gigantic Particle Complex at CERN: The Large Hadron Collider

Experimental High Energy Physics can be studied under two headings. Accelerators and detectors. What sets CERN apart from other centers in the field of experimental particle physics is its ability to develop large collider projects to observe the first moments after the creation of the universe, as well as detectors that can detect collisions at such high energies and numbers. CERN has established colliders that developed gradually in the years after its establishment and has revealed very important scientific discoveries from these colliders.

CERN currently hosts nine accelerators and two decelerators. Some of these accelerators are used to prepare particles accelerated up to certain speeds for subsequent accelerators. The accelerators currently operating at CERN are listed below.

- LINAC3
- LINAC4
- LEIR
- CLEAR
- HIE-ISOLDE
- ELENA
- PS BOOSTER
- Proton Synchrotron
- Super Proton Synchrotron
- Large Hadron Collider (LHC)

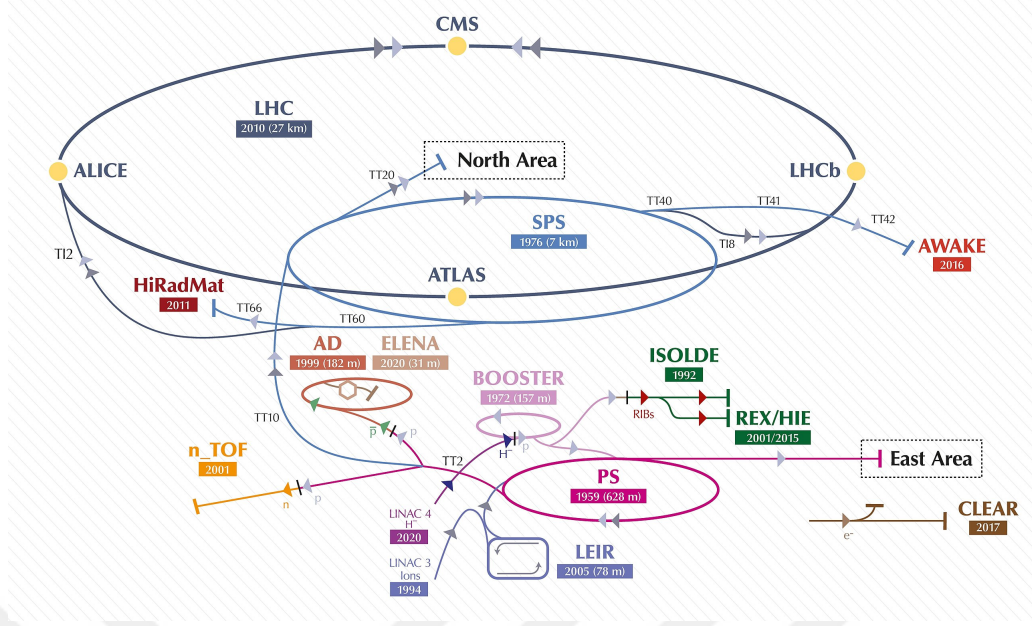


Figure 8: Accelerators at CERN.

2.1.1 LHC

The Large Hadron Collider is a proton-proton collider fed with particles that are accelerated by the Proton Synchrotron Booster (PS Booster), Proton Synchrotron (PS), and Super Proton Synchrotron (SPS) to a certain energy. The negatively charged hydrogen atoms that reached 160 MeV in LINAC4 are transmitted to the PS Booster. During this transmission, the 2 electrons of the hydrogen and its proton are separated and transmitted to the PS Booster. Protons reaching 2 GeV in PS Booster are transmitted to PS. These protons are then accelerated up to 450 GeV in PS and SPS and transferred to the Large Hadron Collider.

In this system, particles are accelerated up to a certain point and then transmitted to the next synchrotron. This strategy increases the number of protons accelerated by each upper synchrotron. This is one of the biggest advantages of installing a cascade accelerator complex.

Where to install the Large Hadron Collider has been a hotly debated topic since its inception. CERN Administration ended these discussions in December 1994. It has been decided that the LHC should be built in a circular tunnel of 26.7 km in circumference, which had previously been excavated for the LEP, as

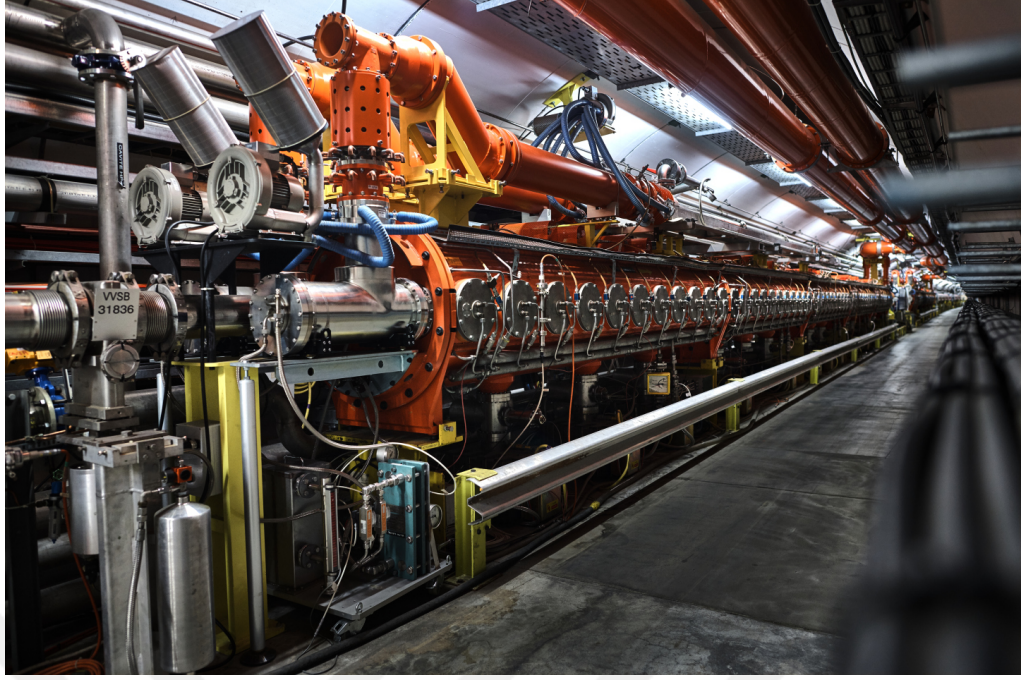


Figure 9: The Super Proton Synchrotron at CERN.

it would be more financially feasible. The LHC is connected to the SPS by 2 connecting segments, each approximately 2.5 km long.

The LHC has the plan to run until the end of 2041. According to this plan, it has 6 "run" periods as well as 6 Long Shutdowns. At the beginning of each year, a yearly detailed plan is provided. During these run periods, each year, there are also some small stops for technical studies. These stops are called Technical Stops and the most important technical stops are generally the End of Year Technical Stops (YETS) since it is generally 3 months long. There are also smaller technical stops during the year, usually one at the beginning of summer and one at the beginning of fall. But since these are generally 1-week long Technical Stops, technical detector studies are mostly done in the YETS.

At Technical Stops and Long Shutdowns, physicists, engineers, and technicians repair and upgrade this massive machine.

LHC, which can accelerate protons up to 4 TeV beam energy when it started to work in 2012, started to operate at 6.5 TeV/proton (13 TeV in a collision) and higher luminosity in 2015. The LHC was designed with a collision energy target

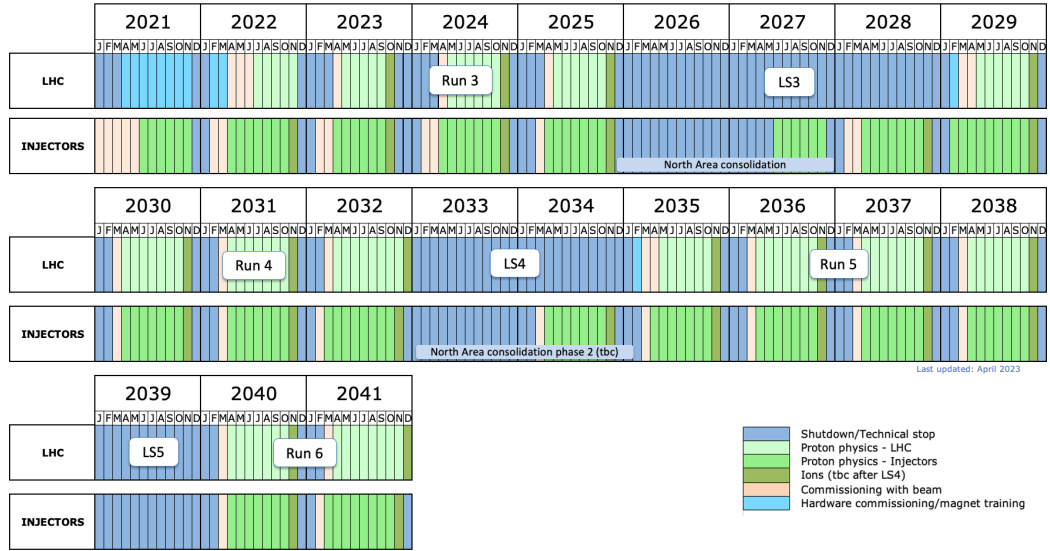


Figure 10: The Long Term Schedule of Large Hadron Collider.

of 14 TeV at the time of its design. The energy targeted in 2015 has almost been reached.

Its maximum total energy of 14 TeV is very close, and after the Long Shutdown 2 (LS2) (2019-2022), in Run 3, an energy of 6.8 TeV per proton (13.6 TeV in a collision) has already been reached (very close to the designed maximum initial energy, 7 TeV per proton)

In LS 2, which lasted from December 2018 to April 2021, LHC upgraded in terms of both impact energy and luminosity. The energy has been updated from 13 TeV to 13.6 TeV, and the luminosity has been updated from 1.3×10^{11} to 1.8×10^{11} (proton per bunch). Of course, the updates have been tested with data from the very beginning of RUN 3. In the first month of Run 3, with ions reaching 6.8 TeV and breaking the world record one more time. The LHC continues operating within RUN 3 with these conditions.

The particles, which reach the desired parameters in the 27 km Large Hadron Collider, are collided head-on at 4 points on the LHC. At these 4 points of the LHC, there are 4 large detectors, each produced from different perspectives. These detectors detect particles emerging from collisions. The detection of particles formed from collisions at this high collision rate and energy level has also led to

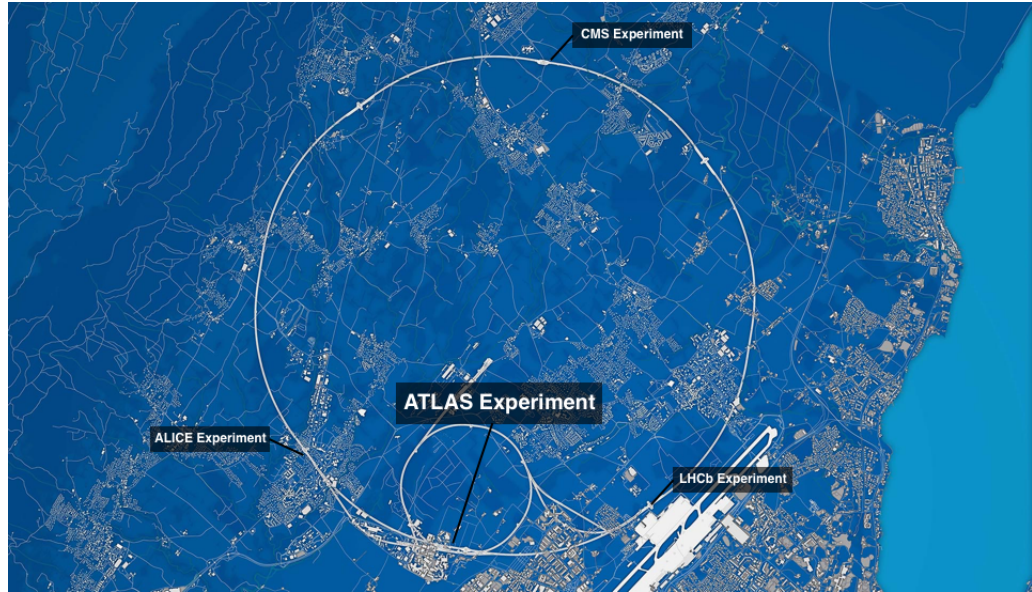


Figure 11: 4 Experiments (ATLAS, CMS, Lhc-b, ALICE) at the Large Hadron Collider.

the emergence of 4 different gigantic detectors produced with very high technology. These 4 detectors are ATLAS, CMS ALICE, and LHC-B.

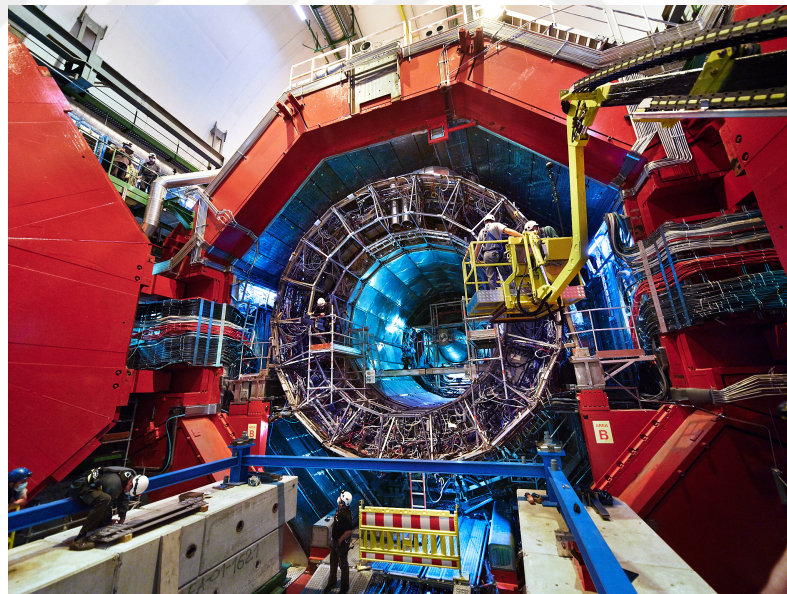


Figure 12: ALICE Experiment.

2.2 *ATLAS Experiment*

The ATLAS (A Toroidal LHC ApparatuS) Detector is the world's largest particle detector by volume, specifically designed to generally meet the LHC's high standards for p-p and A-A collisions. Having a tilted cylindrical shape with a height of 46 meters and a diameter of 25 meters, ATLAS is the world's largest particle detector by volume. Consisting of layers on top of each other like the membranes of an onion, the ATLAS Detector is designed to measure the momentum, energies, and trajectories of the particles formed from collisions, by distinguishing each of the particles from each other.

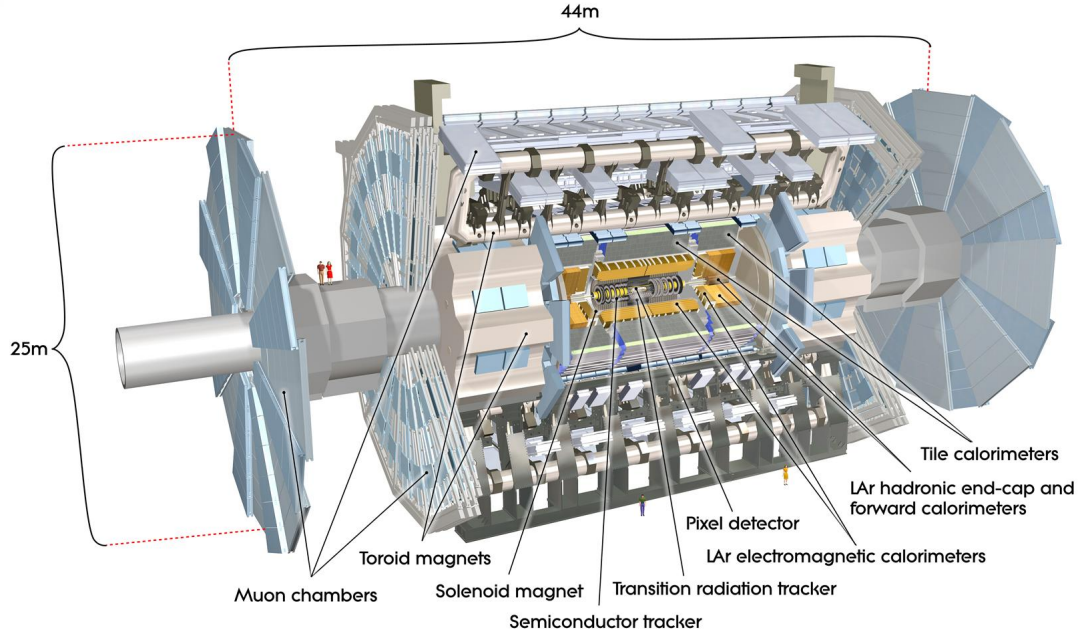


Figure 13: Computer Generated Geometry of ATLAS Experiment.

Particles accelerated up to 6.8 TeV in the Large Hadron Collider reach speeds of up to 99.999999% of the speed of light. At the same time, these particle beams, accelerated in the LHC, focus until their diameters are below 10 micrometers. Thus, 1 billion collisions occur per second in ATLAS. In order to observe such a high number of events in such a short time, it is necessary to design and produce specially designed complex detectors by pushing the limits of technology. ATLAS

is designed to detect these unusual collisions produced by the LHC.

This gigantic detector can be explained under 5 main subsystems as follows:

1. Magnet System
2. Inner Detector
3. Calorimeters
4. Muon Spectrometer
5. DAQ

2.2.1 Magnet System

ATLAS has a unique hybrid magnet system with a diameter of 22 meters and a length of 26 meters. This system consists of 4 large superconducting magnets and creates a magnetic field in a volume of about 12000 cubic meters. We can examine these magnets in two categories according to their design purposes.

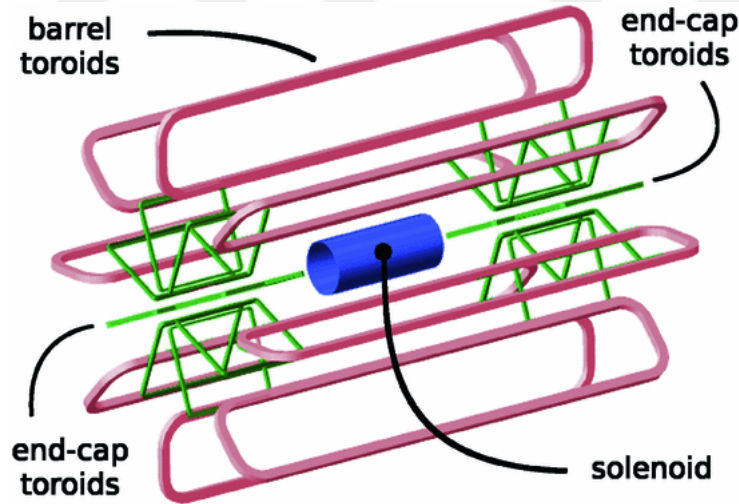


Figure 14: Magnets in ATLAS Detector.

- A Solenoid Surrounding the Inner Detector: A solenoid magnet with an inner diameter of 2.46 meters, an outer diameter of 2.56 meters, and an axis length of 5.8 meters is designed to create a magnetic field of 2 Tesla in the Z-axis direction of ATLAS's Inner Detector System.

- Barrel Toroid and 2 End-Cap Toroids: The reason why these 3 gigantic magnets are explained under the same category is that these 3 magnets are made for the same purpose. These magnets are designed to bend the trajectories of particles entering the muon spectrometer in the magnetic field.



Figure 15: Barrel Toroid Magnet in ATLAS Experiment.

If the particles entering this magnetic field, which is created in a very large volume, are charged, they begin to draw a circular trajectory according to the direction of the magnetic field and their own charge. Although magnetic field generation in such a large volume is very difficult for practical reasons, ATLAS, thanks to the design of these toroid magnets, allows the particles resulting from collisions to move in a very open environment, thus minimizing the multiple scattering effects.

In addition to the Barrel Toroid, there are two toroids placed on the lower and upper bases (if we think of ATLAS as a tilted cylinder). It is to create the Bending power needed at the points.

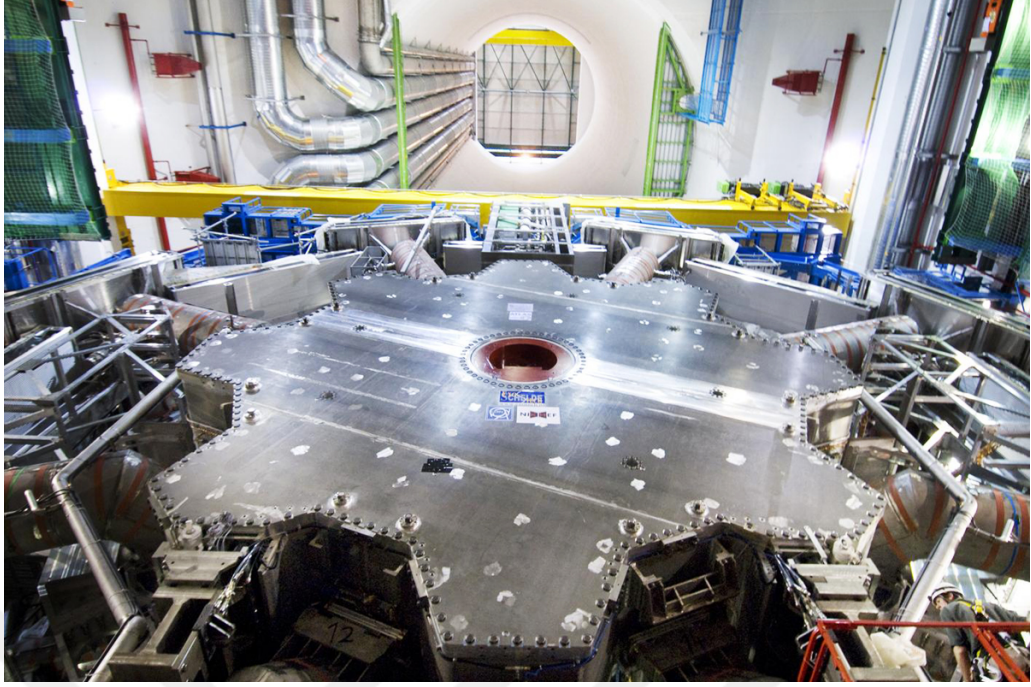


Figure 16: End Cup Magnet in the ATLAS Detector.

2.2.2 Inner Detector

Every 25 ns, 1,000 collisions occur at the center of the ATLAS Detector. This creates a very large track density, especially at points close to collision. ATLAS aimed to solve this problem by using detectors that have fine detector granularity in the inner detector, which will make high-precision measurements in the vicinity of the collision zone.

The inner Detector consists of 3 different subdetector groups Pixel Detector, Semiconductor Tracker (SCT), and Transition Radiation Tracker (TRT). The very compact and sensitive inner detector provides information about the momentum, electrical charge, and direction of the particles emerging from the collisions.

2.2.3 Calorimeters Detector

Particles from the collisions encounter ATLAS Calorimeters after passing through the inner detector. ATLAS Calorimeters absorb all the energy of high-energy particles and stop them (all particles except muons and neutrinos lose all their energy in ATLAS Calorimeters). During this process, it makes precise energy

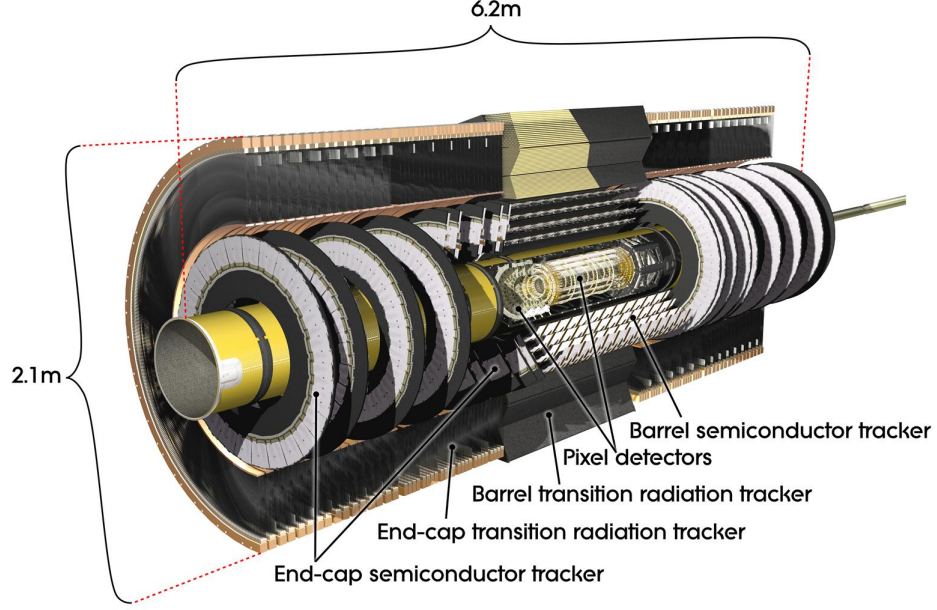


Figure 17: The Inner Detector System of ATLAS Detector.

measurements of particles. ATLAS Calorimeters consist of 2 sub-detector groups: Liquid Argon Electromagnetic Calorimeter and Tile Hadronic Calorimeter.

Particles passing through the calorimetry interact with the atomic nuclei of these detectors. During this interaction, the Electromagnetic Calorimeter measures the energies of electrons and photons, while the Hadronic Calorimeter measures the energies of hadrons.

2.2.4 Muon Spectrometer

One of the key focuses of this thesis is the RPC Maintenance and Upgrade Studies of the ATLAS Muon Spectrometer. The studies will consist of the work done on the ATLAS RPCs, which is one of the subdetectors in this spectrometer. Hence, it's important to explain this subdetector system, ATLAS Muon Spectrometer, and especially the Resistive Plate Chambers as it's done in Chapter 3. In this section, the general overview of the system will be explained in summary.

Muons and neutrinos that escape the Calorimeter due to their high mass encounter the Muon Spectrometer. The spectrometer measures the muon, a particle that retains its energy even after passing through the calorimeter. ATLAS

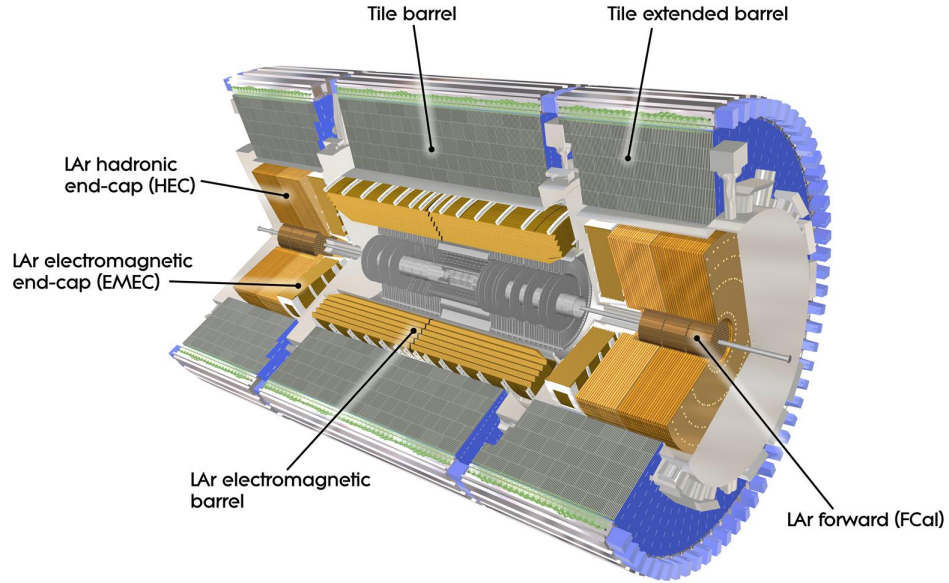


Figure 18: The Calorimeter System of ATLAS Detector.

employs a layered structure in its Muon Spectrometer (and with the help of its Magnet System) to address the challenge of stopping high-mass particles, which are notoriously hard to halt.

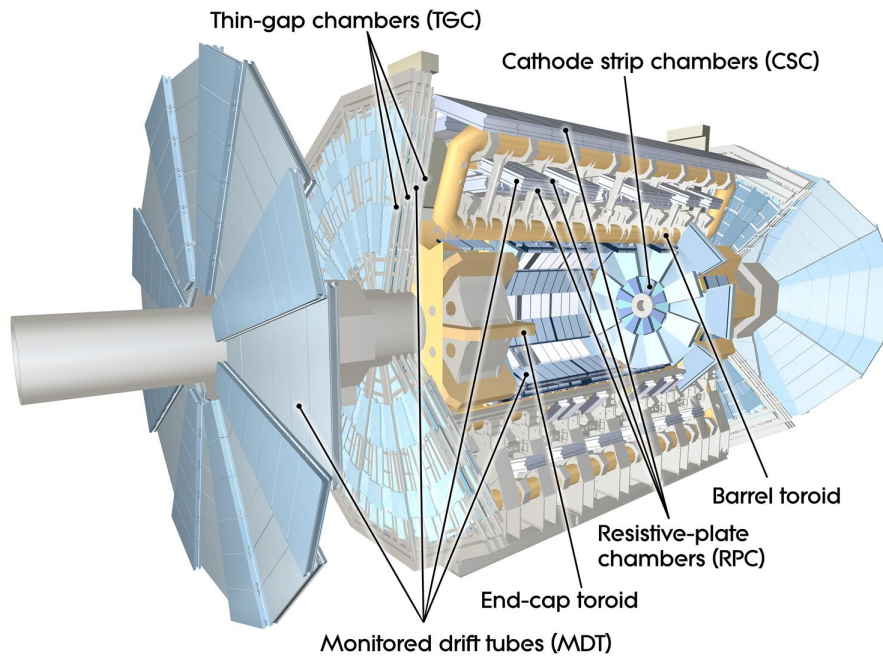


Figure 19: The computer-generated image of ATLAS Muon Spectrometer by CERN-ATLAS Experiment

The ATLAS Muon Spectrometer can be visualized as a cylinder with 3 layers that cover its sides. There are detector types in different combinations in each layer. Barrel Region has RPCs and MDTs in each layer while Endcap Region has TGCs, MDTs, SDCs. ATLAS Muon Spectrometer not only helps to find tracks of muons precisely but also acts as a trigger system. Therefore, each layer of the barrel region and endcap region has different detectors responsible for precision tracking and triggering.

In Barrel Region, MDT acts as precision tracking while RPCs acts as trigger. In the Endcap Region, MDTs and CSCs are tracked, while TGC acts as triggering.



CHAPTER III

STUDIES FOR ATLAS RPC SYSTEM

3.1 *Trigger System and Importance of RPCs in ATLAS Experiment*

The luminosity of the ATLAS Experiment in Run 3 is 1.8×10^{11} . The Trigger System undertakes a very important task to cope with this high luminosity. RPCs and TGCs are able to quickly identify the muons that are produced from the central collision. These muons have a high mass and can surpass the Inner detector and Calorimeter with minimal energy loss. In order to do this, as described in Section 3.3, they gather data from all 3 layers out of 6 layers of detector volume and can manage and refine events that relate to relevant physics within 2.5 microseconds. This filtering event is called the triggering system. Since it is not possible to record all generated events in ATLAS with the present technological capabilities, RPCs and TGCs are detectors that play a critical role in ATLAS's targeted results.

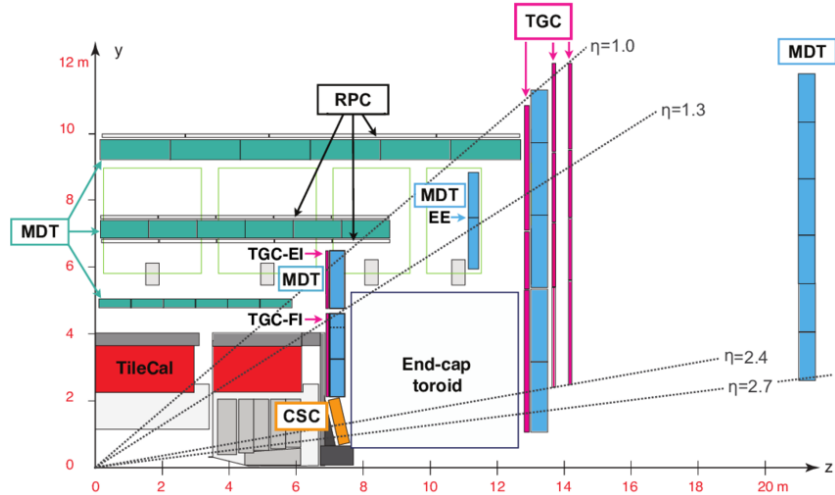


Figure 20: The Muon Spectrometer in a plane containing the beam axis.

3.2 Design of ATLAS Resistive Plate Chambers

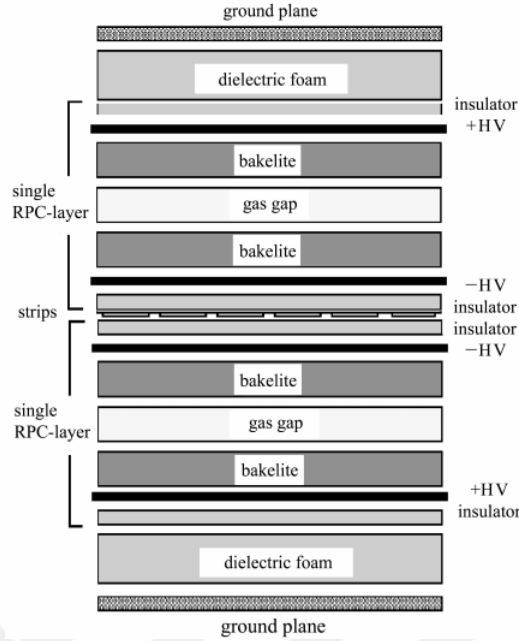


Figure 21: The Schematic of ATLAS Resistive Plate Chambers' Crossection.

As can be seen in Figure 21, ATLAS RPCs consist of gas chambers between 2 parallel platens 2 mm apart. The RPC you see in the figure is a doublet RPC with 2 gas volumes. Gas Volume contains a mixture called Standard RPC Gas Mixture and consists of 94.7% $C_2H_2F_4$, 5% iso- C_4H_{10} , and 0.3% SF_6 . 9.6 kV high voltage is applied to operate in Avalanche Mode. In order to measure two orthogonal coordinates, readout panel strips that are 2.3-3.5 cm wide are used.

Figure 21 is a simple schematic of a module of ATLAS RPC. These modules are placed side by side parallel to the Z direction of ATLAS in order to fill the barrel region.

3.3 ATLAS RPC System: Geometry and Naming

The ATLAS RPC System quickly analyzes the muons to trigger the system. Although it is sufficient to measure muons at 3 points in 3D space to reach the obtained results, ATLAS designed the ATLAS Muon Spectrometer to receive data at 6 points for the measurement of muons. The figure below shows the Z=0 plane

section of ATLAS. Although we have always defined ATLAS as a cylindrical volume in this thesis, Barrel Region actually resembles a tilted prism with a 16-sided polygonal base. RPCs placed side by side to cover the entire lateral surfaces of the prism can thus interact at 3 points with all muons coming towards the barrel region.

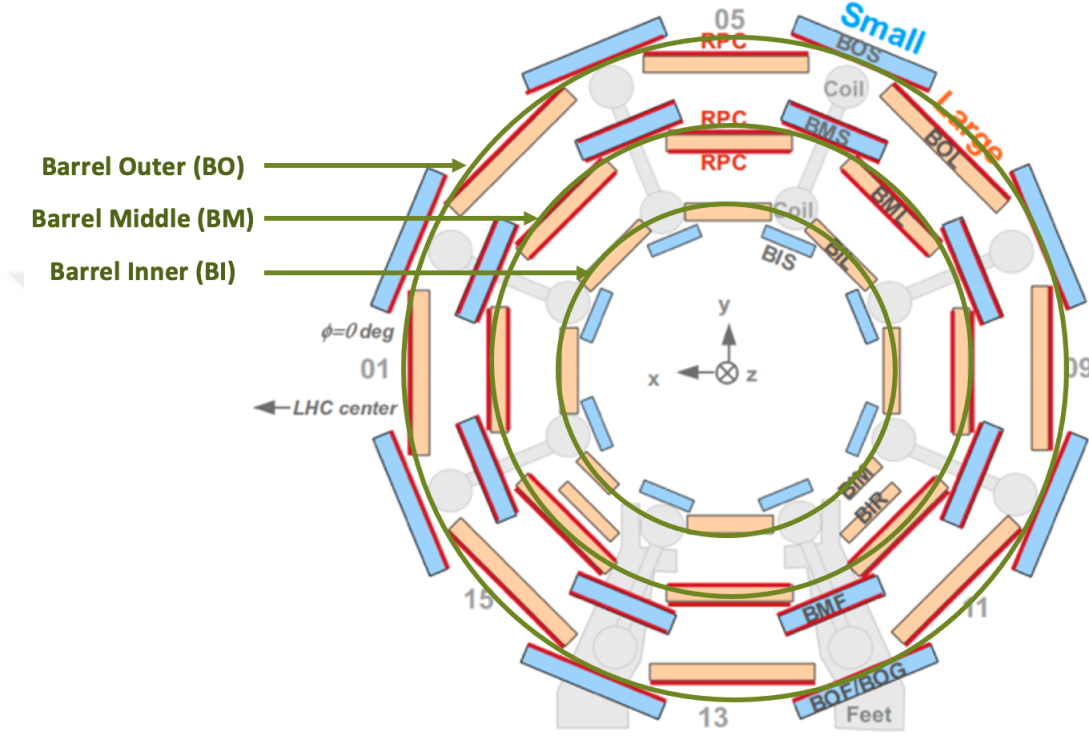


Figure 22: The RPC Chambers in the ATLAS Detector.

Each volume between the center of the ATLAS and these lateral surfaces is called a sector. As can be seen from Figure 22, there are regions called sectors and there are also Barrel Outer (BO), Barrel Middle (BM), and Barrel Inner (BI) regions that are represented with green rings, which are representing the distance from the center through the outer surface. The RPC units are arranged in 3 rows for each sector. While 2 rows of RPC units were placed in the area called Barrel Middle, 1 row of RPCs was placed in the Barrel Outer area. During LS2, with respect to other sectors, a small number of new chambers called BI-RPCs are placed to Barrel Inner.

The RPC Modules that are shown in Figure 21 put side by side in each Barrel

Middle and Barrel Outer regions from $Z = -12.5$ to $Z = 12.5$.

3.4 *ATLAS RPC Gas System*

ATLAS RPCs are gas detectors, as explained in Section 3.2. The wonder of this detector is that it has a very fast response with a special gas mixture and specific gas pressure values. This high-speed responsiveness of RPCs makes them powerful trigger detectors.

While talking about the ATLAS RPC System, a brief explanation of the general principles of RPCs. To put it simply, a muon entering the RPC ionizes the gas in the environment while passing through a gas-filled volume called the gas volume, located between two bakelite plates, and as a result of this ionization, electrons are formed. These electrons are directed from the negative plate to the positive plate in the direction of a constant electric field given to the bakelites.

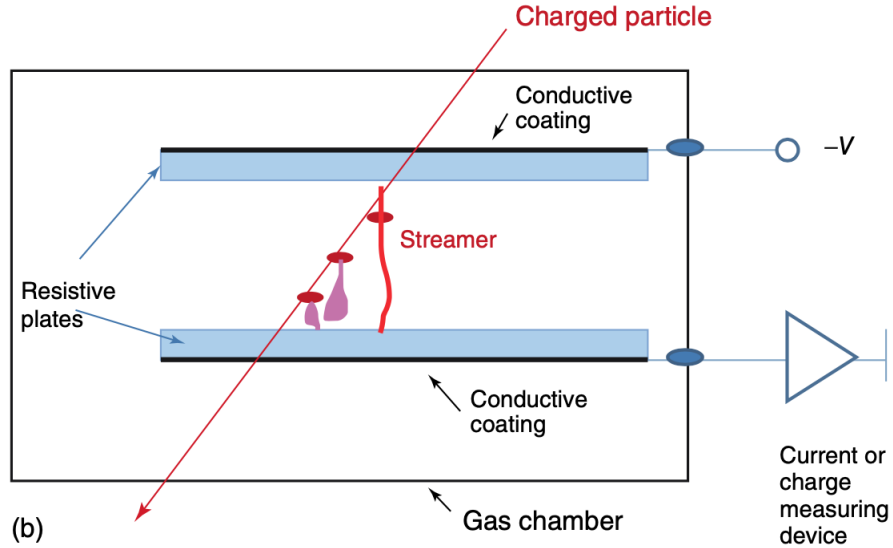


Figure 23: Avalanche effect in Resistive Plate Chambers.

During this orientation, electrons that continue to move in the gas mixture ionize more molecules on their way to Bakelite, creating an avalanche effect, causing more and more electrons. Thanks to this avalanche effect, when electrons reach the plates, the signal of the particle is received with the help of strips and electronics located there.

The gas mixture used in ATLAS RPCs consists of 94.7% $C_2H_2F_4$ (Tetrafluoroethane), 4.7% $i - C_4H_{10}$ (isobutane) and 0.6% SF_6 (sulfur hexafluoride).

These ratios of these gases actually become more understandable when we look at the historical development of gaseous particle detectors. To summarize, the reasons for using these gases in RPCs are explained below:

- $C_2H_2F_4$ (**tetrafluoroethane**): This gas is used because of its ionization property and its ability to absorb UV light, in accordance with the working principle of RPC. Its ability to absorb UV light optimizes signal generation in the detector.
- $i - C_4H_{10}$ (**isobutane**): Isobutane is a popular gas used in many gas detectors. This gas often acts as a "quencher". This limits secondary ionization by absorbing excess photons generated when a high-energy particle collides with gas atoms. This helps the detector reset faster and has a faster response time.
- SF_6 (**sulfur hexafluoride**): Sparks produced in the Avalanche Mode of RPCs can damage the resistive plates over time. This gas has high electrical insulating properties and is therefore used to prevent electric arcing and reduce corrosion that may occur on resistive plates.

The mixture of these gases enables ATLAS RPCs to receive data at high speed and accuracy. This gas mixture and pressure has been carefully optimized so that the detector can operate at the desired performance.

This brief description shows that the RPC must be operated at a certain gas mixture and pressure to operate most efficiently. The gas mixture that is used in these chambers, ATLAS RPC System has 3720 gas volumes in total. These volumes are placed in the ATLAS Spectrometer as mentioned in Section 3.3. The system that provides gas with the required sensitivity to this gigantic detector system is called the ATLAS RPC Gas System.

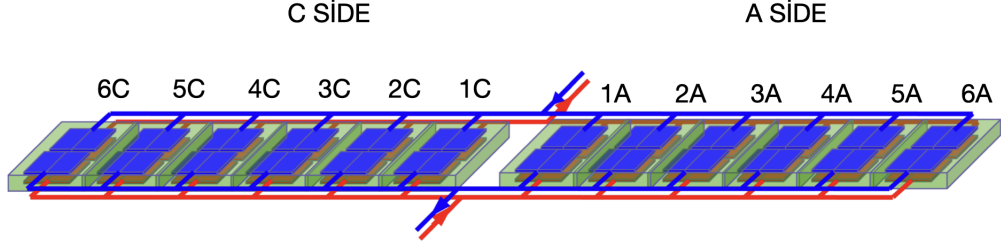


Figure 24: Gas distribution of ATLAS RPCs for a sector.

Figure 24 shows gas connections in only one sector of an RPC located in the Barrel Outer Region. At this point, I think it would be good to name the gas volumes in a doublet in order to facilitate the language in the rest of the thesis. As seen in the double figure, the modules have a gas inlet and outlet from the top and the bottom. Which of them is at the top and which is at the bottom is determined by reference to the beam direction axis. The layer closest to the Beam Direction is called Layer0, while the farthest one is called Layer1.

An RPC unit is seen in the figure. In RPC units, while 1 module is used in some places, RPC units are created by placing two modules side by side in some places. Each module is called DZ. If there are two modules in a unit, these modules are numbered according to their distance from the $Z=0$ plane. DZ1, which is close to the $Z=0$ plane, is called DZ2, which is far.

Gas flow to each barrel region in the sectors in the ATLAS Spectrometer is done with the help of Gas Racks. Below is a schematic representation of which Rack supplies gas to each sector in the ATLAS Gas System.

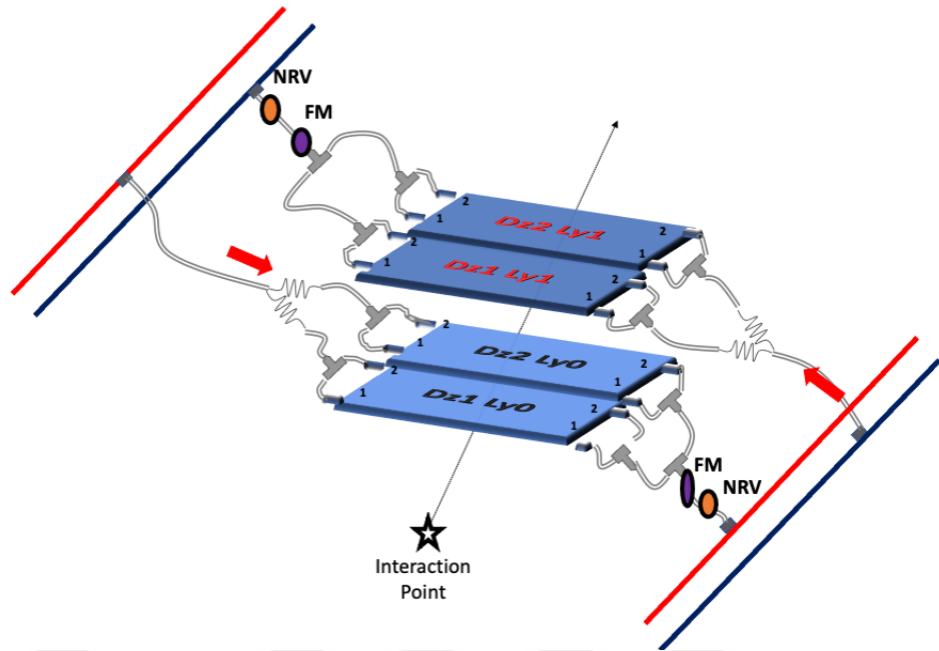


Figure 25: Gas distribution for 1 Resistive Plate Chamber in ATLAS Detector.

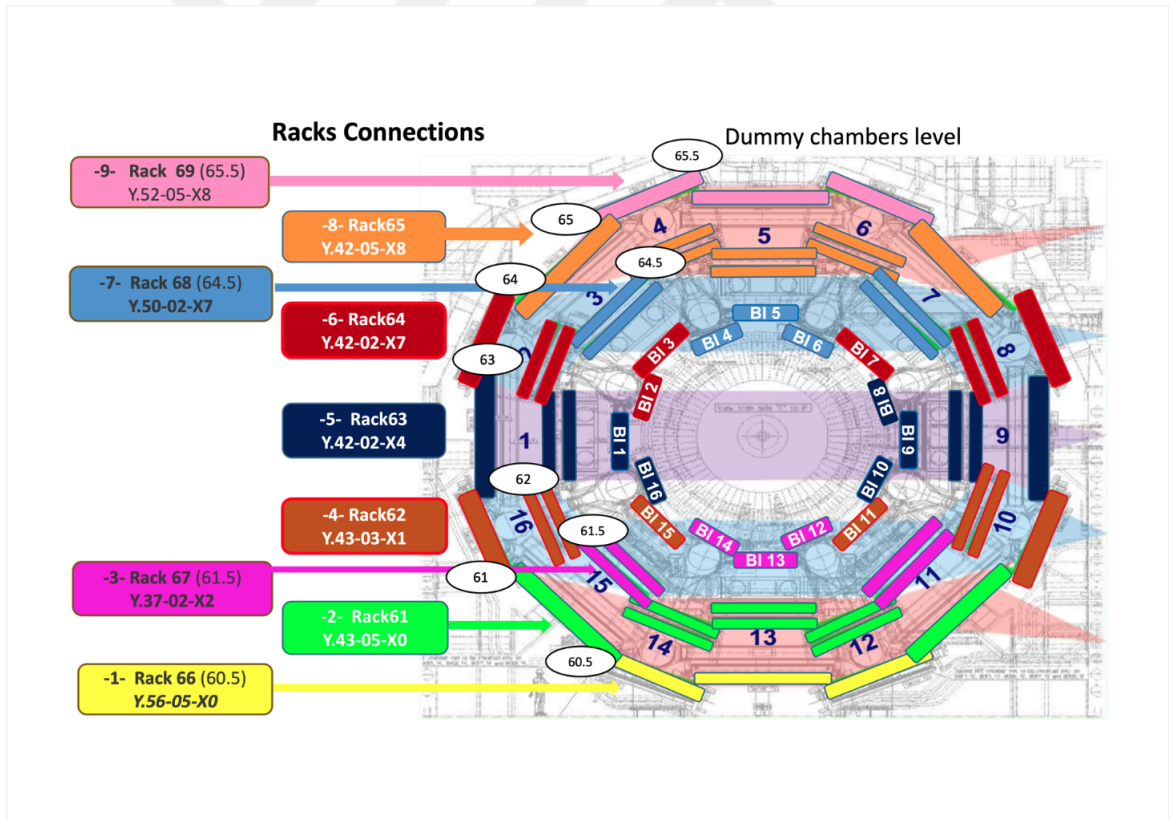


Figure 26: Gas Racks and the chamber connections.

3.5 Gas Leak Problem

ATLAS RPC System has a very critical problem that has been going on for a long time. Each RPC module has gas inlets and outlets for each layer at each corner. Figure 27 shows these inlets and outlet connections.

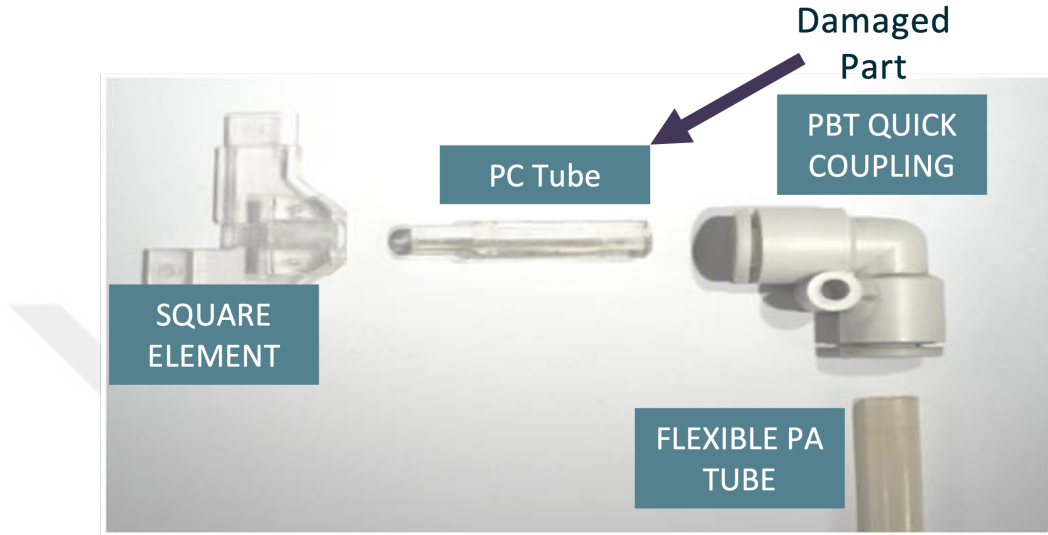


Figure 27: The connectors where leaks occur.

The cross-section of the PCB Tube that is inserted inside the L connection is rectangular. This rectangular shape and the external forces acting on this tube caused a creep, fatigue, or a combination of them ¹. Since the tube, which is exposed to some external forces both periodically and continuously, is more prone to crack formation due to its rectangular crosssection, many cracks have occurred since 2009, and these cracks have progressed and brought the material to the breaking point. From these cracks and/or completely broken inlets, gas mixture that is circulated in ATLAS RPC Gas System leaks through atmosphere.

These gas leaks in ATLAS RPCs are among the critical problems for the ATLAS Experiment for several reasons. These reasons can be summarized as follows:

- **Great Impact on the Operation of ATLAS RPCs:** In order to operate ATLAS Resistive Plate Chambers (RPCs) efficiently, a specific gas mixture

¹The reason for the cracks is not studied in a mechanical engineering perspective yet.

must be present at a particular pressure within each gas volume. However, due to gas leaks, a significant number of chambers don't have the required gas mixture pressure inside the volume. So some of the chambers are not working efficiently because of these gas leaks. Especially if the leaks are at the entrance of the gases, those types of volumes are isolated from the gas system because the gas leaks before any gas reaches the gas volume.

- **Environmental Impact:** The standard gas mixture used in ATLAS RPCs has approximately 1400 GWP. This means that the standard gas mixture used is 1400 times more harmful to the environment than CO₂. It is not difficult to imagine how worried an international organization like CERN is about releasing such a highly harmful gas.
- **High Cost:** The ATLAS RPC Gas System is designed to keep the gas used in a loop. Therefore, the annual gas expenditure foreseen at the time of its design was small. However, for ATLAS, which had to fill the difference caused by these gas leaks constantly, the operation for ATLAS RPCs increased when you compared it with the design studies. This problem started to become even greater as the amount of leakage increased over the years.

Of course ATLAS RPC Team has tried many methods to solve this problem since 2009. But what makes the problem worse is that the inlets-outlets connections where cracks occur are in hard-to-reach places. In addition, there is a service box shown in Figure 28 surrounding these inlets-outlets. These service boxes make the repair of these boxes, which are already difficult to reach, more difficult.

This situation continued until 2023. Repair techniques studied until 2021 were not fast enough to solve this problem. It is known that in creep and/or fatigue events, cracks occur in small numbers at first and then increase exponentially as time goes on. Therefore, since the number of cracks formed in recent years was higher than the number of repairs, an increasing amount of gas leakage was reached at the end of each year. Figure 29 shows the total fresh gas consumption

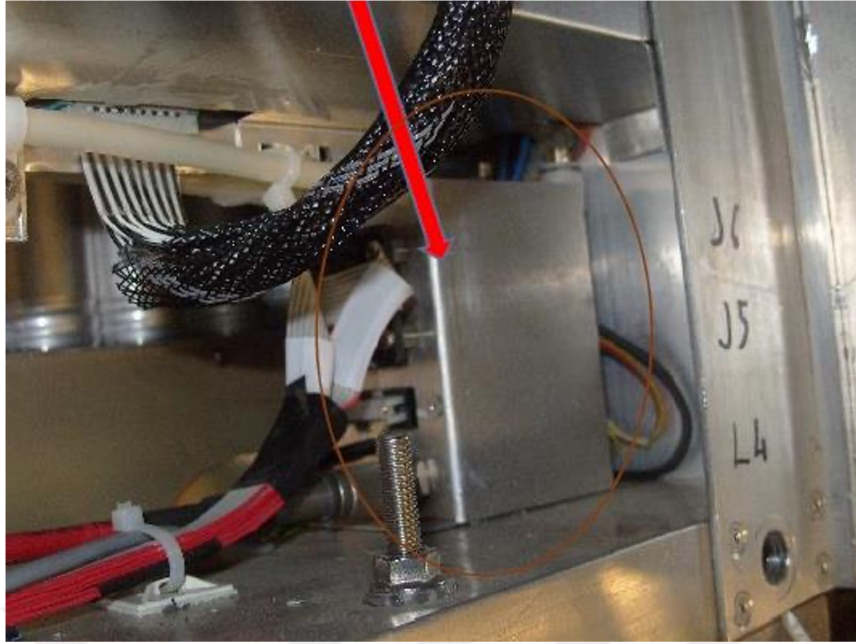


Figure 28: The service box that covers the gas inlets.

due to the gas leaks over the days for some years.

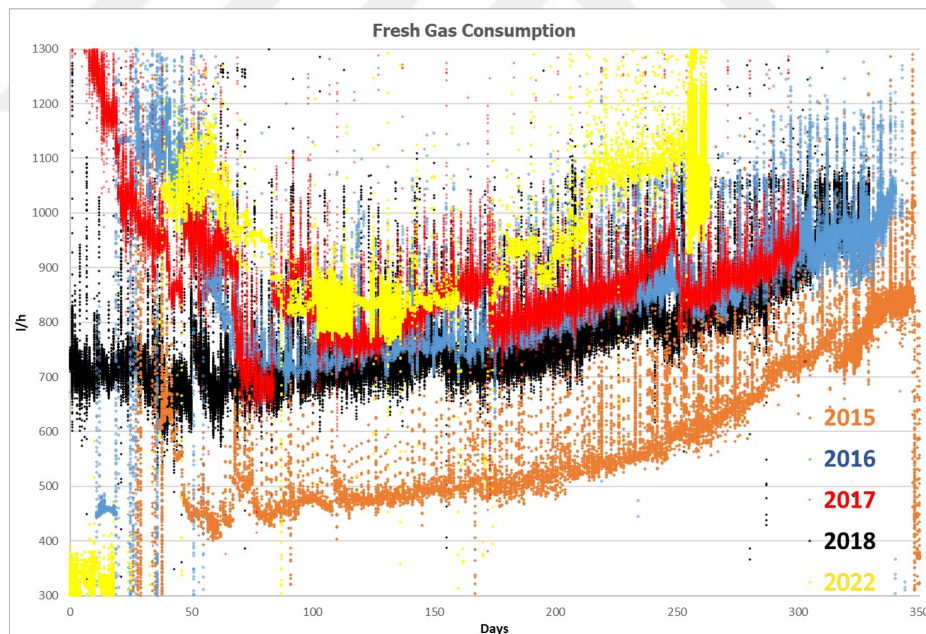


Figure 29: Fresh Gas Consumption over the years.

3.6 *Reparation Studies*

Many techniques have been tested to resolve gas leakage in ATLAS RPCs. The ones that are still used are Standard Reparation Technique and InsertoTubo Technique. Although these techniques have developed and become more effective techniques over the years, they have not reached the speed to solve the leakage problem in ATLAS completely. After the number of new cracks increased, the ATLAS RPC Team decided to develop a new technique to solve this speed of reparation problem. It is important to briefly summarize the first techniques in order to be able to compare them with the new technique, they will be briefly summarized in the next subsections.

3.6.1 InsertoTubo Technique

This technique is generally used when PC Tubes are completely broken². The idea is very simple: Changing the broken tube with a plastic pipe. Although the Inserto Tubo Technique has a high efficiency in repair success, the fact that it cannot be applied in hard-to-reach places and the service box also prevents access to the fasteners makes the technique even slower to be applied.

3.6.2 Standart Reparation Technique

The Standard Repair Technique is the application of a liquid adhesive with the aid of pressure, directly aiming from a syringe to the cracked area. This aiming step is critical because the adhesive must fully cover the cracked area. This led to working with an accuracy of about 1 mm. At this point, hard-to-see connections are examined and pointed with the help of endoscopic cameras. The liquid is then sprayed. A downside to this technique is that if the crack is facing the side where the spray tip cannot be inserted, it becomes even more difficult (or sometimes impossible) to repair that crack.

Even if these 2 techniques couldn't solve the entire problem, up

²Applying this technique for tubes that are not completely broken (which is the case for many) becomes pointless.

to date, they can be considered the reason why ATLAS RPC is still standing.

3.6.3 New Reparation Technique: Resin-based Leak Repair Technique

Although the repair works continued with great effort with the aforementioned techniques, the cracks' formation rate accelerated day by day, and although these techniques were developed and applied skillfully, they could not keep up with the number of new cracks formed. Aware of this situation, the ATLAS RPC Team sought ways to solve this problem more quickly. While searching for these new methods, the Resin-Based Repair Technique³, a technique that had been tried 1-2 times in laboratories in previous years, was found too risky and shelved, came to the fore again. It is aimed to make this idea a viable technique in ATLAS Cavern by conducting deeper Research and Development Studies on the Resin-Based Repair Technique.

3.6.3.1 *The Idea of Technique*

The Foam Repair Technique is actually based on a very simple idea. It's mentioned the service boxes are in the corners of the RPC Modules in previous subsections. The basic idea of the technique is to fill these service boxes with 2-component polyurethane foam. The components of polyurethane are in liquid form before mixing. Then, when mixed, they swell to foam in an exothermic reaction. The basic idea is to mix the ingredients (which are still liquid for a few seconds after mixing) and inject the mixture into these boxes with a hose. Then, the liquid mixture would start to swell in the box and fill the entire box. At the same time, it would surround the inlets and outlets where cracks occur, and repair all gas leakages in that corner.

The Resin Based Foam Technique Studies can be explained in 5 time periods which are divided according to the aim of the period.

³sometimes referred to as the Foam Repair Technique

- Early Studies for Testing the Reliability of Technic: Tests in Turkey between 2021 April-August)
- Choosing the Right Polyurethane Foam: Tests at CERN between 2021 August-November)

3.6.3.2 *Early Study for Testing the Reliability of Technic: Tests in Turkey between 2021 April-August*

The first systematic studies of the Foam Repair Technique started in April 2021 at Boğaziçi University KAHVELab. The main aim of the work, which lasted until August 2021, was to test from a broad perspective whether the idea of the Foam Repair Technique would indeed work in many possible scenarios.

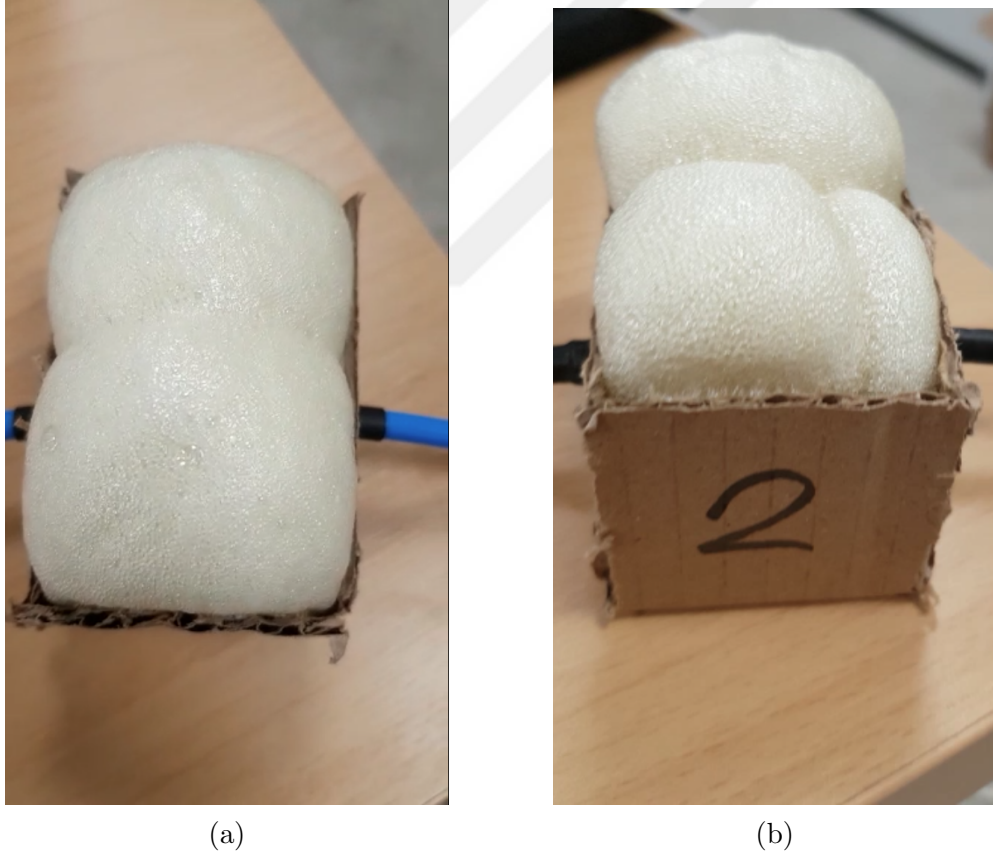


Figure 30: Some photos of preliminary tests done in KAHVELab

In the initial tests, the aim was to understand whether this technique should be studied further. For this purpose, the materials that are required to do mock-up tests were purchased.

Since the foam is the most important component in this technique, the first thing that is done is to search the foam types and market to find the most suitable company to work for. In the purchasing process of polyurethane, Aktif Polyurethane San. Tic. Ltd. Sti⁴. As a result of the discussions and research with the company, the foam we needed was produced. This foam, which will be called as the ActiveFoam1 in this thesis, was brought to KAHVELab to begin the first tests.



Figure 31: The leaky pipe and box for tests.

Components A and B, taken in certain sizes with two syringes, are placed in a cardboard glass and mixed quickly with the help of a wooden mixer in this glass. Then, the resulting mixture is poured into the mock-up box, which was prepared before and shown in Figure 31. The expansion of the foam is then observed. The foam, which cools and hardens after waiting 3 hours, is measured with the Bubbler Test Setup, which we used for the quick Gas Leak Tests shown in Figure 32.

The Gas Leak Test Setup consists of the compressor, the bubbler, the hoses,

⁴www.aktifpoliüretan.com

the box to be tested, and a valve at the outlet of this box, which works with a very simple principle. All elements are connected in series with each other.

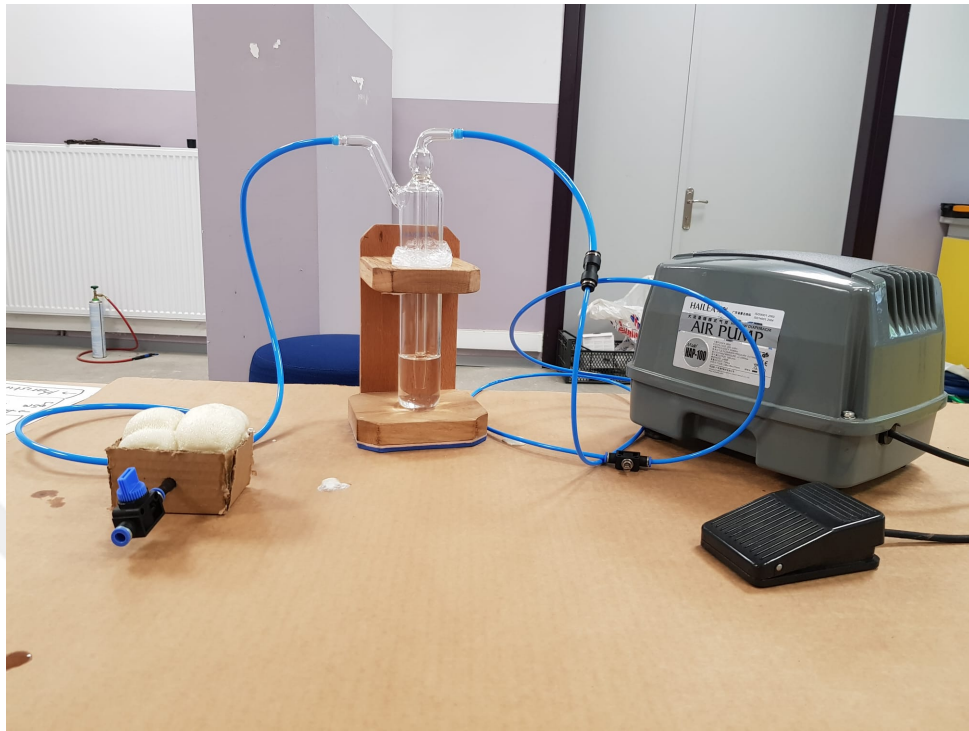


Figure 32: The Bubbler Setup for Gas Leak Tests.

Then, when the valve is in the open position, the compressor is started and gas is supplied to the system. What we expect to see in this case is that the gas creates bubbles in the Bubbler. Then, the valve at the outlet of the box is closed. Although gas is supplied to the system during this process, the bubble formation in the Bubbler is expected to decrease to almost non-existent. This was because there was no more room for the gas to go, making it difficult for the gas flow to come to a standstill, thus creating residual bubbles in the bubbler. (Of course, if the compressor is pressed for a long time, bubbles with a high period are seen in the bubbler due to the compression feature of the gases.) If the application fails and a leak occurs in the mimicking pipe (even though we have closed the valve), the gas supplied from the compressor may come out through this leakage. The flow will continue. And bubbles will continue to appear in the bubbler. This method aims to understand whether the technique is promising or not by classifying the

test results as successful, semi-successful (reduced gas leakage but not completely closed), and unsuccessful.

3.6.3.3 *Choosing the right polyurethane foam (Tests at CERN between 2021 August-November)*

A few products are chosen to test at CERN between several different types of polyurethanes and factories. These products were ESPAK Soft, ESPAK30, ESPAK90, and ActiveFoam1. Each product is tested with the same test setup that is built at CERN. Each product (except ESPAK Soft) was tested 30 times and the results of these tests are below.

Table 1: First Systematical Tests Results

Product	Total Number of Tests	No. of Fully Sealed	No. of Partially Sealed	Failure
ESPAK 30	30	27	1	2
ESPAK 90	30	16	3	11
ActiveFoam1	30	26	3	1
ESPAK SOFT	5	0	0	5

During these tests, we were in touch with Dr. Yalçın Yıldız⁵ and he was trying to produce the foam as we needed. When he visited CERN, he brought new foam which I called ActiveFoam2. Then we tested ActiveFoam2 30 times as we tested the previous products. The result was %100 successful.

Then we chose the top 2 products, ESPAK30 and ActiveFoam2, for aging testing by exposure to gamma radiation. Additional tests were conducted to undergo radiation testing at the CERN Gamma Irradiation Facility. 10 ActiveFoam2 and 10 ESPAK30 samples exposed to 40 Gy in the first radiation test were subjected to the gas test again after radiation. In the second radiation test, only 16 samples of ActiveFoam2 were exposed to 30 Gy due to the current stock status. The results of Radiation Tests are summarized in Table 2.

⁵Chairman of the Board of Aktif Poliüretan

Table 2: Results of Radiation Aging Test

Test No.	Product	Total Radiation Dose	No. of Fully Sealed Boxes Before Radiation	No. of Fully Sealed Boxes After Radiation	No. of Failures after radiation
1	ESPAK 30	40 Gy	10	9	1
1	ActiveFoam2	40 Gy	10	10	0
2	ActiveFoam2	30 Gy	16	16	0

In light of these results, our product in foam studies was chosen as ActiveFoam2.

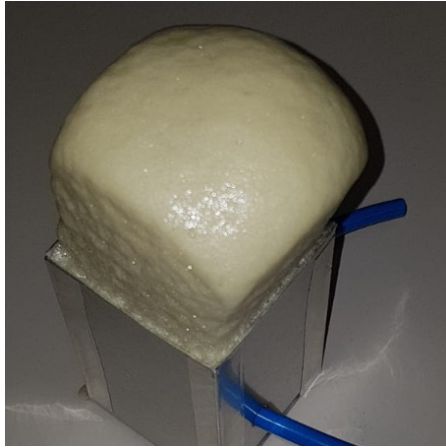
3.6.3.4 Application Method (Tests at CERN and Turkey in between 2021 November-December)

After determining which product to use, it was time to figure out how to apply this technique in ATLAS Cavern in a most efficient way. While discussing how to apply this technique in ATLAS, the required features of the application method were also determined. Whatever the method, both the resulting foam had to have smaller bubbles and be less bubble-free, and the method had to be feasible to implement in ATLAS Cavern.

The reason for wanting to obtain less bubble foam is that the foam obtained in such results both increases the adhesiveness of the material it comes into contact with and gives more successful results in sealing the gas. Assessing the practicality of the Foam Technique in the ATLAS Cavern was a challenging obstacle during research and development.

The ActiveFoam2 type of foam is mixed and applied by high-pressure tanks in the industry. However, since it's not possible to use these kinds of large high-pressure tanks inside the ATLAS Cavern, alternative practical methods were tested. These methods are described below:

- **Manual Mixing by Hand:** Although the manual mixing by hand method seems to be the weakest method among them, the fact that more than 250 tests at the desk were made by hand mixing gave great confidence to those who would apply it in ATLAS Cavern. However, this technique definitely lagged behind the results in the industry, and moreover, it was a bit behind as it was a very open method to human error.



(a)



(b)

Figure 33: The best result of Mixing with Hand at the left and the best result of Static Mixer Tips at the right.



(a)



(b)

Figure 34: The average result of Mixing with Drill at the left and the average result of Mixing with Dremel

- **Static Mixer Tips:** Static Mixer tips are used for mixing many different types of glues and adhesives in the industry. A total of 15 different static mixer tips from 6 different companies were tested, but none of them were able to compete with manual mixing by hand, so they were left out of scope.
- **Manuel Mixing by Drill or Dremel:** After some trials in Turkey, the idea of mixing with a drill emerged. After some research, mixing with Dremel was tested since Dremel can reach much higher revolutions per minute than any drill. This leads a faster mixing speeds and gives more bubble-free results.

The results of the foams produced by these methods can be compared by looking at Figure 35 and Figure 34. As shown from the figures below, the mixing method with Dremel is far better than the others regarding their bubbiness. So it was chosen for use in ATLAS as a main application method.

3.6.3.5 First 100 applications in ATLAS Cavern. (2022 February-March)

These results were made into a presentation and presented to ATLAS Technical Coordination (TC). After the interview, ATLAS TC decided to test this technique on the first 100 boxes selected from the ATLAS RPC System and by this, the results of these boxes would be able to be used to evaluate the effectiveness of the technique.

After this decision, the technique was applied to 100 boxes in ATLAS in February and March 2022. **Of these 100 boxes, 46 of them were selected as boxes with leakage, while the others were selected as boxes without leakage. This is because it was originally planned to use this technique not only as a repair technique but also as a preventative technique. If this foaming technique worked, would it be possible to fill the boxes with no leaks and prevent future leaks before they even occur? In order to seek an answer to this question, boxes with these features have been selected.**

In the tests carried out immediately after the application, the leakage in 46 of the 46 boxes was successfully eliminated. After 6 months, in September 2022, the conditions of the foam-applied boxes were tested with gas tests performed on each layer, and it was observed that there was no change in the hoops. This was considered the first successful result of the foaming technique.

3.6.3.6 Extension of Application in ATLAS Detector (2nd Application in ATLAS Cavern)

After the successful measurements in September, the studies and results were compiled and presented to ATLAS Technical Coordination. After this presentation, ATLAS TC decided to extend the application of this technique to other sectors

in ATLAS. After this point, a very intense organizational process and work were started to carry out a huge repair campaign. As a result of these efforts, the ATLAS Foam Repair Team was established with participants from different countries and universities ⁶. This team gathered at CERN in January and started working. After several training sessions in the laboratory and ATLAS Cavern, the Foam Repair Campaign started at the end of January. Then this technique was applied to 277 boxes in 7 weeks, which corresponded to a total of 200 gas layers.

105 of these 200 gas layers were applied to prevent future leaks, which means there were no leaks before application. 21 boxes were partially treated (due to accessibility problems) and, therefore, partially repaired. 71 gas layers were completely repaired. 3 failures. These 3 failures are examined in detail. It was determined that 1 of them appeared as a human error during the application. In 2 of them, it could not be determined exactly where the gas came out from the chamber. It was suspected that the gas leaks in these chambers were not due to the mentioned inlet/outlet connections' cracks, but due to the loss of function of the glue between the gas gaps of the RPCs. ⁷ occurred during these implementations. As a result of these studies, it was seen that the success rate of the Foam Repair Technique in YETS22/23 was 95.9%.

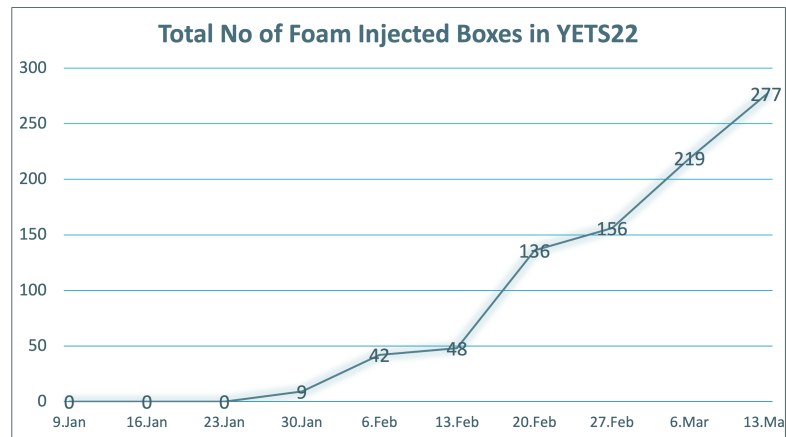
3.7 Results and Discussion of RPC Gas System Studies

It has been understood from the studies carried out at ATLAS that gas leakage problems in the ATLAS RPC Gas System can be transformed into minor issues with creative and effective operational and repair studies.

In Figure 3.7 and Figure 3.7, you see the Fresh Gas Consumptions during 2023 and the years before 2023. As a result, the studies done for the gas system reduce

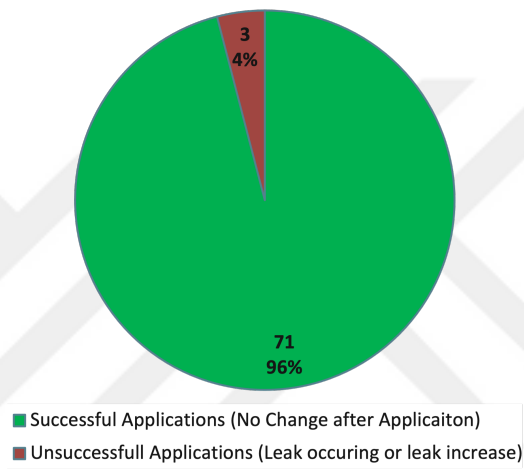
⁶On average, 3 sub-teams (group of 2 people) worked for this job each week. These teams were created with the contributions of İstinye University, Boğaziçi University, Ankara University, University of Bologna, University of Calabria, University of Rome Tor Vergata, and Aristotle University of Thessaloniki

⁷The glue problem that occurred in these gas gaps was noticed during the repairs in standard reparation techniques, and it was determined that such gas leaks continued in 1% of the repaired gas gaps despite the repair of the gas inlets/outlets. It is assumed that these 2 failures are for this reason.



(a)

Success rate



(b)

Figure 35: The Results of the Foam Campaign done in YETS 22/23.

Fresh Gas Consumption and provide a more stable system in 2023.

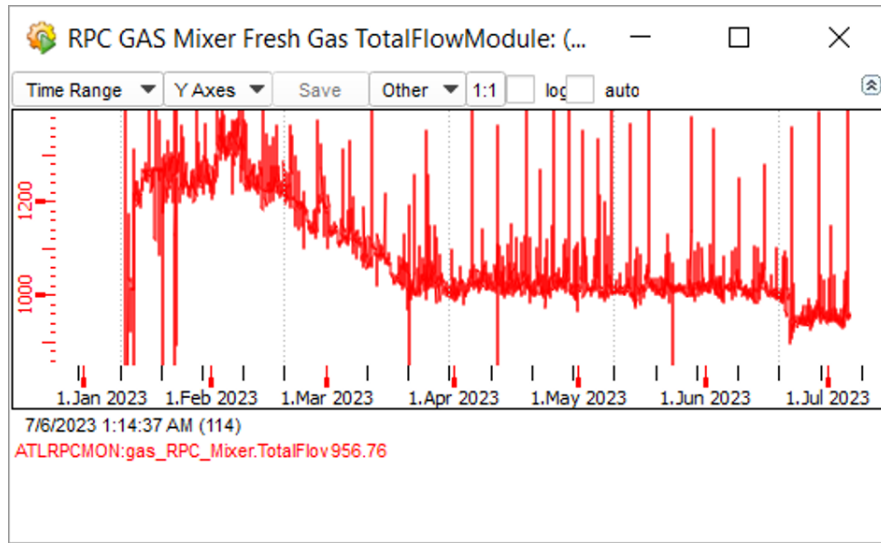


Figure 36: Fresh Gas Consumption in 2023.

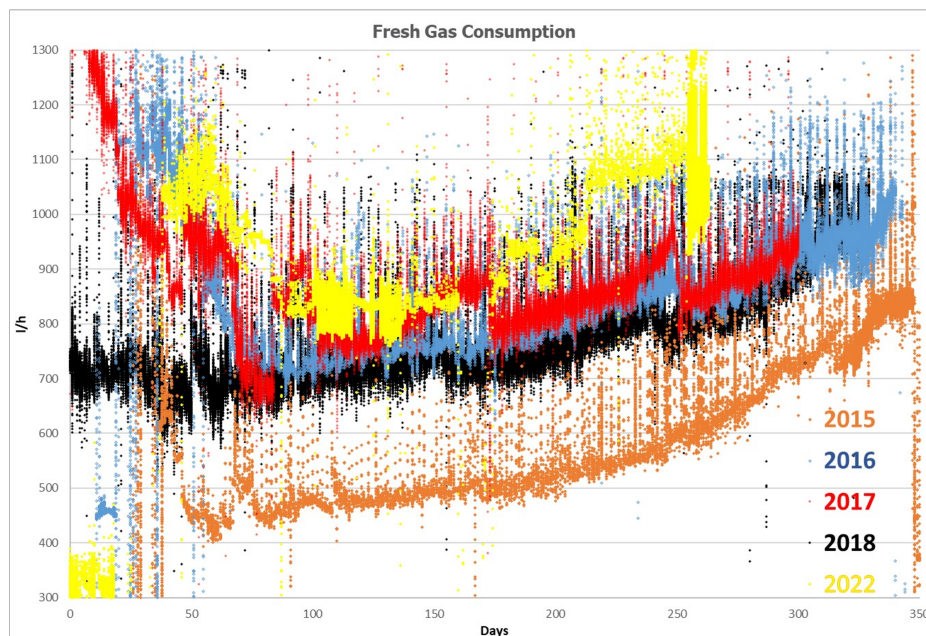


Figure 37: Fresh Gas Consumption before 2023.

CHAPTER IV

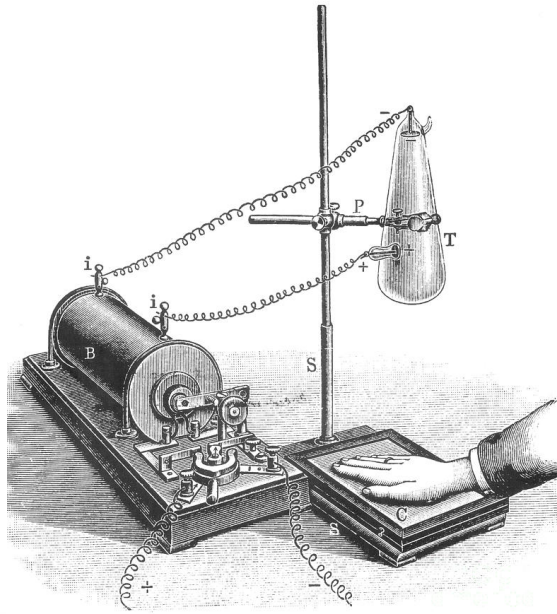
GEANT4 SIMULATION OF MUON TOMOGRAPHY

4.1 Introduction to the Chapter

The idea of viewing any object in 2 or 3 dimensions was born in Roentgen's laboratory 128 years ago. Roentgen was then working on the cathode rays he produced with the Crooks Tube. One day, Roentgen saw a glowing fluorescent surface meters away from the tube during an experiment, despite covering it with thick black cardboard. This is surprising to Roentgen because he knew from previous experiments that the cathode rays produced by the Crooks tube could not get that far out of the tube. Roentgen discovered the cause of this glow, another ray formed by cathode rays, which he called x-rays because he could not identify them at that time. This discovery is a very important discovery since it opened the doors of imaging to us and formed our basic thinking about imaging. In his later studies, Roentgen succeeded in creating the first X-ray radiography photograph in history. In doing so, he correctly combined the basic elements of imaging techniques and successfully performed imaging.

When we examine this example, Roentgen has actually combined elements consisting of a source (photons produced through cathode rays), a detector that can interact with the source (photographic plane), and an object (a human hand) that interacts with the source differently from the environment. Low-density materials allow X-rays to pass through more easily than high-density materials. On the other hand, the photographic plane displayed a black image when it was exposed to high radiation and a white image when the radiation was low. Combining these features, Roentgen created the first x-ray radiography image of his wife's right hand tomographically on the photographic plane.

The developments in electronics and computer technologies affected detector



(a)



(b)

Figure 38: Roentgen's X-Ray Radiography Machine at left and the first result of this machine at right.

technologies; instead of the detectors like the photographic plane that is used by Roentgen, new detectors that acquire data with electronics are started to be used. The data received from the detectors with electronic boards are post-processed with analysis methods.

When we examine historically, such imaging systems have spread to very large areas in the years after X-rays. Imaging methods have been developed for various situations with the combination of many different sources, objects, and detectors, such as Thermal Imaging, Positron Emission Tomography, ultrasonic Imaging, etc.

Muon Tomography studies are currently being made to enhance the clarity of object images by analyzing the data derived from Muon Tomography through various post-processing analysis techniques.

Muon Tomography is one of the most recent of these imaging methods. The basis of this idea, which was put forward in 2003, is again the same 3 trivets. These are:

- Source: Cosmic Muons



Figure 39: X-Ray Computer Tomography.

- Object: Materials with a high atomic number
- A detector system: Detectors that can detect muons

The main purpose of this part of the thesis is to create the most basic simulation of a Muon Tomography Device that can be made in Turkey in the future, using the GEANT4 program. In this section, the details of this simulation study will be discussed.

4.2 Muon Tomography

4.2.1 Origin and Properties of Cosmic Muons

High-energy cosmic rays entering the Earth's atmosphere collide with atoms in the atmosphere and form many particles. These particles travel at almost the speed of light. In the figure below, you can see the process that a cosmic ray creates when it interacts with atoms in the atmosphere.

The point to be noted in this figure is that 2 types of particles can reach the Earth. These are muons and neutrinos. As mentioned in the ATLAS Detector Section, these particles can travel more distances due to their high masses and reach the earth's surface. Since we can detect muons reaching the earth with detectors such as those used in the Muon Spectrometer in the ATLAS Detector,

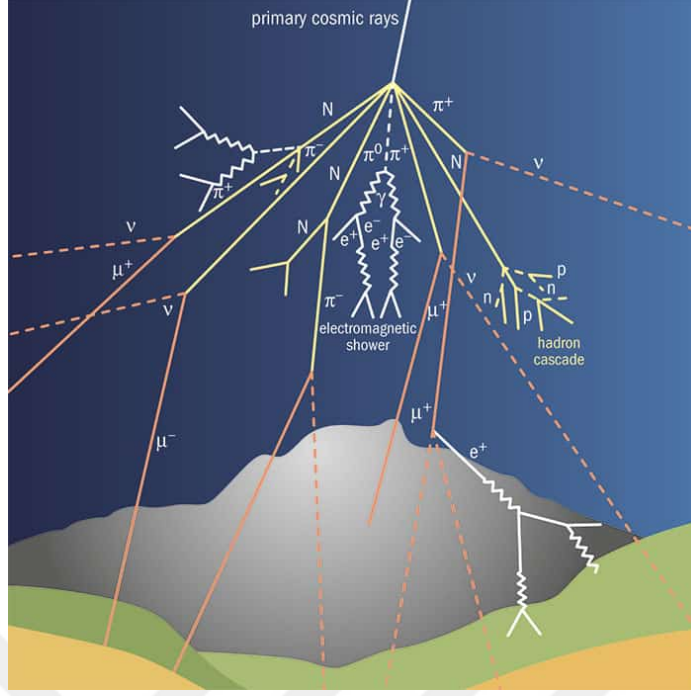


Figure 40: Cosmic Rays the shower it creates.

many studies have been conducted on the use of cosmic muons. Cosmic muons are seen as an ideal source for tomography since muons can also penetrate materials with high atomic numbers due to their high mass.

4.2.2 Interaction of Muons with Matter

4.2.2.1 Multiple Coulomb Scattering (MCS)

When a charged particle, like a muon, passes through a material, it experiences deflection due to Coulomb interactions with atomic nuclei. This is known as Multiple Coulomb Scattering. While these deflections are typically small, they can accumulate over long distances, leading to significant effects.

For thin absorbers, the distribution of scattering angles due to MCS can be approximated by a Gaussian distribution. The root-mean-square (RMS) scattering angle, θ_0 for a particle traversing a thin slab of material is given by:

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p_m} \sqrt{\frac{T}{X_0} \left[1 + 0.038 \ln \left(\frac{T}{X_0} \right) \right]} \quad (1)$$

where

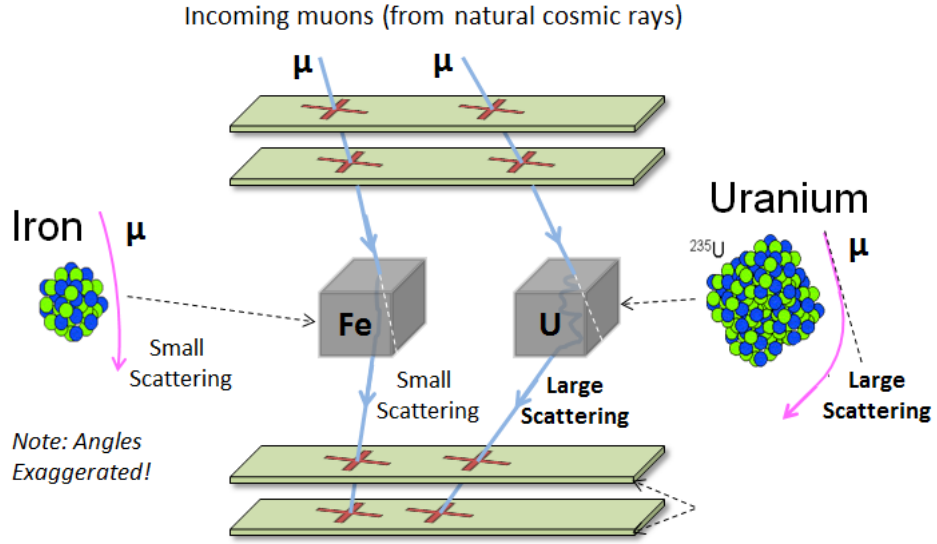


Figure 41: When a muon interacts with matter

c is the speed of light,

β is muon's speed divided by the speed of light,

p_m is the momentum of the muon,

T is the thickness of the material.

and the X_0 which is called as Radiation Length can be expressed as

$$X_0 = \frac{716.4 A_w}{Z(Z+1) \ln \left(\frac{287}{\sqrt{Z}} \right)} (g/cm^2) \quad (2)$$

where

A_w is the atomic weight of the medium in g/mol,

Z is the atomic number of material,

Equation 1 and Equation 2 show that the deviation angle of the muon highly depends on the atomic number (Z) and thickness of the material that the muon interacts with.

4.3 *A Practical Uses of the Multiple Scattering of Muons in High Z Materials: Muon Tomography/Radiography Applications*

These trajectory changes can be reconstructed as a result of post-processing of the received data, thanks to the particle detectors we have in high-energy physics. These detectors could be placed in the areas where detailed scanning is desired, and critical information can be obtained about these areas by using the MCS principle described in Section 4.2.2.1. This advanced technology is called Muon Tomography or Muon Radiography. The only difference between these two is in Tomography, the detectors are placed on more than one side of the target, like sandwiching it, while in Radiography, these detectors are placed on one side of the target, and an image of the scanned area is created with the shading technique.

This technology has many application areas. The most well-known of these, the Muon Tomography Device, which was used in the discovery of a new secret corridor in the Giza Pyramids in 2016, showed the world its potential when used correctly with this project. The study, which won the Nobel Prize in History with this discovery, also managed to attract the attention of the scientific world.

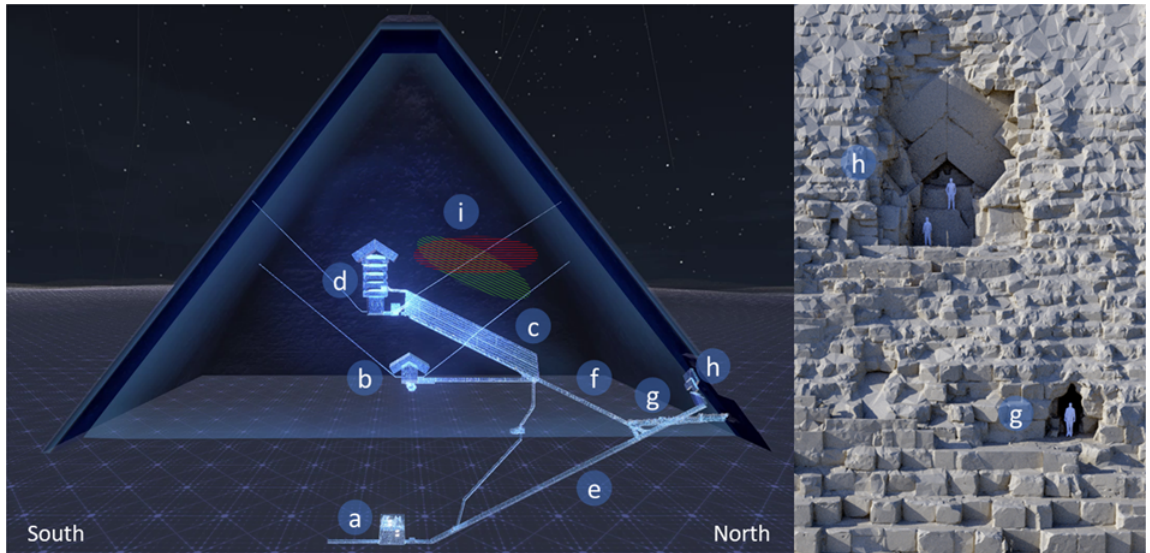


Figure 42: The points where detectors are put in Giza Study.

Of course, although many studies have been done on a device with such great

potential, it takes time to collect enough data to create an image due to the use of cosmic muons as a source.

This technology can also be used to obtain information about the properties of volcanos. As another example, countries can detect nuclear material smuggling in containers at international borders with Muon Tomography. This innovative detection method intercepts potential threats before they cause harm, keeping citizens safe. (see Figure 55).

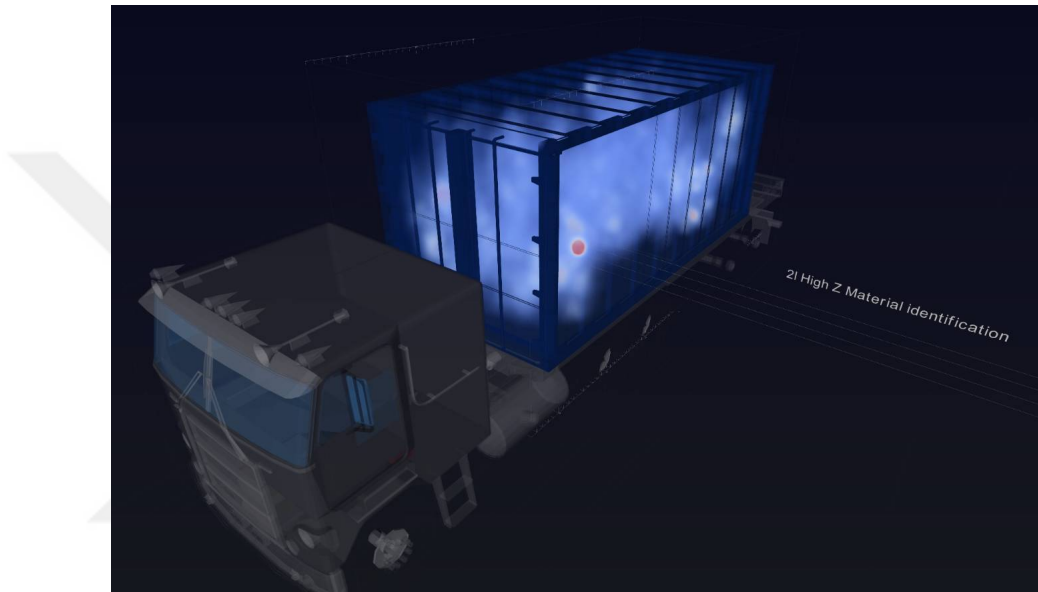


Figure 43: An example for Muon Tomography.

4.4 *GEANT4*

GEometry ANd Tracking, short for GEANT4, is an open-to-use software package written in C++ that was seeded by CERN and KEK in 1993. This software package is specifically used to simulate situations where the need to simulate high-energy particles arises. GEANT4 is used in many fields from nuclear and particle physics to medical physics, from radiation protection to space science, thanks to its ability to simulate the interactions of all kinds of particles with all kinds of matter and the movements of secondary particles formed as a result of these interactions.

4.5 A simulation study on Muon Tomography using GEANT4

Muon tomography is a method used to detect cosmic muons reaching the earth by detectors and detect their trajectories with certain analysis methods. GEANT4 is one of the most popular programs in this field with its detailed physics models, flexible geometry definition, and Visualization tools.

Thanks to these features, GEANT4, a program that can simulate in detail how muons interact with matter and what kind of trajectory they follow as a result of these interactions, has a very important place in studies for designing and optimizing more efficient muon tomography systems.

The aim is to have a basic muon tomography simulation to make deeper studies in the future and have some insights about the following question with the basic Muon Tomography Simulation: "Which detectors in the ATLAS Muon Spectrometer can be used in the Muon Tomography with POCA Method?" by comparing their spatial resolutions (see Section 4.5.2).

For each detector's spatial resolution, there are sub-simulations that test the imaging of the target's material (different atomic numbers) and different thicknesses of the materials) as it will be explained in Section 4.5.3. These parameters are very important parameters since, in future studies, the efficiency of the muon tomography can be increased by optimizing the results.

As it's briefly mentioned in Section 4.1, the trivets of a muon tomography which are the source (cosmic muons), The Detector System, the Target, and the Post-processing analysis (Section 4.6) is needed to be added to the simulation. The following 4 subsections will explain the details of how these 4 trivets were created in the computer environment with GEANT4 and Phyton3.

4.5.1 Source: Cosmic Muons and ParticleGeneration in GEANT4

High-energy cosmic rays entering the Earth's atmosphere collide with atoms in the atmosphere and form many particles. These particles travel at almost the speed of light. In Figure 40 below, you can see the process that a cosmic ray creates

when it interacts with atoms in the atmosphere.

The point to be noted in this figure is that 2 types of particles can reach the Earth. These are muons and neutrinos. As mentioned in Section 2.2.4, these particles can travel more distances due to their high masses and reach the earth's surface. Since we can detect muons reaching the earth with detectors such as those used in the Muon Spectrometer in the ATLAS Detector, many studies have been conducted on the use of cosmic muons. Cosmic muons are seen as an ideal source for tomography since muons can also penetrate materials with high atomic numbers due to their high mass.

There are several sophisticated ways to generate cosmic muons in GEANT4. In addition to the existence of cosmic muon generators called CRY that can be integrated with GEANT4, creating a cosmic muon shower with some preliminary processes to be created in GEANT4 is possible.

This thesis randomly generates cosmic muons from a rectangular plate at the center (0,0,100). This allows for more time to be spent on the sensitive detector and post-processing aspects of the simulation during the limited time in master studies. Momentum directions of these created muons are determined by randomly choosing the theta angle between 355 degrees and 1 degree and the phi angle between 0 and 360 degrees to the normal surface of the plate in order to increase the running speed of the code. Muons in the simulation are generated in the direction of this origin and momentum. The energies of muons in the simulation are randomly chosen in a Gaussian distribution with a mean value of 3 GeV, similar to the energies of cosmic muons.

Although the simulation with cosmic muons is more inefficient than the studies, it is considered appropriate as a starting step.

4.5.2 Detector System - Detector Construction

In the first few months, my thesis aimed to create a comprehensive simulation of Muon Tomography using ATLAS RPCs.

After conducting studies in the first six months, it became clear that simulating

the Avalanche effect in RPCs through GEANT4 required the addition of other programs like Garfield++. Recent experimental data indicates that the Avalanche event in RPC differs from GEANT4 simulations, even when the Garfield program is used. It's realized that studying this kind of big problem should be addressed over a longer period of time.

From this point on, it was decided to make use of GEANT4's SensetiveDetector library without simulating the physical events that occur during particle detection inside the detectors to be used in the simulation. Thanks to this library, the active volume of the detector is added to the GEANT4 simulation as a sensitive detector. Each particle interacting with this sensitive volume is detected by the detector. After the first step of this interaction, this particle's x, y, and z positions at the first step are recorded in an output file.

In the first simulation 4.7.1, ideal detectors are used, and the waypoints of muons are recorded as if detectors had an infinite resolution.

Then, in the second simulation 4.7.2, the detector systems have finite spatial resolutions of 1 cm, 1 mm, and 100 μ m is added to the simulation since the detectors at ATLAS Spectrometer have spatial resolutions from 1 cm to 50 μ m. Detectors in ATLAS Muon Spectrometer examined in 2 categories in Section 2.2.4. The Trigger Detectors (RPCs and TGCs) and the Tracking Detectors (MDTs and CSCs) have different spatial resolutions in the range of the order of magnitude. Since as ATLAS TR, we've been a part of the ATLAS RPC Team for several years, the first aim is to check if the ATLAS RPCs are capable of being used in Muon Tomography. Then, the other detectors, such as MDTs and CSCs will be tested with 100 μ m resolution since their spatial resolutions are 80 μ m and 50 μ m, respectively. Then all these results are compared and discussed.

The Detector System is added to the simulation as ideal rectangular prism volumes 3 on top, and on the bottom. The X-Z cross-section of the setup without a target is shown in Figure 44. You can see that the detectors (3 black prisms at the top and 3 black prisms at the bottom have dimensions 50cm $\times$ 50cm $\times$ 1mm.

The blue prism at the top of the detectors is the prism whose surface is used as a source.

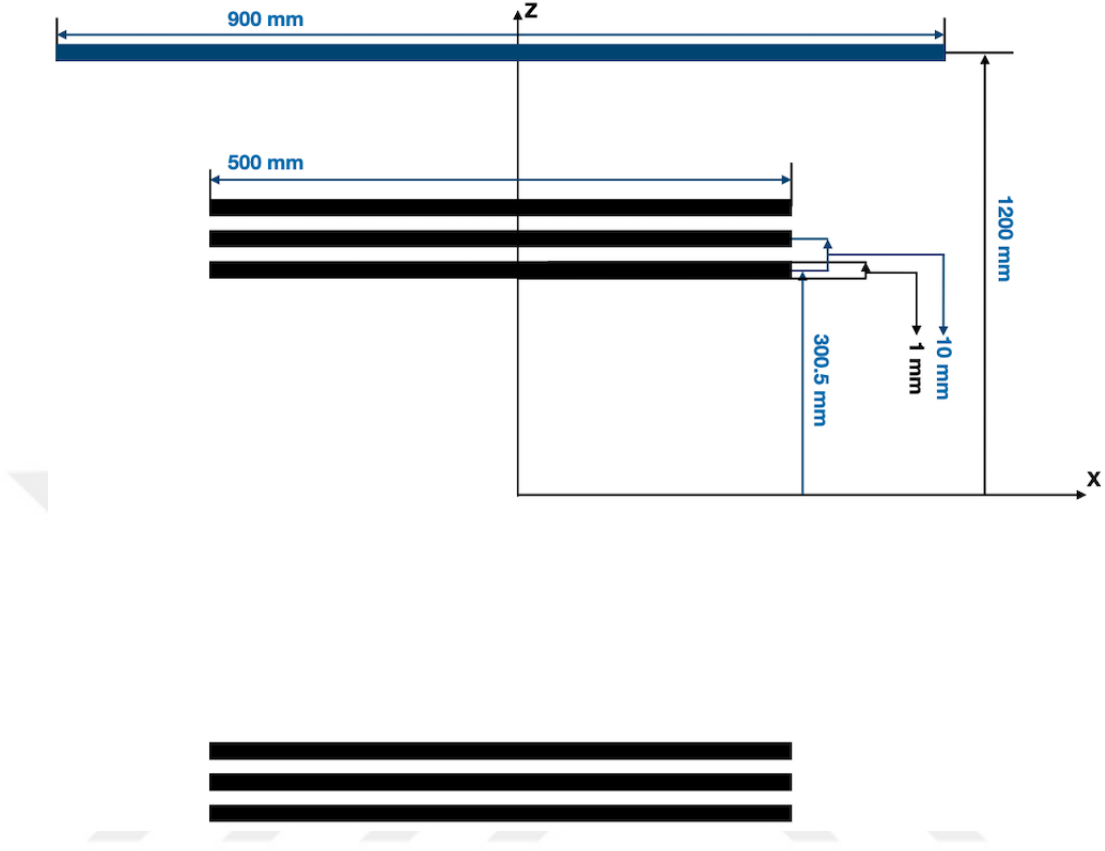


Figure 44: X-Z Cros section of the Setup without a Target.

4.5.3 The Target

Target, in imaging technologies, is the place/region or object you want to image. The properties of the targets in muon tomographies vary greatly according to the usage of muon tomography. For example, in a Muon Tomography designed for border security, the targets are materials with a high atomic number in the order of cm, while the target in the detection of a volcanic mountain can be a very large cave.

Since this thesis aims to make a generic design that works with ATLAS detectors rather than a detailed design according to the application area, the targets consist of rectangular prisms with x-y sides are 10 cm while the thicknesses are 1 cm, 5 cm, 10 cm, 15 cm.

In each simulation and/or sub-simulation, various results were compared by changing the position, shape, and thickness of the target.

Mainly, there are 2 different setups in the simulations with targets. First, there might be a Pb box at the center of the world as it's shown in Figure 57 and Figure 56, or 4 boxes placed, as shown in Figure 58 and Figure 59. These 4 targets' materials and thicknesses are changed in different simulations.

4.5.4 Output of GEANT4 Simulation

This GEANT4 simulation run gives an output with 5 columns. Each line contains information about when a particle interacts with the sensitive volumes in the simulation. Table 3 below and 6 in the appendices, shows a small section of the output file from the simulation. As can be seen in this table, the 1st column contains the Event Number, the 2nd column contains the Sensitive Volume's ID, and the 3rd, 4th, and 5th columns contain the x,y, and z values where the particle is detected.

Table 3: Output Data Sample from GEANT4 Simulation

EVENT NO	DETECTOR ID	X(mm)	Y(mm)	Z(mm)
1900	0	170.375	56.7428	322
1900	1	169.374	52.8663	311
1900	2	168.373	48.9898	300
1900	3	113.681	-162.809	-301
1900	4	112.68	-166.685	-312
1900	5	111.679	-170.562	-323
1902	0	-194.974	13.7923	322
1902	1	-197.895	16.5301	311
1902	2	-200.817	19.268	300
1903	0	219.952	-141.931	322
1903	1	219.021	-145.825	311

1903	2	218.089	-149.718	300
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4.6 *Post Processing Algorithm*

Before going into the details of the algorithm of the analysis code written for Post-Processing, let's briefly explain the Point of Closest Approach used in this simulation study.

4.6.1 Point of Closest Approach (POCA) Method

Point of Closest Approach, or POCA in short, is an analysis method that helps us find the points where two lines are closest to each other in 3-dimensional space. This method, which is frequently used in 3D imaging, was also used for Muon Tomography in this simulation.

4.6.1.1 *Parametric Equation of a Line:*

Parametric equations of lines are often used to describe lines in 3-dimensional spaces. The parametric equation of each line defined depending on a parameter to indicate any point on the line can be represented as:

$$\text{Line 1: } r(\lambda) = a + \lambda b \quad (3)$$

where a is the starting point of the line, b is the direction vector of the line, λ is the parameter in real numbers.

Here, as the value of λ changes, a different point is reached on the line.

Especially in Physics and Engineering, it is a form used when it is desired to operate on any point on lines and/or surfaces in 2 and 3-dimensional spaces.

4.6.1.2 *Point of Closest Approach:*

Let's define the incoming and outgoing trajectories of muons as the following lines:

$$\text{Line 1: } r1 = a1 + \lambda b1 \quad (4)$$

$$\text{Line 2: } r2 = a2 + \mu b2 \quad (5)$$

Here, as the value of λ changes, a different point on the $r1$ line is reached. Likewise, as the value of μ changes, a different point is reached on the line $r2$.

For example:

For $\lambda = 0$, $r1 = a1$. That is, we get the starting point of the $r1$ line.

For $\lambda = 1$, $r1 = a1 + b1$. This specifies the point on the line $r1$ when we move one unit along the $b1$ direction vector. Similarly, the same applies to μ .

These parameters are used to determine the closest points between two lines. Minimizing the square of the distance between two lines, the values of λ and μ indicate the positions of the closest points between the two lines.

Then we can find the distance between the two lines by subtracting these two parametric equations from each other.

$$d(\lambda, \mu) = |(a1 + \lambda b1) - (a2 + \mu b2)| \quad (6)$$

In order to solve this equation for minimum λ and μ , first we need to take the square of this distance.

$$d^2(\lambda, \mu) = |(a1 + \lambda b1) - (a2 + \mu b2)|^2 \quad (7)$$

Then, we need to take its derivatives with respect to λ and μ and set them equal to zero.

$$\frac{\partial d^2(\lambda, \mu)}{\partial \lambda} = \frac{\partial |(a1 + \lambda b1) - (a2 + \mu b2)|^2}{\partial \lambda} = 0 \quad (8)$$

$$\frac{\partial d^2(\lambda, \mu)}{\partial \mu} = \frac{\partial |(a1 + \lambda b1) - (a2 + \mu b2)|^2}{\partial \mu} = 0 \quad (9)$$

From the solution of these equations, the formulation of the following points λ_{min} and μ_{min} is reached shown in Equation 10 and Equation 11.

$$\lambda_{min} = ((a2 - a1) \cdot b1)/(b1 \cdot b1) \quad (10)$$

$$\lambda_{min} = ((a1 - a2) \cdot b2)/(b2 \cdot b2) \quad (11)$$

These 2 points found are the positions of the 2 closest points on the muon's incoming and outgoing lines.

Finally, to find the midpoints of these 2 points in 3D space, these points are added together and divided into two.

$$p_i = \frac{\lambda_{min} + \mu_{min}}{2} \quad (12)$$

Thus, the midpoint of the distance between the closest points between the two lines is found.

In this thesis, the point found is accepted as the point where two lines intersect as a single scattering assumption, and these points are drawn as a result by using Python3.

4.6.2 Post Processing Algorithm in This Thesis

The algorithm working in the post-processing part of this simulation study finds the poca points of the particles as follows and prints them to another file.

Then, the calculation of how much these incoming and outgoing lines deviate from each other in 3 dimensions is done as follows, and these values are used for the output.

4.6.3 Visualization of Results

These points are then plotted in 3D space. There are 2 types of plots in Section 4.7. As an example, Figure 45 shows the Raw POCAs, which means plotting the POCAs directly in 3D space, while Figure 46 shows a plot of these POCAs into a histogram at Z=0 plane and while plotting them, the angle deviation is calculated by POCA approach and added as a parameter for each bin to color the points

with respect to bin's total angle deviation. With this strategy, the higher angle deviations due to high Z materials can be detected easily with higher frequency dots. As a summary, dots plotted in more red indicate higher angle deviations on that point which means there is a higher Z material in that point with respect to the environment.



4.7 Results and Discussions

The simulation parameters are listed below and categorized into 2 parts: Infinite Spatial Resolution and Finite Spatial Resolution.

Table 4: Simulation Parameters with Infinite Resolution Detectors in GEANT4 where "T" stands for the thickness of the target and "M" for the material of the target.

Sim No:	World Medium	T1	M1	T2	M2	T3	M3	T4	M4
1	Vacuum	1 cm	$_{82}Pb$	5 cm	$_{82}Pb$	10 cm	$_{82}Pb$	15 cm	$_{82}Pb$
2	Air	1 cm	$_{82}Pb$	5 cm	$_{82}Pb$	10 cm	$_{82}Pb$	15 cm	$_{82}Pb$
3	Vacuum	15 cm	$_{82}Pb$	15 cm	$_{92}U$	15 cm	$_{26}Fe$	15 cm	$_{13}Al$
4	Air	15 cm	$_{82}Pb$	15 cm	$_{92}U$	15 cm	$_{26}Fe$	15 cm	$_{13}Al$
5	Air	1 cm	$_{82}Pb$	1 cm	$_{92}U$	1 cm	$_{26}Fe$	1 cm	$_{13}Al$

Table 5: Simulation Parameters with Finite Resolution Detectors in GEANT4

Sim No:	World Medium	T1	M1	T2	M2	T3	M3	T4	M4
6	Vacuum	1 cm	$_{82}Pb$	5 cm	$_{82}Pb$	10 cm	$_{82}Pb$	15 cm	$_{82}Pb$
7	Air	1 cm	$_{82}Pb$	5 cm	$_{82}Pb$	10 cm	$_{82}Pb$	15 cm	$_{82}Pb$
8	Air	15 cm	$_{82}Pb$	15 cm	$_{92}U$	15 cm	$_{26}Fe$	15 cm	$_{13}Al$

4.7.1 The Results and Discussion for Infinite Resolution: Simulation 1,2,3,4 and 5

As it's seen from the figures below, with infinite resolution detectors, it's possible to detect the high Z materials with triplet detector volumes that have a similar design to BI78-RPCs but a prototype one¹.

As it's seen from Figure 45 and Figure 46, it's obviously seen that with the POCA Algorithm, it's possible to detect the high Z Materials. Also, the edges of the shapes are well drawn with and without air.

In Figure 45, we can see that when the thickness of the same material ($_{82}Pb$) is reduced to 1 cm, differentiating it from the surroundings becomes harder.

In Figure 47, you can see how different atomic numbers are detected. Since $_{13}Al$ has the lowest Atomic Number value, it's harder to distinguish it from the

¹ATLAS RPC Team generally produces prototypes of any new detector for performance studies. In this thesis, 50 cm X 50 cm X 1mm detector volumes are used in the simulation as the prototype of new BIS78 RPCs' gas volumes. It's important to note that spatial resolutions of these detector volumes in the simulation change!

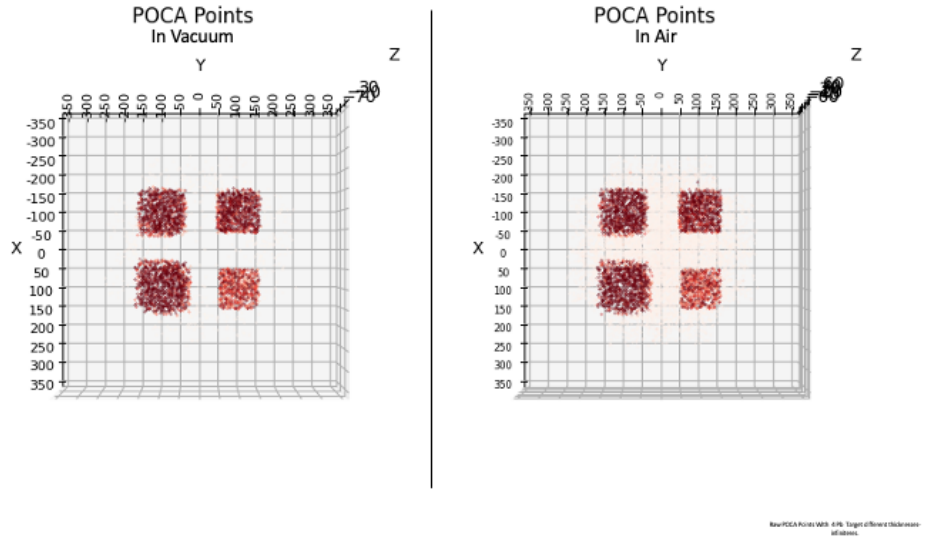


Figure 45: The Raw Poca Points of Simulation 1 and 2

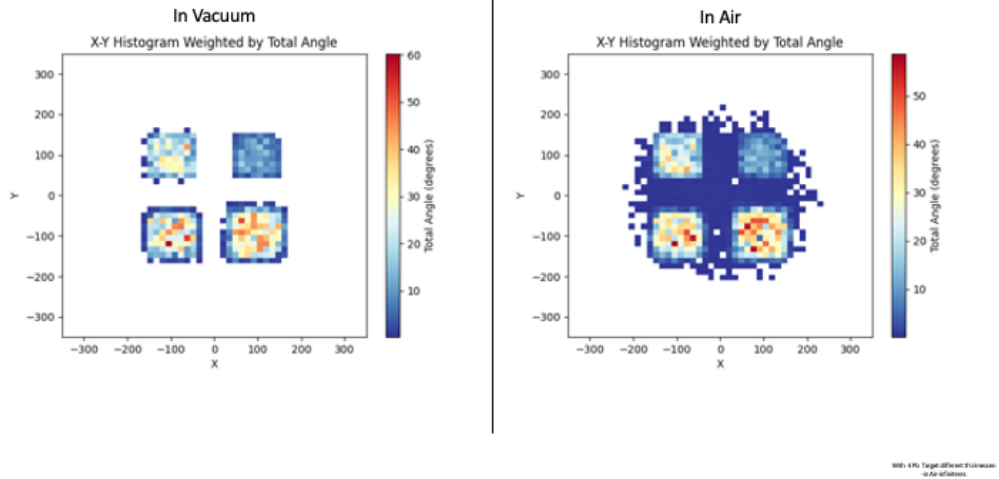


Figure 46: The x-y Histogram of Raw Poca Points Weighted by Total Angle - Simulation 1 and 2.

environment with respect to other higher Z materials such as Lead ($_{82}Pb$), Iron ($_{26}Fe$) and Uranium ($_{92}U$). And it's obvious that ($_{92}U$) is the easiest to detect. In Simulation 4, the thicknesses of the materials are 15 cm. Now, if you look at Figure 48, which is the result of Simulation 5, the thicknesses of the 4 elements are reduced to 1 cm. When you compare Figure 3 with Figure 4, it is seen that the detection of $_{13}Al$ target is getting harder and harder. The reason for this is that

the thickness of the already low atomic number Aluminum target is also reduced to 1 cm, and the muons are exposed to lower angle deviation when interacting with this target.

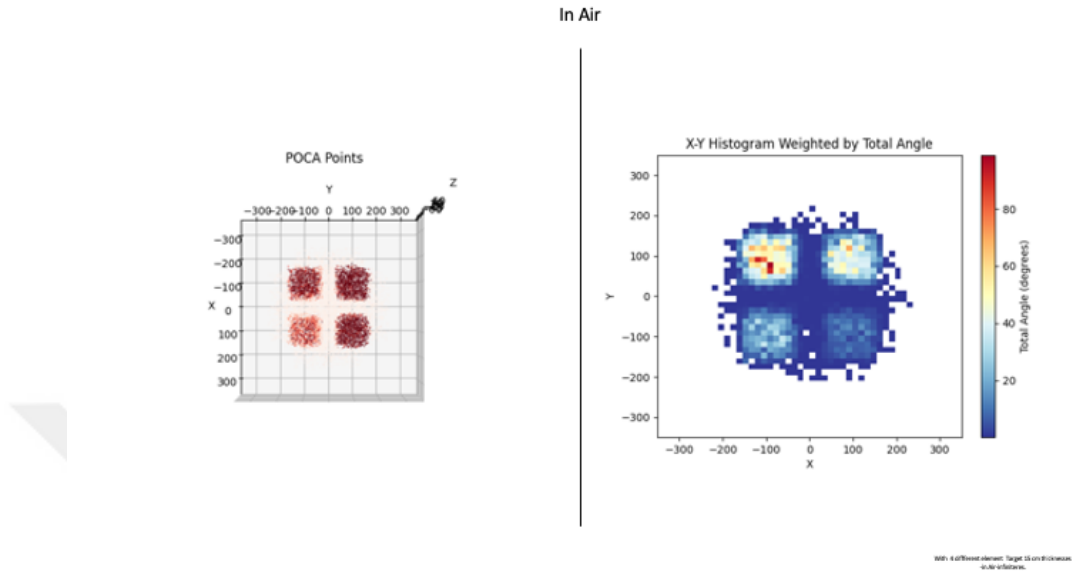


Figure 47: The Raw Poca Points of Simulation 4 and 5

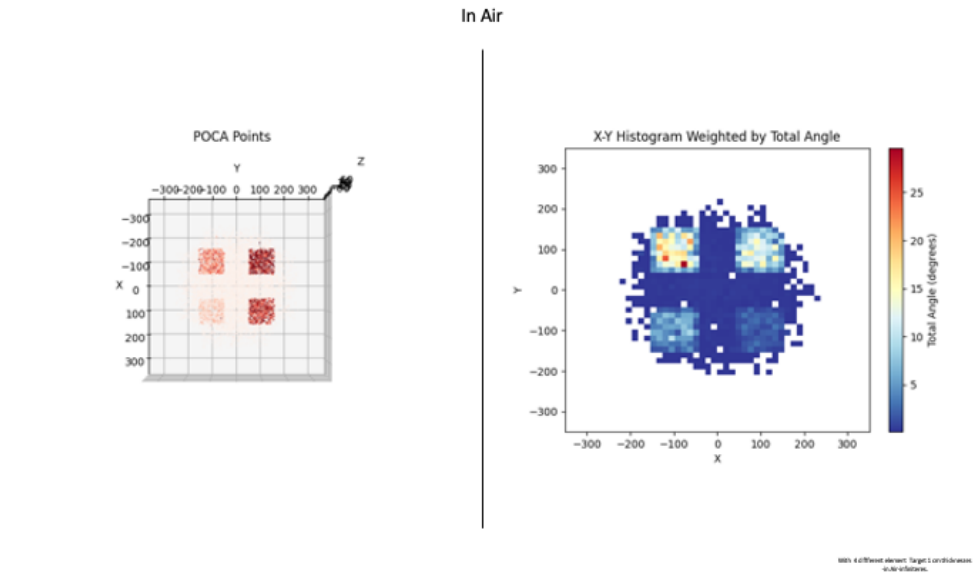


Figure 48: The x-y Historam of Raw Poca Points Weighted by Total Angle - Simulation 4 and 5.

4.7.2 The Results and Discussion of Simulation 5,6,7,8

In this category, simulations are done to measure the spatial resolution limits of the POCA Method. So, in the same detector conditions, only one prisma(Pb) is put at the center of the World rather than 4 different elements as a first step.

As it's seen from Figure 49, with a $1\mu\text{m}$ resolution detector 2D image result of a cube at the center has a dimensions of $10\text{cm}\times 10\text{cm}\times 10\text{cm}$. Figure 50 shows the results of a detector that has a spatial resolution of 1 mm, and Figure 51 shows 1 cm. Figure 52 shows the muon tomography result without a target.

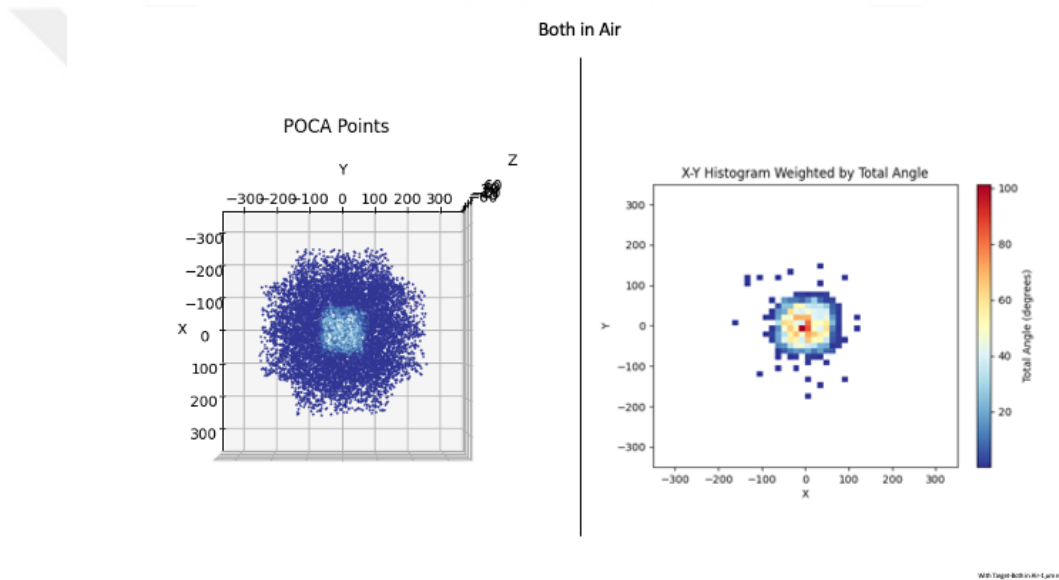


Figure 49: Results of Post-Processing of $1\mu\text{m}$ spatial resolution detectors with a target.

When we examined these figures, the decrease in spatial resolution brought the image, which we obtained only with POCA method and deviation angel filter, to a point where the shape of the box could no longer be detected at 1 mm resolution. However, when you compare it with the results of the "without target" simulation (52, it's possible to say that there is a high Z material in the world we scan.

When we compared Figure 52 (without target) and Figure 51 (the results of detectors with 1 cm resolution), with each other, it was seen that we could

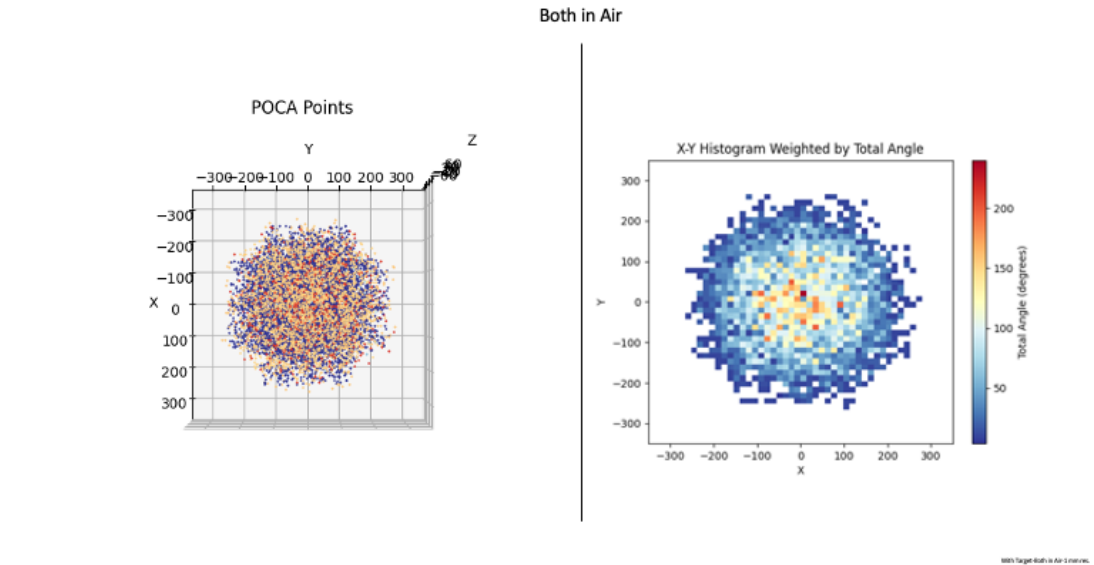


Figure 50: Results of Post-Processing of 1 mm spatial resolution detectors with a target.

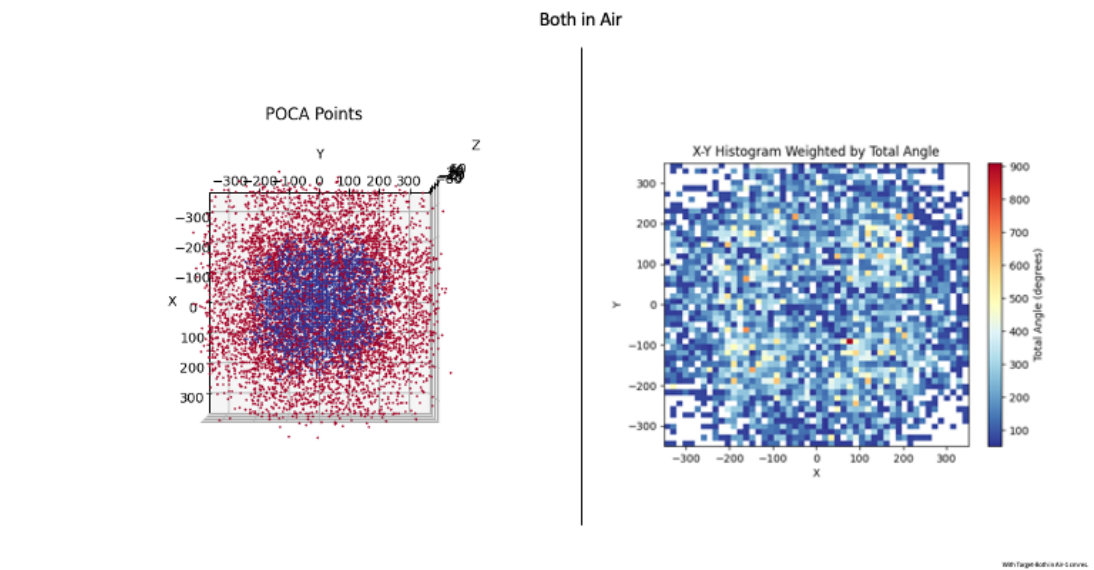


Figure 51: Results of Post-Processing of 1 cm spatial resolution detectors with a target.

no longer detect whether there was a target in the scanned area with our post-processing method.

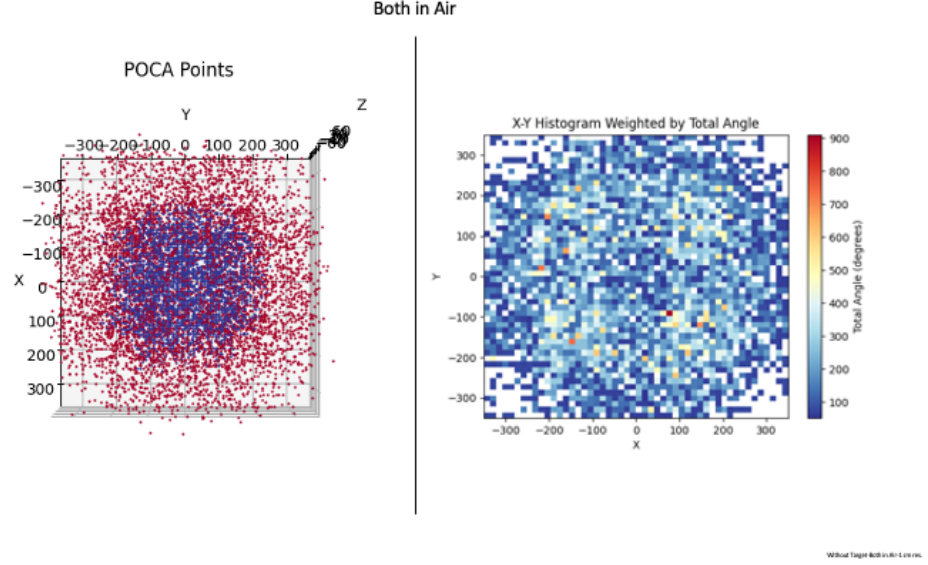


Figure 52: Results of Post-Processing of 1 cm spatial resolution detectors without a target..

4.7.3 Substraction of Background Data

In order to solve this situation, it was decided to use the "Background Subtraction" method, which is frequently used in High Energy Physics. The histogram in Figure 51, which is the result of detectors with 1 cm resolution, and the histogram in Figure 52, which was created without a target, were subtracted. As a result of this process, the following result was obtained.

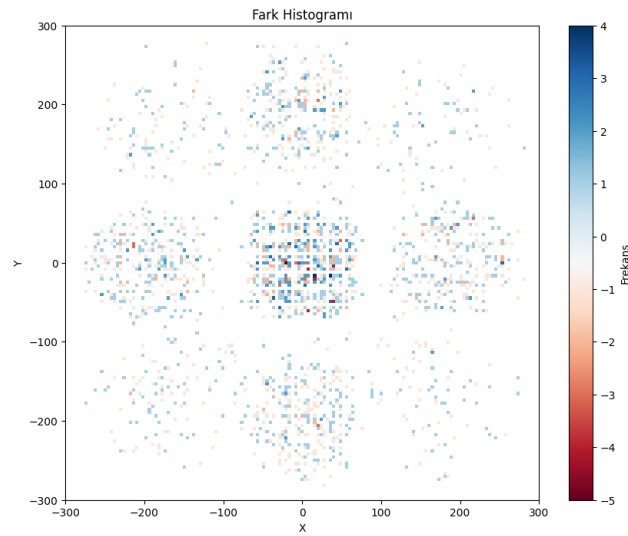


Figure 53: The Histogram Difference for a ($_{82}Pb$) box

As can be seen in Figure 53, with this filtering method, it has become possible to detect the ($_{82}Pb$) box in the center with detectors with 1 cm resolution.

In order to verify this result, instead of 1 target in the center, the box consisting of 4 different elements was placed as in Simulation 7 (see Figure 58 and Figure 59) and this filter was applied again, and the result in Figure 54 below was reached.

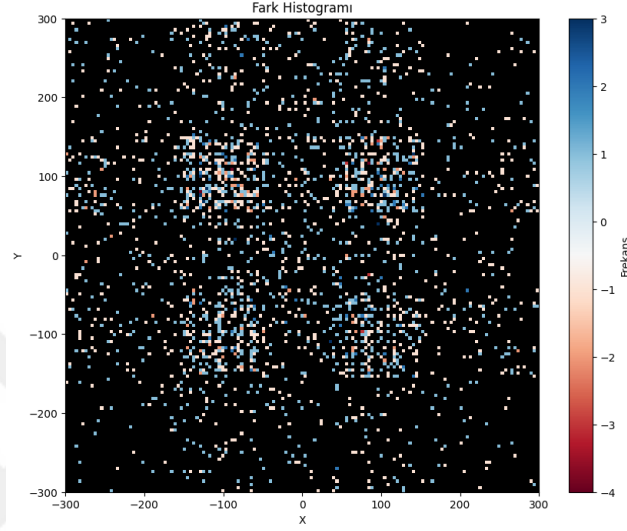


Figure 54: The Histogram Difference for 4 different elements boxes. In this image, the zeros (completely white pixels) turned to black to observe the data better.

As can be seen in this figure, the capability of detection decreases from the one with the highest atomic number to the lowest. However, the detection of Uranium and Lead can still be done relatively. Note that the black background was actually white, as it's seen from the Frequency Range at the right of the plot. All whites were replaced with blacks to see the result more effectively.

4.7.4 General Discussion about Future Design

The purpose of this chapter was to predict which detectors in the ATLAS Muon Spectrometer can be used in Muon Tomography. It was understood from the results of the simulations that all the detectors (especially ATLAS RPCs) in the ATLAS Muon Spectrometer could be used in Muon Tomography when various post-processing methods were used. It's shown that the spatial resolution of 1 cm detector volumes, which is equal to the spatial resolution of RPCs (the lowest resolution), can also be used to determine the shapes of materials with high atomic numbers by using the background subtraction method.

CHAPTER V

CONCLUSION AND IDEAS FOR THE FUTURE

5.1 *Conclusion and Future Studies for ATLAS RPC Muon Spectrometer*

5.1.1 Conclusion

It has been understood from the studies carried out at ATLAS that gas leakage problems in the ATLAS RPC Gas System can be transformed into minor issues with creative and effective operational studies.

5.1.2 Future Studies

The workforce in ATLAS's creative and effective studies should be increased and sustained. Studies to improve and systematize collaborations, such as the one with the ATLAS Sustainability Forum, have started in recent months. Thus, a much larger campaign will be carried out systematically, reducing the gas leakage problem immediately. This extension of team studies should be carried out to increase the number of Injector Experts, which is the most important part of the team to be expanded. Thus, the parallel application capacity of the technique will be increased, and it will be possible to eliminate these gas leaks that occur at hundreds of points in a shorter time.

Also, the Research and Development Studies for Foam Reparation Technique must be carried out in a more organized way. In order to do that a Research and Development Team by İstinye Institute members are established and studies for deeper R%D has started.

The first aims of R%D studies are

- Design Studies for Automatization of Injection Step Tests of the Second Injection Idea
- Tests of More Vertical Sectors

- Studies for Replacing the clay method with a new one

On the other hand, the advantages of operational tests and leak repair work were cumulatively seen in the Fresh Gas Consumption values 2023. It is necessary to find the bugs in the ATLAS RPC Gas System by performing such tests continuously and eliminating them immediately.

5.2 Conclusion and Future Studies for Muon Tomography Studies

5.2.1 Conclusion and Future Studies

Muon Tomography Simulation studies with GEANT4 have shown that detectors in the ATLAS Muon Spectrometer, including ATLAS RPCs, can in principle be used for Muon Tomography. This study not only enabled us to confirm this knowledge, but also created a very healthy basis for PhD studies, which is the next step in an academic career.

After this point, longer-term plans can be made to carry out a Muon Tomography study in Turkey with various collaborations with the ATLAS RPC Team. The usage area of this tomography device to be made can be in many subjects. It is possible to work on a design that will be used in many areas, from examining a historical region of Turkey with this device to homeland security.

Of course, before these studies, the GEANT4 simulation presented in this thesis needs to be made more realistic in terms of Detector Physics and Cosmic Muon Generation. In addition, Post-Processing Methods need to be developed in order to create the image to be created in a faster time.

APPENDIX A

EXTRAS FOR CHAPTER 4

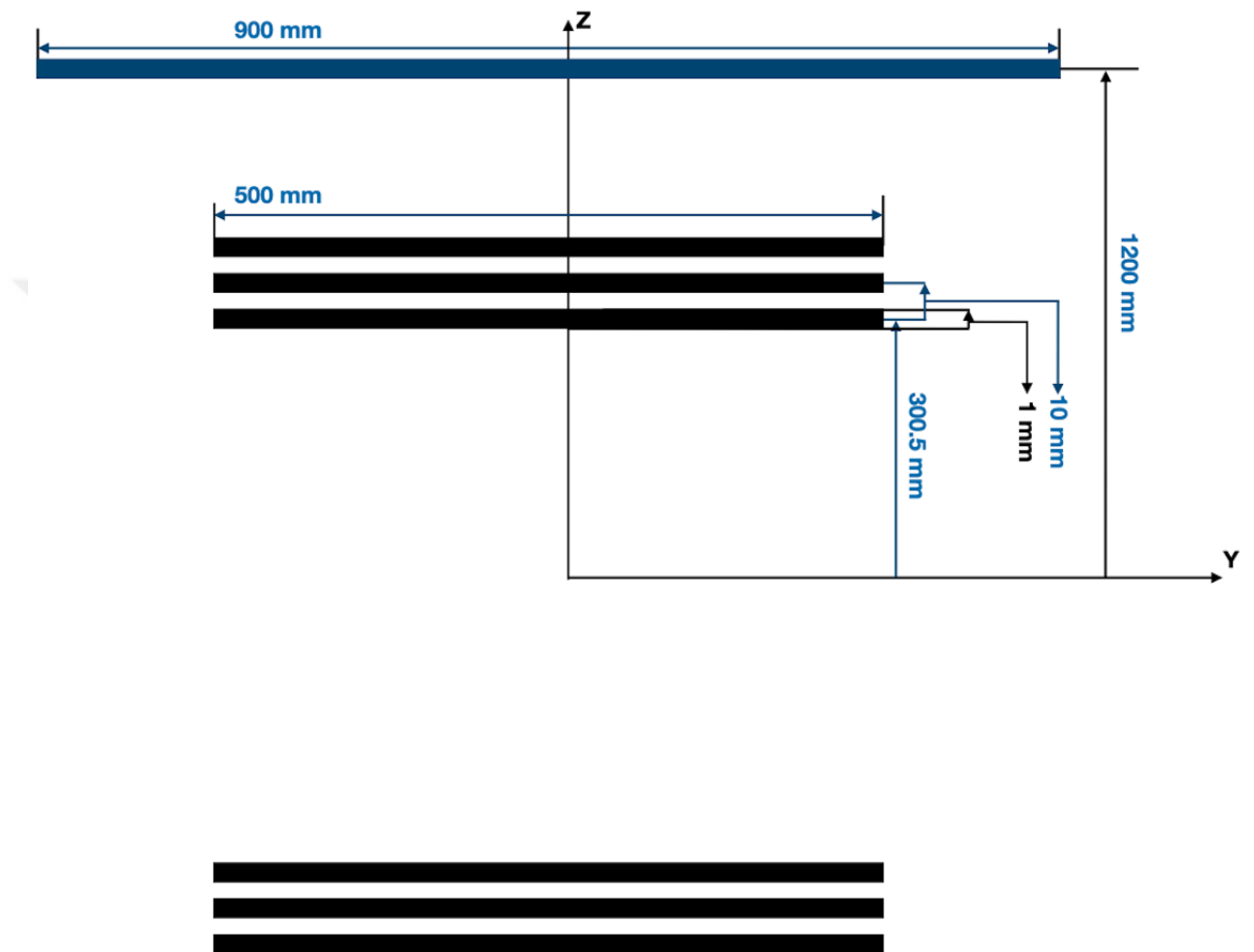


Figure 55: Y-Z Cross-Section of the Setup without a target .”in mm”

Table 6: Output Data Sample from GEANT4 Simulation

EVENT NO	DETECTOR ID	X(mm)	Y(mm)	Z(mm)
1900	0	170.375	56.7428	322
1900	1	169.374	52.8663	311
1900	2	168.373	48.9898	300
1900	3	113.681	-162.809	-301
1900	4	112.68	-166.685	-312
1900	5	111.679	-170.562	-323
1902	0	-194.974	13.7923	322
1902	1	-197.895	16.5301	311
1902	2	-200.817	19.268	300
1903	0	219.952	-141.931	322
1903	1	219.021	-145.825	311
1903	2	218.089	-149.718	300
1906	0	-26.9184	180.862	322
1906	1	-26.6431	184.856	311
1906	2	-26.3678	188.85	300
1909	0	132.69	-180.163	322
1909	1	129.164	-178.267	311
1909	2	125.637	-176.372	300
1909	3	-67.0373	-72.8034	-301
1909	4	-70.5638	-70.9078	-312
1909	5	-74.0903	-69.0122	-323
1922	0	-226.945	170.016	322
1922	1	-226.9	174.019	311
1922	2	-226.856	178.023	300
1926	0	-56.3806	230.747	322

1926	1	-52.4117	231.274	311
1926	2	-48.4428	231.8	300
1935	0	127.899	96.4816	322
1935	1	127.677	92.4841	311
1935	2	127.455	88.4865	300
1935	3	115.328	-129.923	-301
1935	4	115.106	-133.921	-312
1935	5	114.884	-137.918	-323
1936	0	241.09	162.124	322
1936	1	240.103	166.004	311
1936	2	239.117	169.885	300
1937	0	240.711	139.166	322
1937	1	242.806	135.754	311
1937	2	244.9	132.342	300
1944	0	-83.6901	9.59835	322
1944	1	-79.6928	9.37288	311
1944	2	-75.6955	9.14742	300
1944	3	148.749	-7.11222	-301
1944	4	152.926	-7.48148	-312
1944	5	157.102	-7.85074	-323
1968	2	18.7567	-127.91	300
1968	3	-32.0923	78.8908	-301
1968	4	-33.0141	82.6201	-312
1968	5	-33.936	86.3493	-323
1972	0	206.577	163.366	322
1972	1	206.911	167.356	311
1972	2	207.246	171.346	300
1975	0	171.484	-191.736	322

1975	1	171.076	-195.718	311
1975	2	170.667	-199.701	300
1979	0	-222.03	106.317	322
1979	1	-222.441	102.335	311
1979	2	-222.853	98.3522	300
1979	3	-245.335	-119.235	-301
1979	4	-245.746	-123.218	-312
1979	5	-246.158	-127.2	-323



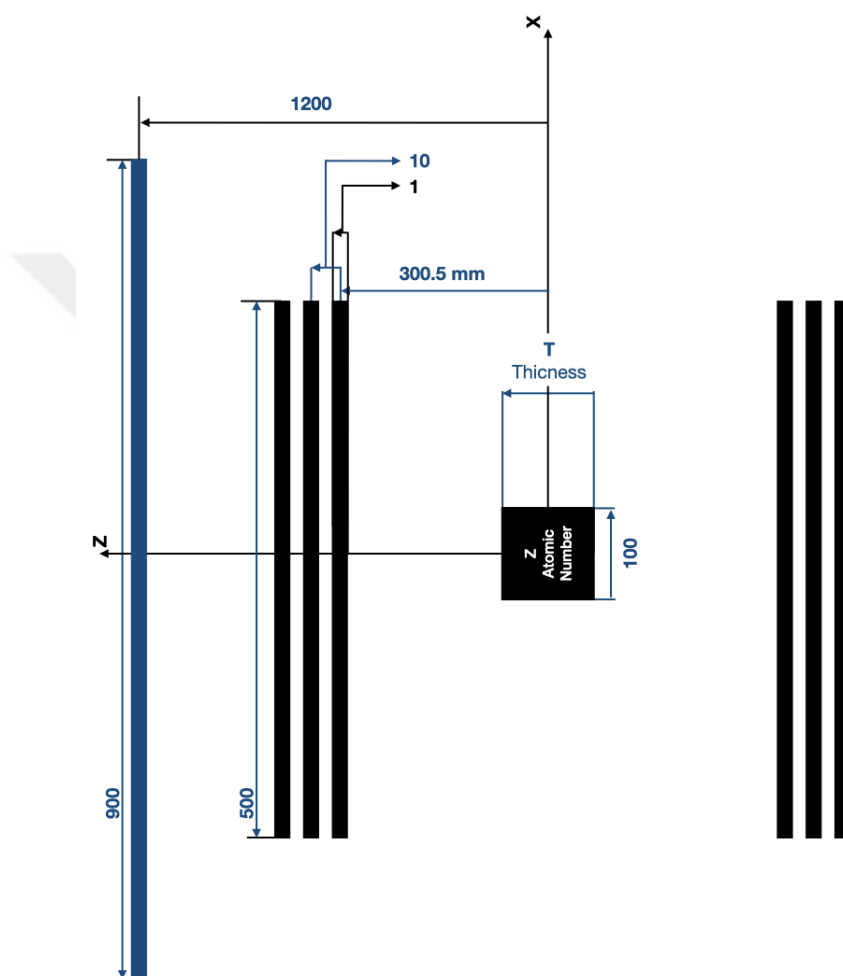


Figure 56: Y-Z Cross-Section of the Setup with 1 target.”in mm”

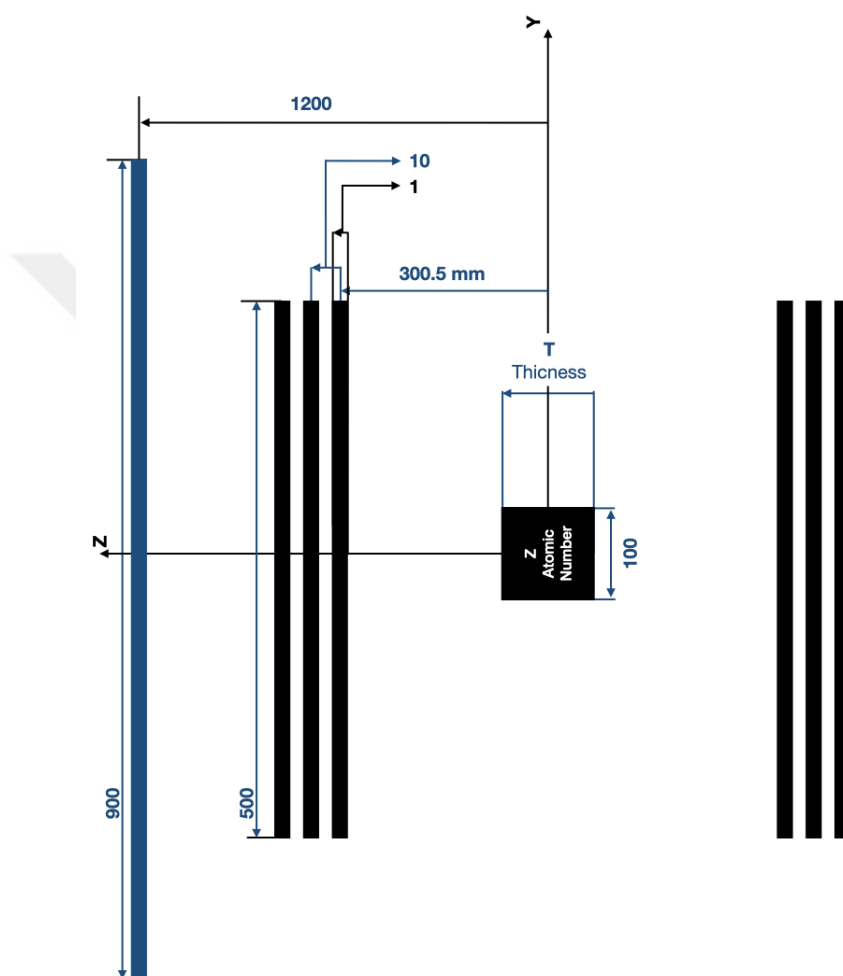


Figure 57: Y-Z Cross-Section of the Setup with 1 target.”in mm”

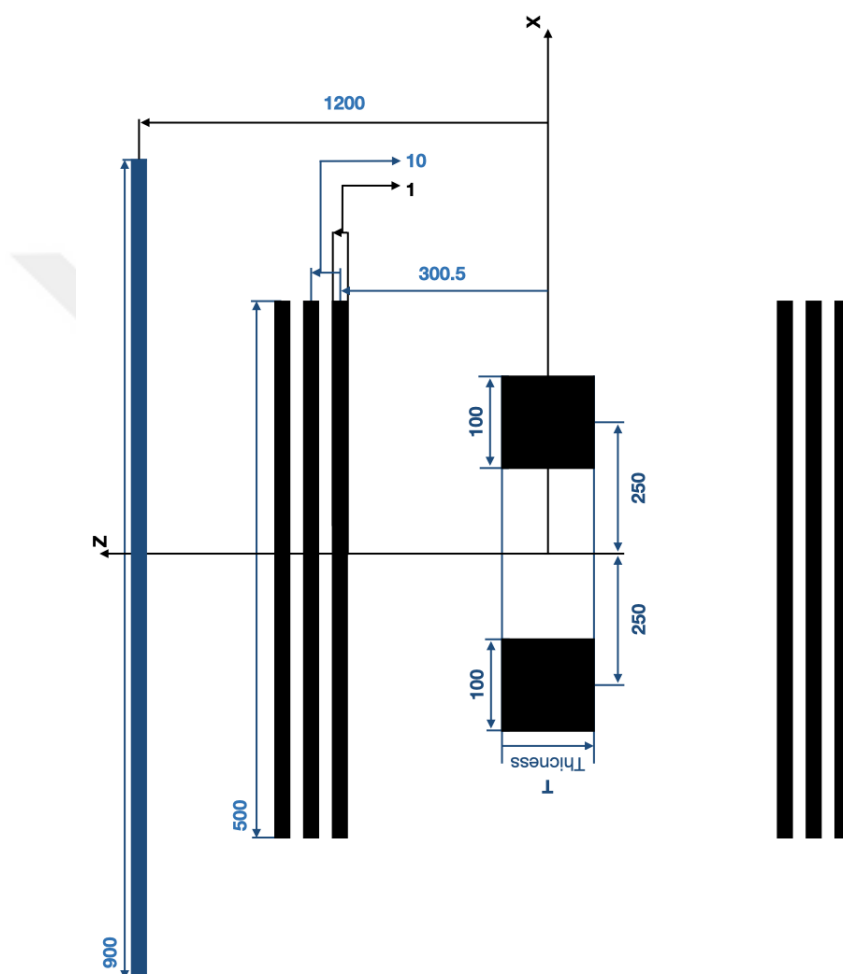


Figure 58: X-Z Cross-Section of the Setup with 4 targets.”in mm”

Figure 59: Y-Z Cros-Section of the Setup with 4 targets. "in mm"

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VITA

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