



DEPARTMENT OF
PHYSICS

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BSc in Physics Engineering

LIGHT FRAGMENT DETECTION USING RESISTIVE PLATE CHAMBERS

CONTRIBUTION TO GSI EXPERIMENT S249

MASTER IN PHYSICS ENGINEERING

NOVA University Lisbon

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ABSTRACT

This will be my abstract.

Keywords: Resistive plate chamber, Quasi-free scattering, Gaseous detectors, One keyword more, The last keyword

RESUMO

Este vai ser o meu resumo.

Palavras-chave: Câmara de placas resistivas, Dispersão quase livre, Detetores gasosos, A última palavra-chave

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ACRONYMS

| | |
|----------------|---|
| CALIFA | CALorimeter for In-Flight detection of gamma-rays and charged pArticles (<i>p. 16</i>) |
| DAQ | Data Acquisition (<i>pp. 19, 20</i>) |
| FRS | FRagment Separator (<i>p. 13</i>) |
| GLAD | GSI Large Acceptance Dipole (<i>p. 16</i>) |
| GSI | GSI Helmholtzzentrum für Schwerionenforschung (<i>p. 13</i>) |
| NeuLAND | New Large-Area Neutron Detector (<i>p. 16</i>) |
| QFS | Quasi-free Scattering (<i>pp. 9–12, 17, 19</i>) |
| R3B | Reactions with Relativistic Radioactive Beams (<i>p. 16</i>) |
| RPC | Resistive Plate Chamber (<i>p. 16</i>) |
| ToFD | Time-of-Flight Detector (<i>p. 16</i>) |

INTRODUCTION

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

Sir William Lawrence Bragg

1.1 Introduction

Since the birth of Nuclear Physics, with the discovery of the atomic nucleus by Ernest Rutherford in 1911 [1], this area has proved to be a fascinating field for scientific research displaying a rich variety of quantum phenomena. Many features of the nucleons in the nucleus exhibited are similar to the structure and behavior of atomic electrons in the atom. Similar descriptions for energy levels and shells, spins and angular momentum have emerged.

But there are some differences:

1. The dominating force inside the nucleus is the strong force rather than the electromagnetic one.
2. Since the strong force is short range and attractive, the potential in which the nucleons exist is created by all the other nucleons in contrast to the force between the atomic electrons and the spatially separated positive charge of the nucleus.

Two fundamental models—the liquid-drop model and the shell model—represent key milestones in the development of understanding the nucleus. Their reconciliation explains many nuclear phenomena, particularly the emergence of magic numbers and the behavior of exotic nuclei.

1.1.1 The Liquid-drop Model

The liquid-drop model, first formulated comprehensively by Weizsäcker [2] and discussed in detail by Bethe and Bacher in 1936 [3], treats the nucleus analogously to a charged droplet of incompressible fluid. This model emphasizes collective properties of the nucleus, such as binding energy, surface tension, and Coulomb repulsion among protons.

The semi-empirical mass formula (also called the Bethe-Weizsäcker formula) captures essential trends:

$$B(A, Z) = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} \pm \delta(N, Z)$$

where each term accounts for volume, surface, Coulomb, asymmetry, and pairing effects respectively.

While successful at explaining global nuclear properties—such as the approximate binding energy per nucleon—it could not account for observed anomalies in nuclear stability, such as nuclei at specific nucleon numbers (2, 8, 20, 28, 50, 82, 126) exhibiting enhanced stability: the magic numbers.

1.1.2 The Shell Model

The limitations of the liquid-drop model led to the proposal of the nuclear shell model, developed independently by Maria Goeppert Mayer [4] and by Haxel, Jensen, and Suess [5] in the late 1940s. Mayer and Jensen later collaborated on a comprehensive treatment of the model [6], and were jointly awarded the Nobel Prize in Physics in 1963 for their contributions. Their work, expanding on the early suggestions of Elsasser [7], showed that nucleons move in quantized energy levels within a mean potential well created by all other nucleons—analogous to electrons in atomic orbitals.

Initially, it was thought that a simple three-dimensional harmonic oscillator potential could describe the structure. However, it was soon realized that including a strong spin-orbit coupling term, where the nucleon's spin couples to its orbital motion, was critical to reproduce the magic numbers observed experimentally [8].

In particular, spin-orbit splitting lifts the degeneracy of orbital states, energetically favoring high-angular-momentum states (e.g., $j = l + 1/2$), thus producing large energy gaps at specific nucleon numbers—those corresponding to the magic numbers.

The modified energy level filling, based on this strong spin-orbit interaction, led to a successful explanation for the pronounced nuclear stability at nucleon numbers:

$$2, 8, 20, 28, 50, 82, 126$$

for both protons and neutrons separately [8].

1.1.2.1 Magic Numbers and Shell Closures

In the shell model:

- A closed shell means that all available states at a given energy are filled.
- Nuclei with both proton and neutron numbers equal to magic numbers (so-called doubly magic nuclei, e.g., ^{16}O , ^{208}Pb) exhibit especially high binding energies, spherical shapes, and relatively low excitation spectra.

Haxel, Jensen, and Suess [5] provided a succinct explanation showing how a strong spin-orbit coupling splits the energy levels such that filling up the states naturally reproduces the magic numbers.

1.1.2.2 Extension to Exotic Nuclei

The classic shell model was originally built based on stable and near- β -stable nuclei. However, advances in experimental techniques have allowed the study of exotic nuclei—nuclei far from stability, with unusual neutron-to-proton ratios.

In these systems [9]:

- Traditional magic numbers can weaken or even disappear .
- New magic numbers (e.g., $N = 16$, $N = 34$) can emerge.
- Nuclear deformations become more common, especially near the so-called "island of inversion" (around $N = 20$).
- Phenomena like neutron halos emerge.

This phenomena has led to the concept of shell evolution, where the shell structure depends on the balance between the nuclear force components (central, spin-orbit, and tensor interactions) and changes with proton-neutron ratios.

1.1.3 Conclusion

In summary, the liquid-drop model offered a macroscopic view of nuclear behavior, while the shell model introduced microscopic structure and quantization effects that explain nuclear stability at magic numbers. The discovery of exotic nuclei has highlighted that the shell structure itself is dynamic and evolves under extreme conditions, demonstrating the richness and complexity of nuclear structure beyond the stable valley.

The quest for obtaining a model that will adequately describe the nucleus in all areas of stability, as well as at the extremes of nuclear existence has been motivating the last 60 years of nuclear physics and has led to the designing of new laboratories, such as the the FAIR facility.

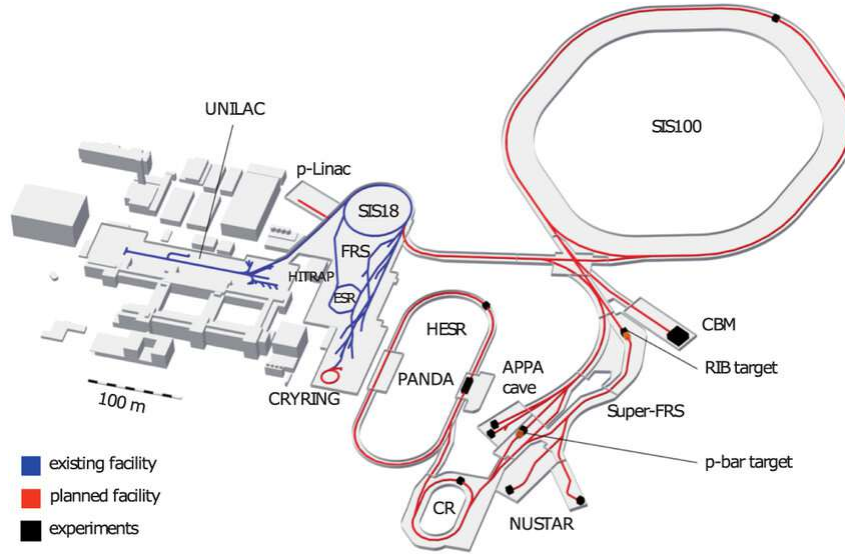


Figure 1.1: Layout of GSI-FAIR with the existing and planned beamlines shown in blue and red, respectively. The experimental sites are marked in black (figure: GSI Darmstadt). © Copyright: GSI/FAIR.

1.2 The FAIR Facility

The Facility for Antiproton and Ion Research (FAIR), currently under construction adjacent to the existing GSI¹ in Darmstadt, Germany, represents one of the most ambitious research infrastructures worldwide for exploring the structure of matter and the evolution of the universe. FAIR will provide intense, high-quality beams of protons, antiprotons, and ions—ranging from hydrogen to uranium—enabling unique access to a wide range of unexplored regimes in hadronic, nuclear, atomic, and plasma physics, as well as interdisciplinary and applied sciences.

The FAIR accelerator complex, seen in Figure 1.1, is centered around the superconducting synchrotron SIS100 [10], which, with its 100 Tm magnetic rigidity and 1100 m circumference, will serve as the backbone for beam delivery. The accelerator system is complemented by specialized storage rings and the Super-FRS fragment separator [11], facilitating the production and manipulation of both stable and exotic radioactive beams with intensities and purities that exceed those of existing facilities by several orders of magnitude.

FAIR’s scientific program is structured around four foundational experimental pillars [12–14]:

- APPA – Atomic Physics, Plasma Physics, and Applications [15]

The APPA collaboration focuses on high-precision studies in atomic and plasma physics, particularly utilizing highly charged ions and high-intensity ion beams.

¹GSI Helmholtzzentrum für Schwerionenforschung

This enables research into correlated electron dynamics under ultra-strong electromagnetic fields, tests of quantum electrodynamics (QED) in critical regimes, and the investigation of high energy density matter relevant to astrophysical phenomena and fusion technologies. APPA also addresses applied sciences such as materials modification and radiation biology under cosmic-ray-like ion bombardment.

- CBM – Compressed Baryonic Matter [16]

The CBM experiment aims to map the QCD phase diagram at high baryon densities and moderate temperatures, a region largely inaccessible to collider experiments like those at RHIC and LHC. Using high-intensity heavy-ion beams from SIS100, CBM will explore the properties of dense nuclear matter, the nuclear equation of state, and search for signals of deconfinement, chiral symmetry restoration, and the QCD critical point. It features the measurement of rare probes such as dileptons, open and hidden charm, and multi-strange hyperons with unprecedented statistics.

- PANDA – AntiProton ANnihilation at DArmstadt [17]

PANDA will utilize antiproton beams stored and cooled in the High Energy Storage Ring (HESR) to investigate the structure of hadrons and their interactions. Its focus includes charmonium spectroscopy, the identification of exotic states such as hybrids and glueballs, and studies of the hadron mass generation mechanism via gluonic dynamics. PANDA's precision measurements are expected to yield insights into the strong force at the confinement scale, extending beyond the capabilities of previous antiproton experiments.

- NuSTAR – Nuclear Structure, Astrophysics, and Reactions [18]

The NuSTAR collaboration (Nuclear Structure, Astrophysics and Reactions) lies at the heart of FAIR's mission to investigate nuclei far from stability and their relevance in cosmic nucleosynthesis. NuSTAR's scientific objectives include exploring the structure of nuclei near the drip lines, understanding the processes driving the astrophysical r-process, and studying fundamental interactions and symmetries through decay modes and reaction dynamics of exotic nuclei.

Central to NuSTAR is the Super-FRS, a high-resolution, multi-stage fragment separator designed to deliver intense, isotope-pure beams of radioactive ions. These beams will allow exploration of previously inaccessible regions of the nuclear chart. A vital component of NuSTAR is the R3B (Reactions with Relativistic Radioactive Beams) collaboration, which is dedicated to reaction studies in inverse kinematics using high-energy exotic nuclei. R3B will enable kinematically complete measurements of a wide variety of reaction channels (e.g., knockout, breakup, Coulomb excitation), providing deep insights into nuclear forces, shell evolution, and exotic decay modes. The R3B setup combines active and passive detectors in a versatile setup optimized for the coincident detection of charged particles, neutrons, and γ -rays.

1.3 Author's Contribution and Thesis Overview

DIRECT REACTIONS AS SPECTROSCOPIC TOOLS

"Nature hides her secrets because of her essential loftiness, but not by means of ruse."

Albert Einstein

"The art of simplicity is a puzzle of complexity."

Douglas Horton

2.1 Introduction

The structure of atomic nuclei—how protons and neutrons arrange themselves in shells, how they correlate, and how these features evolve across the nuclear chart—has been at the heart of nuclear physics for decades. To unravel this structure, nuclear physicists have long relied on direct reaction mechanisms, in which a projectile interacts with a target nucleus in a controlled and selective way, producing clean signatures of specific internal configurations. Among these, transfer reactions and knockout reactions have historically provided the foundational experimental pathways for exploring the single-particle nature of the nucleus.

2.2 Transfer Reactions

Nucleon transfer reactions, such as (d,p) , (p,d) , or (t,α) , involve the exchange of one or more nucleons between the projectile and the target. In the classic (d,p) reaction, for instance, a neutron is transferred from a deuteron to the target nucleus, leaving the residual system in a state that reveals the properties of the added neutron orbital.

These reactions have played a central role in defining the shell model: by measuring angular distributions and comparing them to reaction theory (e.g., using the distorted wave Born approximation, DWBA), one can extract:

- The orbital angular momentum l of the transferred nucleon (via angular distribution patterns).
- The spectroscopic factor, quantifying the overlap between the initial and final nuclear states.

Transfer reactions are best suited for stable or long-lived nuclei at relatively low energies (5–50 MeV/u), where they benefit from high cross-sections and well-developed theoretical frameworks. However, they become experimentally challenging for short-lived isotopes and high- Z systems, especially where targets cannot be fabricated.

2.3 Knockout Reactions

With the advent of radioactive beam facilities, transfer methods began to be complemented—and in some cases replaced—by nucleon knockout reactions, particularly in inverse kinematics. In a knockout reaction, such as $(A, A-1)$, a high-energy projectile nucleus collides with a light target (e.g., ${}^2\text{Be}$, C, or H), and a single nucleon is suddenly removed from the projectile.

Knockout reactions operate in the sudden approximation: the interaction is fast enough that the removed nucleon doesn't reconfigure its wavefunction during the process. The resulting residual nucleus and its kinematics encode the structural information of the pre-existing configuration.

By measuring the momentum distribution of the residual fragment and comparing it with theoretical predictions (e.g., via the eikonal reaction model or Glauber theory), one obtains:

- The l -value of the knocked-out nucleon (from the width and shape of the distribution).
- The spectroscopic strength, linked to orbital occupancy.

Knockout reactions revolutionized structure studies of exotic nuclei, especially those near the drip lines, by enabling measurements of systems that could only be formed in-flight.

2.4 From Knockout to Quasi-Free Scattering

While both transfer and knockout reactions have yielded profound insights, their selectivity and interpretability face limitations. Transfer reactions are constrained by target availability

and are often restricted to stable systems. Knockout reactions, although experimentally versatile, involve complex reaction dynamics with model dependencies that grow in neutron-rich environments and at higher energies.

To transcend these limitations, quasi-free scattering has re-emerged as a uniquely powerful probe. Conceptually close to knockout, but kinematically richer and theoretically cleaner in many regimes, quasi-free scattering reactions like $(e,e'p)$ and $(p,2p)$ offer direct access to the momentum and separation energy of individual nucleons in their initial nuclear orbitals. In high-energy kinematics, and under the impulse approximation, the scattering process isolates the interaction between the probe and a single nucleon, while the remaining nucleus acts as a spectator.

This progression—from transfer, to knockout, to quasi-free scattering—represents not just an evolution of experimental technique, but a deepening of our ability to map the quantum landscape inside the nucleus, from its shell structure to the underlying many-body correlations.

2.5 Quasi-free Scattering Reactions

2.5.1 Introduction to Quasi-Free Scattering

Quasi-free Scattering (QFS) has emerged as one of the most powerful tools in nuclear physics to probe the single-particle structure and correlations within atomic nuclei. It encompasses a class of reactions in which an incident probe (either an electron or a proton) interacts predominantly with a single nucleon in the nucleus, while the remaining nucleons act as passive spectators. Under kinematic conditions favoring large momentum and energy transfer, and small final-state interactions (FSI), the process can be approximated by the impulse approximation (IA)—a simplification in which the nuclear many-body system is treated as a collection of quasi-free, independent nucleons.

2.5.2 Historical Context and the Electron-Induced Paradigm

The conceptual and experimental foundations of QFS were established in the 1960s, particularly with the pioneering review by Jacob and Maris (1966) [19], which systematized the theoretical framework for electron-induced QFS reactions of the type $(e,e'p)$. In these reactions, a high-energy electron transfers a well-defined amount of momentum and energy to a proton within the target nucleus, which is then ejected and detected in coincidence with the scattered electron. The kinematic constraints of such experiments enable the reconstruction of the missing energy and momentum of the ejected nucleon, which provides a direct spectroscopic window into the bound-state wavefunction.

This formalism was further refined in the 1973 follow-up by the same authors [20], which accounted for distortions in both the incoming and outgoing waves due to the nuclear potential—introducing the Distorted Wave Impulse Approximation (DWIA). These early $(e,e'p)$ experiments, primarily conducted at SLAC and Saclay, provided critical

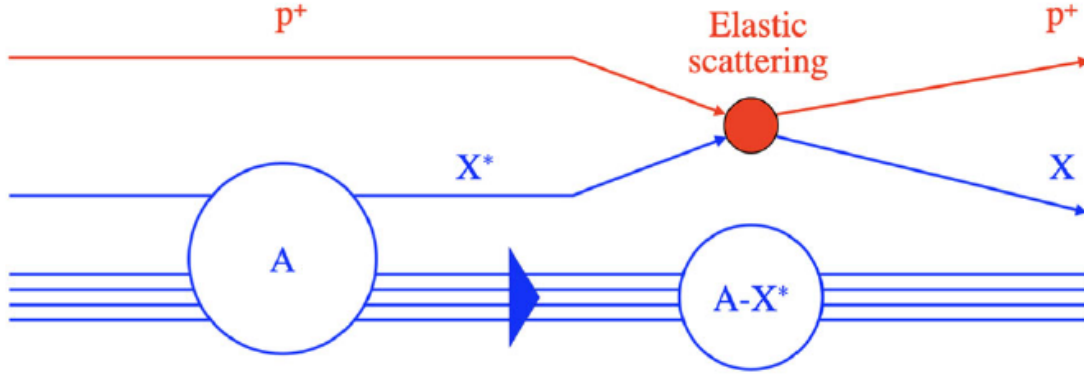


Figure 2.1: Schematic diagram of a QFS reaction induced by a proton p^+ on a nucleus A via elastic scattering off the virtual constituent particle X^* . Three real particles are generated in the final state: the scattered proton p^+ , the knock-out cluster X and the spectator nuclear fragment ($A-X^*$). Reprinted figure from Ref. [21]

benchmarks for understanding shell structure, spectroscopic factors, and occupancy probabilities, particularly in medium-mass nuclei like ^{16}O and ^{40}Ca . However, the method remained largely confined to stable nuclei due to the limitations in electron beam-target combinations.

2.5.3 Proton-Induced QFS and DWIA Evolution

In parallel, the use of proton-induced QFS—such as $(p,2p)$ or (p,pn) reactions—gained traction as an alternative means to probe the same physics with hadronic probes. While the complexity of the nucleon-nucleon (NN) interaction and stronger final-state interactions initially complicated the analysis, the development of DWIA for hadronic probes enabled the extraction of momentum distributions and spectroscopic observables with comparable reliability. These reactions offered higher cross-sections and better experimental accessibility, though at the cost of increased theoretical uncertainty due to ambiguities in the NN scattering amplitude and optical potentials.

2.5.4 The Modern Era: Inverse Kinematics and Exotic Nuclei

A transformative leap occurred in the 21st century with the advent of inverse kinematics QFS using radioactive ion beams (RIBs) and hydrogen targets. As comprehensively reviewed by Panin et al. (2021) [21], modern QFS experiments at facilities such as RIKEN, GSI/FAIR, and FRIB utilize high-energy beams of neutron- or proton-rich nuclei impinging on proton-rich targets. The resulting reactions—such as $(p,2p)$, (p,pn) , or $(p,p\alpha)$ —enable the study of short-lived and exotic systems far from stability, including halo nuclei, nuclei near the neutron drip line, and those within the so-called "island of inversion."

These experiments exploit complete kinematic reconstruction techniques, coincident γ -ray detection, and high-resolution tracking of all final-state particles. This allows the identification of orbital angular momentum (l) of removed nucleons via momentum distributions, providing a model-independent probe of nuclear shell structure. Moreover, inverse kinematics QFS has facilitated the spectroscopy of unbound states, the quantification of short-range correlations (SRCs), and insights into clustering phenomena in light and medium-mass nuclei.

2.5.5 Benchmark and Current Frontiers

QFS today occupies a unique position among reaction mechanisms, bridging single-particle and correlated many-body dynamics. Benchmarked by decades of electron-induced QFS data, modern $(p, 2p)/(p, pn)$ measurements are now used to:

- Test shell evolution in neutron-rich isotopes.
- Quantify spectroscopic factors and their reduction (quenching).
- Investigate SRCs in asymmetric nuclear matter.
- Map the extent of the island of inversion.
- Explore the nature of unbound and resonant nuclear states.

Theoretical advancements, notably the eikonal DWIA and relativistic frameworks, allow consistent comparisons between experiment and shell-model or *ab initio* structure predictions. Future developments—such as the integration of machine learning in reaction theory, or the use of polarized beams and targets—promise even finer resolution of nuclear substructure.

EXPERIMENT

"Somewhere, something
incredible is waiting to be
known."

Carl Sagan

3.1 Context and Goal of the Experiment

The proposed experiment, detailed in research proposal G-24-00249 [22], aims to investigate the structure of the neutron-rich fluorine isotope, ^{25}F , through one-proton knockout reactions. This study is motivated by the "drastic extension of the neutron drip line for $Z=9$ compared to $Z=8$ isotopes," a phenomenon that remains poorly understood [23]. The experiment seeks to elucidate how the ^{24}O core is polarized by the presence of an additional proton in ^{25}F , thereby shedding light on the mechanisms responsible for the observed drip line extension.

The experiment will employ the quasi-free scattering (QFS) reaction $^{25}\text{F}(p,2p)^{24}\text{O}$ in inverse kinematics, effectively knocking out a deeply bound valence proton from the ^{25}F nucleus [24]. This approach will utilize the R3B experimental setup, including the high-efficiency neutron detector NeuLAND [25], to achieve complete kinematic measurements and obtain accurate spectroscopic information on the populated final states of ^{24}O . By analyzing the experimental data, researchers aim to determine the extent to which the single $d_{5/2}$ proton in ^{25}F modifies the structure of the core nucleons, potentially indicating deformation or polarization of the ^{24}O core [26].

Ultimately, the goal of this experiment is to provide a more detailed understanding of the nuclear structure of neutron-rich fluorine isotopes and the underlying reasons for the extended neutron drip line at $Z=9$. The results will contribute to a more comprehensive picture of nuclear forces and structure in exotic nuclei, addressing a fundamental question in nuclear physics.

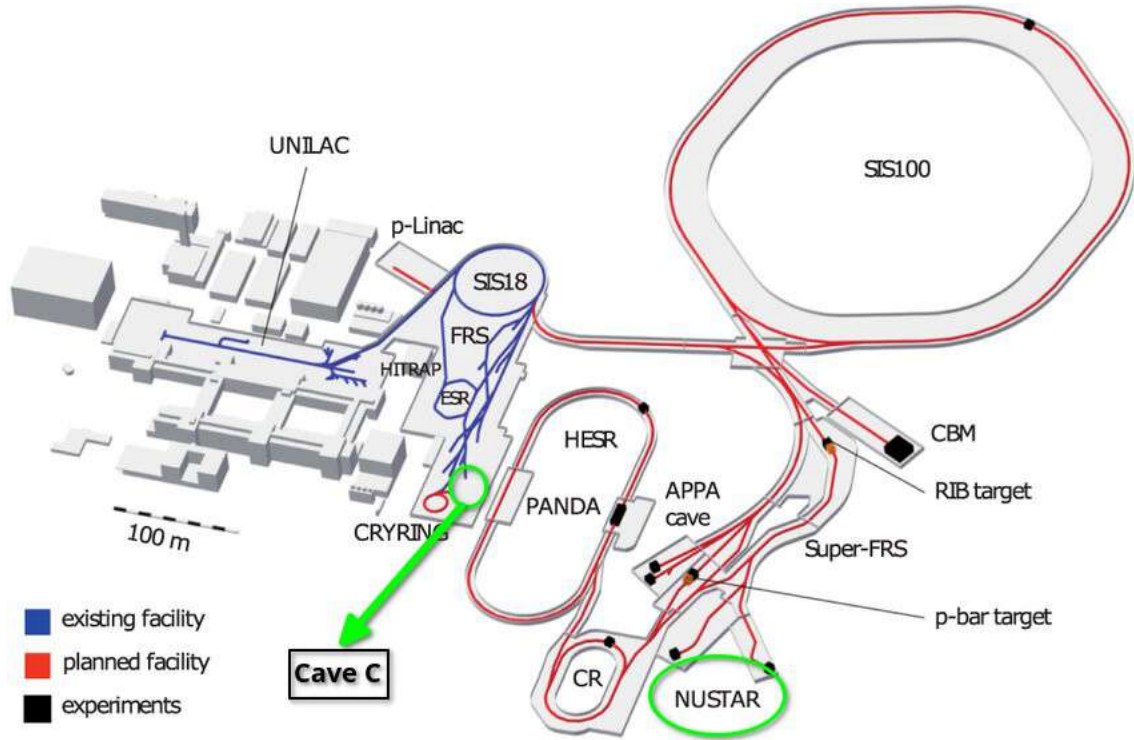


Figure 3.1: Layout of GSI-FAIR with Cave C highlighted, where the prototype of the future NUSTAR R3B setup stands and where this experiment took place.

3.2 The GSI Accelerator System

GSI Helmholtzzentrum für Schwerionenforschung (GSI)

GSI

FRagment Separator (FRS)

FRS

3.2.1 Beam used in Experiment

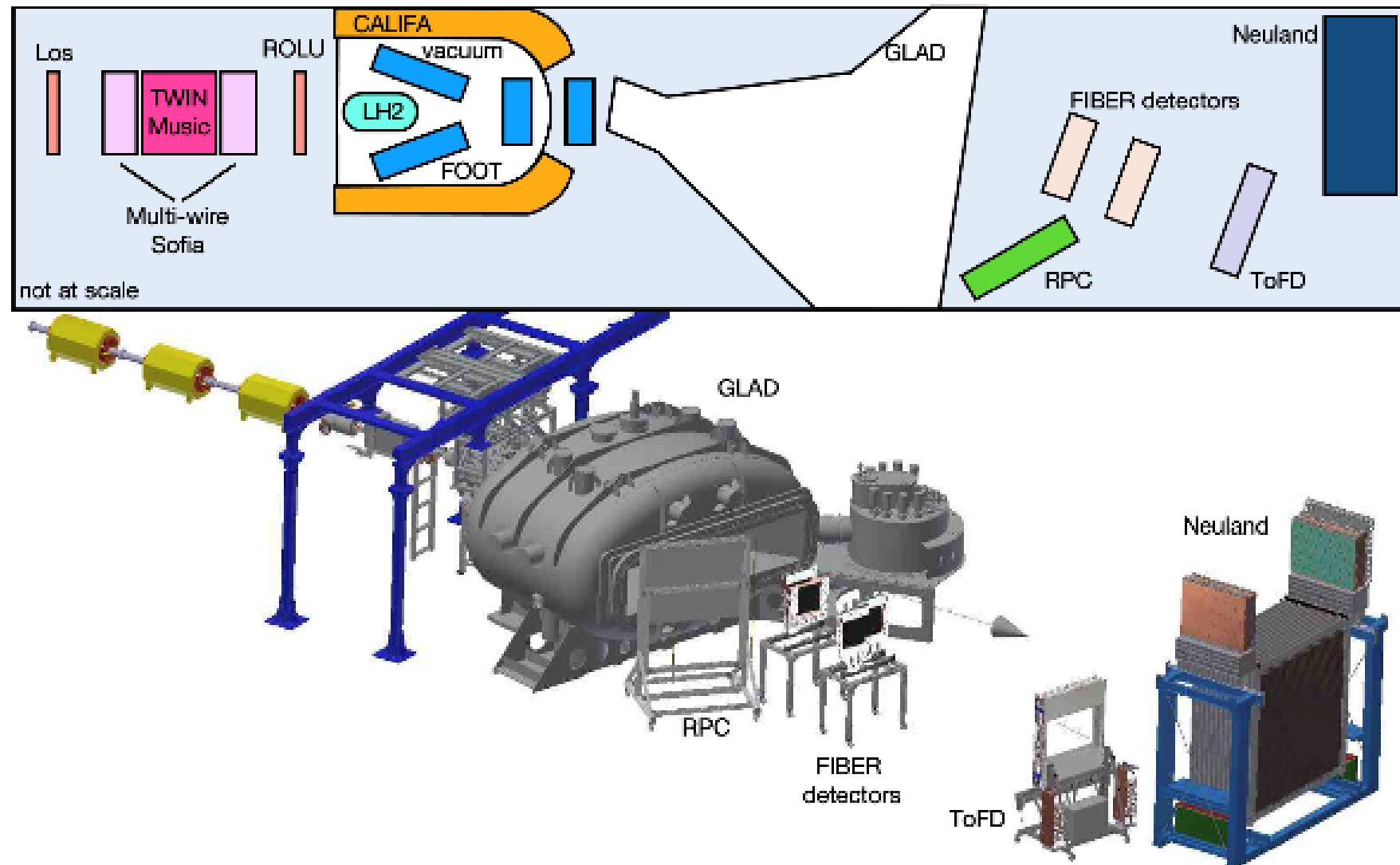
In the proposed experiment [22], a ^{40}Ar primary beam with an energy of 700 MeV/u is employed to produce a secondary beam containing the ^{25}F isotope of interest. The primary beam impinges on a beryllium target located at the FRS, inducing nuclear fragmentation reactions. This process generates a cocktail beam consisting of various isotopes, including ^{25}F , which is then selected and guided towards the experimental setup in Cave C.

The FRS is used to separate and purify the secondary beam, ensuring a sufficient intensity of ^{25}F for the subsequent experiment. LISE++ simulations, using the EPAX3.1a production model, predict an intensity of approximately 30 ions per second (pps) of ^{25}F on the secondary target. The total intensity of the secondary cocktail beam in Cave C is expected to be below 700 pps, with a purity of around 5% for ^{25}F . The relatively low

total intensity allows for data acquisition without significant downscaling of triggers and minimizes dead time.

In Cave C, the ^{25}F secondary beam interacts with a liquid hydrogen (LH2) target, which serves as the reaction target for the one-proton knockout reaction $^{25}\text{F}(p,2p)^{24}\text{O}$. The LH2 target is positioned in the center of the CALIFA calorimeter, enabling the detection of outgoing protons from the reaction. The use of a 150 mm thick LH2 cell maximizes the reaction yield, compensating for the low intensity of the ^{25}F beam.

3.3 R3B Setup



15
Figure 3.2:

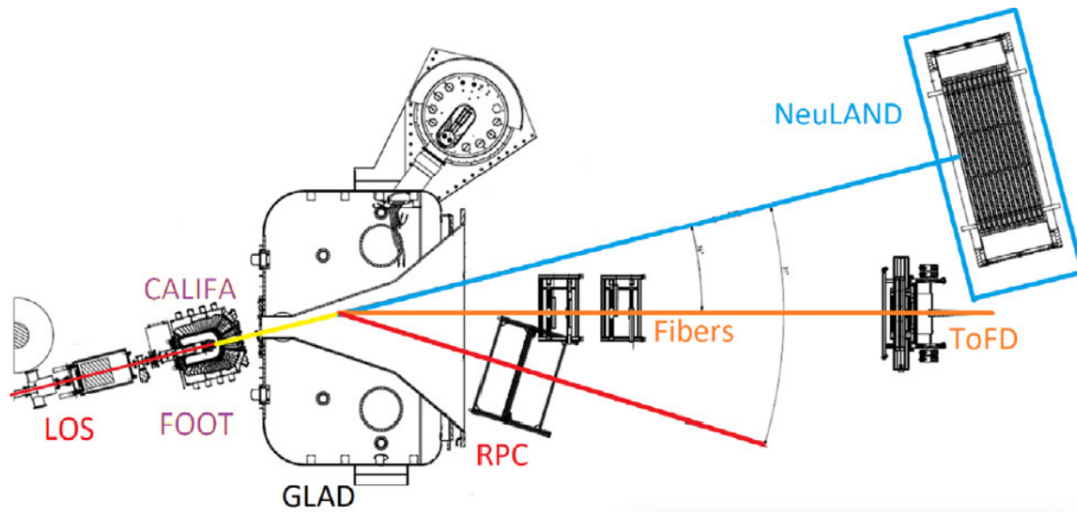


Figure 3.3: Schematic representation of the R3B setup with beam lines.

Reactions with Relativistic Radioactive Beams (R3B)

R3B

Time-of-Flight Detector (ToFD)

ToFD

New Large-Area Neutron Detector (NeuLAND)

NeuLAND

GSI Large Acceptance Dipole (GLAD)

GLAD

CALorimeter for In-Flight detection of gamma-rays and charged pArticles (CALIFA)

CALIFA

Resistive Plate Chamber (RPC)

RPC

3.3.1 Role of each detector

3.3.1.1 MWPCs

3.3.1.2 TwinMUSIC

3.3.1.3 LOS (Large-area Optical System)

Function: Measures the time of flight (ToF) and beam position.

How it works:

- Uses fast scintillators and photomultipliers (PMTs).
- Provides a reference start signal for ToF measurements.

- Crucial for precise velocity determination of incoming beam particles.

Importance: Helps in identifying incoming beam particles before they interact with the target.

3.3.1.4 ROLU

3.3.1.5 CALIFA (CALorimeter for In-Flight detection of γ -rays and light charged particles)

Function: A gamma-ray and charged-particle calorimeter surrounding the reaction target.

Structure:

- High granularity for precise energy and angle measurements.
- Covers nearly 4 around the reaction point.

Detects:

- γ -rays from nuclear de-excitation.
- Light charged particles (e.g., protons, alphas).
- Helps in reconstructing excited states of nuclear fragments.

Technology:

- CsI(Tl) scintillators coupled to SiPMs or PMTs.
- High energy resolution for γ -ray spectroscopy.

3.3.1.6 FOOTs

3.3.1.7 GLAD (GSI Large Acceptance Dipole Magnet)

Function: Bends charged particles to determine their momentum.

Key properties:

- Superconducting dipole magnet.
- Large acceptance (~ 80 msr) to handle high-energy reaction products.
- Used in combination with tracking detectors to reconstruct fragment momenta.

Why it's important:

- Essential for measuring momentum distributions, a key observable in QFS and knockout reactions.
- Helps reconstruct the missing momentum of removed nucleons.

3.3.1.8 NeuLAND (New Large-Area Neutron Detector)

Function: Detects neutrons produced in nuclear reactions [25].

Why it's crucial:

- Neutron knockout and quasi-free scattering involve neutron-rich final states.
- Neutron detection is challenging but necessary for reconstructing the full reaction kinematics.

Technology:

- Plastic scintillator bars with time-of-flight (ToF) measurement.
- Very fast response (~ 100 ps time resolution) to distinguish multiple neutrons.
- Large area (~ 30 m²) to maximize detection efficiency.

What it measures:

- Neutron energy via ToF.
- Angular distribution of emitted neutrons.

Advantage:

- Much improved over its predecessor LAND [27], providing higher detection efficiency for multi-neutron events.

3.3.1.9 Fiber Trackers

Function: Track charged particles after the reaction.

Technology:

- Consists of plastic scintillating fibers.
- Read out by SiPMs (Silicon Photomultipliers).

Why it matters:

- Provides precise position information.
- Works in conjunction with other tracking detectors to reconstruct fragment trajectories.

3.3.1.10 ToFD (Time-of-Flight Detector)

Function: Measures the velocity of charged fragments for mass identification [28].

Why it's needed:

- In QFS and fragmentation reactions, products have different masses and need to be distinguished.
- ToF combined with tracking and momentum measurement allows isotope separation.

Technology:

- Plastic scintillators with fast timing resolution (~ 50 ps).
- High-speed photomultiplier tubes (PMTs) for precise ToF measurements.

3.3.2 Particular Role of RPC

[29]

3.3.3 Main DAQ

Each detector is connected to the main Data Acquisition (DAQ), everytime they have a trigger, they send a trigger request to the main DAQ. If multiple detectors send a trigger request, it is considered an event to register and the main DAQ sends an accept signal, allowing every detector to save that signal.

All of these saved signals of each detector are then saved in a common *lmd* file containing every detectors data separated by event.

There's a synchronization signal with around 10 Hz to make sure every detector is synchronized.

3.4 Personal Contribution to the Experiment

"What we observe is not nature itself, but nature exposed to our method of questioning."

Werner Heisenberg

"The scientist is not a person who gives the right answers, but one who asks the right questions — and builds the tools to answer them."

Claude Lévi-Strauss
(paraphrased)

"Precision is not just about measurement — it is about insight."

4.1 History of RPCs/ Introduction

4.2 Properties

4.3 Build (components, electronics, gas mixture, DAQ, etc.)

DAQ

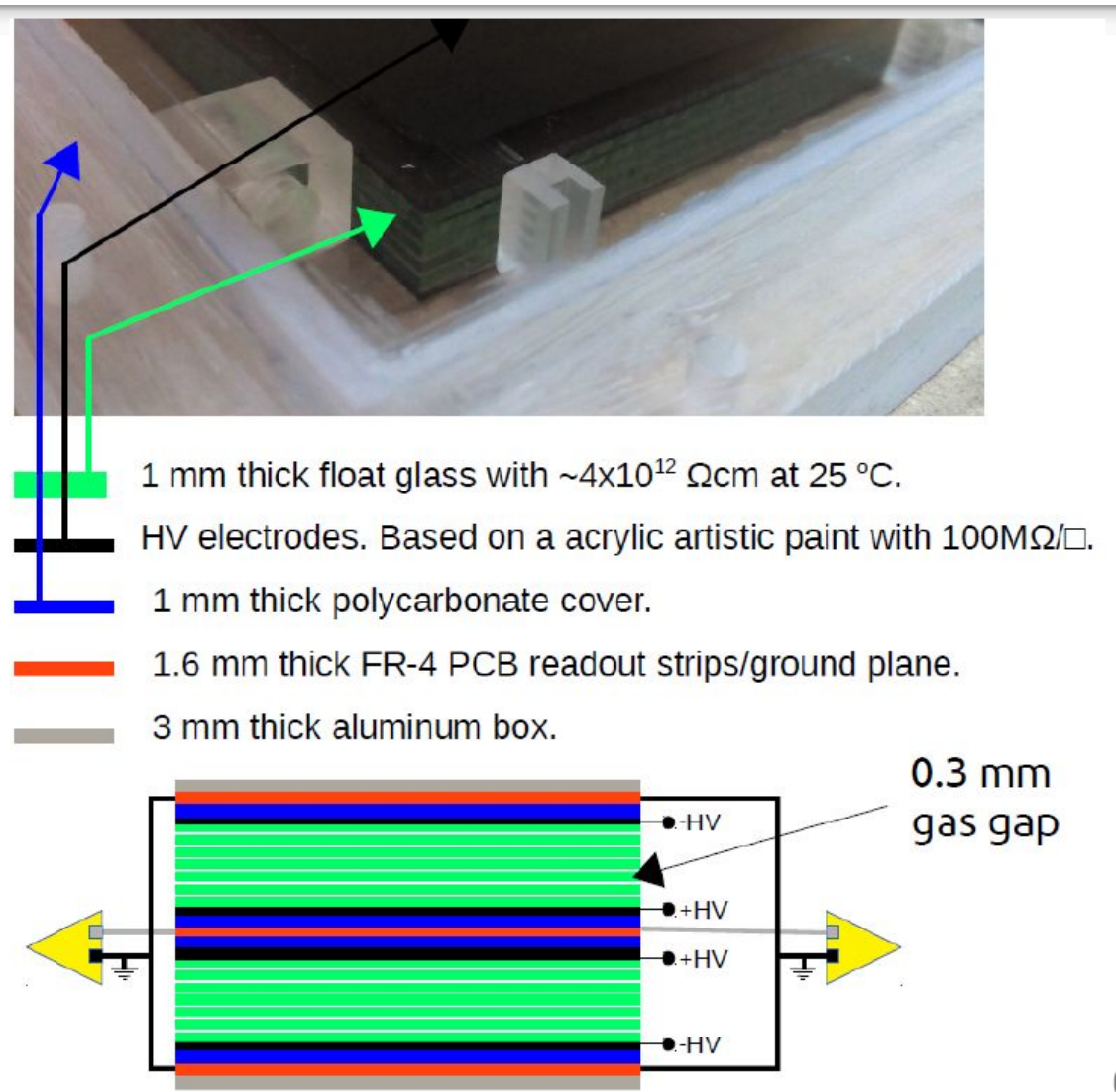


Figure 4.1: Schematic representation of the RPC.

4.3.1 RPC Build

- Active area of $1550 \times 1250 \text{ mm}^2 = 1.9 \text{ m}^2$.
- Two modules composed 6 gap RPC glass stacks.
- Gas mixture of $\text{C}_2\text{H}_2\text{F}_4$ (98%) and SF_6 (2%).
- Readout strips 3 cm width (placed in the middle of the two modules).
- Readout in both sides of the strips

4.3.2 RPC Electronics

4.3.3 RPC Gas Mixture

4.3.3.1 Pressure

The working pressure inside the chamber is lower than atmospheric pressure. This ends up being helpful because the atmospheric pressure itself compresses the RPC and makes everything tidy, aligned and without gaps.

4.3.3.2 Understanding the Role of the Gas Mixture in Resistive Plate Chambers (RPCs)

The gas mixture used in the Resistive Plate Chamber (RPC) at R3B consists of:

- 98% $C_2H_2F_4$ (Tetrafluoroethane, also known as R-134a, or Freon).
- 2% SF_6 (Sulfur Hexafluoride).

This specific gas combination plays a critical role in ionization, charge transport, avalanche formation, and quenching mechanisms inside the RPC. Below, the physics behind each component and their contributions to RPC performance are presented.

4.3.3.3 Role of $C_2H_2F_4$ (Tetrafluoroethane - Freon)

Primary Function: Ionization Medium and Avalanche Formation

$C_2H_2F_4$ is the main working gas, meaning that it provides the environment in which the ionization and charge multiplication take place.

Key Physics:

1. Ionization by Charged Particles

- When a charged particle (e.g., a proton, electron, or ion) passes through the RPC, it ionizes the gas molecules, creating free electrons and positive ions.
- The number of ionization events depends on the stopping power (dE/dx) of the particle.

2. Electron Acceleration and Avalanche Formation

- The electric field inside the RPC accelerates the free electrons, leading to electron impact ionization.
- This results in an avalanche process, where an initial electron triggers a chain reaction of ionization events.
- $C_2H_2F_4$ has a moderate first ionization energy (11.7 eV), making it an efficient medium for this multiplication process.

3. High Electron Attachment and Low Diffusivity

- Unlike noble gases (which have high electron mobility), $C_2H_2F_4$ has moderate electron attachment properties.
- This prevents excessive diffusion of electrons, leading to more localized avalanches.
- The electron mean free path is controlled to ensure controlled charge multiplication.

Why $C_2H_2F_4$ is Used Instead of Noble Gases?

- Noble gases like argon have too high a mobility, leading to excessive charge spread and loss of spatial resolution.
- $C_2H_2F_4$ is a polyatomic gas, meaning that it has multiple molecular vibrational modes, which help in absorbing excess energy and controlling the growth of the avalanche.

4.3.3.4 Role of SF_6 (Sulfur Hexafluoride)

Primary Function: Quenching Agent and Sparking Suppression

Although only 2% of the mixture, SF_6 is crucial for ensuring that the detector operates in a controlled avalanche mode rather than a full electrical breakdown (streamer mode).

Key Physics:

1. Electron Capture and Avalanche Control

- SF_6 is a strong electronegative gas, meaning it has a very high affinity for capturing free electrons.
- This limits the size of the avalanche, preventing uncontrolled charge growth.
- By capturing electrons, SF_6 reduces the risk of streamer formation, which would cause sparking and damage the RPC.

2. Suppression of Discharges

- SF_6 raises the dielectric strength of the gas mixture.
- This prevents full electrical breakdown, where a single avalanche could trigger an arc discharge across the plates.

3. Quenching of Excited Molecules

- SF_6 also helps in the de-excitation process by absorbing excess energy from excited $C_2H_2F_4$ molecules.
- This prevents UV photon emission, which could trigger secondary avalanches and reduce timing resolution.

4.3.3.5 RPC Operating Regimes and How the Gas Mixture Affects Them

Three Operating Modes of an RPC:

1. Avalanche Mode (Preferred Mode)

- The gas mixture ensures that charge multiplication occurs in a localized and controlled way.
- SF_6 limits the avalanche size, allowing the detector to operate in a stable mode with high timing precision.

2. Streamer Mode (Unwanted)

- If SF_6 were absent or insufficient, excessive charge buildup could lead to a transition from an avalanche to a streamer discharge.
- This would reduce spatial resolution and could permanently damage the RPC electrodes.

3. Breakdown Mode (Detector Failure)

- If the gas mixture fails to prevent excessive charge growth, the detector enters a self-sustaining discharge, which can permanently damage the plates.

4.3.3.6 Final Thoughts

This 98% $\text{C}_2\text{H}_2\text{F}_4$ + 2% SF_6 mixture is carefully chosen to:

- Optimize avalanche growth for fast timing resolution.
- Prevent streamers and discharges that could damage the RPC.
- Ensure high efficiency in detecting charged particles.
- Provide a fast recovery time, allowing the RPC to operate at high rates.

4.4 Previous Experiments and Results

First Beam time at R3B:

RPC efficiency higher than 95 %. Good synchrony between RPC and the other detectors. Detector and DAQ were stable during the two weeks of beam time.

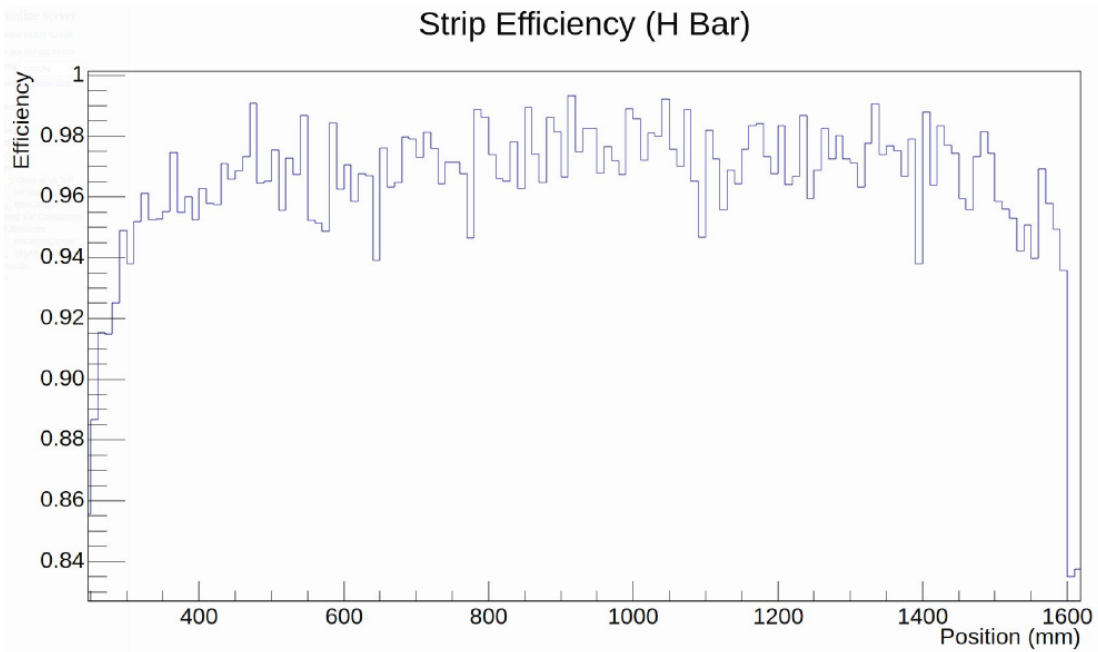


Figure 4.2: RPC Strip Efficiency

4.5 Preparation for an Experiment

Before each experiment Flash the RPC with SF_6 to dry out the interior. An alternative (SF_6 is expensive) is to use Nitrogen. One has to be careful with the pressure because if it's too high it can inflate the RPC and damage it. This process takes about a week.

When preparing to insert the gas mixture in the RPC, to check if there are no leaks, one opens the gas bottles with the mass controllers closed and then closes the bottles and checks if the pressure drops in the gas line.

Then insert the gas mixture, place one vertical NeuLAND bar on each side and calibrate in coincidence with cosmic rays. This enables us to adjust the voltage of the electrodes and find the working point of the RPC. This process takes about a week.

4.6 Calibration

SIMULATIONS

Whenever there is a problem, it usually lies between the chair and the monitor.

5.1 Geant4

Geant4 [\[30\]](#).

5.2 ROOT

ROOT [\[31\]](#).

5.3 R3BRoot

R3BRoot [\[32\]](#).

5.4 Plots

5.5 Conclusions for the Experiment

RESULTS

This is the results chapter
epigraph.

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NOVATHESIS COVERS SHOWCASE

This Appendix shows examples of covers for some of the supported Schools. When the Schools have very similar covers (e.g., all the schools from Universidade do Minho), just one cover is shown. If the covers for MSc dissertations and PhD thesis are considerable different (e.g., for FCT-NOVA and UMinho), then both are shown.

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Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

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imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

A.1 A section here

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Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

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Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetur at, consectetur sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui.

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Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.

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id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

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Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

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Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

APPENDIX 2 LOREM IPSUM

This is a test with citing something [**ecoop12-dias**] in the appendix.

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