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The new readout system of the ASACUSA scintillating tracker

MASTER DEGREE IN PHYSICS

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To my antimatter friends

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Introduction

Since its theorization in 1928 by P. M. A. Dirac, who firstly succeeded in bringing together the newly born theories of quantum mechanics and special relativity, the antimatter assumed a central role in particle physics, due to the possibility to use it as a probe to investigate new particle interactions and to test fundamental Nature symmetries postulated by theory.

The first discovered antiparticle was the antimatter counterpart of the electron, the positron, which was observed in cosmic rays by C. Anderson in 1932. It was then the turn of the antiproton, produced at the Bevatron accelerator in 1955, followed one year later by the antineutron at the same accelerator. These discoveries confirmed Dirac's hypothesis that for every particle an antiparticle should exist with the same mass and spin, but with opposite magnetic moment and charge. This symmetry between matter and antimatter was tested by several experiments, leading to the discovery of the violation of the fundamental discrete symmetries C (charge conjugation), P (parity) and T (time reversal), but confirming the validity of the so-called CPT theorem, whose direct consequence is the equality of the amount of matter and antimatter in the universe. Since astrophysical observations have not confirmed yet this hypothesis, several experiments were designed to test the CPT theorem, comparing the particles and antiparticles properties, by producing antimatter.

Nowadays, the world only antimatter factory is the AD/ELENA facility at CERN, where different experiments use antiproton beams to synthesize cold antihydrogen, i.e. an antiatom made by a positron and an antiproton bound together, and study its interactions with the ordinary matter or its behaviour in the earth gravitational field. In this framework, the ASACUSA collaboration operates its experiment about the hyperfine spectroscopy of the antihydrogen. To do that, ASACUSA developed a new model of particle trap, called cusp trap, to bring together positrons and antiprotons and produce a cold antihydrogen beam adequate for the spectroscopy techniques. To monitor the transport of positrons and antiprotons and the synthesis of the antihydrogen, a dedicated detector placed around the cusp trap is needed, in particular to track the products of the annihilation of the antiprotons with the trap walls.

This tracking detector was first designed and built in 2008, then upgraded in 2011 to be used also in proton-antiproton annihilation experiments in the ASACUSA collaboration. The first versions of the detector, now called DANTE (Detector for ANnihilation Tracking Experiment), consisted of several planes of extruded scintillating plastic bars, with a section of $1.5 \times 1.9 \text{ cm}^2$ and a length of 96 cm, readout by 1 mm diameter WLS (WaveLength Shifter) fibers coupled with 64 channels MAPMTs (Multi Anode PhotoMultiplier Tubes). In 2021, the detector has been upgraded, changing the MAPMT light readout system with a SiPM-based one. This thesis work has followed the upgrade, from the preliminary tests on the single parts of the detector, to the commissioning with cosmic rays in the INSULAB laboratory in Como. The detector will be moved to CERN in April 2022 to be positioned in the ASACUSA experimental area.

In the first chapter of this thesis, a brief historical introduction on the anti-matter discovery and the birth of the antimatter factories is presented, together with the most important experiments that used antiprotons and antihydrogen for antimatter studies. The second part of Chapter 1 presents the bases of antiproton physics and the most used techniques for antihydrogen synthesis and trapping. The first part of Chapter 2 is dedicated to the Antiproton Decelerator at CERN, describing the antiproton production, the cooling techniques and the experiments in the AD/ELENA facility, together with their experimental goals and measurement methods. The second part of the chapter describes in detail the ASACUSA experiment, its beamline and the antihydrogen synthesis in the cusp trap, together with a brief digression about the hyperfine splitting of the antihydrogen.

Chapter 3 is devoted to the description of the physics of plastic scintillators and their light readout systems, focusing on the PMT and SiPM technology. In the second half of this chapter, the DANTE detector is presented, underlying the differences between the 2008/2011 versions and the 2021 upgraded one. The mechanics, the readout electronics and the Data AcQuisition are described in detail. In Chapter 4, the preliminary tests on the single components of the DANTE detector are presented, from the used experimental setups to the data analysis and the results. In particular, the tests concerned the light attenuation along the scintillating bars, the noise characteristics of the SiPMs and the light yield in terms of number of photoelectrons of the signal generated by a MIP inside the scintillating bar.

The last chapter is dedicated to the analysis of the detection efficiency of four planes of the DANTE detector, together with the estimation of their spatial resolution. The experimental setups and the algorithms for the efficiency maximization, the cluster identification and the hit position reconstruction are discussed in detail as well as the results.

CHAPTER 1

The antiproton physics

In the first part of this chapter a brief historical introduction from the antimatter discovery to the last antihydrogen based experiments will be presented, along with the development of antiprotons factories at CERN. In the second part, the bases of antiproton annihilation physics will be treated, presenting the characteristics of the products of such an interaction. Given that the topic of this thesis is the development of a detector for trapped antimatter studies, the last part of the chapter will present the different techniques for trapping antiparticles and for the antihydrogen synthesis in electromagnetic traps.

1.1 A brief history of antimatter

1.1.1 Antiparticles discovery and broken symmetries

In the early 1900 new discoveries and experiments led to the birth of two main theories, whose goals were to give an explanation of phenomena beyond the domain of classical physics: special relativity and quantum mechanics. The first, theorized by Albert Einstein in 1905 [1], described the motion of bodies moving at velocities close to the speed of light and the subsequent relation between energy and mass, whereas the latter, firstly introduced by Max Planck and then developed by Niels Bohr, Erwin Schrödinger and Werner Heisenberg, provided a description of the interactions at the atomic and subatomic scale. The problem arose when relativistic particles were observed - for instance in cosmic rays by

Domenico Pacini [2] and Victor Hess [3] - for which the quantum theory did not work, until its relativistic adaptation by the British physicist Paul Dirac in 1928 [4]. Rewriting the Klein-Gordon equation (setting $\hbar = c = 1$)

$$E^2 = p^2 + m^2$$

(where E is the energy of a particle with rest mass m and momentum p) with the quantum formalism and looking for a linear expression for time and space derivatives, he wrote his famous equation for an electron that moves at relativistic velocity:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0 \quad (1.1)$$

where m is the mass of the electron, ∂_μ the 4-gradient, γ^μ the gamma matrices and ψ the Dirac spinor for the electron. This equation has two possible solutions, one for a particle with a positive energy and the other with a negative one. In addition, introducing the electromagnetic coupling, the Dirac equation takes the following form:

$$(i\gamma^\mu \partial_\mu - m - e\gamma^\mu A_\mu)\psi = 0$$

where e is the charge of the electron and A_μ is the electromagnetic potential. The second solution corresponds to a particle with a charge and a magnetic moment opposite to the electron ones. Dirac called it "antiparticle", but its effective existence was in doubt until the anti-electron was discovered by Carl Anderson in 1932 in cosmic rays using a cloud chamber and a magnetic field [5]. He observed the track (that can be seen in Figure 1.1) of such a particle and he called it "positron" (e^+).

The search of antiparticles was naturally extended to the antiproton ($\bar{p}$). Since 1932, the $\bar{p}$ was widely looked for in cosmic rays and these observations allowed to populate the so-called "zoo" of elementary particles, together with their corresponding antimatter counterparts, like $\mu^\pm$, $\pi^\pm$ and $K^\pm$. However, these particles had a mass significantly smaller than the one of the proton. The antiproton was discovered more than twenty years later the Anderson result, in 1955 by O. Chamberlain, E. Segré, C. Wiegand and T. Ypsilantis at the Lawrence Berkeley National Laboratory, artificially produced by the Bevatron accelerator [6]. With an energy of the proton beam right above the antiproton production threshold (~ 6 GeV), the team designed an experimental setup to discriminate antiprotons from negative pions (produced in the interaction between the beam and the target, used to produce the antiprotons) using the time-of-flight technique and two Cherenkov counters, as well as a photographic emulsion to detect the annihilation of an antiproton with its ordinary matter counterpart, as can be seen in Figure 1.2. In the same article [6], the first measurement of the antiproton mass was presented: a discrepancy of about 5 percent from the proton mass was

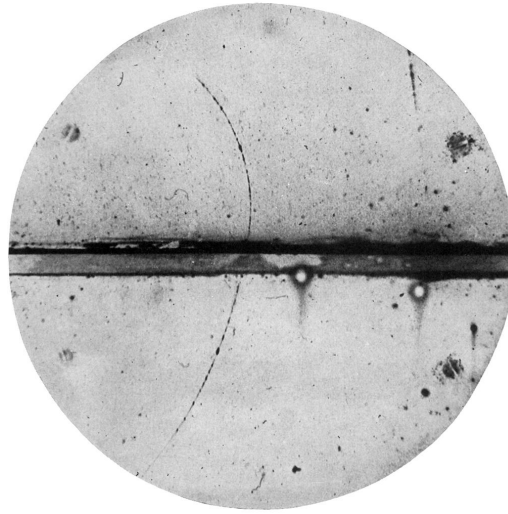


FIGURE 1.1: First observation of a track of a 63 MeV positron in the Anderson cloud chamber crossing a 6 mm lead plate [5].

measured, indicating that the new discovered particle was in fact an antiproton. The antineutron was observed a year later at the Bevatron by another team led by B. Cork [7], completing the puzzle of the first family of antiparticles.

Together with the discovery of new particles, the validation of some theoretical properties was investigated, in particular in the field of fundamental symmetries. In 1956, T. D. Lee, C. N. Yang and C. S. Wu designed and performed experiments to study the possibility of the parity (P) violation in weak decays, where they found an asymmetry that led not only to the direct violation of P , but also of the charge conjugation (C) symmetry [8] [9]. In 1964, also the violation of the CP combined symmetry was observed at the AGS in Brookhaven by J. Cronin and V. Fitch in the $K^0 - \bar{K}^0$ neutral kaon system [10]. A few years before, Schwinger had introduced the invariance of the combination of the three discrete symmetries CPT in the context of the Lagrangian field theory [11], that had led to a theorem proved later by Bell [12], Lüders [13] and Pauli [14]. The CPT theorem implies that, due to the invariance of the CPT symmetry, if a combination of two symmetries is violated, the other one is violated too. So, in Cronin's and Fitch's experiment also the time reversal symmetry T was indirectly observed. The direct proof of the T violation was then experimentally observed by the BABAR experiment in 2012 [15].

Given the CPT theorem, the behavior of matter and antimatter was thought to be symmetrical, but the abundance of ordinary matter and the absence of large amounts of antimatter in the close-by universe - that cannot be explained by the small values of the corrections due to C and CP violations - motivated



FIGURE 1.2: First observation of an antiproton annihilation event detected using a photographic emulsion at the Bevatron. The antiproton enters from the top of the image (the track labeled as "L") and travels about $430\ \mu\text{m}$ before the annihilation with a proton producing nine different charged particles¹.

the need of new experiments to test *CPT* using antimatter as a probe. Such experiments required the development of a method to produce and control many antiparticles, as described in the next section.

1.1.2 Antiproton factories and experiments

After the observation of the antiproton, beams of such a particle were used by different experiments to perform annihilation cross-section measurements and to estimate the antiparticles lifetimes. To do so, a collimated and stable beam was required, but the antiproton production technique developed at the Bevatron (using a high energy proton beam impinging on a metal target) led to an impure $\bar{p}$ beam, contaminated by other negative particles such as negative pions. To avoid that background, electrostatic separators were used, but a method to collect antiprotons produced near the momentum of maximum yield (without the selection of other particles) had to be investigated. Thanks to the work of S. van der Meer on cooling techniques [16], the birth of the so-called antiproton factories able to provide stable $\bar{p}$ beams was possible. The two most important areas in the '80s were located at CERN (Figure 1.3) and Fermilab (Figure 1.4) [17].

¹<https://www2.lbl.gov/Science-Articles/Archive/sabl/2005/October/01-antiproton.html>

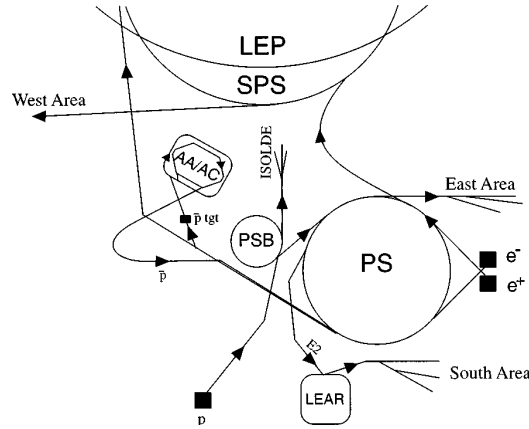


FIGURE 1.3: The CERN antiproton factory (not to scale) in 1983: the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), the Antiproton Collector (AC) and Accumulator (AA). The figure shows also the Super Proton Synchrotron (SPS) used to study $p - \bar{p}$ collisions and the Large Electron-Positron collider used in the '90s to study $e^+ - e^-$ collisions [17].

The goal was to produce a large amount of $\bar{p}$ s, to store them for enough time to study their properties and to generate a beam with the right luminosity for experiments and for a collider.

In 1978 CERN announced that several hundreds of antiprotons with a momentum of 2.1 GeV/c were produced and stored for 85 hours in the ICE (Initial Cooling Experiment) ring [18]. ICE was a storage ring built for testing new cooling techniques (such as stochastic and electron cooling, which will be discussed in Section 2.1) in order to accumulate antiprotons for a $p - \bar{p}$ collider [19]. The antiprotons storage allowed to measure more precisely their lifetime (the limit was set at 32 hours), a task that had not been achieved by previous experiments, due to the high contamination of the beam.

In 1981 the first proton-antiproton collision was produced at the ISR (Intersecting Storage Rings) at CERN [20], opening the way to the S $\bar{p}$ pS (Super antiproton proton Synchrotron) machine, that allowed the UA1 and UA2 experiments to discover the W and Z bosons in 1983 [21]. These experiments required to stack several times 10^{10} particles before the acceleration in the S $\bar{p}$ pS up to 300 GeV, so the Antiproton Accumulator (AA) and the Antiproton Collector were built to debunch, precool and store $\bar{p}$ s [22].

1.1.3 Slowing antiprotons

High precision $\bar{p}$ experiments require in general the isolation of particles to avoid the interaction with the ordinary matter and the state of rest of the antimatter

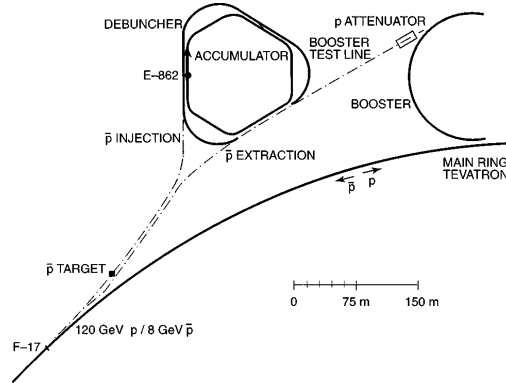


FIGURE 1.4: The Fermilab antiproton factory: the Debuncher and the Accumulator had the same function of the CERN AC/AA complex. The factory provided $\bar{p}$ beams to the Tevatron ring to study $p - \bar{p}$ collisions [17].

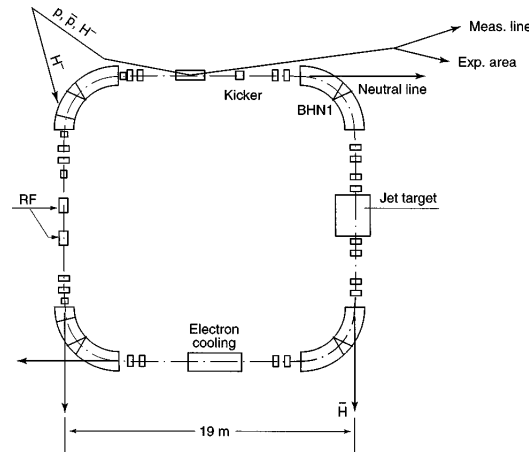


FIGURE 1.5: The CERN Low Energy Antiproton Ring (LEAR) scheme. The antiproton beam was injected from the PS on the left and ejected into an experimental hall on the right [17].

in the laboratory frame to observe it for a long time. Since antiprotons were produced at high energy by the factories described in the previous section, the same cooling techniques - used to reduce the large momentum spread, typical of an antiproton beam - were applied to slow down antiparticles to the MeV/c momentum range. To do so, the Low Energy Antiproton Ring (LEAR) was developed and built at CERN in 1982 [23] (Figure 1.5). Antiprotons from the AA were decelerated by the PS and were injected in LEAR, where cooling was applied after a few cycles. At approximately 100 MeV/c, the beam was extracted and sent to different experimental lines where $\bar{p}$ cross-section experiments took place:

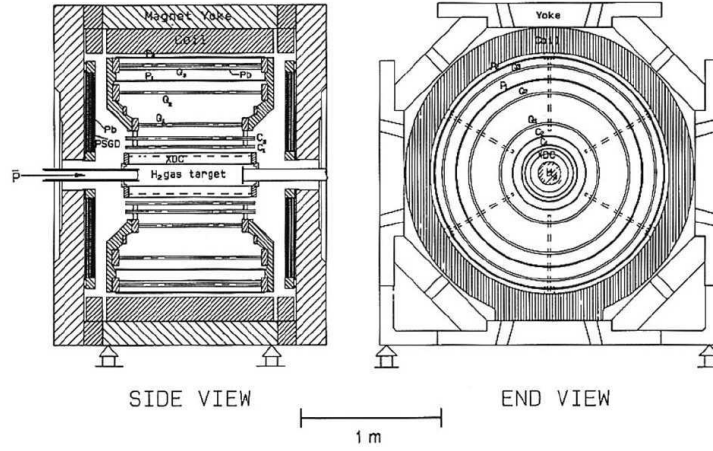


FIGURE 1.6: Scheme of the ASTERIX detector: it consisted in a X-ray drift chamber placed around a gas target for the particle identification, a set of MW-PCs (Multi Wire Proportional Chamber) for the tracking and two wire planes endcap detectors [27].

- ASTERIX (Antiproton STop ExpeRiment on Initial X-rays) was designed to study $\bar{p} - p$ annihilations using a H_2 target and observing the emitted X-ray spectrum (Figure 1.6) [24];
- OBELIX (PS201) consisted in an open-axial spectrometer surrounding a gaseous or liquid target (H_2 or D_2). Placing another H_2 target 2 m downstream, the experiment could also investigate $\bar{n} - n$ and $\bar{n} - p$ annihilations (Figure 1.7) [25];
- Crystal BARRel focused its goals on the search of glueballs (gg) and hybrid mesons ($g\bar{q}q$) produced in in-flight annihilations between $\bar{p}$ and p or n of the liquid hydrogen and on the study of $\bar{p} - p$ and $\bar{p} - n$ interactions (Figure 1.8) [26].

Using the LEAR slow $\bar{p}$ beam, in 1995 antihydrogen atoms ($\bar{H} \equiv \bar{p}e^+$) were observed for the first time by G. Baur *et al.* [28]. The interaction between $\bar{p}$ and a Xe gaseous target produced a e^+/e^- pair, followed by the capture of the positron by the $\bar{p}$ itself:

$$\bar{p} + Z \rightarrow \bar{p} + e^+ + e^- + Z \rightarrow \bar{H} + Z + e^-$$

This idea had been previously developed by a group of physicists at Fermilab [29] and taken up by the JETSET collaboration, leading to the cited measurement performed by the PS210 experiment. The Xe target was placed in the middle of one of the straight sections of the decelerator ring; after the interaction, the

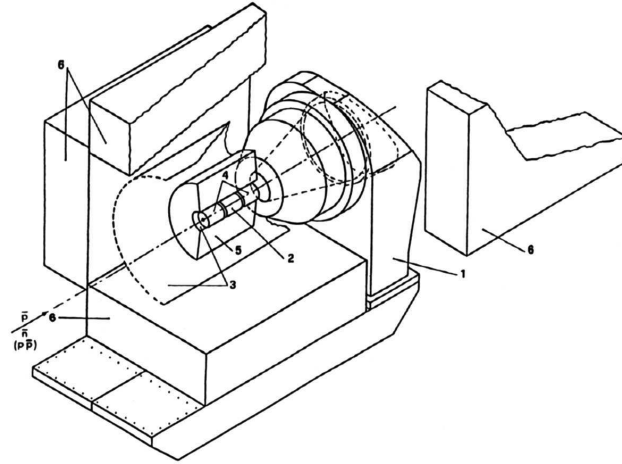


FIGURE 1.7: Scheme of the OBELIX detector: (1) the axial field magnet, (2, 4) the spiral projection chamber, (3) the time of flight detector, (5) the jet drift chamber and (6) the high angular resolution gamma detector [26].

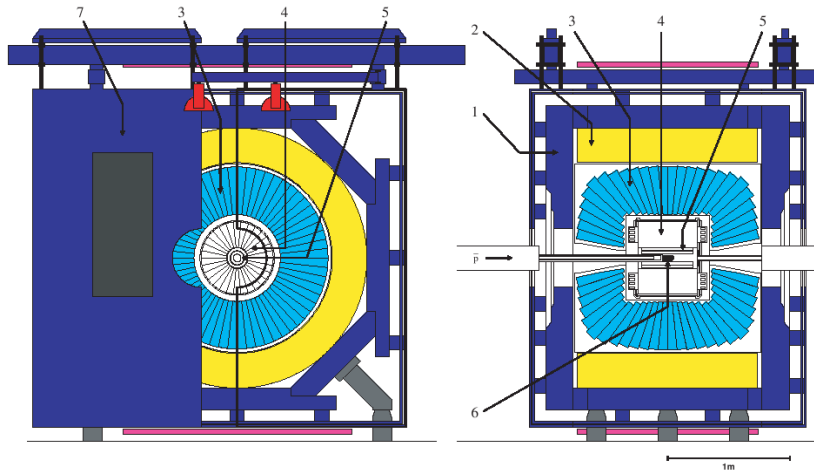


FIGURE 1.8: Scheme of the Crystal BARRel detector: (1, 7) the magnetic joke, (2) the magnetic coils, (3) the CsI barrel calorimeter, (4) the jet drift chamber, (5) the MWPCs and (6) the target [26].

$\bar{H}$ atoms (neutral) were separated from the beam by the bending magnet at the corner of the ring and exited from LEAR tangentially to the experimental area (Figure 1.9). The group used the JETSET detector [31] to detect at least 9

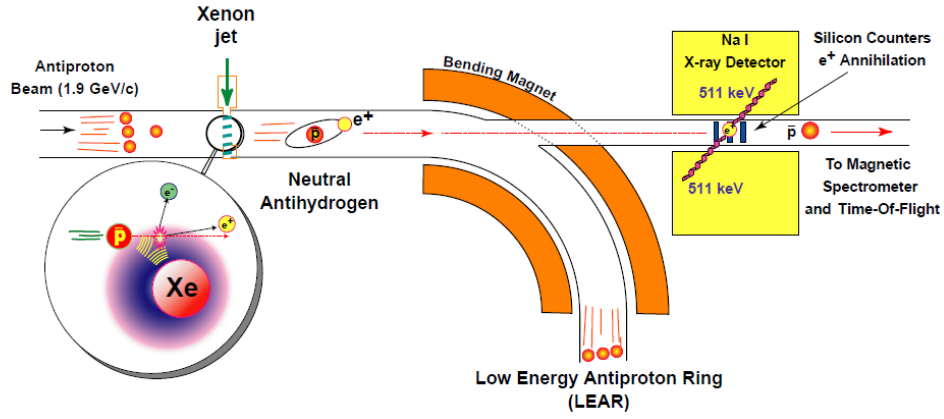


FIGURE 1.9: First $\bar{H}$ production at LEAR: the LEAR $\bar{p}$ beam interacted with a Xe gaseous target and $\bar{H}$ atoms were created; the antihydrogen atoms (neutral) flew to the detector where they annihilated [30].

antihydrogen atoms using only 17 hours of beam time: the $\bar{H}$ atoms interacted with a set of three silicon counters which measured the energy loss of the $\bar{p}$ and the kinetic energy of the e^+ constituting the antihydrogen. The positron annihilated and the two 511 keV gamma rays were detected in coincidence using NaI scintillators; a Time Of Flight (TOF) detector measured the speed of the remaining antiproton.

The problem of the PS210 measurement was that the $\bar{H}$ atoms were produced with a momentum of around 1.94 GeV/c (namely, the momentum of the antiprotons in the LEAR beam), not allowing a precise investigation of the antihydrogen properties, that requires to keep it under observation for a long time. A method to produce a relatively large number of antiatoms at rest was needed. To produce low energy $\bar{H}$ s it is necessary to combine low energy positrons and antiprotons, *i.e.* trapping and cooling them. This technique was firstly introduced in 1986 in the TRAP collaboration by G. Gabrielse *et al.* [32], where the trapping of antiprotons in a Penning trap (described in detail in Section 1.3) was successfully demonstrated. During the following years, they succeeded in trapping $\bar{p}$ s at keV energies, cooling them to the meV range using a dense electron cloud, allowing a precise study of the antiproton-proton inertial mass ratio to an accuracy of 10^{-8} [33] [34]. This measurement opened the era of trapping antiparticles at cold temperatures to create antiatoms. Despite that, the advent of the Large Hadron Collider required the relocation of the funds, resulting in the

decommissioning of LEAR in 1996. Therefore, CERN started a study to produce, with a less expensive and simplified method, slow antiprotons for an antihydrogen program, resulting in the CERN Antiproton Decelerator (AD) project [30].

1.1.4 The AD era

In 1996 the LEAR facility was closed to be substituted by the Antiproton Decelerator project, whose main goal would be the production and trapping of cold antihydrogen and antiprotonic atoms [35]. AD replaced three machines (AC, AA and LEAR), reusing parts of the former antiproton facility and including in its design the deceleration RF (Radio Frequency) cavity and electron cooling. AD started its operations in 2000. The 25 GeV proton beam from the PS generated a 3.5 GeV $\bar{p}$ beam which was slowed down and delivered at lower energies (~ 5.3 MeV) to three main experiments: ASACUSA (Atomic Spectroscopy And Collision Using Slow Antiprotons), ATHENA (ApparaTus for High precision Experiment on Neutral Antimatter) and ATRAP (Antihydrogen TRAP) (Figure 1.10). The three experiments goal was the test of the *CPT* theorem by

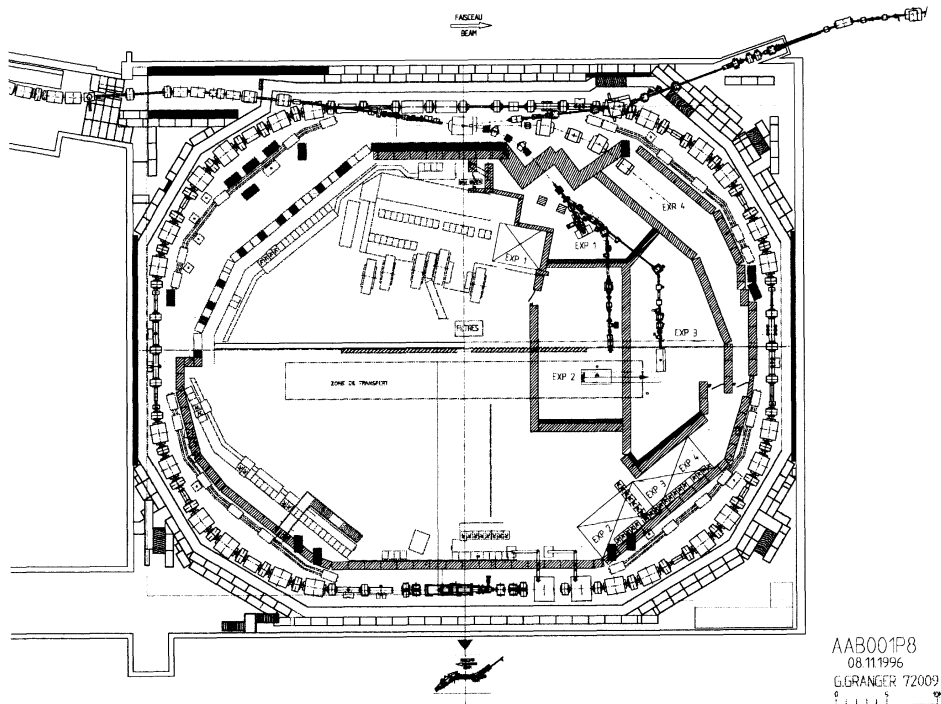


FIGURE 1.10: AD and the AD hall in 2000: on the left-upper side the PS extracted beamline, in the center the three AD experimental lines of ASACUSA, ATRAP and ATHENA [36].

producing and studying cold $\bar{H}$ atoms with spectroscopic methods, comparing them to their ordinary matter counterparts. In particular:

- **ATHENA** used a nested Penning trap where antiparticles, previously cooled and accumulated in separated traps, were mixed to create cold $\bar{H}$ s. Antiatoms then annihilated with the trap walls producing two back-to-back 511 keV photons and charged mesons, which were detected by a system of two layers of microstrip silicon detectors and 192 CsI crystals (Figure 1.11). With this technique, the collaboration achieved in 2002 the first production of 131 ± 22 antihydrogen atoms at very low energy in a cryogenic environment [37];

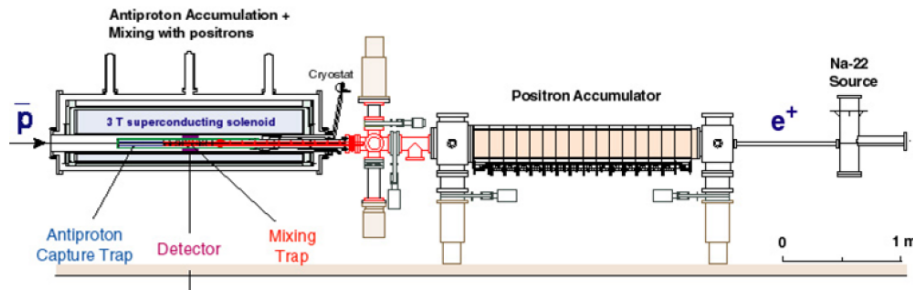


FIGURE 1.11: Scheme of the ATHENA apparatus [38].

- **ATRAP** used the same technique as ATHENA, adding a variable electric field in order to measure the distribution of antihydrogen over levels with binding energies of 4-7 meV. Ionized $\bar{H}$ atoms, *i.e.* their constituent antiprotons, were ejected from the trap by a detection well and annihilated upon contact with the electrode at the end of the trap (Figure 1.12). The annihilation products were detected by scintillating paddles and fibers, providing the number of produced and ionized antihydrogen atoms [39];
- **ASACUSA**, besides the production of antihydrogen and the study of its hyperfine structure, focused its research also on the study of the antiprotonic helium ($\bar{p}\text{He}^+$) and the $\bar{p} - p$ annihilation cross section. For the first goal, the collaboration used a different field configuration for the trap, called Cusp Trap [41]. In addition, to slow down a larger number of antiprotons in the keV energy range, a Radio Frequency Quadrupole Decelerator (RFQD) and a MUSASHI (Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigations) accumulator were used. A detailed description of the ASACUSA experiment will be presented in Chapter 2.

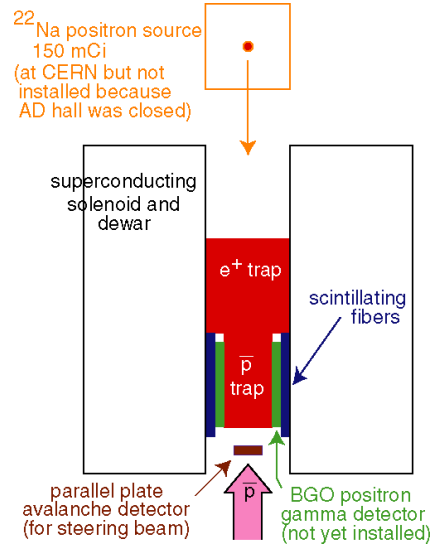


FIGURE 1.12: Scheme of the ATRAP experiment [40].

In 2012, the ALPHA collaboration (who succeeded to ATHENA) reported the first measurement of the antihydrogen spectrum [42]. Using microwaves tuned with a precise frequency on the antiatom transitions, a flip of the magnetic moment orientation was induced, freeing the antiatoms from the trap, where a magnetic field had been set to act on a specific orientation of the magnetic moment. Antihydrogen then annihilated with the walls of the trap and could be detected. This demonstrated the possibility to act on the antihydrogen atoms, given their properties, leading to an improvement of the precision in the measurements.

In 2021, the ELENA (Extra Low ENergy Antiproton) ring began its operation. This new decelerator will slow antiprotons from AD down to 100 keV, increasing the luminosity of the beam, as well as the number of antiprotons that can be trapped, by a factor of 10 to 100. ELENA is also able to deliver beams almost simultaneously to all experiments in the AD hall, increasing the beam time for every collaboration [43].

The current AD hall and its experiments will be presented in detail in Chapter 2.

1.2 Bases of $\bar{p}$ annihilation physics

To understand the design of a detector for $\bar{p}$ annihilations, it is important to study the products of such a process. Since $\bar{p}$ and nucleons are not elementary particles, the interaction takes place at the quark level. However, not all the quark pairs annihilate, producing a large number of decay channels in which

quarks can recombine in different mesons: this process is called *rearrangement*, and an example is shown in Figure 1.13. Indicating with m the mass of the

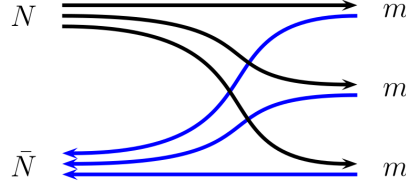


FIGURE 1.13: Rearrangement of the quarks and antiquarks from an interaction between a nucleon and an antinucleon into a set of three mesons [44].

proton or antiproton and m_1, m_2 etc. the final mesons masses, annihilation at rest is possible if

$$2m \geq m_1 + m_2 + \dots$$

So, considering a $\bar{p} - N$ (antiproton - nucleon) interaction, an amount of ~ 1880 MeV is available and up to 13 pions can be produced. This energy is divided between the rest masses of the products and their kinetic energy. Depending on whether the antiproton interacts with a proton or a neutron, an even or odd number of charged pions is produced due to charge conservation. Table 1.1 (extracted from [45]) presents a set of possible products of antiproton annihilations: since the detector presented in this thesis is able to reconstruct only charged particles, neutral mesons channels are not shown. The mean number of pions in the final state from $\bar{p} - p$ annihilation can be deduced by the Gaussian fit shown in Figure 1.14 from the Crystal BARRel data and is 5.03 ± 0.05 . This means that the mean number of *prongs* (charged pions) in the final state is 3.05 ± 0.04 . This number is adequate to reconstruct the annihilation vertex precisely, if all the products were detected, which depends on the geometry of the detector. Another parameter that has to be considered while designing an annihilation detector is the mean energy of the pions from the annihilation event. Given that the rest masses of the pions are

$$m_{\pi^\pm} \simeq 140 \text{ MeV}/c^2 \quad m_{\pi^0} \simeq 135 \text{ MeV}/c^2 \quad (1.2)$$

and, as said above, the available energy in a $\bar{p} - p$ annihilation at rest is ~ 1880 MeV, the mean kinetic energy per pion is

$$E_\pi \simeq 230 \text{ MeV/pion} \quad (1.3)$$

when a mean number of pions of 5 per annihilation is considered. This is confirmed observing the data from the Crystal BARRel collaboration in Figure 1.15: the most probable value of the measured energy is in fact around 230 MeV.

TABLE 1.1: Secondary products and branching ratios of antiproton-proton and antiproton-neutron annihilations. The branching ratios of neutral mesons channels have been omitted. This table is extracted from [45].

$\bar{p} - p$		
<i>products</i>		<i>BR(%)</i>
$2\pi^+ + 2\pi^- + N\pi^0$	$N \in [0, \dots, 3]$	47.30
$\pi^+ + \pi^- + N\pi^0$	$N \in [0, \dots, 3]$	41.53
$3\pi^+ + 3\pi^- + N\pi^0$	$N \geq 0$	4.25
$K^\pm + K^0 + \pi^\mp + \pi^0$		0.47
$K^\pm + K^0 + \pi^\mp$		0.46
$K^+ + K^- + NK^0$	$N \in [0, 1]$	0.34
$K^+ + K^- + \pi^0$		0.24
$K^+ + K^-$		0.10

$\bar{p} - n$		
$2\pi^- + 2\pi^+ + N\pi^0$	$N \in [0, 1]$	59.7
$3\pi^- + 2\pi^+ + N\pi^0$	$N \geq 0$	27.6
$\pi^- + N\pi^0$	$N \geq 0$	16.4
$4\pi^- + 3\pi^+ + N\pi^0$	$N \geq 0$	0.39

The peak at around 800 MeV/c in the π^0 momentum distribution is due to $\rho\pi$ production, better visible in this plot because of an artifact of the experimental resolution of the detector, which was better for the recoiling π^0 than for the $\pi^\pm$ ones [26].

1.3 Antihydrogen production

As introduced before, the antihydrogen atom (made of an antiproton $\bar{p}$ and a bounded positron e^+) allows to test the CPT theorem, thanks to the study of its excitation spectrum and the comparison with its ordinary matter counterpart, which is known with a high precision (for instance, the 1S-2S transition was measured with a precision of $\Delta E/E \sim 10^{-14}$ [46]). Antihydrogen is also a perfect candidate to measure the gravitational effect on antimatter given its neutrality: the extreme weakness of gravity compared for instance with the electromagnetic force, does not in fact allow to use charged particles for such measurements.

The precise study of antiatoms requires to keep them under observation for a relatively long time, so the recombination of $\bar{p}$ and e^+ has to happen almost

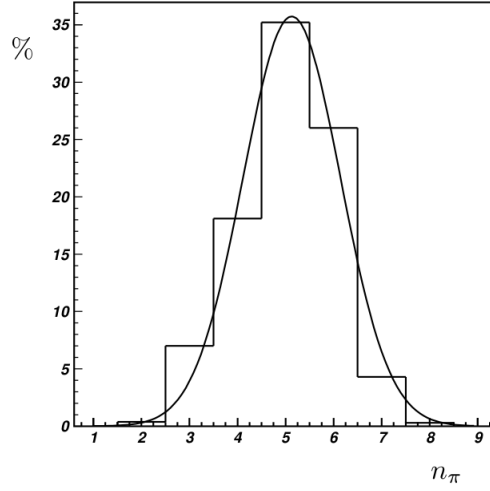


FIGURE 1.14: The pion multiplicity distribution from Crystal BARrel data and a Gaussian fit of the peak to estimate the mean number of pions in a $\bar{p} - p$ annihilation [26].

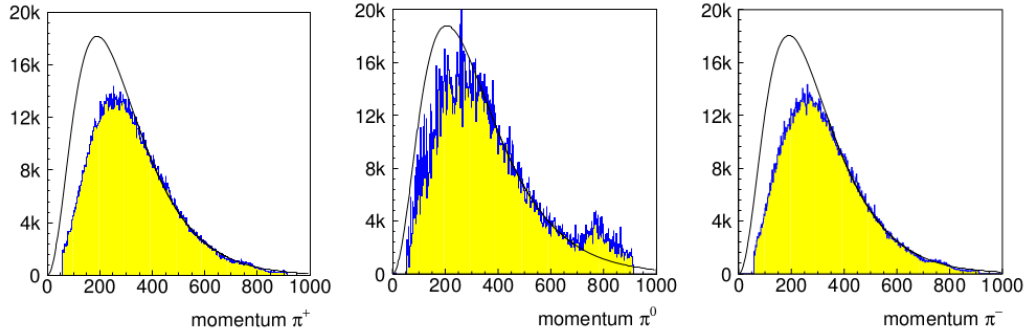


FIGURE 1.15: The momentum distribution (in MeV/c) of charged and neutral pions in $\bar{p} - p$ annihilations. The black line is a fit with a Maxwell-Boltzmann momentum distribution [26].

at rest. As explained in Section 1.1.3, the interaction of the antiprotons with a gas allowed the production of the first sample of $\bar{H}$ atoms, which, given the relativistic beam, could not be trapped. To produce them at rest, a cooling and trapping technique is required both for antiprotons and positrons. For the latter, the buffer gas cooling scheme is currently one of the most successful methods [47]: the positrons emitted by a ^{22}Na source are trapped by a potential well and confined by a magnetic field, after having lost kinetic energy via inelastic collisions with a gas injected in the trap. On the other hand, the first and most common method to trap antiprotons is based on the so-called Penning trap [32]:

- the $\bar{p}$ s (of a beam from a decelerator) are slowed down crossing thin degrader foils, colliding with its atoms and losing their kinetic energy. This step causes also an important decrease of the intensity of the $\bar{p}$ beam, due to the annihilations between the antiprotons and the nucleons of the foil;
- the survived and slowed antiprotons enter in the Penning-Malmberg trap (shown in Figure 1.16). It is formed by a set of cylindrical electrodes which generate an electric potential that confines axially the charged particles entering the trap. A strong magnetic field ($\sim 1\text{-}5\text{ T}$) causes them to have a small-radius cyclic motion around the axis of the trap, confining them in the radial direction and preventing the interaction with the trap walls;
- the antiprotons inside the trap have an energy in the keV range, so they have to be cooled again to reach lower energies in order to be able to combine with positrons. This can be done by making the $\bar{p}$ interact with preloaded electrons in temperature equilibrium with the trap.

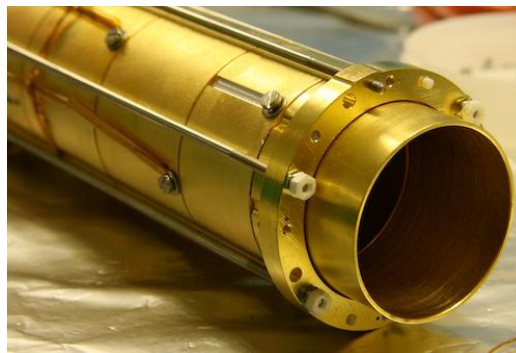
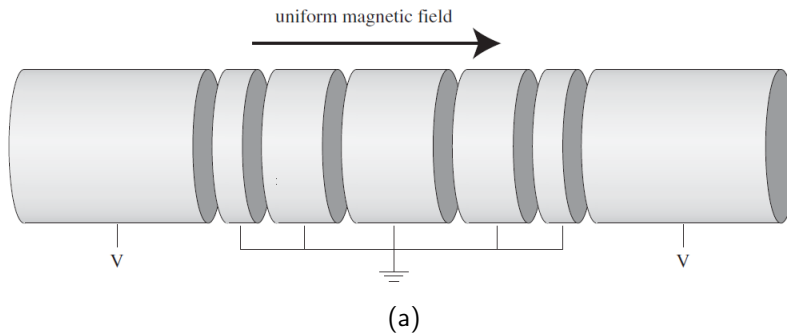


FIGURE 1.16: (a) Scheme of the electrodes in a Penning-Malmberg trap for the axial confining potential well. The direction of the magnetic field for the radial confinement is shown [48]. (b) Detail of the ALPHA Penning trap [49].

At this point, the previously accumulated positrons are injected in the Penning-Malmberg trap to be merged with the antiproton cloud. Two methods can be followed to synthesize antihydrogen: making the two constituents interact directly or go through an intermediate step and generate positronium (a bound state of an electron and a positron) and making it collide with the antiproton cloud. In particular, if the positronium is created in an excited state, the probability of $\bar{H}$ synthesis increases [50]. The first method is based on a modified version of the Penning-Malmberg trap: the so-called nested Penning trap. This configuration allows to bring positrons and antiprotons together in the trap and to mix them with the lowest possible relative energy. This happens modulating in two steps the electric potential inside the trap, loading the antiprotons into the side wells of the positron plasma firstly and mixing them together in a second moment, as shown in Figure 1.17. The resulting antihydrogen atoms are less energetic than having them formed merging directly the two clouds [48].

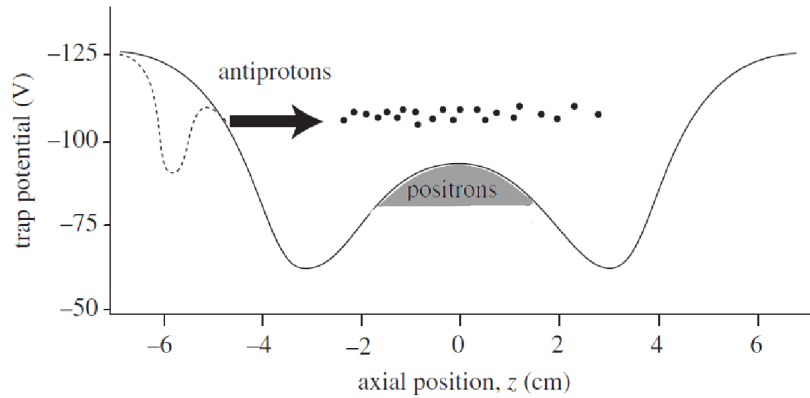


FIGURE 1.17: The nested Penning trap configuration: positrons are stored inside the trap by a negative potential and antiprotons are injected modifying it [48].

The so-formed antihydrogen atoms are neutral so they are insensitive to the electric potential. However, $\bar{H}$ has a small magnetic dipole moment which can be used to confine antiatoms applying a high magnetic field. Antihydrogen is trapped in a minimum of this field, provided by two axially separated, but coaxial coils. In the transverse direction, the minimum can be provided by a multipole field over the entire length of the well. The magnetic moment of the $\bar{H}$ atoms depends on which state they are in and it is the smallest in the ground state. So, depending on the magnitude of the magnetic field, it is possible to trap antiatoms in particular states.

These trapping techniques are adopted by the antihydrogen experiments located at the Antiproton Decelerator, which will be briefly described in Chapter 2.

CHAPTER 2

The ASACUSA experiment

As anticipated in Chapter 1, a detailed discussion of the ASACUSA collaboration and its experimental setup for the hyperfine spectroscopy of the antihydrogen will be presented in this chapter. The first part of the chapter is dedicated to the Antiproton Decelerator and the AD hall, where the ASACUSA experiment is located, together with the experimental lines of other collaborations working on antimatter. In the second part, the ASACUSA experimental apparatus and the antihydrogen production method are presented.

2.1 AD and the AD hall

Since its commissioning in 1996, the Antiproton Decelerator provides a beam of low energy (~ 5.3 MeV) antiprotons to different antimatter physics experiments, situated in the so called AD hall, within the accelerator ring, and it is currently the world only source of slow $\bar{p}$ s. AD is a synchrotron ring with a length of 182 m and 90% of its equipment comes from the former AC, AA and LEAR, such as the target area, the injection/ejection lines, the magnets, the power supplies, the radio-frequency cavities and the stochastic and electron cooling. Nowadays, 6 collaborations are running or are setting up their experiment focusing on antihydrogen production, to perform precision tests of the *CPT* theorem and to measure the gravity acceleration of antimatter [51]. In Figure 2.1 AD and the extracted experimental beamlines are shown, along with the ELENA ring

(Figure 2.2), which is fully operative since the end of the Long Shutdown 2 (LS2). A detail of the AD ring is shown in Figure 2.3.

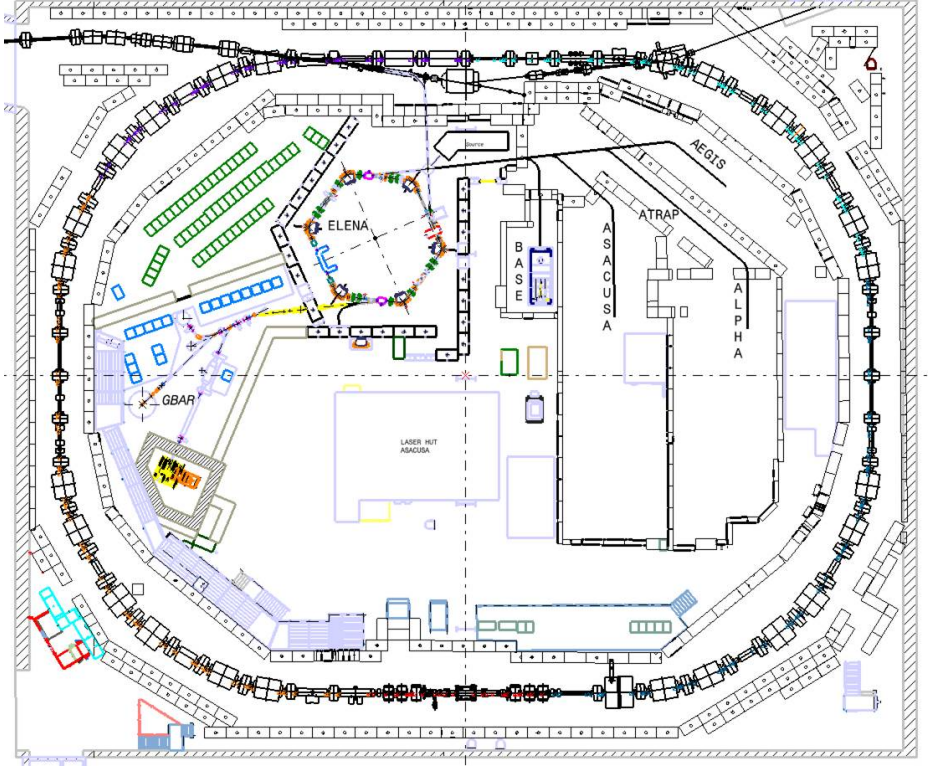


FIGURE 2.1: The current configuration of the AD hall at the CERN Antimatter Factory. The AD ring and the extracted beamlines are shown, along with the ELENA ring and the collaborations' experimental areas [52].

2.1.1 Antiprotons production

Antiprotons are produced by the collision between the PS proton beam, with an energy up to 26 GeV and an intensity of 10^{13} protons/s, and an Iridium target. The target is a cylinder with a diameter of 3 mm and a length of 50 mm, embedded in graphite and water cooled. The antiprotons are produced via the following reaction:

$$p + N \rightarrow N^* + p + \bar{p} + X \quad (2.1)$$

where p is the incident proton, N is a nucleus of the target material, $\bar{p}$ the produced antiproton and N^* and X the excited nucleus and the other particles resulting from the interaction. The antiprotons have a wide angular distribution (in the 50-100 mrad range) in the laboratory frame with respect to the primary

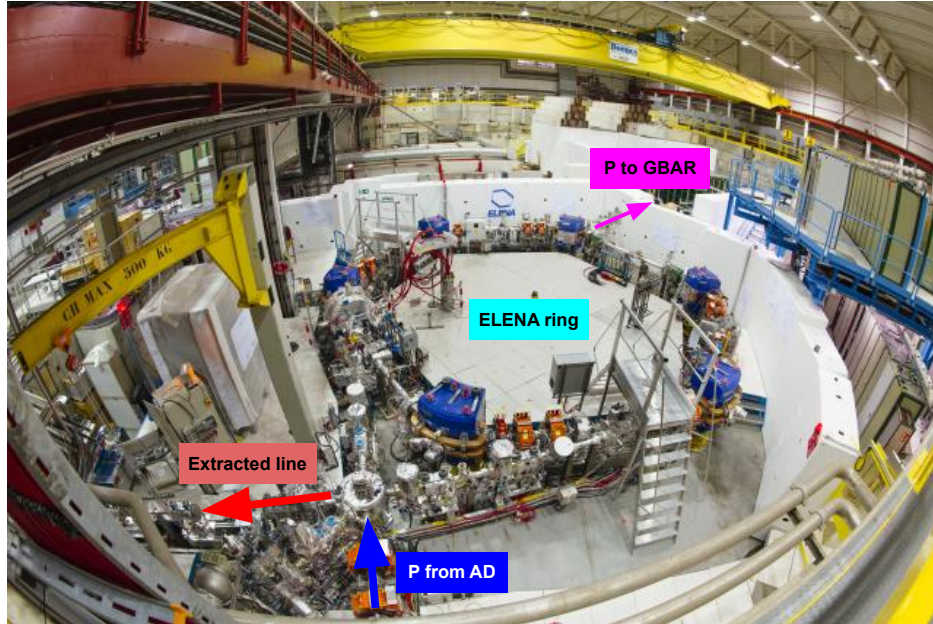


FIGURE 2.2: Picture of the ELENA ring at the antimatter factory at CERN¹. The antiproton beam from AD comes from below and is injected in ELENA and then extracted and delivered to the experimental lines at the left side of the image. The GBAR experiment has a dedicated extracted line on the upper-right of the image.

beam direction and also a wide range of energies, so they need to be focused by a magnetic horn, placed after the target. The horn is optimized to collect antiprotons with a momentum around 3.5 GeV/c and a spread $\Delta p/p \sim 6\%$ [54]. The AD target area is shown in Figure 2.4 and a detail of the target station with the iridium target and the magnetic horn is visible in Figure 2.5. The antiproton beam is then separated from the incident beam and from the other generated particles by an achromatic momentum analyzer, called "dogleg", and injected in AD.

2.1.2 The AD cycle

After the injection in AD, the antiprotons are slowed down in a series of deceleration and cooling steps, during the AD cycle (Figure 2.6). A bunch of 25 ns containing $\sim 5 \times 10^7$ antiprotons is rotated of $\pi/2$ in the longitudinal phase-space by RF fields. Due to its large momentum spread, to fit the decelerating RF cavity requirements the beam has to be cooled. The cooling techniques used

¹<https://home.cern/fr/node/4325>

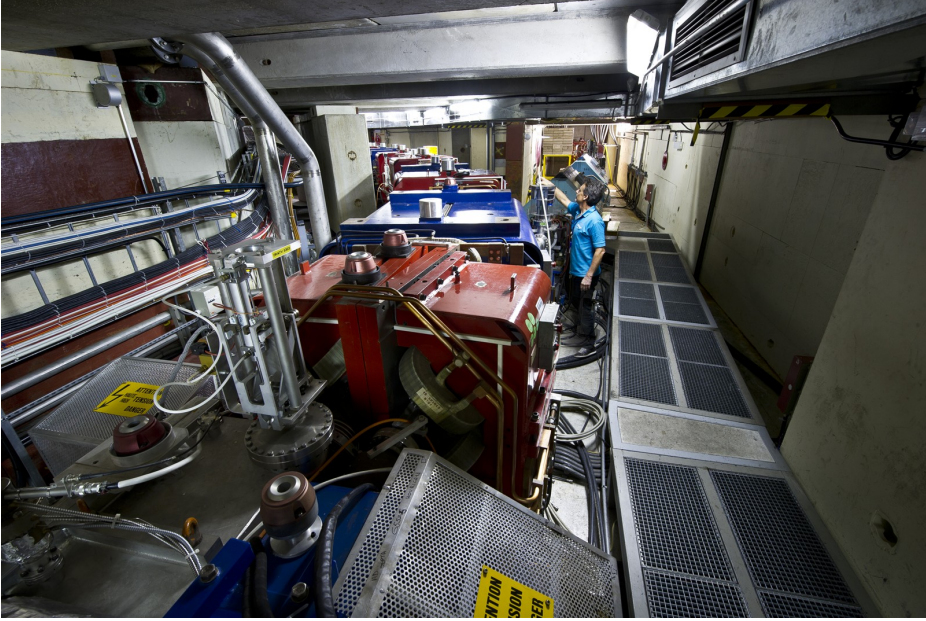


FIGURE 2.3: Picture of a detail of the AD ring. In the upper-right it is possible to see the incoming line from the AD target area. In the center, the AD bending magnets (with the blue magnet case) and the quadrupoles (with the red magnet case). The person gives the idea of the dimensions [53].

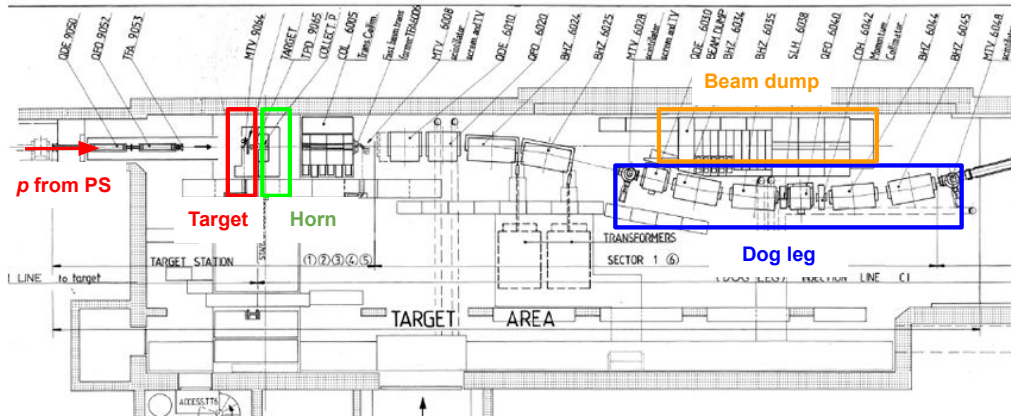


FIGURE 2.4: The scheme of the AD target area: on the left, the target and the magnetic horn; in the center, the primary beam dump; on the right, the "dogleg" and the antiproton line to AD [55].

in AD are the following [57]:

- *stochastic cooling*: the Δp_i and Δx_i deviations in momentum and trans-

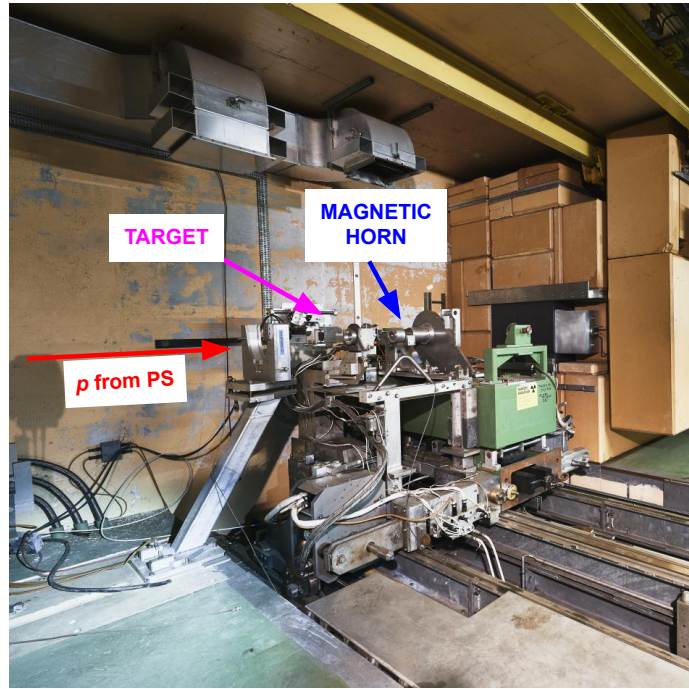


FIGURE 2.5: A picture of the AD target station in the AD target area. The direction of the incoming PS proton beam is depicted and the iridium target and the magnetic horn are visible [56].

verse position of small subgroups of antiprotons (relative to all the $\bar{p}$ s orbiting in AD) are detected by so-called "pickup" electrodes placed along the ring. The resulting signals are sent to steering electrodes located in the opposite side of AD, which correct the $\bar{p}$ s orbits in a feedback-like scheme;

- *electron cooling*: the AD beam merges with a collinear electron beam in a dedicated 2 m long section of the ring. Since the $\bar{p}$ and e^- velocities are matched, in the center-of-mass frame the particles are in the same low temperature bath and collisions transfer the "heat" from the antiprotons to the electrons, cooling them.

Using these methods in sequence, together with the deceleration steps, the final beam at the end of the 110 s cycle is a bunch of $\sim 3 \times 10^7$ antiprotons with a length of ~ 150 ns and a kinetic energy of 5.3 MeV.

Since the final energy is still too large for an efficient antiproton trapping, up to now experiments have used degrader foils to reduce more the energy of the antiparticles; in this step, 99% of the beam intensity is lost. As said before, since the end of 2021, the ELENA ring decelerates the 5.3 MeV antiproton beam

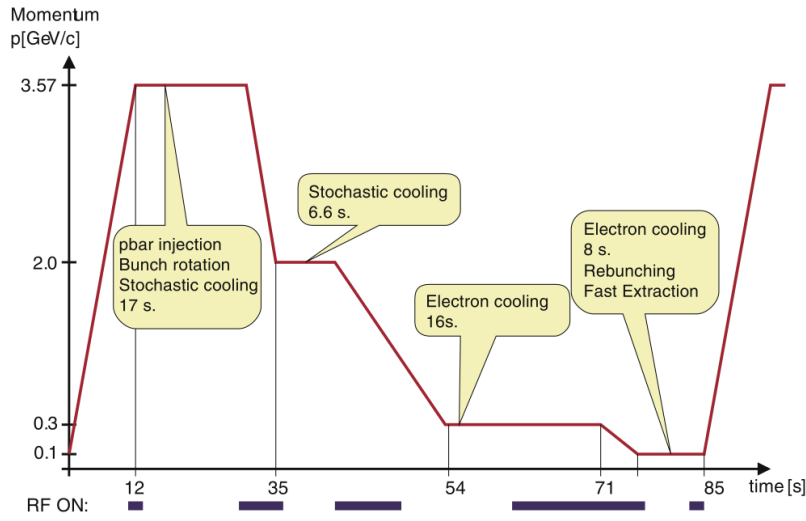


FIGURE 2.6: The AD deceleration and cooling cycle: the $\bar{p}$ momentum as a function of elapsed time is shown, along with the duration of every cooling and deceleration step. In blue, below the time axis, the time intervals during which the deceleration RF field is on [45].

from AD down to 100 keV, and then delivers this very low energy beam to the extracted lines. Moreover, these lines use electrostatic devices, with a cost-effective improvement and reducing the sensitivity to magnetic perturbation [58].

2.1.3 Experiments in the AD hall

Six collaborations have installed, or are in preparation to install, different anti-matter experiments in the AD hall, in particular within the AD ring: ALPHA, AEGIS, GBAR, BASE, PUMA and ASACUSA. They will be presented briefly in the following sub-sections. Since the detector treated in this thesis is going to be installed in the last one, the ASACUSA experiment will be discussed separately in Section 2.2. Some of the previous AD experiments have been presented in Section 1.1.4.

ALPHA: Antihydrogen Laser PHysics Apparatus

The ALPHA experiment [59] began its operation in 2006, as an improvement of the ATHENA one. The original goal was to demonstrate the trapping of antihydrogen atoms using a superconducting magnet trap. The collaboration succeeded in 2010 managing to trap antihydrogen atoms and to observe then, in 2011, the interaction between antimatter and electromagnetic radiation. In

2016, they measured the 1S-2S transition in trapped antihydrogen, excited by a laser, reaching a precision of about 10^{-12} [60]. The ALPHA-2 apparatus used for these measurements is based on a nested Penning trap (Figure 2.7) coupled with a transverse octupole and two solenoidal mirror coils for the $\bar{H}$ trapping. ALPHA-g is going to be the next setup for the measurement of the gravitational g constant of antimatter. The detection system consists in a set of silicon tracking detectors and a Time Projection Chamber (TPC), placed around the antihydrogen trap and used as annihilation detectors.

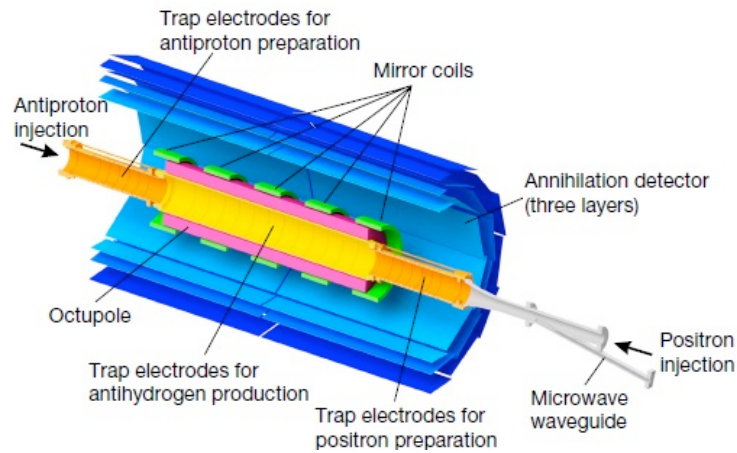


FIGURE 2.7: The ALPHA-2 trap scheme [59].

AEgIS: Antihydrogen Experiment Gravity Interferometry Spectroscopy

The AEgIS experiment [61] intends to measure the behaviour of antimatter in the Earth gravitational field. The measurement is based on the production of a pulsed antihydrogen horizontal beam that crosses a set of gratings; a position sensitive detector is used to measure the vertical drift of the antiatoms.

The experiment detects the Talbot-Lau fringes produced by a set of three planes of periodic gratings, a method that is basically a classical-analogue of an interferometer, the so-called Moiré deflectometer. The measurement requires a position sensitive detector with a very high spatial resolution, better than $10\ \mu\text{m}$. The collaboration has chosen the photographic emulsion technology, performing a R&D program on a hybrid detector combining a MCP (Multi Channel Plate) with a Timepix silicon position sensitive detector. In Figure 2.8 the antihydrogen beam production and the Moiré deflectometer are shown.

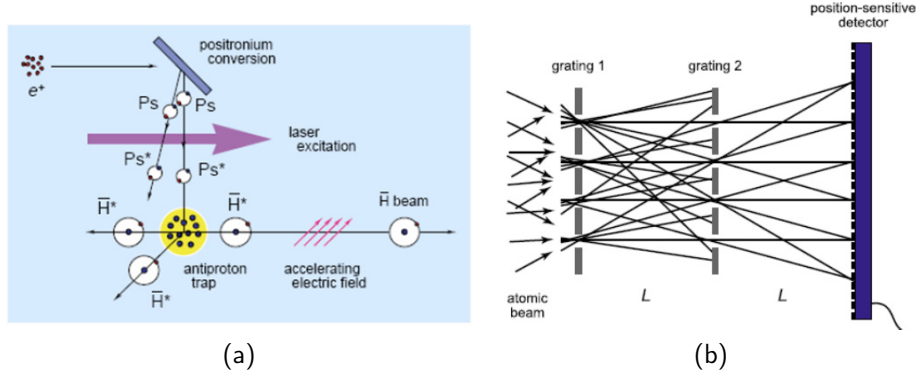


FIGURE 2.8: The AEgIS experiment measurement principle: (a) antihydrogen pulsed beam production and (b) the Moiré deflectometer principle [62].

GBAR: Gravitational Behaviour of Anti-Hydrogen at Rest

The GBAR experiment [63] aims to measure the gravity acceleration of anti-matter at rest to test the Weak Equivalence Principle (WEP), which states that the trajectory of a test particle is independent of its composition when gravity is the only active force. To do that, the collaboration produces antihydrogen ions, cools them to μK temperatures, photo-detaches the outer positron by a laser pulse, leaving the neutral antiatom to perform a free fall, and measures its acceleration, with a first estimated precision of 1%. Unlike the other experiments, GBAR produces positrons using a small electron linear accelerator and a target to gain a high production rate with respect to the common radioactive sources. A MicroMEGAS tracker detector and a scintillator-bar TOF array detect the annihilation of the antiatom and measure its free fall time. In Figure 2.9 the measurement scheme of GBAR is presented.

BASE: Baryon Antibaryon Symmetry Experiment

The BASE [64] experiment goal is to test the CPT symmetry by comparing the proton and antiproton magnetic moments with high precision. The g -factors (i.e. the magnetic moment in units of the nuclear magneton) are measured as the ratio of the spin-precession frequency to the cyclotron frequency. Using a double Penning trap, the collaboration expects to measure $\delta g/g$ with a precision of 10^{-9} . The measurement is performed by detecting the induced signal of a trapped antiproton in one of the trap rings (Figure 2.10). In 2022 the collaboration has announced the most precise measurement of the antiproton-to-proton charge-mass ratio, calculated with an uncertainty of 1.6×10^{-13} [65].

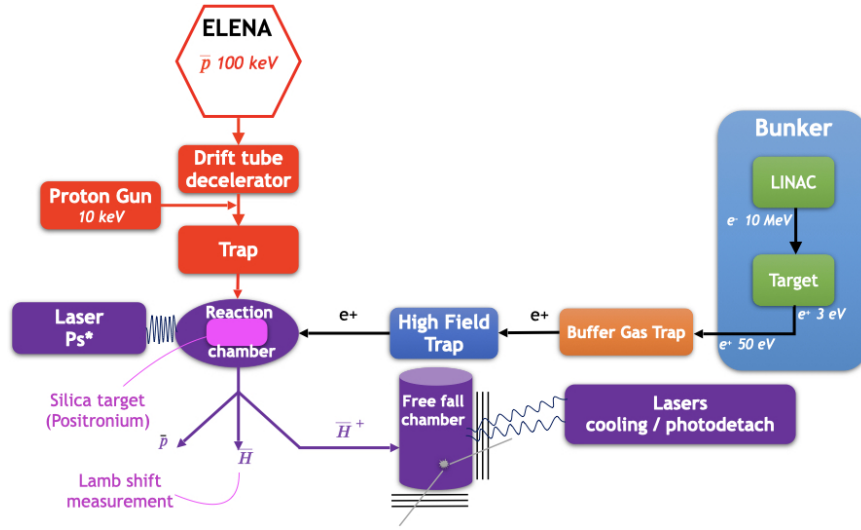


FIGURE 2.9: The GBAR measurement scheme [63].

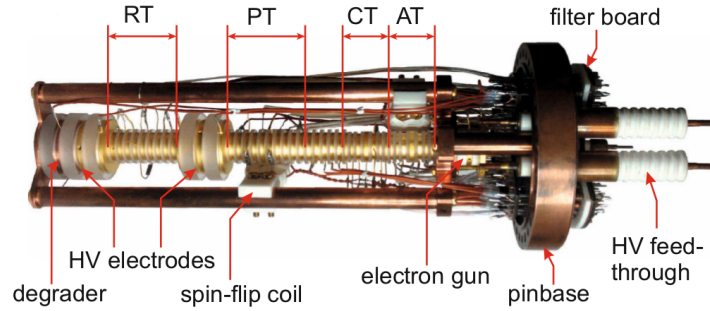


FIGURE 2.10: The BASE double Penning trap: RT is the reservoir trap, PT the precision trap, CT the cooling trap and AT the analysis trap. The combined PT/AT trap allows the frequencies measurement [64].

PUMA: antiProton Unstable Matter Annihilation

The PUMA experiment [66] aims to use the antiprotons from the AD/ELENA facility as a probe to study short-lived isotopes at the ISOLDE facility, located a few hundred meters from the antimatter factory. The collaboration expects to store and transport 10^9 antiprotons in a dedicated transportable trap (Figure 2.11). The antiprotons are captured at the end of the GBAR beamline. A TPC is placed around the interaction region between the antiprotons and the unstable nuclei to detect annihilation products to study the thick neutron skin in radioactive elements.

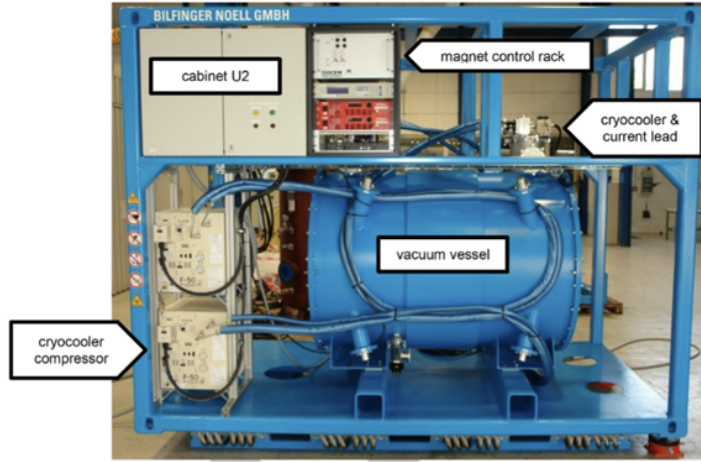


FIGURE 2.11: The PUMA transportable trap².

2.2 The ASACUSA collaboration

The ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration is an international collaboration based at the Antiproton Decelerator at CERN. The main goals of ASACUSA are the following:

- the production and hyperfine spectroscopy of antihydrogen to test the *CPT* symmetry [67];
- the laser spectroscopy of antiprotonic helium for a precise measurement of the mass ratio between the antiproton and the electron [68];
- the study of the antiproton annihilation cross section with atoms and nuclei at low energy (< 100 eV) [69];
- the fragmentation studies in $\bar{p}$ –nucleus annihilations [70].

Since the subject of the present thesis is the upgrade of the detector surrounding the cusp trap for the antihydrogen synthesis, only the first point will be explained in detail in the following.

To measure the hyperfine splitting (HfS) of the ground state of the antihydrogen with a relative precision of $\Delta\nu_{HfS}/\nu_{HfS} \approx 10^{-6}$ - unlike the other experiments presented before that trap antihydrogen and perform the measurement inside the trap (the most precise measurement, 3.5×10^{-4} , was reached by ALPHA [71]) - ASACUSA uses a technology based on the production of a

²<https://ep-news.web.cern.ch/puma-antiprotons-probe-surface-radioactive-nuclei>

polarized antihydrogen beam and the use of a Rabi spectrometer. The advantages of such an approach are the relatively high temperature acceptance (50 to 100 K) for the apparatus and the possibility to perform very high precision spectroscopy measurements in a field-free region, i.e. outside of the mixing trap, where strong inhomogeneous magnetic fields are present. In 2012 the collaboration succeeded in producing the first antihydrogen beam in such a way [72]. New studies will have to be performed to accumulate a number of antihydrogen atoms in the beam large enough to reach the expected precision in the spectroscopy measurements.

2.2.1 The antihydrogen hyperfine splitting

To understand the ASACUSA experimental setup for the spectroscopy of the antihydrogen, a brief discussion on the (anti)hydrogen hyperfine structure is reported.

The hyperfine structure of the 1S state of the (anti)hydrogen is due to the coupling between the total angular momentum of the electron (positron) and the one of the proton (antiproton). If F is the quantum number related to the total spin of the state, $F = 0$ corresponds to a singlet state and $F = 1$ to a triplet state. In presence of a magnetic field $\vec{B}$, it is possible to split the degenerated triplet state and the energy levels of the resulting states shift due to the interaction of the magnetic moment of the atom $\vec{\mu}$ and the magnetic field. The behaviour of the spectrum in presence of a magnetic field is described by the Breit-Rabi formulae [73] and is shown in Figure 2.12. The states that increase energy in an external magnetic field are called Low-Field Seekers (LFS) and the states that do the opposite High-Field Seekers (HFS). The consequence is that (anti)atoms in LFS states drift towards lower field regions, while HFS (anti)atoms towards large field ones.

This fact can be used to separate the different atoms populations in the mixing trap and in the spectroscopy apparatus. The ASACUSA experiment allows to measure the π_1 and the σ_1 transitions (see Figure 2.12) to estimate the hyperfine splitting frequency ν_{HfS} . The transition frequency between those two states in hydrogen has been measured precisely within a maser experiment which yielded $\nu_{HfS} = 1420405751.768 \pm 0.002$ Hz [74]. A significant deviation from this value could be a hint of an asymmetry between matter and antimatter and should be explained by alternative theories like those included in the Standard Model Extension (SME) [75], not treated here.

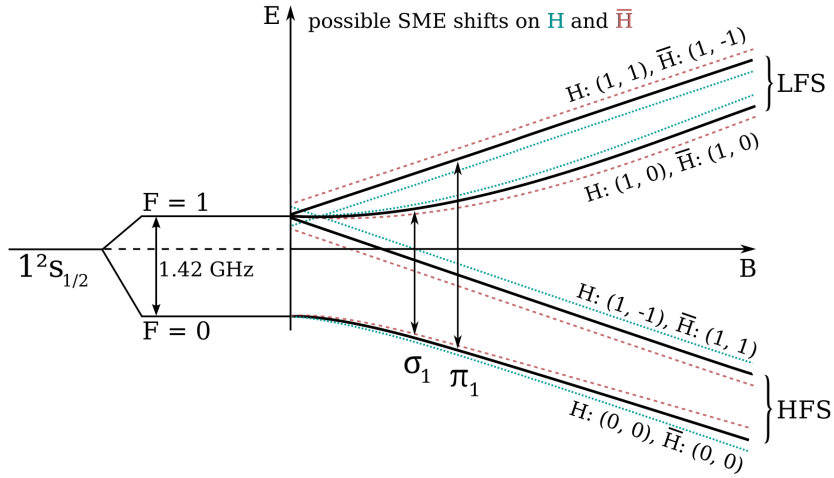


FIGURE 2.12: The antihydrogen hyperfine splitting in presence of a magnetic field. H and $\bar{H}$ represent the hydrogen and antihydrogen states. The blue and red dashed lines show the spectra in the context of the Standard Model Extension. The black arrows show the transitions measurable with the ASACUSA experimental setup [70].

2.2.2 The ASACUSA beamline

The ASACUSA experimental setup (a picture is visible in Figure 2.13) for the measurement of the hyperfine transition frequency is based on the Rabi spectrometer, from the original idea of the Nobel prize Isidor Rabi in 1938 [76].

The Rabi spectrometer consists in a spin-polarized source, a spin-flip inducing resonator and a spin selector. The first step is easily achievable when ordinary matter is used (for instance, hydrogen atoms polarized by a magnetic field [77]), but requires a dedicated setup if working with antimatter, since its production presents several difficulties. Figure 2.14 presents a comparison between the scheme of the original Rabi setup (bottom) and the ASACUSA one (top). The polarized antihydrogen beam enters in a region with an oscillating magnetic field superimposed to a smaller homogeneous one: the antiatoms spins align to the last field and a spin-flip is induced if their resonance frequency is the same as the one of the oscillating magnetic field. At this point, another inhomogeneous magnetic field focuses or de-focuses the antiatoms depending on whether they are low- or high-field seekers. The focused ones annihilate in a dedicated detector at the end of the line. The transition frequency of the hyperfine splitting can be determined by scanning the frequency of the oscillating magnetic field and monitoring the number of detected antiatoms.

As said before, a crucial part of the measurement is represented by the antihy-

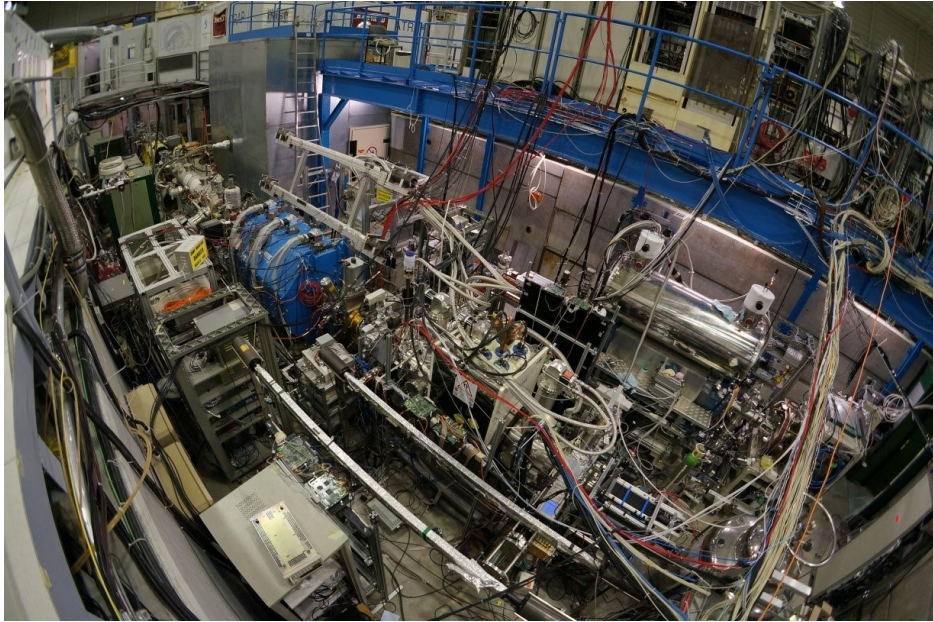


FIGURE 2.13: The ASACUSA experimental area with the antihydrogen cusp trap experiment setup³.

drogen production. The setup developed by ASACUSA for this goal is shown in Figure 2.15. In general, the $\bar{H}$ synthesis is based on a three-body recombination process, but the resulting atoms are produced in Rydberg states, i.e. with a very high principal quantum number n , so they are not suitable for hyperfine spectroscopy (where atoms in the 1S state are required). To avoid that, ASACUSA adopts a different trap scheme from the generally used Penning ones, which is called *cusp trap*. In this trap, Rydberg atoms are trapped for a time long enough to decay to the ground state.

The first constituent of an antihydrogen atom is the positron. In the ASACUSA experiment, positrons are produced with an energy up to 546 keV via β^+ decay by a ^{22}Na radioactive source with an activity up to 2 GBq. The positrons are slowed down to eV energies by a Ne moderator and transferred to the buffer gas trap. This trap, called positron pre-accumulator, is a Multi-Ring electrode Trap (MRT) surrounded by a superconducting magnet that provides radial confinement [78]. The positrons are cooled again by the interaction with the buffer N_2 gas down to ~ 25 meV. After 30 s of accumulation, they are ejected from the trap and magnetically guided in bunches to the cusp trap. For the antihydrogen synthesis, $\sim 5 \times 10^7$ e^+ are accumulated in the cusp trap and compressed to

³<https://home.cern/news/news/physics/antimatter-experiment-produces-first-beam-antihydrogen>

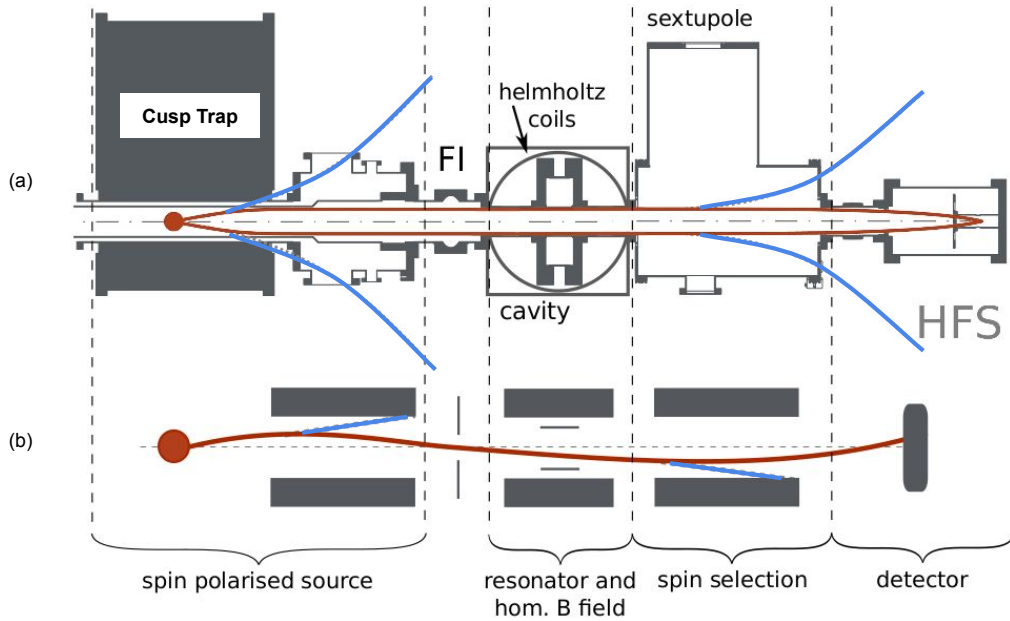


FIGURE 2.14: The comparison between the scheme of the original Rabi setup (b) and the ASACUSA one (a) for the HfS spectroscopy. The red line represents the antihydrogen beam from the mixing point (red dot) to the end of the line. The blue lines represent the de-focused atoms. The element denoted by FI is the Field Ionizer, that rejects the atoms not in the ground state [70].

form a dense plasma.

The second element required to form $\bar{H}$ is the antiproton. In the experimental runs before the LS2, the 5.3 MeV beam from AD was slowed down to 115 keV by a Radio Frequency Quadrupole Decelerator (RFQD) designed specifically for the ASACUSA antiproton beamline. Using this device and some degrader foils, approximately 10^6 antiprotons per AD cycle were trapped, corresponding to the 3% of the initial number of particles in AD and however 10 times more than the ones of the other experiments that used only degrader foils. Since 2021, being able to use the ELENA 100 keV beam, the RFQD has been removed and to maximize the trapping efficiency only one Al foil is needed, which should allow to trap a fraction of 80% of the incoming beam (estimated with simulations) [79].

The first trapping and accumulation of antiprotons in the line is performed by the MUSASHI antiproton accumulator. It is composed by a Multi-Ring electrode Trap (MRT) (Figure 2.16) and a superconducting solenoid. The MRT is a Penning-Malmberg trap with 14 electrode rings positioned orthogonally to the beam for the axial confinement, while the 5 T magnetic field generated by the

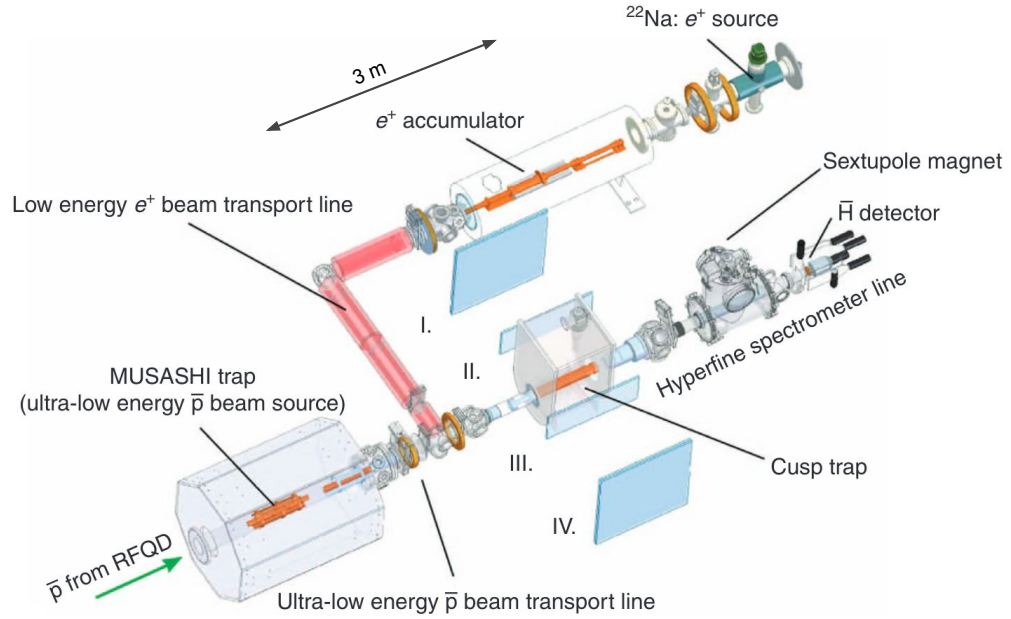


FIGURE 2.15: The ASACUSA setup for antihydrogen production. The shown elements are the following: the MUSASHI trap for the antiprotons preliminary trapping and accumulation, the positron source and the dedicated accumulator and transport line to the mixing region, the cusp trap, the scintillating bars detector for the annihilation products tracking (labeled as I-IV, subject of this thesis work) and the hyperfine spectroscopy line with the antihydrogen detector [72].



FIGURE 2.16: The MUSASHI multi-ring electrode trap [80].

solenoid provides the radial one. After crossing the first (upstream) electrode of the trap, the antiproton bunch reaches the last (downstream) one which is biased at a negative potential reflecting the particles backward. At this point, the upstream ring is biased as well, creating a harmonic potential to confine the antiprotons. Before the bunch arrival, the trap is filled by electrons to cool the $\bar{p}$ s via collisions. The electron cooling plasma loses the acquired energy via synchrotron radiation and can be used several times. The electrons are then removed by opening the trap for a short time (~ 550 ns) without disturbing the stacked antiprotons, that are compressed by the rotating wall technique. At the end, $\bar{p}$ s are extracted, by dedicated electrodes, with an energy of 1.5 eV and a spread of 0.23 ± 0.02 eV [81], and adiabatically transported over a distance of 2.5 m to the cusp trap.

2.2.3 The ASACUSA cusp trap

The heart of the ASACUSA experimental setup is the double cusp trap [82], i.e. the mixing trap for the synthesis of the antihydrogen. The trap consists in a MRT and a superconducting pair of anti-Helmholtz coils, which generate a magnetic field with two zero points and diverging field lines (Figure 2.17). The

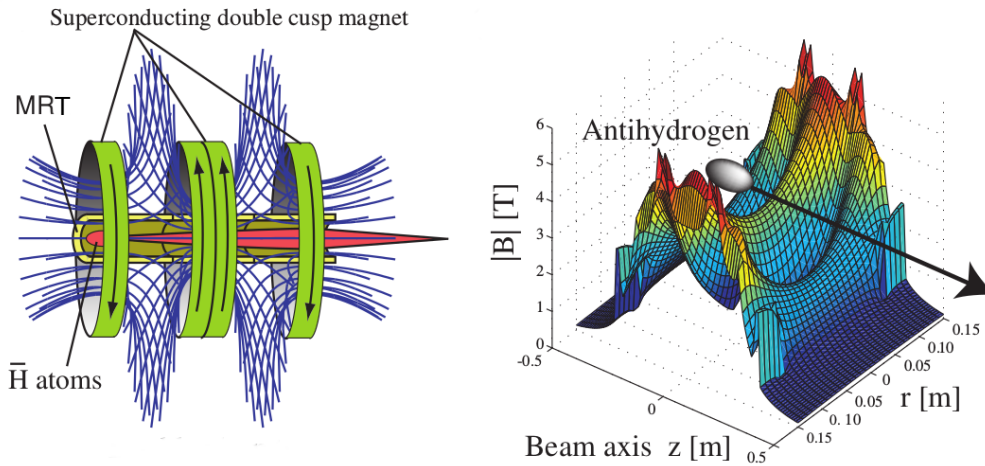


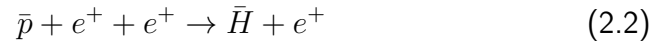
FIGURE 2.17: The double cusp trap magnetic field. Left: schematic drawing of the double cusp trap with the MRT and the magnetic field lines. Right: 3D plot of the magnetic field strength and the mixing region [83].

electric potential for the antihydrogen synthesis is shown in Figure 2.18. The procedure for the mixing consists in different steps:

- the positrons are injected in the trap by the Φ_1 potential and immediately trapped switching to the Φ_2 potential. They thermalize via synchrotron

radiation with the trap and form a non-neutral plasma. Then, they are compressed in the center of the nested potential Φ_3 ;

- the antiprotons from MUSASHI are injected in the cusp trap by the Φ_4 potential and confined by immediately re-switching it to the Φ_3 potential;
- antihydrogen atoms are created by a three-body recombination, with a second positron adopting the third-body role:



- due to their neutrality, $\bar{H}$ atoms move freely in the trap; some of them can reach the Field-Ionization Trap (FIT). If the atoms are in an excited Rydberg state, they are ionized and the remaining antiprotons are trapped in the FIT. The FIT can be repeatedly opened and the trapped antiprotons annihilate with the trap walls; the annihilation products can be detected to estimate how many antiatoms have been produced.

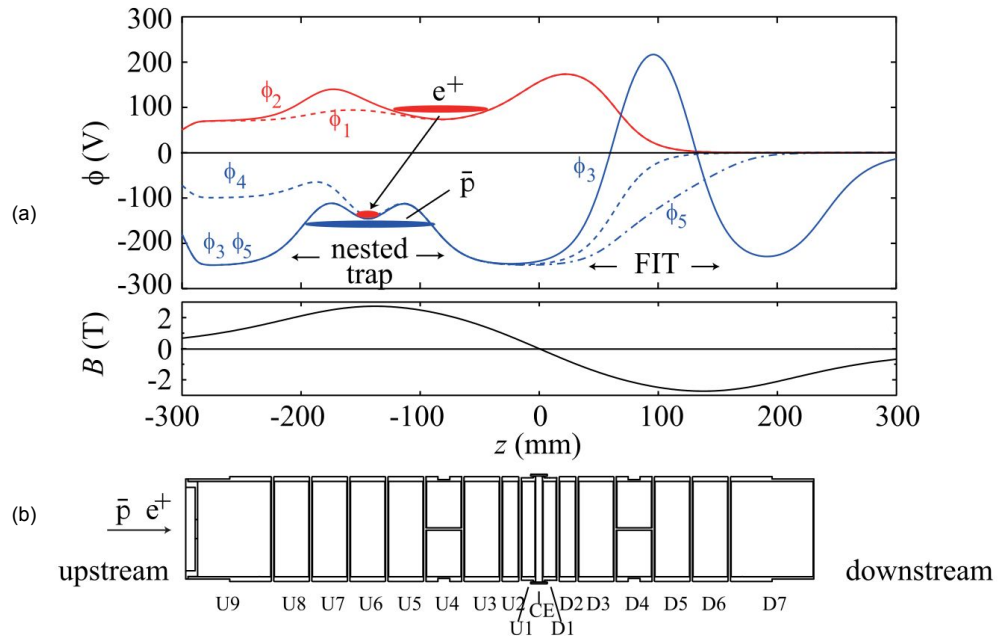


FIGURE 2.18: (a) The cusp trap electric potential configuration. The different potentials used to trap and mix positrons and antiprotons are explained in the text. (b) The scheme of the multi-ring electrode trap that generates the electric potential [82].

Two different detectors are responsible of the tracking of the annihilation products: the ASACUSA MicroMEGAS Tracker (AMT) and the Detector for ANnihilation Tracking Experiment (DANTE). The first is composed of two layers of MicroMEGAS (Micro-MEsh Gaseous Structure) detectors and a layer of scintillators, while the second is made of 8 scintillating bar planes. In Chapter 3, a detailed description of the scintillating bars, the light readout, the electronics and the data acquisition of DANTE is presented, being the subject of this thesis work.

CHAPTER 3

The scintillating bars tracker

The heart of this thesis work is the upgrade of the DANTE detector, that has been done designing a new mechanics, changing the light readout from Multi Anode PhotoMultiplier Tubes (MAPMT) to Silicon PhotoMultipliers (SiPM) and adapting the front-end electronics. The scintillating bars tracker has to reconstruct the annihilation vertex of the pions produced inside the ASACUSA cusp trap and along the beamline. The requirements on the detector features for this purpose are described in the first section of this chapter. A brief discussion on the scintillator characteristics and on the photosensors is presented in the following sections. The last part of the chapter focuses on the description of the previous versions of the detector and the upgrade steps are then presented in detail.

3.1 Physics motivations for a scintillator tracker

The tracking detector presented in this thesis work has to identify the tracks of the annihilation products generated inside the volume of the cusp trap in the ASACUSA beamline, and to reconstruct the annihilation vertex. Moreover the detector has to determine the time instant of the annihilation interaction. These goals are fundamental to monitor all the steps in the $\bar{p}$ trapping sequence, from the antiproton transport from the MUSASHI trap to the cusp trap, to the subsequent mixing with the positrons in the mixing region. An on-line monitoring of the processes inside the trap and along the beamline is crucial to tune correctly

the cusp trap parameters (electric and magnetic fields, potential switching, etc.). The inner tracker (the AMT) can reconstruct very precisely the position of the annihilation vertex, being located inside the cusp trap, but it covers only a few tens of cm around the mixing region. The DANTE detector has been designed to satisfy the experiment requirements, taking advantage of the following features:

- since the detector has to cover a large area (almost 1 m in length) and has to be placed in different configurations within the narrow spaces of the ASACUSA experimental area, plastic scintillating bars have been chosen for this purpose. In fact, plastic scintillators (as explained in Section 3.2.2) are easily manufacturable in different geometries and shapes;
- plastic scintillators are largely used in MIP (Minimum Ionizing Particle) detectors as they are cheap and light. In fact, as explained in Section 1.2, the pions produced in annihilations have an average momentum of $\sim 230 \text{ MeV}/c$, thus behaving as MIPs in plastic materials (as shown in Figure 3.1);
- the spatial resolution achievable with the scintillating bars used for the tracker is of the order of a cm, that is enough for the position reconstruction on the beam axis, to understand where on the beamline the annihilations happen;
- the data acquisition described in Section 3.3.4 can operate both the analog and digital detector readout. The digital one in particular allows to reach high time resolutions [84], to detect the events in the first μs of the mixing in the trap.

The scintillation mechanism of the chosen scintillators and the light readout system are described in the next sections.

3.2 Characteristics of a scintillating detector

3.2.1 Light production in plastic scintillators

Some materials, when excited by ionizing radiation, are characterized by the luminescence phenomenon, i.e. the emission of the absorbed energy in the form of a light flash. They are called scintillators and the emission occurs usually in the visible light range. If the re-emission happens in a time $< 10^{-8} \text{ s}$, the process is called fluorescence, otherwise it is called phosphorescence which corresponds to a light emission that can happen also a long time after the irradiation of the material. Scintillating detectors are usually made of fluorescent material, in order

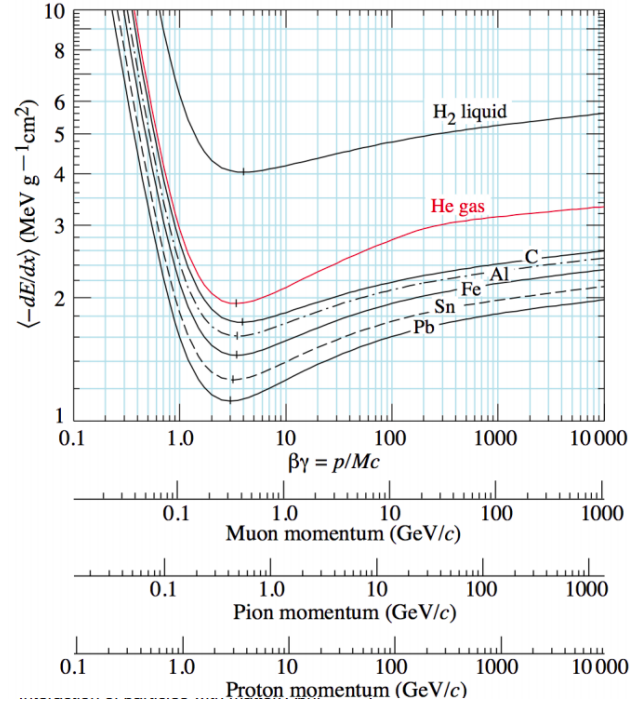


FIGURE 3.1: Bethe-Bloch curve for different materials and particle momenta. Note that the pions in the range 200-500 MeV/c are MIPs in all the materials presented in the plot [85].

to reach a good timing resolution and to have the possibility to work in high rate conditions.

The light emission can be described by considering both the fluorescent and phosphorescent components, with a two exponential function (Figure 3.2) [86]:

$$N(t) = A \exp^{-\frac{t}{\tau_f}} + B \exp^{-\frac{t}{\tau_s}} \quad (3.1)$$

where $N(t)$ is the number of photons emitted at the instant t , τ_f is the decay time of the fast component and τ_s of the slow one. The rising part of the curve can be neglected because it is much shorter than the decay time. The pulse-shape discrimination technique for particle identification is based on the analysis of these two components, but it will be not treated here.

In general, the materials used for scintillator detectors can be divided in two main categories: inorganic and organic scintillators. The former are mainly inorganic alkali halides crystals doped with activator impurities. Due to the high atomic number Z and large density, they are characterized by a large scintillation efficiency and a large stopping power (i.e. the radiation can be totally absorbed),

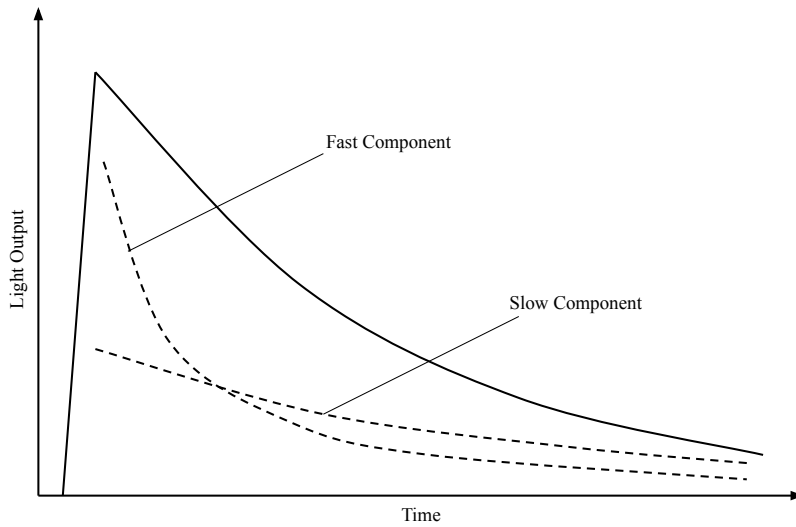


FIGURE 3.2: Scintillator light output as a function of time. The fast component and the slow one are shown as dashed lines, whereas the solid one represents the total emission [86].

but they have rather long emission times ($\sim 10^2$ ns) and they are usually expensive. On the other hand, organic scintillators are plastic-like, i.e. they are aromatic hydrocarbon compounds containing benzene rings. They are typically characterized by a very fast decay time (few ns or less) and a low Z . They can be produced in different shapes and they are usually cheaper than the inorganic scintillators.

Since this thesis work is about a detector made by organic scintillator bars, a brief description of the scintillating process in organic materials will be given below, whereas a complete analysis can be found in [87].

The light emission in organic scintillators is due to the de-excitation of the molecules valence electrons from an excited state to the ground state. In general, the molecules spectrum (Figure 3.3) is divided in singlet (S_1 , S_2 , etc.) and triplet (T_1 , T_2 , etc.) states; the ground state is a singlet (S_0) and this configuration for organic materials is called π -electron structure. For the molecules used in scintillators, the energy spacing between the ground state and the first singlet excited state S_1 is around 3 or 4 eV, whereas the spacing between higher states is usually smaller. Each level presents itself as a series of sub-levels due to the rotational and vibrational modes of the molecules. The typical spacing among these levels is of the order of 0.15 eV. Since these spacings are large compared with the average thermal energies (~ 0.025 eV), at room temperature it is possible to consider all the molecules in the ground state.

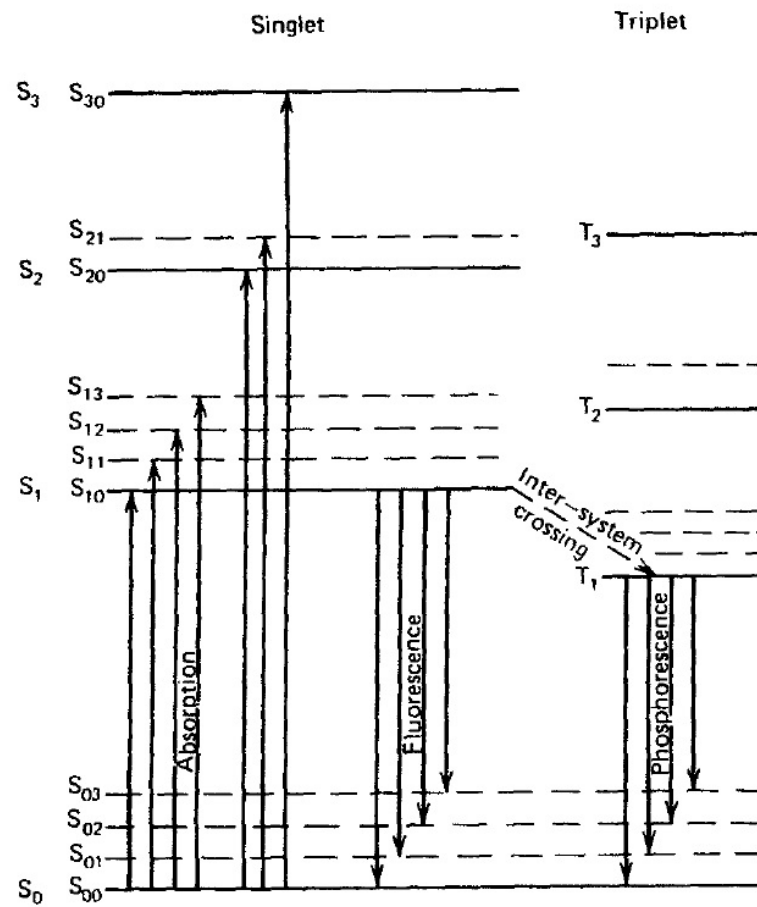


FIGURE 3.3: Scintillator molecule spectrum and possible transitions between states. Fluorescence and phosphorescence transitions are also indicated [87].

When a charged particle crosses the scintillator, it releases some of its kinetic energy inside the material. The higher singlet excited electronic states are quickly de-excited (in a time of the order of ps) via internal conversion to the first excited electronic states S_1 without the emission of radiation. The same process happens for the vibrational sub-states and the net effect is the production of a large population of molecules in the S_1 state. The de-excitation from S_1 to the ground state generates a light emission. This process happens with a typical time of the order of ns and contributes to the fast component of the emission. When the de-excitation happens between the S_1 state and a vibrational sub-level of the ground state, the released energy is less than the one required for the S_0 - S_1 transition and the scintillator is transparent to its emitted light. The de-excitation to the ground state cannot be detected due to the self-absorption.

A similar process occurs in the triplet part, since the electrons are in the T_1

state. The transition between this state and the S_0 ground state is in general forbidden, but it is actually possible via the interactions among molecules. The lifetime of the T_1 state is thus longer than the S_1 one ($> 10^{-3}$ s); therefore the T_1 - T_0 transition is responsible for the delayed or slow component of the light emission in a scintillator.

3.2.2 Plastic scintillator types and production

Organic scintillators can be divided in three main categories depending on their structure [87]:

- organic crystals: characterized by a crystalline lattice, these materials have a very large scintillation efficiency (i.e. the largest light output per energy unit) and a detection efficiency that depends on the orientation of the impinging particle with respect to the crystal axis. The most common are Anthracene ($C_{14}H_{10}$) and Stilbene ($C_{14}H_{12}$). They are in general fragile and difficult to obtain in large sizes and different shapes;
- liquid scintillators: they are solutions of one or more organic scintillators in an organic solvent. The energy of the impinging particle is mainly absorbed by the solvent and then passed to the solute via non-radiative processes. The most common solutes are PPO ($C_{15}H_{11}NO$) and POPOP ($C_{24}H_{16}N_2O_2$), while the solvents are xylene, benzene and toluene. Due to their liquid nature, they can be adapted to different containers and can be doped adding to the solvent different materials (for instance, boron for neutron capture and wavelength shifters to adapt the light emission to the used photodetector);
- plastic scintillators: they are solutions of organic scintillators in a solvent polymerized to form a solid. The solutes are the same used in liquid scintillators and the most common solvents are polystyrene (PS), polyvinyltoluene (PVT) and polymethylmethacrylate (PMMA). Plastic scintillators have a very fast response (~ 2 -3 ns) and can be produced in various shapes.

Due to their use in this thesis work, the production process of plastic scintillating bars is briefly described.

Plastic scintillators can be made using an extrusion technique that allows to produce bars of almost any length and cross-section, as explained in [88]. The extrusion technique involves the use of polystyrene pellets or powder doped with a scintillating material to produce scintillating polystyrene pellets. These pellets are molten and passed through a die of the extruder to obtain the desired shape. A step of the extrusion process is visible in Figure 3.4. An advantage of the

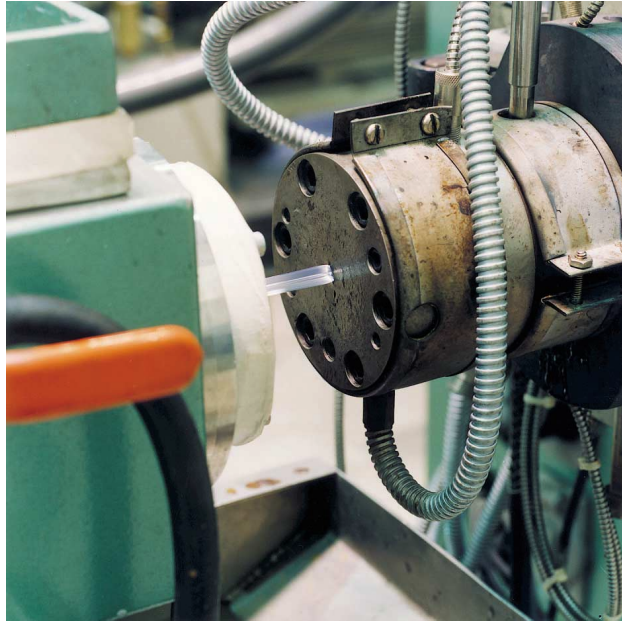


FIGURE 3.4: Triangular extruded bar exiting from the die of an extruder [88].

extrusion process is that a hole can be easily added along the entire length of the extruded bar. This is very helpful for the light collection. These plastic scintillators have in fact a poor attenuation length, that causes a light loss along its path from the emission point to the photodetector. A method to efficiently collect and transport the scintillating light has to be taken into account and it is well fulfilled by the WaveLength Shifter (WLS) fibers described in the next section. Another problem that can reduce the collected light is represented by the losses at the scintillator surface: since the scintillating light is emitted isotropically, a fraction of the photons can have an incidence angle which is smaller than the critical angle¹ and can be transmitted and then lost. This effect can be minimized by covering the scintillator surface with a reflecting material or a white diffusing paint, like TiO_2 .

An example of the final product of the extrusion process is the squared bar shown in Figure 3.5.

3.2.3 Scintillating light collection

As said before, the scintillation light has to be collected and transported in an efficient way to the photodetector. Until the spread of the optical fiber

¹It is the angle defined as the angle of incidence on a separation surface between two mediums, that causes a total internal reflection.

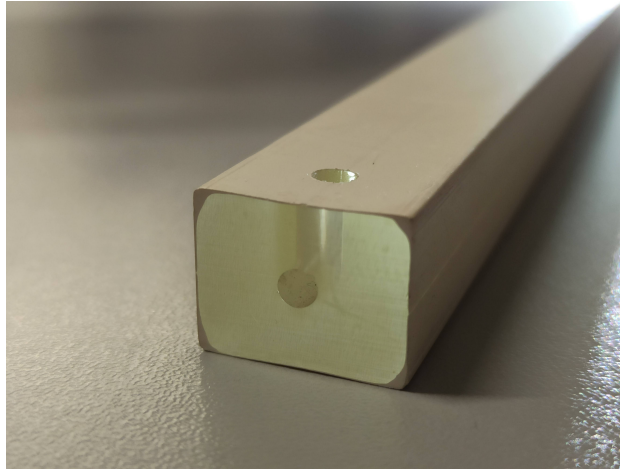


FIGURE 3.5: Extruded rectangular cross-section bar; the holes for the WLS fiber and for the glue are visible.

technology, the so-called light guides were commonly used to collect the light from scintillators. The guides were plexiglass pieces, manufactured in different shapes to collect all the possible light on one side and to perfectly couple to the light detector on the other side. However, these devices had non-negligible sizes (e.g. a length of the order of 1-10 cm), increasing the amount of material used in the detector which they were part of.

Nowadays, light guides have been replaced by WLS optical fibers. The light produced inside the scintillator is collected by the fiber that shifts the wavelength into the spectral range acceptance of the photodetector. This technique allows to transport light at relatively long distances without massive losses, to design a more compact detector, and to reach a better coupling with the photodetectors, in particular with small ones.

WLS fibers are optical fibers made of plastic scintillator and usually with a round cross-section with a diameter from 0.2 to 2 mm. The core is made of polystyrene (with a refractive index n of 1.60) and the cladding (the external part) is made of PMMA with a refractive index of 1.42. The core is doped with a WLS material to absorb the light from the scintillator and re-emit it isotropically inside the fiber with a smaller wavelength. Due to the smaller n of the cladding, the light that impinges on the separation surface between the core and the cladding is internally reflected, but only if the incidence angle is larger than the critical angle, that is typically $\sim 70^\circ$. The critical angle can be reduced adding another layer of cladding: the fiber is then formed by a core ($n = 1.60$), an inner cladding ($n = 1.49$) and an outer cladding ($n = 1.42$). With this configuration, the light capture efficiency increases from 3.1% to 5.4%. The

single-clad and double-clad fibers and the light propagation principle are shown in Figure 3.6. All the quantities presented in this section are extracted from [89].

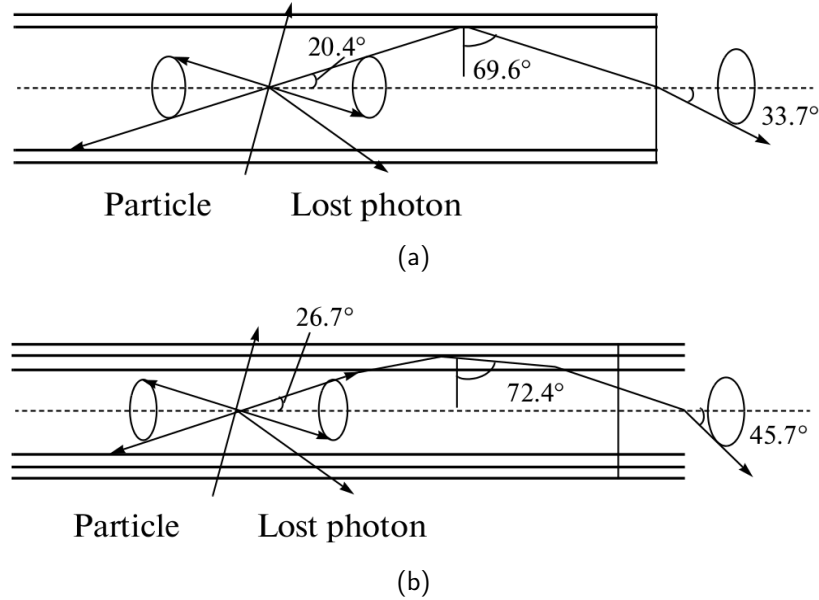


FIGURE 3.6: The light propagation in single- (a) and double- (b) clad WLS fibers [89].

WLS fibers are more transparent to their own emission than scintillators, resulting in a longer attenuation length. This means that the light can be collected in any point of the scintillator and transported to the photodetector with very small losses. The typical attenuation length for WLS fibers ranges from 3 m to 4.5 m. The fibers can be maintained in position inside a scintillator using an epoxy glue. The glue allows in addition a better optical coupling between the scintillator and the fiber itself. The increase in efficiency and light collection with and without glue is reported in [90]: the efficiency of a scintillating bar read out by one WLS fiber increases from $\sim 55\%$ without glue to $\sim 90\%$ with the glue. An example of WLS fibers used for light readout in a shashlik electromagnetic calorimeter is shown in Figure 3.7.

3.2.4 Scintillating light detection

The light produced by a scintillator and transported by a WLS fiber has to be detected by a photosensor and converted in an electric signal. A photodetector should have the following features [89]:

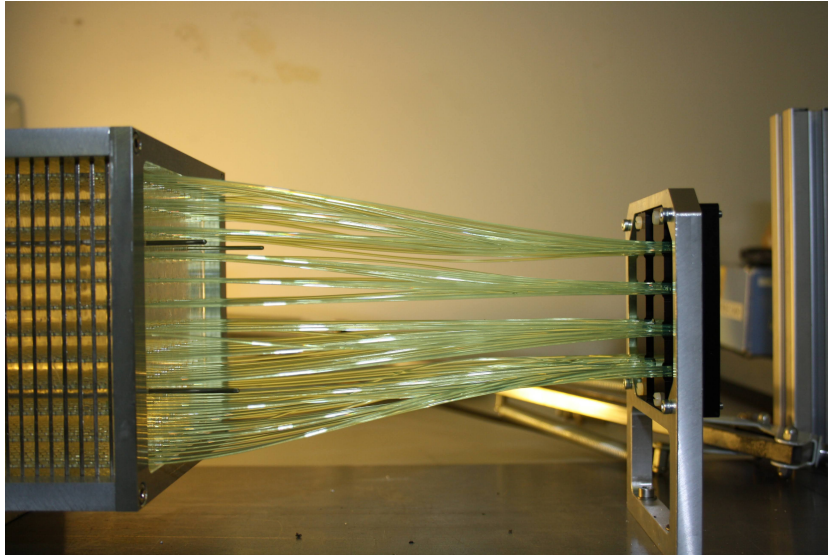


FIGURE 3.7: WLS fibers used for light readout in a shashlik electromagnetic calorimeter.

- large light sensitivity, since the scintillator light yield may be of only a few photons;
- large light collection uniformity and stability in different conditions (e.g. time stability and temperature independence);
- compactness;
- good radiation hardness and insensitivity to strong magnetic fields;
- low costs.

Nowadays, several technologies allow to satisfy some of these requirements and the choice among different photodetector types is based on the purpose of the experiment where they have to be used and on a trade-off between performance and cost. In the following, two of the most used photodetectors are presented; they represent the old and the new light readout systems of the detector subject of this thesis.

PhotoMultiplier Tubes

Historically, the most common used photodevice is the PhotoMultiplier Tube (PMT). It consists in a vacuum tube containing a photocathode, several dynodes and an anode. The incident photons from a scintillator extract photoelectrons

from the cathode via the photoelectric effect. These electrons are accelerated by a focusing electrode on the first dynode where they are multiplied freeing other electrons via secondary electron emission. This process ends on the last dynode, the anode, where the electron cascade is collected and the corresponding current is read. This technique allows to detect very low light signals thanks to the large gain (up to 10^7) provided by the multiplication effect and the high voltage applied to the dynodes. The operation scheme of a PMT is shown in Figure 3.8.

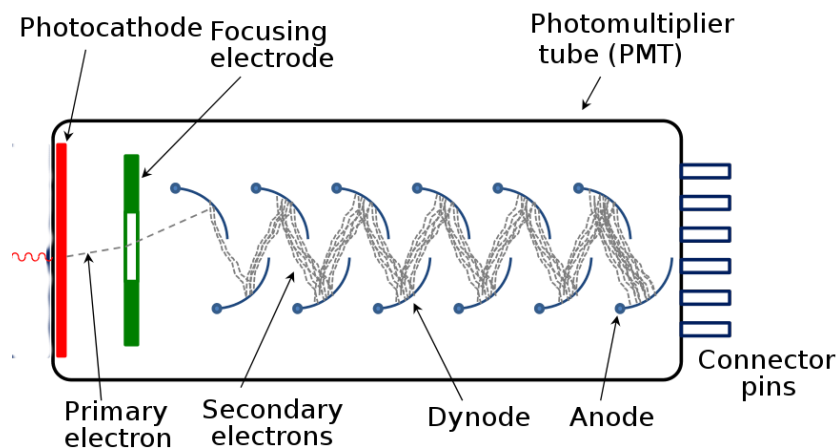


FIGURE 3.8: The operation scheme of a PhotoMultiplier Tube².

If several scintillators have to be readout, instead of using one PMT for each channel, devices like MultiAnode PhotoMultiplier Tubes (MAPMTs) can be employed. These photodetectors are equipped with a single cathode, a series of dynodes which collect photoelectrons from one section of the cathode each and a segmented anode for multichannel readout. The MAPMT works like many different PMTs operating at the same voltage and in the same case. An example of a MAPMT is shown in Figure 3.9.

PMTs and MAPMTs are characterized by a very large gain, that allows to detect low light levels without the need of an external amplifier. Thus, the signal of a PMT features a smaller noise with respect to the one of other devices, resulting in a large Signal to Noise Ratio (SNR).

On the other hand, several disadvantages have to be listed:

- a high voltage of operation;
- the inability to operate in strong magnetic field regions, due to the large amount of low energy free electrons flowing in the tube between dynodes

²https://en.wikipedia.org/wiki/Scintillation_counter

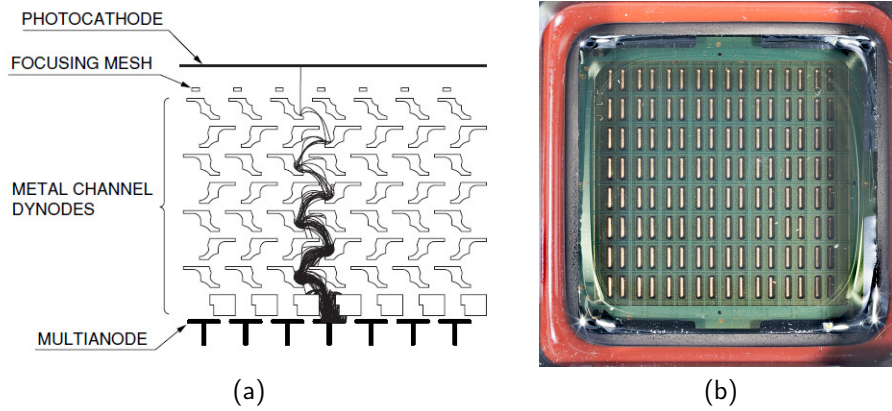


FIGURE 3.9: (a) MAPMT operation scheme; (b) the cathode of a HAMA-MATSU H8804 8x8 Multianode 12-stage Photomultiplier Tube³.

[87]. This problem can be partially solved by using a magnetic shield placed around the PMT, but with the obvious increase of material and size in the detector;

- the low quantum efficiency of the commonly used photocathodes (not higher than $\sim 25\%$ in the typical spectral range of the scintillator light) [89];
- the crosstalk between neighboring channels in MAPMTs due to the broadening of the primary photoelectron flow and the spread of the incident light on the photocathode, because of the light divergence at the exit of the fiber or the scintillator [91].

Silicon PhotoMultipliers

Since the beginning of the 21st century, Silicon PhotoMultipliers have been used in accelerator-based particle and nuclear physics experiments [92], substituting, when possible, the PhotoMultiplier Tube technology for scintillation light detection.

A Silicon PhotoMultiplier (SiPM) is a matrix of Avalanche PhotoDiodes (APDs) operating in Geiger mode and readout in parallel via a common silicon substrate. In particular, an APD is a solid state detector based on a $p-n$ junction biased in reverse mode a few Volts below the breakdown voltage. When a light photon interacts with the silicon in the depletion region, electron-hole pairs are created and begin to drift to the multiplication region due to the applied

³<http://lampes-et-tubes.info/pm/pm176.php?l=f>

bias. There, an avalanche is generated amplifying the signal, that is collected by a metallic electrode on the n^+ side (the signal is due to the electrons).

The APD can be operated in proportional mode to have an output proportional to the energy deposited by the incident photons inside the diode. In Geiger mode instead, the bias voltage is large enough to generate an uncontrolled avalanche that allows to have an amplification gain up to 10^6 [93], comparable with the one of the PMTs. This feature allows the single photon detection, not possible in proportional mode due to the large noise compared to the signal generated by one single pair. The avalanche effect is stopped by a quenching resistor in series in the readout circuit of the APD. In Geiger mode, photons of different energies generate the same signal, so the APD is in fact a digital detector, i.e. it responds only to the passage of the particle but not to its energy deposit. A scheme of an APD and its working principle are shown in Figure 3.10.

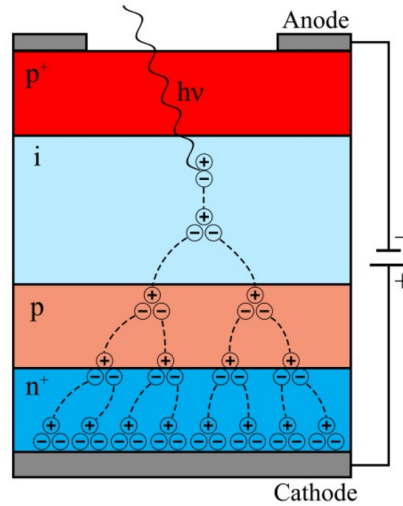


FIGURE 3.10: The APD scheme and working principle: a photon interacts with the silicon and a hole-electron pair is created. Due to the applied bias, an avalanche is generated and collected by the n^+ electrode [94].

In a SiPM, hundreds of APDs of small size ($\sim 20 - 100 \mu\text{m}^2$) operate with a bias voltage in the $\sim 30 - 70 \text{ V}$ range, a value 10 – 20% above the breakdown one [93]. Since the output is the sum of the signals of every APD, the SiPM signal is proportional to the number of the triggered cells, i.e. it is proportional to the number of photons impinging on the whole sensitive area. If the intensity of the incident light is not too large with respect to the number of cells, the SiPM behaves then as an analog detector [95]. This means that, if the SiPM is coupled with a scintillator, the output signal is proportional to the energy released in the scintillator by the incident radiation. The pixels (cells) are separated by

non-photosensitive strips, called trenches, which prevent the cross-talk between adjacent cells. A HPK S10931-3050P SiPM, with a zoom on the individual APDs, is shown in Figure 3.11.

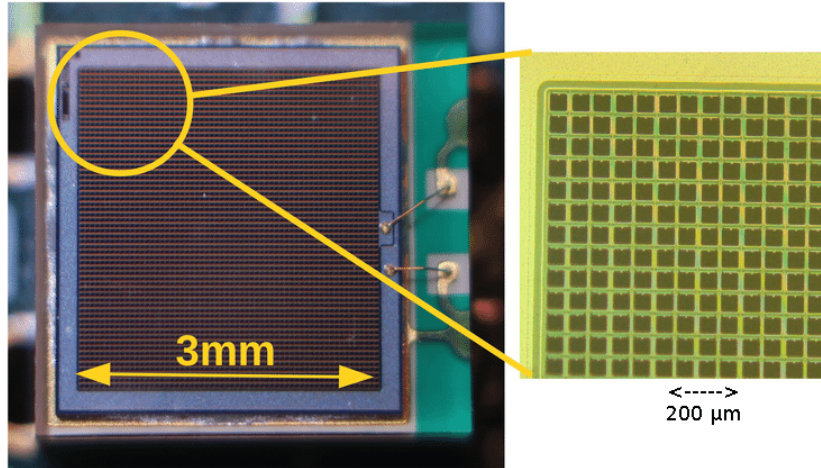


FIGURE 3.11: A HPK S10931-3050P SiPM with a zoom on the individual APDs. The trenches between pixels are visible. Dimensions are reported as a reference [96].

The main features of a SiPM are the following [97]:

- **Photon Detection Efficiency (PDE):** it is defined as the efficiency to absorb a photon and produce a measurable signal. In PMTs, the main contribution is the Quantum Efficiency (QE) of the cathode. In SiPMs, it depends on the wavelength of the incident light: for photon energies above the Si band gap (1.1 eV) the QE is around unity. Nevertheless, other effects have to be taken into account in a SiPM:
 - the losses on the entrance window, due to reflections and absorptions in the protective material; usually, more than 90% of transmission can be achieved;
 - the losses in the non-sensitive area, i.e. in the trenches among adjacent cells. The ratio between the sensitive area and the total surface of the SiPM is defined by the *fill factor*; for small pixel sizes ($\sim 10 \mu\text{m}^2$) the fill factor is around 30%, while for large ones ($> 50 \mu\text{m}^2$) a value of 80% can be reached. In Figure 3.12 two pixels of two SiPMs with a different fill factor are shown, where the trenches and the active area are well visible;
 - the breakdown probability, i.e. the probability for a single electron to generate an avalanche. It depends on the bias voltage applied to the

junction, so it is important to tune correctly the power supply to have the best trade-off between signal detection and noise generation, both triggered by an electron-hole pair.

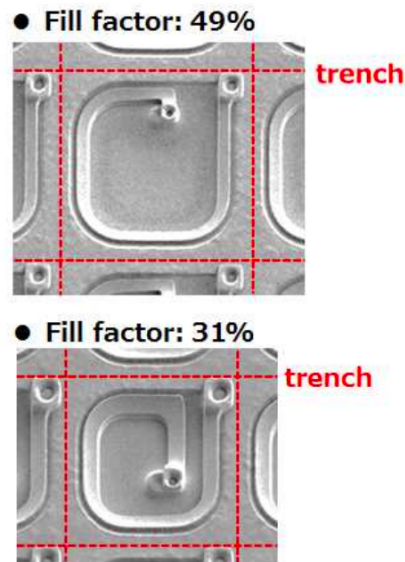


FIGURE 3.12: Microscope images of two SiPMs pixels with different fill factors. The trenches are indicated, while in the center the sensitive area is visible. The picture is extracted from [98].

- **Dark Count Rate (DCR):** it is defined as the rate of detected events without a light impinging on the SiPM. It is due to thermal generated electron-hole pairs in the depletion region, which can drift in the multiplication region and trigger a breakdown shower. This effect is temperature dependent (in particular in Si it doubles every 10°C) and bias dependent. Typical dark count rates at room temperature are $10^5 - 10^6 \text{ Hz/mm}^2$ [97]. An example of DCR measurements as a function of the overvoltage and the temperature is reported in the plot in Figure 3.13.
- **Optical Cross-Talk (OCT):** the OCT occurs when the photons produced in the shower generate an avalanche in another cell. The result is that the signal is larger than the one that is triggered only by the primary event. If the emitted photon is absorbed directly in the sensitive layer, it is called *prompt* OCT and it occurs a few ps after the primary detection and so it is indistinguishable. The *delayed* OCT occurs instead if the emitted photon is absorbed outside the depletion region, so the generated charge carriers trigger the avalanche a few ns after the main event, since they need time to

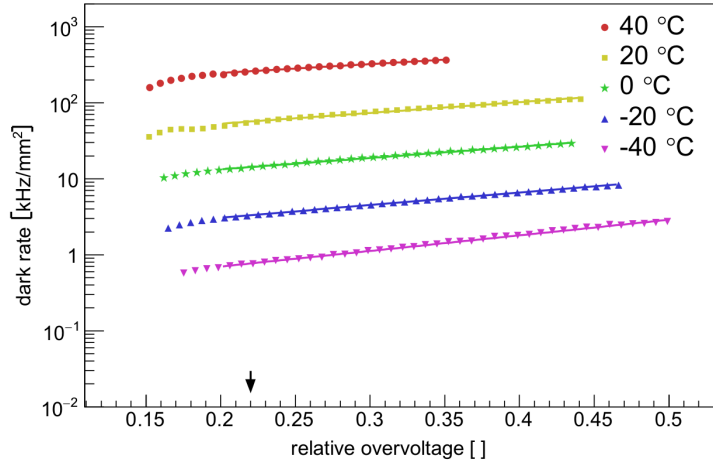


FIGURE 3.13: Dark Count Rate (DCR) of a FBK NUV-HD SiPM as a function of the relative overvoltage and the temperature. The arrow indicates the nominal operating overvoltage [99].

drift in the multiplication region. The delayed OCT is then separated from the main event. A scheme of the OCT processes is shown in Figure 3.14. Decreasing the bias voltage and using trenches among adjacent cells are examples of methods which reduce the OCT, but make the PDE worse.

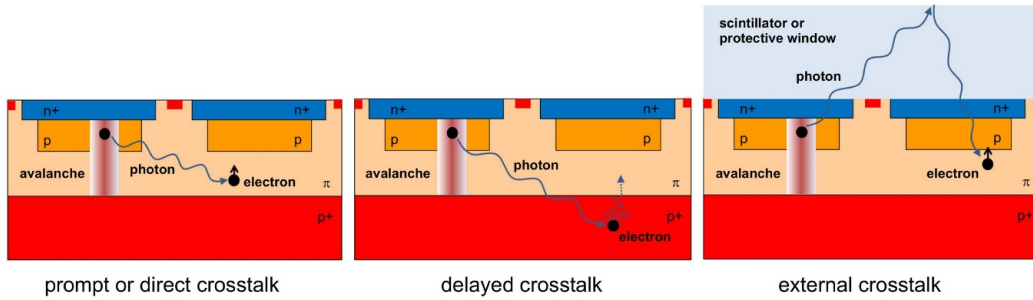


FIGURE 3.14: Optical Cross-Talk processes: prompt OCT, delayed OCT and external OCT (same as prompt OCT but the emitted photon is first reflected by the scintillator, the entrance window or the Si itself before being re-absorbed in the sensitive region) [96].

- **Afterpulses:** they are events triggered by freed charge carriers previously trapped in the multiplication region. Since these carriers are generated by a primary event avalanche, the afterpulse happens mostly in the same cell where the first event occurred and so it is considered a purely correlated noise. The afterpulses are usually detected from few ns to hundreds of ns

after the primary event and so can be distinguished from it. The afterpulses probability depends on the recovery time of the cell, i.e. the time until a cell is again fully sensitive after a breakdown: the shorter the recovery time, the larger the probability.

- **Single Photon Time Resolution (SPTR):** it is mainly determined by the front-end electronics but with a very fast readout a FWHM of 80 ps was measured [100], making the SiPMs very fast devices, suitable for timing applications such as Time Of Flight measurements and trigger systems.

In Figure 3.15 the correlation between the number of photoelectrons detected by a SiPM and the time difference between subsequent events is shown. All the noise effects described above are well visible and correspondingly labeled. In general,

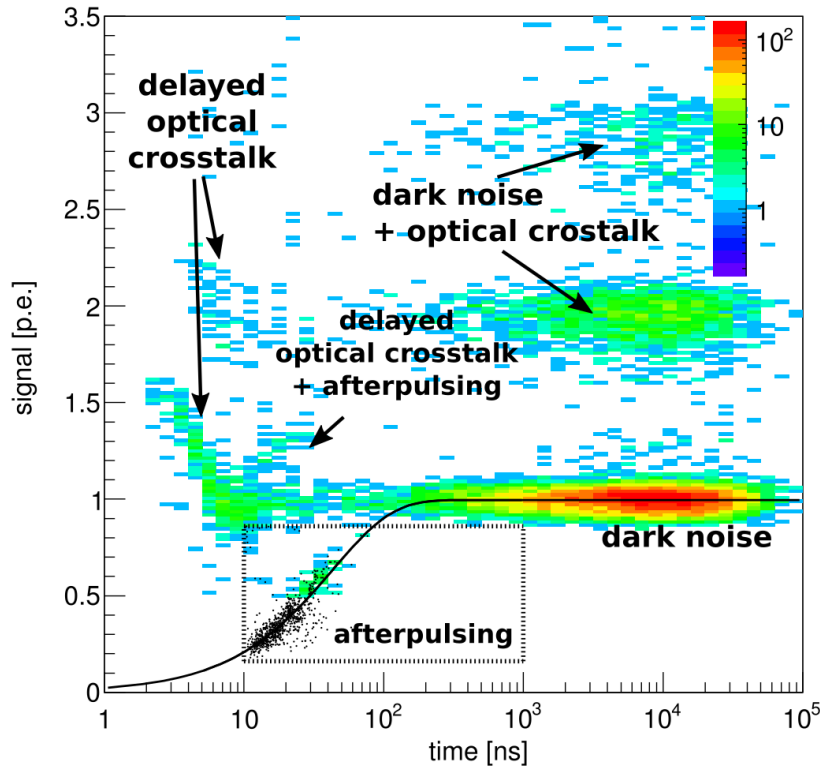


FIGURE 3.15: Plot showing the correlation between the number of photoelectrons detected by a SiPM and the time difference between subsequent events. The typical SiPM noise effects are labeled [99].

a trade-off has always to be found between the high detection performances and the noise caused by the effects listed above. Anyway, the SiPM technology has the following advantages:

- the low bias voltage;
- the insensitivity to magnetic fields;
- the small sizes of these sensors;
- the easier coupling with optical fibers with respect to the PMTs;
- the lower costs compared to the PMT ones.

The upgrade from a PMT light readout system to a SiPM one for the detector subject of this thesis work, described in the next sections, has been decided taking into account these advantages.

3.3 The DANTE scintillating tracker

The Detector for ANnihilation Tracking Experiment (DANTE) is composed of 8 planes, usable in different configurations (described in the following) to adapt to the geometry requirements for the annihilation vertex reconstruction and to the small spaces of the ASACUSA experimental area around the cusp trap.

Each plane contains 60 bars of plastic scintillator (Polystyrene Dow Styron 663 W + 1% PPO + 0.03% POPOP) with a rectangular section of $1.5 \times 1.9 \text{ cm}^2$ and a length of 96 cm. A white TiO_2 coating is painted on the bars surface to improve the light collection, preventing losses and optical cross-talk between contiguous bars. They have been provided by the Fermi National Accelerator Laboratory (FNAL) and obtained with the extrusion process described in section 3.2.3. Each bar has a hole at its center with a diameter of 2.5 mm for the WLS fiber for the scintillating light collection and two holes on the side on both extremities for the fiber gluing inside the central hole. A picture of the front of a virgin bar is shown in Figure 3.16.

The chosen fiber type is the Kuraray⁴ WLS Y-11 (200)M of 1.0 mm diameter; it has an emission peak at 476 nm and an attenuation length of more than 3.5 m, depending on the wavelength of the emission spectrum (as shown in Figure 3.17). The fiber is glued inside the central hole of every bar by means of an epoxy E30 glue by PROCHIMA⁵. The glue maintains the fiber in position and provides a good optical coupling between the fiber itself and the bar. The gluing process is the following:

- the bar and the fiber inserted in its own central hole are placed on a small-angle tilted plane;

⁴<https://www.kuraray.com>

⁵<https://www.prochima.com>

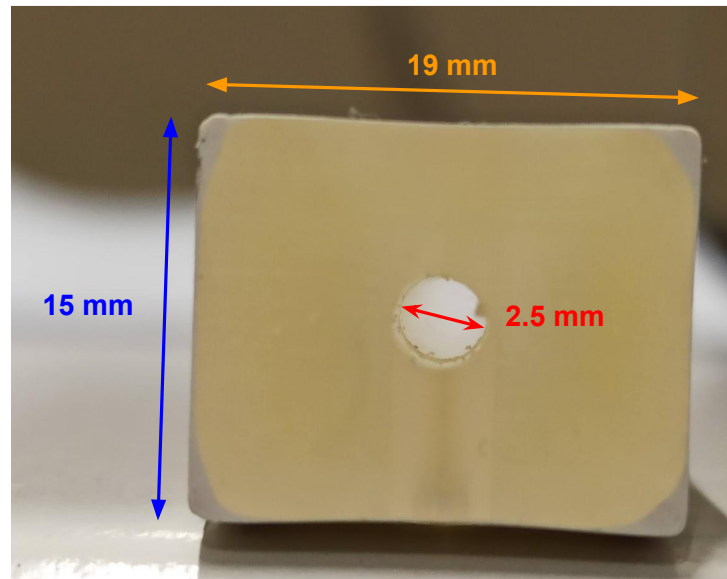


FIGURE 3.16: Virgin scintillating bar front view with sizes. The hole in the center for the WLS fiber is visible, while the one for the gluing has been drilled afterwards.

- one 5 ml syringe filled with glue is inserted in the extremity hole of the bar on the lower side and an empty one on the upper side (Figure 3.18a);
- by pushing slowly the glue into the bar, the fiber is glued and the small tilt angle allows to avoid air bubbles formation;
- when the empty syringe piston starts to rise, it means that the glue has reached the upper side of the bar. The glue drying needs ~ 8 -12 hours.

The holes are filled with a silicone glue and the two bar surfaces at the extremities without the TiO_2 are covered with black tape (Figure 3.18b). Sixty bars of this type form a single *plane*, that can be used alone to track only a coordinate of an incident particle or in pair with another plane, but with the bars positioned perpendicularly to the first ones, to detect precisely the particle hit position. This last configuration, called XY configuration, represents a *module*. Using pairs of modules, the angle of a particle track can be measured, so different modules (up to 4, because the single planes are at least 8), positioned around the ASACUSA cusp trap, allow to reconstruct in 3D the annihilation vertex, detecting the products that exit from the trap, as shown in the scheme in Figure 3.19.

The first version of this detector was commissioned in 2008. Then, in 2011, the mechanical support and the front-end electronics were modified. In 2021,

the detector has been upgraded changing the light readout system, the front-end electronics and the bars mechanical support. In the following sections the past versions are briefly presented and a detailed description of the upgrade is discussed.

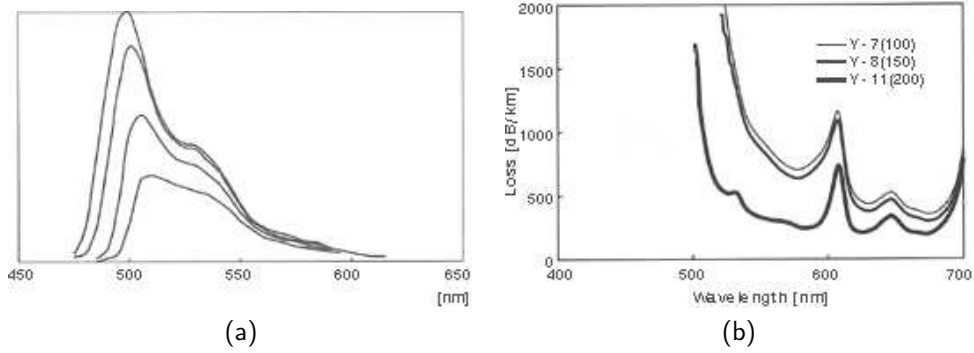


FIGURE 3.17: (a) Kuraray Y-11 fiber emission spectrum. (b) Light yield attenuation expressed in dB/km as a function of the wavelength⁶.

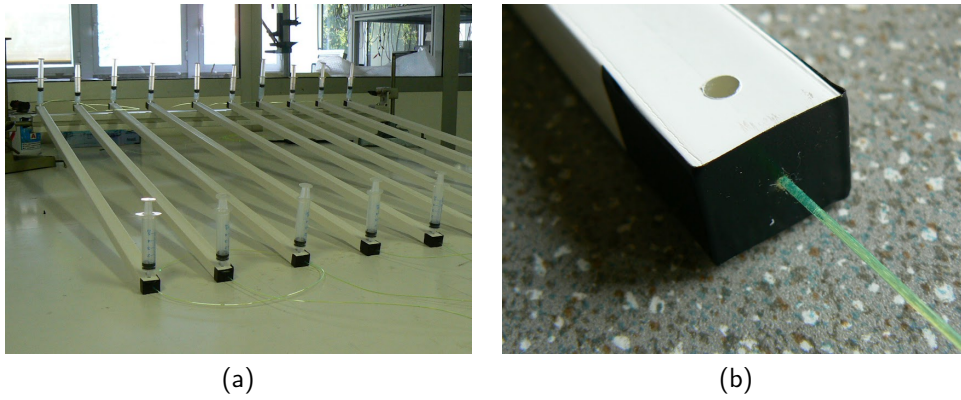


FIGURE 3.18: (a) The fiber gluing process inside the scintillating bars placed on a tilted plane. (b) Final result with a fiber glued inside a bar and the black tape to cover its extremity.

3.3.1 The 2008/2011 detector versions

A detailed description and characterization of the 2008 detector version can be found in [102]. The WLS fibers came out from both sides of the bars in

⁶<http://kuraraypsf.jp/psf/ws.html>

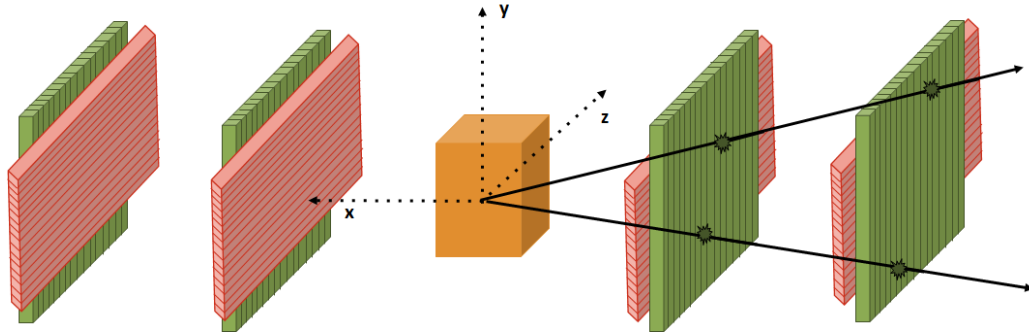


FIGURE 3.19: Annihilation vertex reconstruction scheme: the planes in a XY configuration can detect the particle track in 3D and reconstruct the annihilation vertex inside the trap [101].

every plane: on one side, the fibers were read together by a P30CW5 PMT for the trigger, while on the other side two Hamamatsu 64-channels MAPMTs (R7600-M64/H7546B) provided the multichannel readout. Each MAPMT read only half of the bars per plane to minimize the cross-talk between adjacent channels. The PhotoMultiplier signals were processed by a Front-End Board (FEB) equipped with the VA64TAP2.1 and LS64_2 ASICs⁷. The FEBs of every plane were controlled by a repeater board to interface the front-end with the I/O VME⁸ readout system. The detector operated in selftrigger mode, with the trigger generated by a VME trigger board based on an ALTERA Cyclone II FPGA⁹. The maximum acquisition rate with this setup was of about 600 Hz [103]. The FEBs were connected directly to the PhotoMultipliers by dedicated sockets, as shown in Figure 3.20. The detector was arranged in 4 different modules; inside each module a metallic structure kept two layers (planes) of bars in place (Figure 3.21) and the whole module box was hanging on a dedicated support that was positioned near the cusp trap in the ASACUSA experimental area (Figure 3.22).

One of the problems of the 2008 detector version was the cross-talk in the MAPMTs channels due to the mis-alignment between the fibers and the PMT entrance window. This can be easily seen in the residuals distribution of the reconstructed hit positions of one of the planes, presented in Figure 3.23, extracted from [102].

In the 2011 version of the detector, the bars were re-arranged to form 10 different planes which could operate independently as part of modules and not

⁷Application-Specific Integrated Circuit

⁸Versa Module Eurocard. The VME bus is a computer bus standard developed by Motorola.

⁹Field Programmable Gate Array

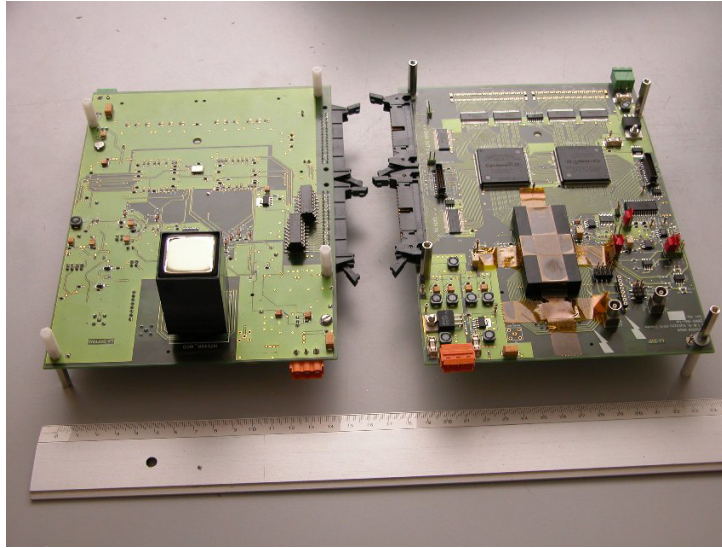


FIGURE 3.20: The Front-End board used in the 2008 version of the detector. On the left, it is possible to see the PMT attached directly to the board [102].



FIGURE 3.21: A detail of the mechanical support of the bars in the 2008 version. It is possible to see two bars of two different planes inside one module overlapping in the box corner.

necessarily in pairs. In this way the maximum solid angle coverage in scattering experiments was reached, as reported in [104]. A single plane consisted in a frame made of $3 \times 3 \text{ cm}^2$ aluminum rods, that supported two black PVC planes, which provided the support and the darkening of the scintillating bars. A 1 cm height cork layer helped to maintain the bars in position and matched the bars plane

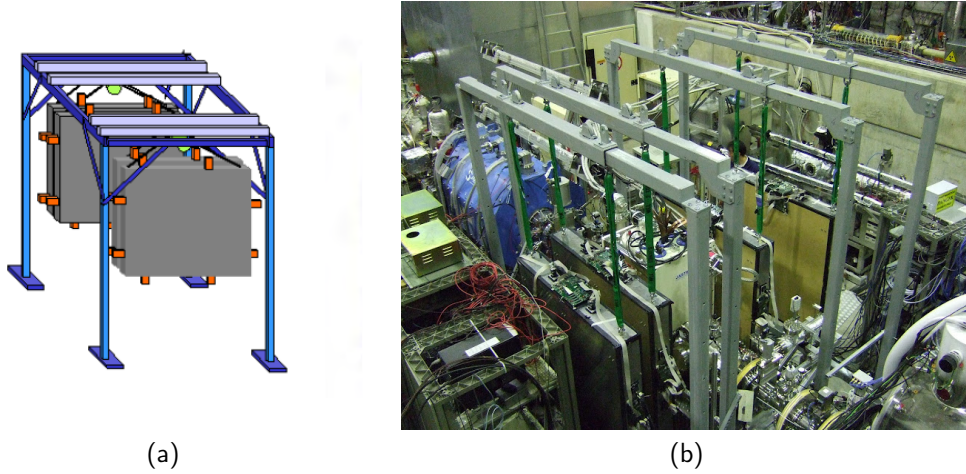


FIGURE 3.22: (a) A scheme of the 2008 detector. The four modules and their mechanical support are shown [103]. (b) The 2008 detector installed around the cusp trap in the ASACUSA experimental area.

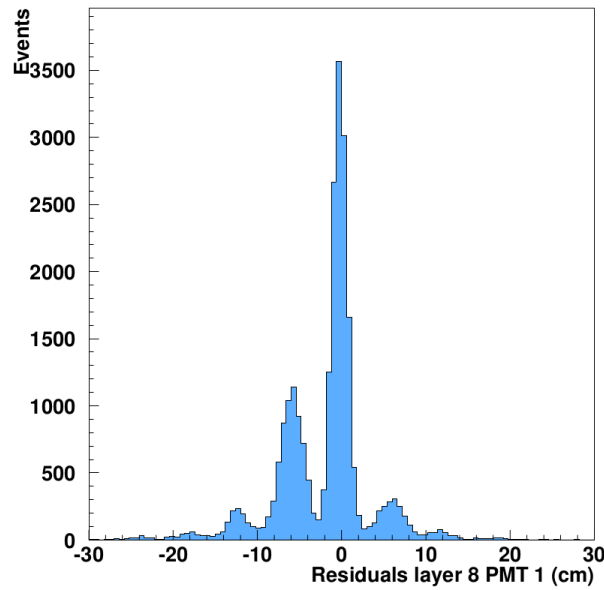


FIGURE 3.23: The effect of cross-talk on the residuals distribution of the reconstructed hit positions. The distribution should consist of a single central peak; the appearance of the other peaks is due to the cross-talk [102].

to the PVC upper layer. A scheme of the mechanics is shown in Figure 3.24. Although the aluminum frame had been designed to avoid large bending angles of the fibers, they were anyway stretched (Figure 3.25a), resulting sometimes in a

displacement in the coupler mask with the PMT, as can be seen in Figure 3.25b.

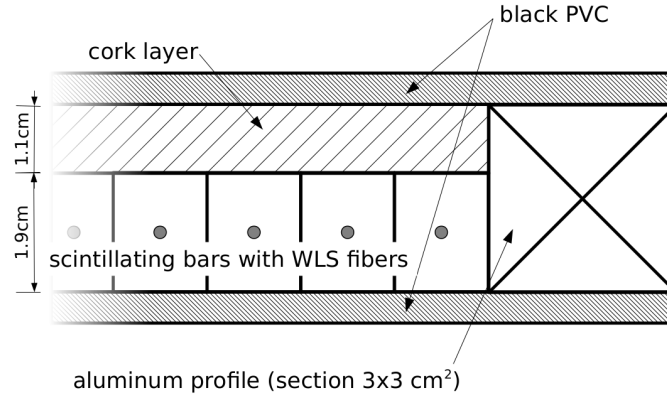


FIGURE 3.24: A scheme of the mechanics of the 2011 detector version [84].

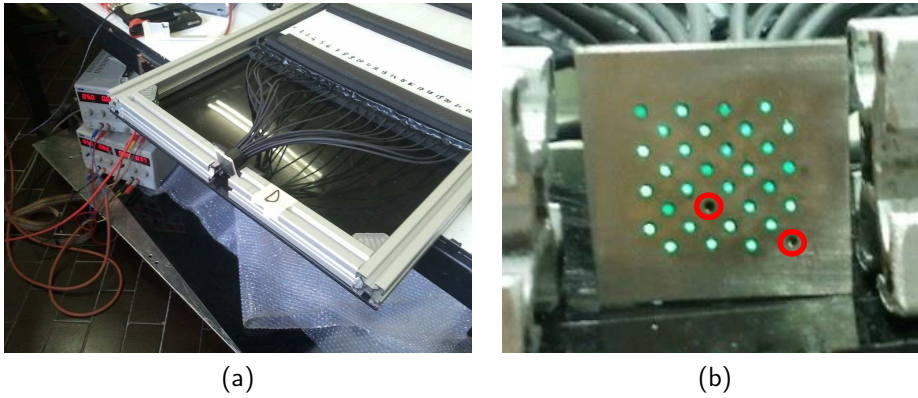


FIGURE 3.25: 2011 detector version problems: (a) a picture of a small plane where bent fibers can be seen; (b) fibers-PMT coupler, where the displacement of 2 fibers is visible within the red circles.

On the other hand, the planes supporting mechanics was improved using the same aluminum tubes of the frame, making the planes lighter than in the previous version and easy to handle. An example of a free-standing plane of the 2011 detector version is shown in Figure 3.26.

In the 2011 version, also the front-end electronics was upgraded, by the design of a FEB based on the MAROC3 ASIC (since this ASIC is still in use in the 2021 version, it will be described in detail in Section 3.3.3).



FIGURE 3.26: A picture of a free-standing plane of the 2011 detector version [84].

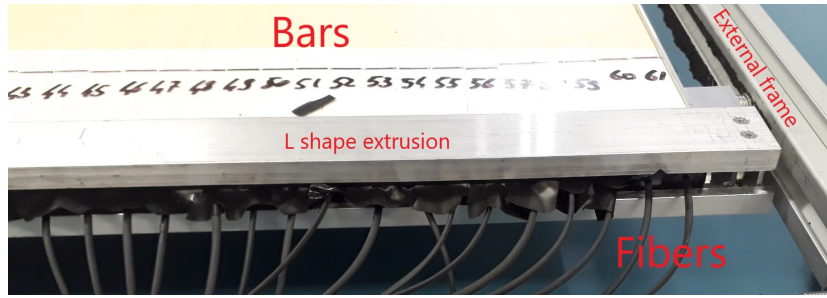
3.3.2 The 2021 upgrade of the detector

The 2021 upgrade of DANTE involved a new mechanics support of the bars in the plane, a new light readout system based on SiPMs and the new front-end electronics to correctly adapt the signals from the new photodetectors to the front-end MAROC3 board. In this section the first two items are presented, while the electronics has a dedicated section (Section 3.3.3).

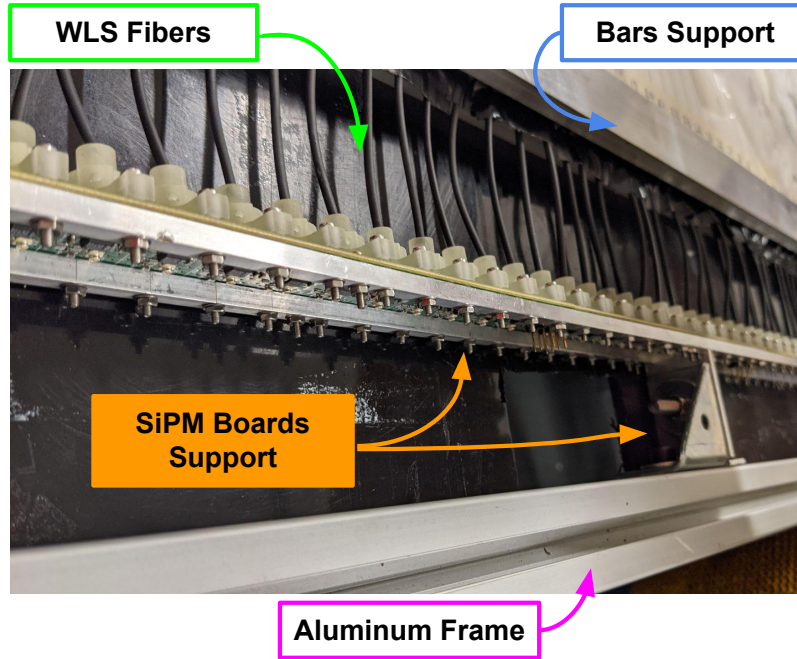
The new mechanical support

In the 2021 design, the scintillating bars (60 per plane) are self-sustained, to make the coupling with the photodetectors easier and to avoid a direct contact between the bars and the PVC panels, that could warp under the bars weight. The 2011

aluminum frame was adapted to host four L-shaped aluminum extrusions that keep in place the bars from the fibers sides, allowing space enough for them to exit from the bars and reach the photodetectors. With this configuration, the bars are positioned in the middle of the plane, i.e. ~ 1.3 cm from both external sides of the PVC layers (as shown in the scheme in Figure 3.27a) and additional layers of other materials are not required to avoid the bars movements during changes of positions in the laboratory and in the experimental area.



(a)



(b)

FIGURE 3.27: 2021 detector version new mechanics: (a) the L-shaped aluminum extrusions, the aluminum external frame and the bars with the fibers are visible; (b) detail on the mechanical support of the SiPM boards.

TABLE 3.1: Characteristics of the AdvanSiD ASD RGB1S-P SiPM.

Parameter	Value
Active Area	$1 \times 1 \text{ mm}^2$
# Cells	625
Cell Size	$40 \text{ } \mu\text{m} \times 40 \text{ } \mu\text{m}$
Cell Fill Factor	60%
Quenching Resistance	550 k Ω
Cell Capacitance	90 fF
Recharge Time Constant	50 ns
Peak Sensitive λ	550 nm
Breakdown Voltage	27 V
PDE	32.5%
DCR	$< 100 \text{ kHz/mm}^2$ 2 V OV ¹¹
Gain	2.7×10^6

Since the photosensors (SiPMs, presented in the next section) are placed closer to the bars compared to the previous versions of the detector, the WLS fibers have been cut on one side (the readout side) to a length of ~ 10 cm. On the other side, the fibers were obscured with black tape.

A mechanical support for the SiPM front-end boards was also designed, integrating the boards themselves as a structural part of the mechanics, to have a sturdier structure and a higher rigidity, as shown in Figure 3.27b.

The new photosensors and coupling system

The fundamental change in the 2021 upgrade is the substitution of the PMTs light readout system with the one based on Silicon PhotoMultipliers. The chosen SiPMs are the ASD RGB1S-P SiPMs provided by AdvanSiD¹⁰, with an active area of $1 \times 1 \text{ mm}^2$, covered and protected by a transparent epoxy layer and located inside a SMD plastic package of $2.03 \times 2.48 \times 1.30 \text{ mm}^3$ (with a mechanical tolerance of 0.15 mm). The sensitive part is composed of 625 cells, each one with a size of $40 \text{ } \mu\text{m} \times 40 \text{ } \mu\text{m}$, with a fill factor of 60%. A summary of the SiPMs characteristics is presented in Table 3.1 and a scheme of the SiPM with the dimensions in mm is depicted in Figure 3.28.

Since the sensitive area and the diameter of the WLS fiber have the same dimension (1 mm), a perfect coupling between these two elements is required to avoid light losses. The SiPM package sets the constraints of a possible coupler

¹⁰<https://advansid.com/products/product-detail/asd-rgb-nuv-4s-p>

¹¹Over Voltage, i.e. voltage over the Breakdown Voltage.

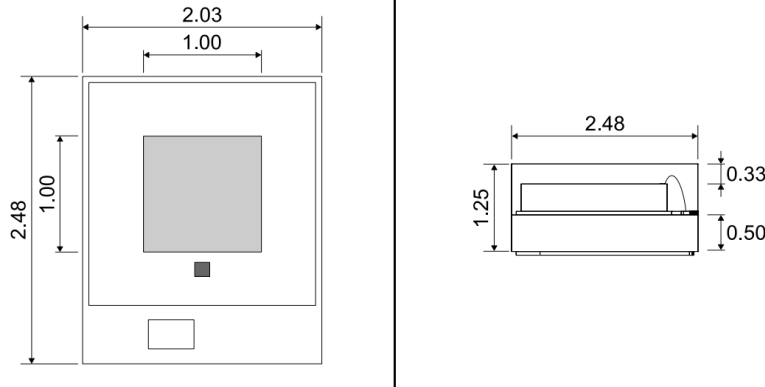


FIGURE 3.28: Scheme of the SiPM with the dimensions in mm. The active area is the one colored in light gray.

that keeps in position the fiber in front of the sensitive area. To determine the precision required for the manufacturing of the coupler, an analysis of the position of the sensitive area with respect to the SiPM housing has been performed. Using a high resolution photo camera, pictures of 98 SiPMs were taken and analyzed with an online tool [105]. Considering the picture in Figure 3.29, the position of the A,B,C,D points was determined in the reference system set by the x and y coordinates for every examined SiPM. The standard deviations of the found coordinates were calculated, resulting of the order of 10^{-2} mm. Keeping in mind the mechanical tolerance of 0.15 mm on the sizes reported in the SiPM datasheet, the result of the analysis allows to use directly the sizes reported in the datasheet.

The coupler was designed as a socket-holder system 3D printed in HT250 resin with a Project 2500 Pro machine, that works with the material jetting technology, which allows to get the required printing precision. The socket is a 7 mm diameter cylinder with a central hole for the WLS fiber. After the cut, the fibers were glued with epoxy glue in the cylinders and polished. A picture of the fibers inside the sockets is shown in Figure 3.30a. The holder that hosts the socket has a rectangular shaped hole where the SiPM is located and allows the correct coupling with the fiber in front of the sensitive area. The holder is secured to the SiPM front-end board with 2 M2 screws which couple the whole system with the mechanics. A picture of the holder is shown in Figure 3.30b, while the positioning of the holder on the SiPM front-end board is presented in Figure 3.31.

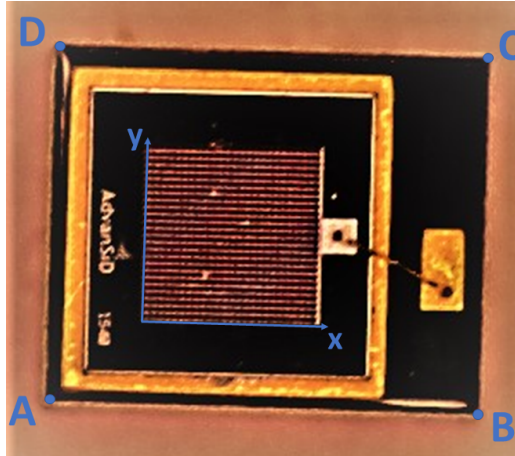


FIGURE 3.29: Scheme of the SiPM with the sensitive area and the housing, that sets the constraints on the positioning of the coupler with the WLS fiber. The letters identify the vertices used to measure the displacement of the sensitive area with respect to the plastic housing.

3.3.3 The readout electronics

The detector readout electronics is composed of three different electronic boards: the SiPM front-end board (SiPM FEB), the MAROC3 board and the VME Cyclone Board (VCB). In this section all the boards will be presented, while the final version of the Data Acquisition (DAQ) is presented in Section 3.3.4.

The SiPM FEB

The SiPM front-end board provides the bias voltage for the depletion of the SiPMs and the power supply for the first stage of the amplification of the SiPMs signals. It is equipped with an AD8002 op-amp¹² used as a dual cascade non-inverting amplifier with a total gain of ~ 46 . The schematic of the amplifier electronic chain is depicted in Figure 3.32. A single SiPM FEB hosts 12 surface mounted SiPMs on the side facing the bars and the fibers, and the amplifiers on the other side, together with the surface mounted connectors by Hirose¹³ for the coaxial cables which transport the signals of each channel to the MAROC3 board. Every channel on the board has the same size of the corresponding bar, simplifying the correct coupling and the mechanics. 5 FEBs are needed for each plane, in order to read all the 60 bars. The pictures of the SiPMs side and the amplifiers side of the FEB are shown in Figure 3.33.

¹²<https://www.analog.com/media/en/technical-documentation/data-sheets/AD8002.pdf>

¹³<https://www.hirose.com/en/product>

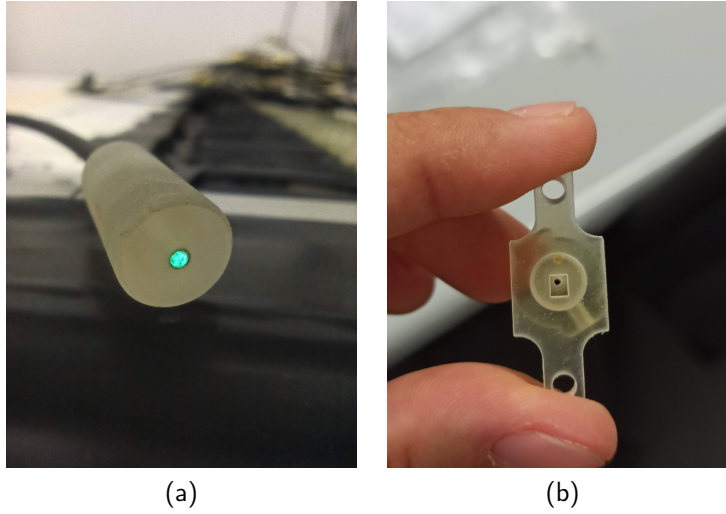


FIGURE 3.30: Pictures of the socket-holder coupling system: (a) the WLS fiber glued and polished inside the 3D printed cylinder socket; (b) the holder that hosts the socket, viewed from behind; the hole in the socket for the fiber and the rectangular hole for the SiPM are visible; the two holes at the sides are for the screws which secure the holder to the boards and the mechanics.

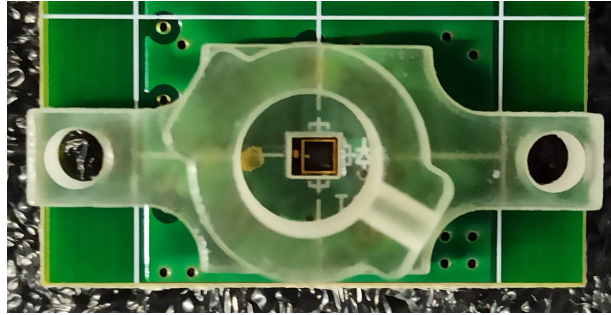


FIGURE 3.31: Picture of the holder mounted on the SiPM board.

The MAROC3 board

The second stage of the front-end electronics is represented by the MAROC3 Front-End Board. The board is equipped with the MAROC3 ASIC (Multi Anode ReadOut Chip) [106], developed by the Omega group at LAL¹⁴, originally for the ATLAS luminometer [107]. The ASIC is manufactured with the Si-Ge 0.35 μm technology and enclosed in a CQFP240 package and operates with a power supply of 3.5 V. It has been designed to readout 64 channels from a Multi Anode PMT,

¹⁴<https://portail.polytechnique.edu/omega>

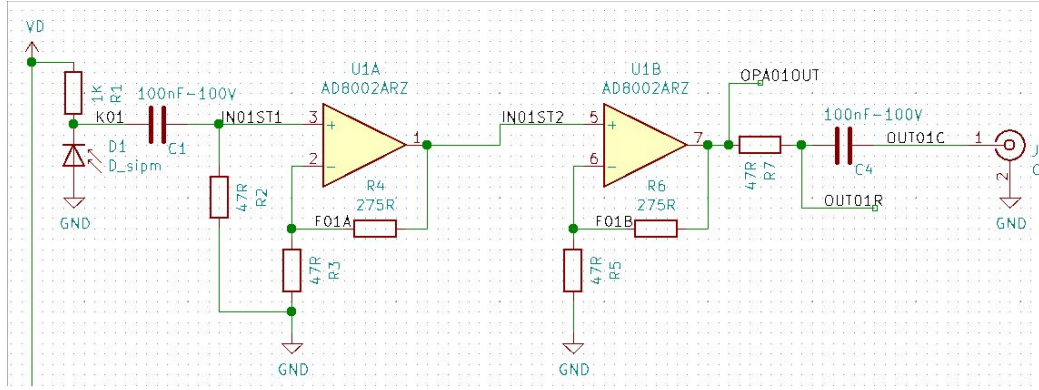
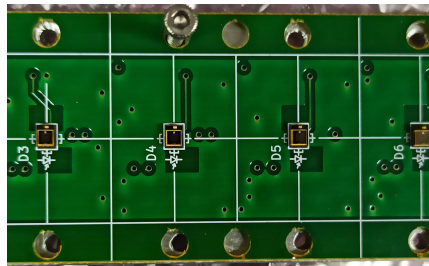
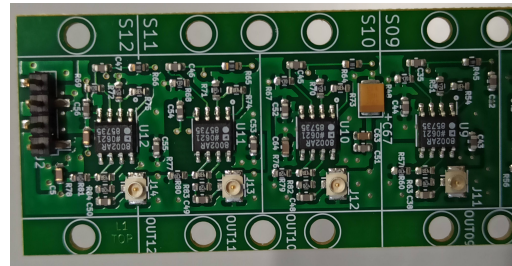


FIGURE 3.32: Scheme of the amplifier chain mounted on the SiPM FEB.



(a)



(b)

FIGURE 3.33: Pictures of the SiPMs Front-End Board: (a) the SiPMs side with 4 visible surface mounted SiPMs in the center of each channel; (b) the amplifiers side, where the AD8002 op-amps, the electronics components and the Hirose connectors are visible.

while for the DANTE detector it is expected to amplify, shape and discriminate the 60 SiPM signals of one plane. Each input channel consists in a 8-bit tunable gain pre-amplifier with a low input impedance and a low bias current. The gain can be tuned from 0 to a factor of 4. The amplified signal feeds then two different circuits: the analog circuit and the so-called digital one (represented in the scheme shown in Figure 3.34). In particular:

- the analog part consists of a slow CRRC² shaper with tunable capacitances to select the peaking time and gain and two Sample&Hold circuits to measure the signal amplitude and the baseline with two tunable hold signals. In this thesis work, only the peak of the signal is detected. The sampled signal is sent out by a 5 MHz clock multiplexer.
- the digital part has two switchable fast shapers and a discriminator, for the generation of the trigger.

The ASIC provides also the analog sums, that are 8 signals corresponding to the sum of groups of 8 channels. A 12-bit Wilkinson ADC is also embedded in the chip, but not used in this thesis work.

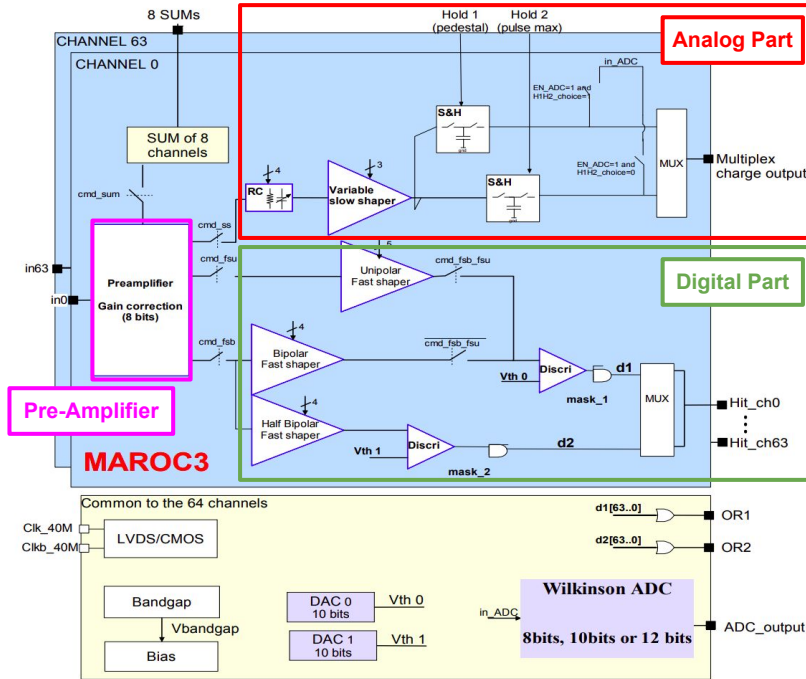


FIGURE 3.34: Scheme of the MAROC3 ASIC architecture [106].

The supply of the bias voltages and the readout of the MAROC3 are performed by the MAROC3 board, shown in Figure 3.35. This board is equipped with the

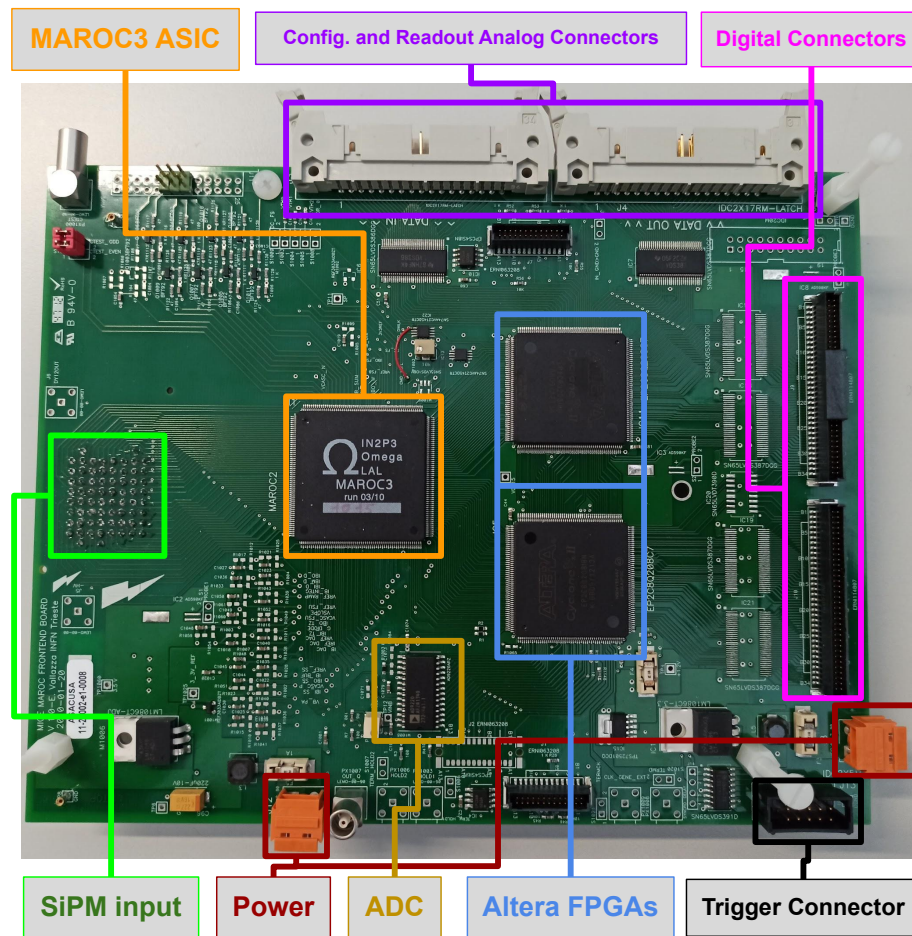


FIGURE 3.35: Picture of the MAROC3 Front-End Board with labels.

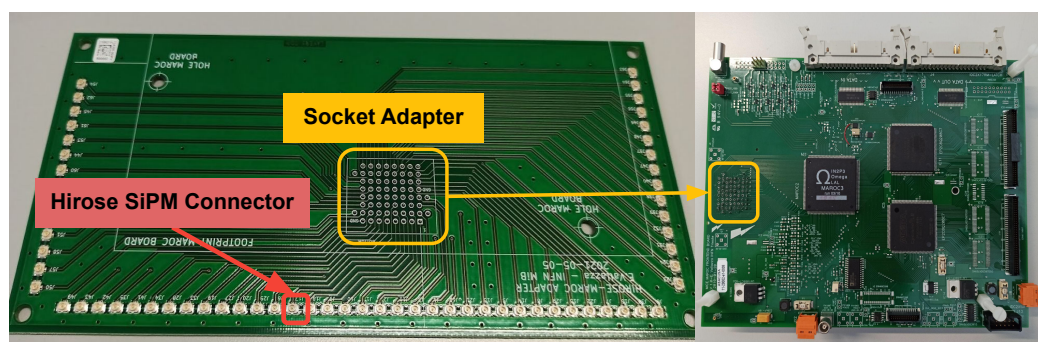


FIGURE 3.36: Picture of the MAROC3 socket adapter to connect the Hirose SiPM coaxial cables to the MAROC3 FEB socket.

analog and digital I/O connectors, a dedicated connector for the trigger signals, the 12-bit AD9220 ADC for the digitization of the MAROC3 multiplexed signal and two ALTERA Cyclone II FPGAs (model EP2C8Q208I8N) for the configuration and the readout of the MAROC3 ASIC. A 64 pin socket mounted on the board provides the connection between the MAROC3 inputs and the MAPMT used in the 2011 version of the detector. In the 2021 version, an adapter board is required to connect the 60 SiPM coaxial cables to the MAROC3 board socket, by directly plugging it under the MAROC3 FEB. A picture of this adapter is shown in Figure 3.36.

The VME Cyclone Board (VCB)

The VME Cyclone Board (VCB) is a custom VME board equipped with a programmable ALTERA Cyclone II FPGA (model EP2C50F484C8N), 2 32 differential I/O high density connectors for the communication with the MAROC3 boards, 4 TTL IN signals, 2 TTL OUT signals, 2 NIM IN signals, 2 NIM OUT signals, 1 DIN 56 I/O signals connector for the daughter board and 2 VME connectors. A picture of the board is shown in Figure 3.37. This board has the following tasks:

- to load the configuration mask in all the MAROC3 ASICs on the FEBs by means of a 3-wire serial bus. Given that each FEB has 4-wire outputs connected to the VCB, the load data can be read back to check for any transmission and loading error;
- to generate the trigger signal by processing, with the trigger logic implemented in the FPGA, all the trigger output signals from the FEBs;
- to readout the data from all the FEBs and to send them to the VME controller via the VME bus.

The communication with each FEB is performed with 3 Ethernet cables, connected to the VCB via a dedicated adapter. The PC with the DAQ software is equipped with a CAEN A2818 controller connected via optical fiber to the CAEN V2718 VME module.

3.3.4 The Data Acquisition

The scheme of the Data Acquisition (DAQ) is presented in Figure 3.38. In the final DAQ configuration, 2 VCBs are used to process and generate the trigger signal with the desired logic and to configure and readout all the 8 MAROC3 FEBs. The DAQ procedure can be summarized as follows:

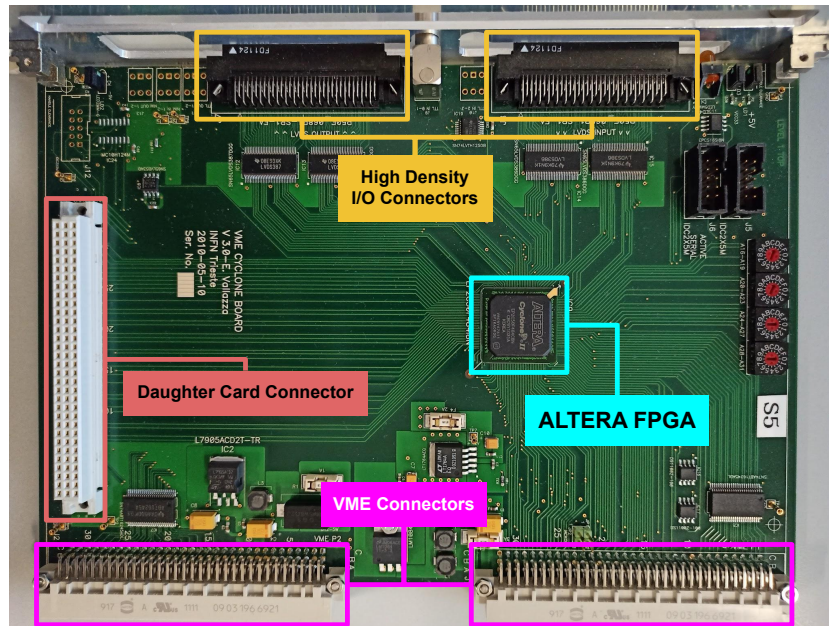


FIGURE 3.37: Picture of the VME Cyclone Board (VCB) with labels. The board is used to readout and control the MAROC3 FEBs.

- at the start of the DAQ, the MAROC3 configuration mask is loaded in all the MAROC3 ASICs on the FEBs and checked;
- the master VCB generates the reset signals and the configuration and sends them to all the MAROC3 FEBs;
- the MAROC3 digital signals (discriminated after the fast shaper) are processed in the FPGAs on the FEBs to generate the single plane trigger which is sent to the daughter VCB; the final trigger signal is processed and sent to the master VCB;
- the master VCB generates the busy signal which is sent to the FEBs, where the hold signal is in turn generated to sample the analog signal;
- the MAROC3 analog signals are digitized by the ADC mounted on the board and sent to the VCB for the readout.

The DAQ software is written in C, with Tcl/Tk¹⁵ for the Graphic User Interface (GUI), which is shown in Figure 3.39. The data are stored in HBOOK [108] ntuples, which can be processed to be saved in ROOT [109] trees for the analysis.

¹⁵<https://www.tcl.tk/>

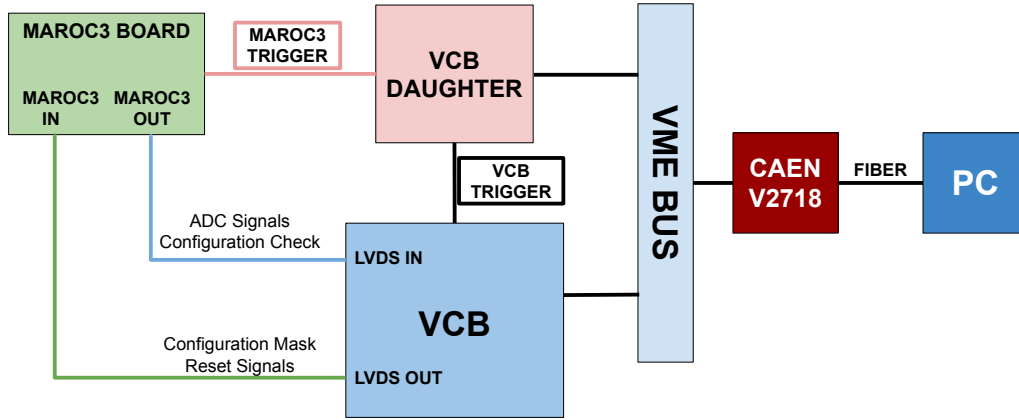


FIGURE 3.38: The scheme of the DAQ with the used boards and connections.

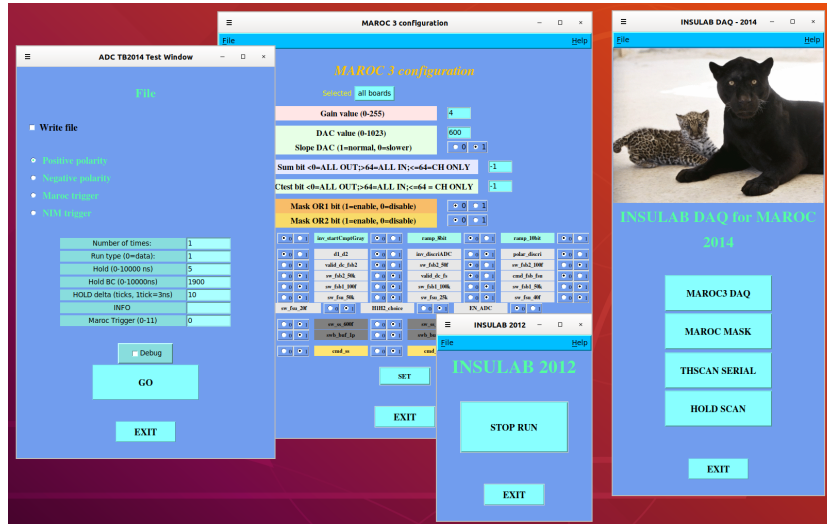


FIGURE 3.39: Picture of the DAQ software GUI written in C and Tcl/Tk.

The preliminary tests and the characterization of the single parts of the detector will be presented in Chapter 4.

CHAPTER 4

The preliminary tests

To understand the behaviour of the whole DANTE detector, it is important to study the characteristics of its single parts. Different preliminary tests were performed about the light loss in the bar-fiber system, the behaviour of the SiPM FEBs, the SiPMs dark noise and the light output of the bars. In this chapter all these tests are presented together with the different experimental setups, the data analysis procedure and the results. The data analysis was performed using the numpy [110], matplotlib [111], scipy.optimize [112] and lmfit [113] Python3 packages.

4.1 The bar-fiber light attenuation

4.1.1 The experimental setup

The first preliminary test allowed to determine the signal degradation as a function of the distance between the photosensor and the hit position of a particle on the scintillating bar.

Two bars, of the same kind of the ones used in the final version of the detector, were readout by two (previously studied in [114]) FBK-irst (Fondazione Bruno Kessler) $400\ 50 \times 50\ \mu\text{m}^2$ cells SiPMs, whose signals were amplified by the prototype circuit used for the SiPM FEBs (Front-End Boards) in the DANTE detector (Section 3.3.3). The SiPMs were biased at 41 V. The amplified signals were processed by the MAROC3 ASIC, with the pre-amplifier gain set to 4 and

the hold of the Sample&Hold circuit set to 5 ns. A picture of the SiPMs coupled with the WLS fibers and of the amplifier is shown in Figure 4.1.

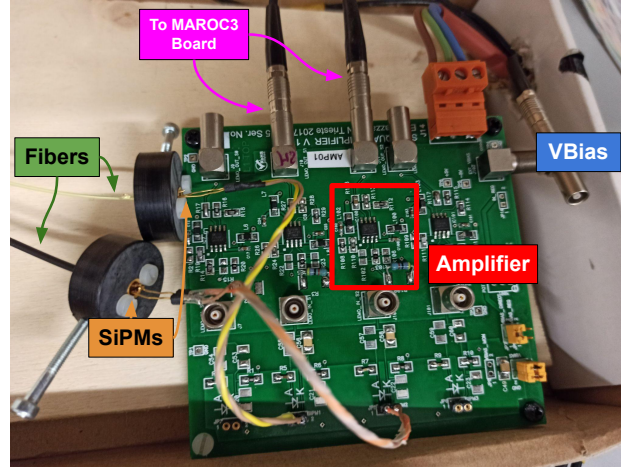


FIGURE 4.1: Picture of the SiPMs coupled with the fibers of the two bars under test and the amplifier.

The measurement was performed in the INSULAB laboratory using cosmic rays. The setup used and shown in Figure 4.2 consists of:

- two plastic scintillators readout by PMTs, used in coincidence for the trigger generation;
- four AGILE silicon microstrip detectors [115] in a XY configuration for the cosmic rays tracking. The single side silicon detector has an active area of $9.5 \times 9.5 \text{ cm}^2$, with a thickness of $410 \text{ }\mu\text{m}$ and a strip readout pitch of $242 \text{ }\mu\text{m}$ (1 floating strip scheme). The spatial resolution of the detector is $30 \text{ }\mu\text{m}$. The single XY module is called Beam Chamber (BC) and it is visible in Figure 4.3;
- the two bars readout by SiPMs as described above.

The Data AcQuisition (DAQ) procedure saved the xy coordinates in cm in a DST file only for single cluster events in both the BCs, together with the Pulse Heights (PH) of the two channels readout by the MAROC3.

4.1.2 The data analysis

The main goal of this analysis was to study the behaviour of the signal produced by a particle crossing the scintillating bar as a function of the distance between the particle hit position on the bar itself and the SiPM. To do that, the tracks

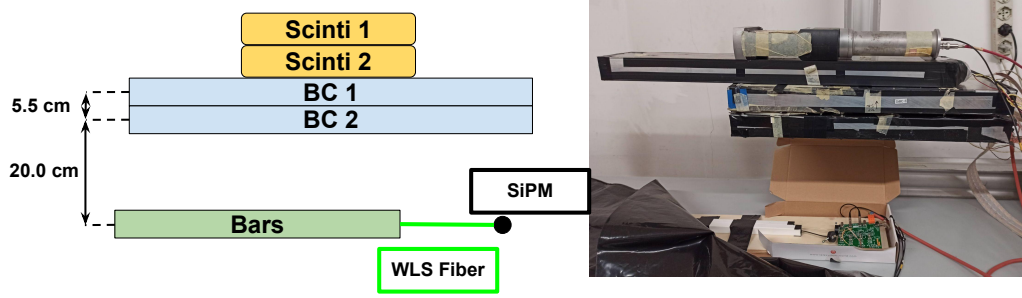


FIGURE 4.2: Scheme and picture of the experimental setup for the bar length scan.

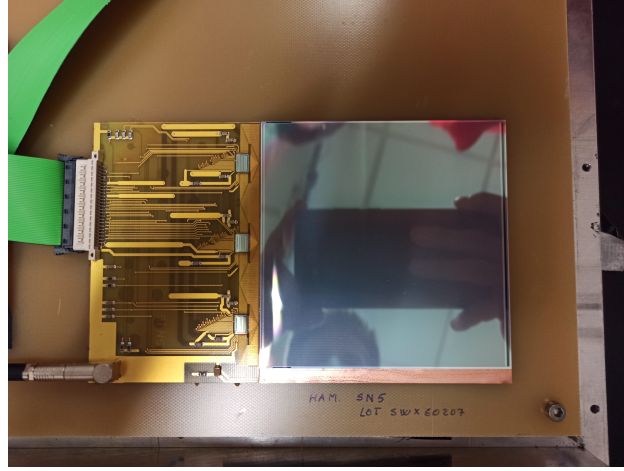


FIGURE 4.3: Picture of the inside of a Beam Chamber: a single AGILE detector is visible, while the one with the strips in the other direction is placed below it.

of the incoming cosmic rays had to be reconstructed to select the particles that crossed the bar and to identify the corresponding signal in the PH spectrum. The raw PH spectra of the two bars under test are shown in Figure 4.4.

The x and y positions detected by the BCs are shown in Figure 4.5. Taking into account the scheme in Figure 4.6a, the x coordinate of the hit position of the incoming cosmic rays on the bars plane can be reconstructed calculating the impinging angle with respect to the vertical axis in the following way:

$$\theta_x = \arctan\left(\frac{x_2 - x_1}{z_2 - z_1}\right) \quad (4.1)$$

where θ_x is the angle on the x coordinate, x_i is the x coordinate of the i^{th} BC and z_i is its vertical position; the same was done for the θ_y angle, using the y_i coordinates. The angular distributions are shown in Figure 4.7. The x_{bars}

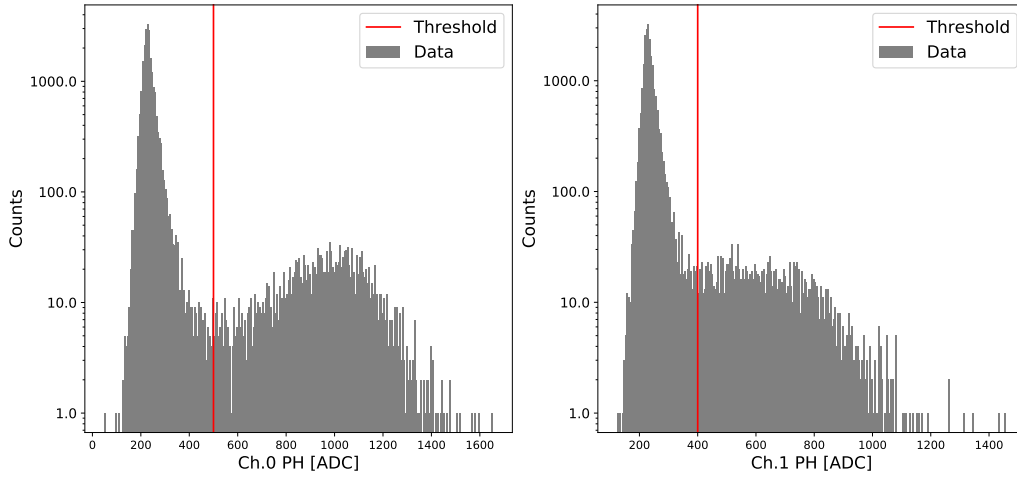


FIGURE 4.4: Raw PH spectra of the bars in the preliminary tests. The red lines are the thresholds on the PH used in the analysis to determine the events in which the particle has crossed the bar.

coordinate is then calculated (the same for the $ybars$ one):

$$xbars = \tan \theta_x \cdot (zbars - z_1) + x_1 \quad (4.2)$$

where $zbars$ is the vertical position of the bars. The 2D distribution of all the tracks on the bars plane is shown in Figure 4.8a. Among these, the tracks of the particles that had crossed the bars and produced a signal were selected as the ones corresponding to a PH above a given threshold, set to discriminate the events from the noise. The resulting 2D distribution is shown in Figure 4.8b; the plot has been obtained applying a cut also in the angle distribution, to discriminate better the two bars and to avoid to count the particles which have crossed both the bars. The accepted angular range (represented by the red lines in Figure 4.7) was $[-1.0, 1.0]$ mrad.

Since the bars were not aligned with respect to the strip direction of the BCs (as it can be seen in Figure 4.8b), to select precisely the area of interest on the 2D tracks distribution inside the bars, a method to rotate the coordinates has been developed. Once selected a single bar, the y projection of the 2D tracks distribution was fitted with a gaussian function to estimate its center and its width (Figure 4.9). Then the coordinates were rotated of an angle α using the following relations:

$$\begin{cases} x_{Rot} &= xbars \cdot \cos \alpha + ybars \cdot \sin \alpha \\ y_{Rot} &= -xbars \cdot \sin \alpha + ybars \cdot \cos \alpha \end{cases}$$

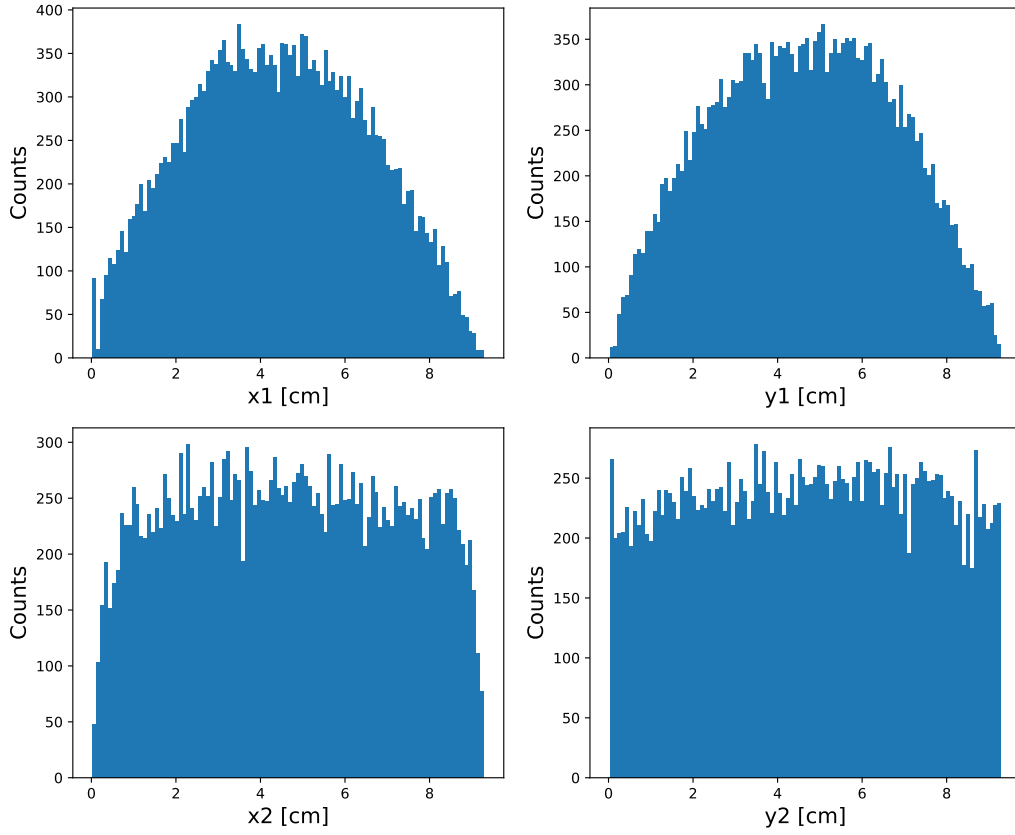


FIGURE 4.5: Hit profiles on the silicon planes of the BCs in one data run of the bar scan length.

where x_{Rot} and y_{Rot} are the $xbars$ and $ybars$ coordinates after the rotation. The y projection was then re-fitted. This was done for 100 angles in the range $[-10.0^\circ, 10.0^\circ]$ and the extracted centers and widths were plotted as a function of the α angle. In particular, as shown in Figure 4.10, the width increases if the misalignment between the bars and the BCs is larger. The width is instead minimized if the bar is aligned; so the rotation angle corresponding to the minimum has been found by fitting the estimated widths with a 2 degree polynomial function. The coordinates were then rotated using this angle.

The fiducial cuts that define the area of interest of the cosmic ray hits are shown in red in Figure 4.11, superimposed on the efficiency map of the two bars, defined as the ratio between the two 2D histograms shown in Figure 4.8, i.e. the number of the hits on the bars plane corresponding to the events with a PH above the set threshold, divided by the total number of the hits on the bars plane. The y coordinate of the center of the geometric cut region was found with the method explained before (i.e. by fitting the y projection of the bars 2D

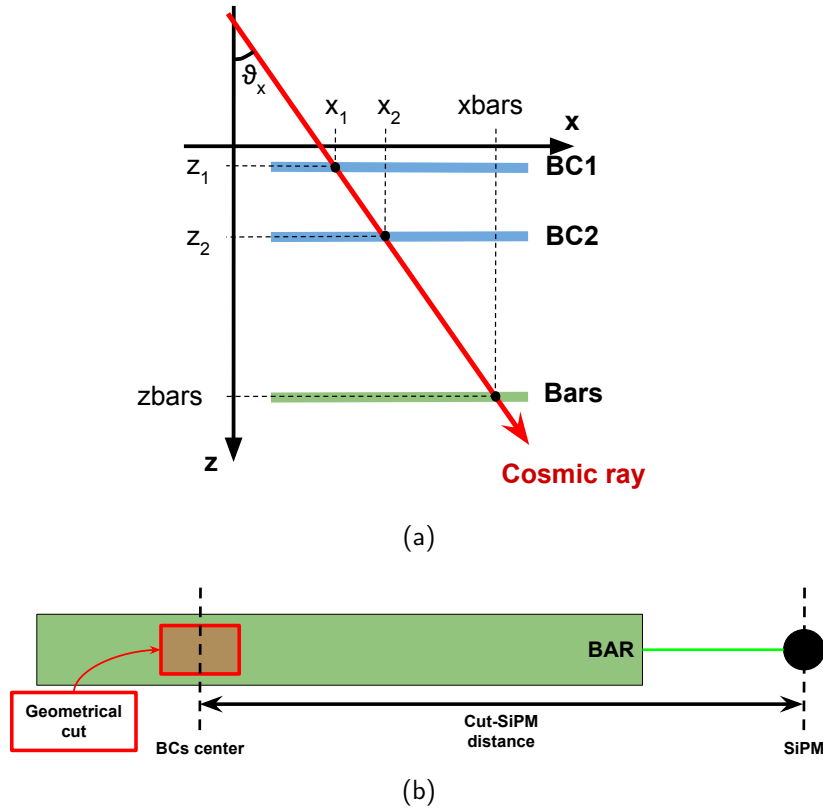


FIGURE 4.6: (a) Scheme of the tracks reconstruction method in the bar length scan, where the x and z coordinates are indicated. (b) Reference frame for the bar length scan.

tracks distribution); the width was set to 1.2 cm, even though the real bar width is 1.5 cm, to avoid counting the particles that crossed the bars at the borders depositing less energy inside the scintillators with respect to the particles that hit the bars in their centers. In the x direction, the region of interest was 5 cm wide and centered around the center of the BCs. The average distance in the x direction between the crossing position of the cosmic ray and the SiPM was measured as shown in Figure 4.6b.

In Figure 4.12 the PH spectra of the two bars are shown: the grey histograms are the raw PH spectra without any selection, while the red ones are the PHs corresponding to the particles that crossed the bars in the regions of interest. With these selections in position, the physics events were "cleaned" with respect to the noise ones and have been associated to the corresponding distance with respect to the SiPM. Nevertheless, it is possible to spot a few noise events at low PH: these events correspond to the inefficiencies of the bars, for which a

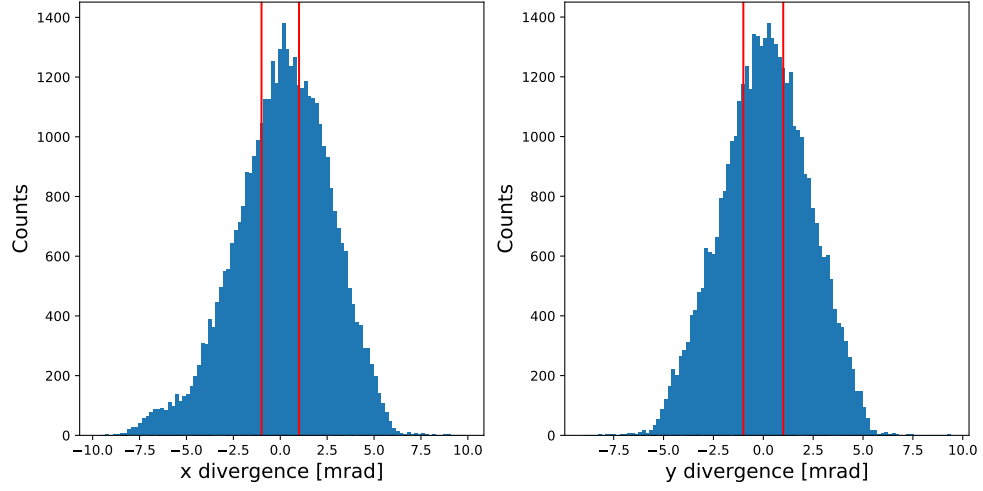


FIGURE 4.7: Angular distribution for the incoming cosmic rays in the bar length scan. The red lines indicate the angular range used to select the tracks with small angles with respect to the vertical axis for the analysis. The asymmetry in the x angular distribution is due to a non-perfect alignment between the silicon detectors and the trigger scintillators along the x direction.

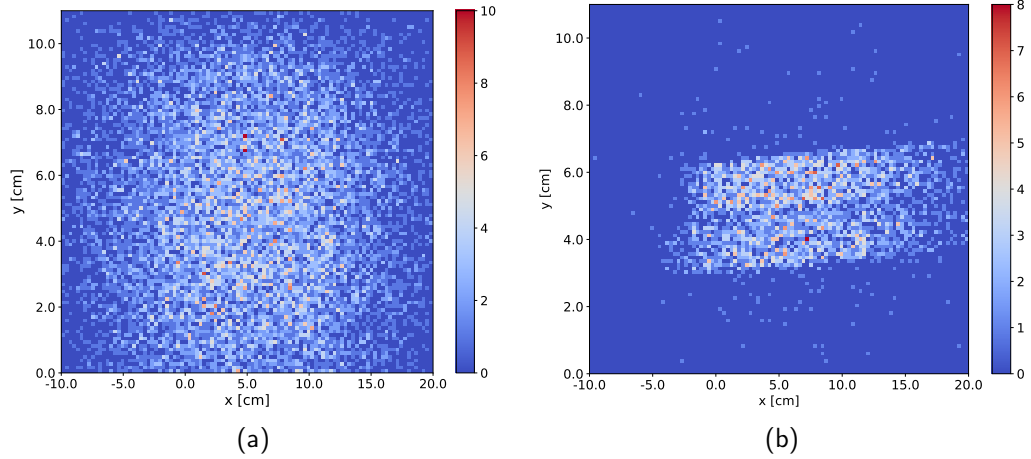


FIGURE 4.8: Hits 2D distributions on the bars plane in the bar length scan: (a) distribution of all the cosmic rays tracks; (b) distribution of the tracks corresponding to the events with a PH over the set threshold. This plot was obtained applying also a cut in the angular distribution to discriminate better the two bars. In this run, the farthest side of the bars from the SiPMs was placed under the solid angle defined by the BCs and thus the bars edge is visible.

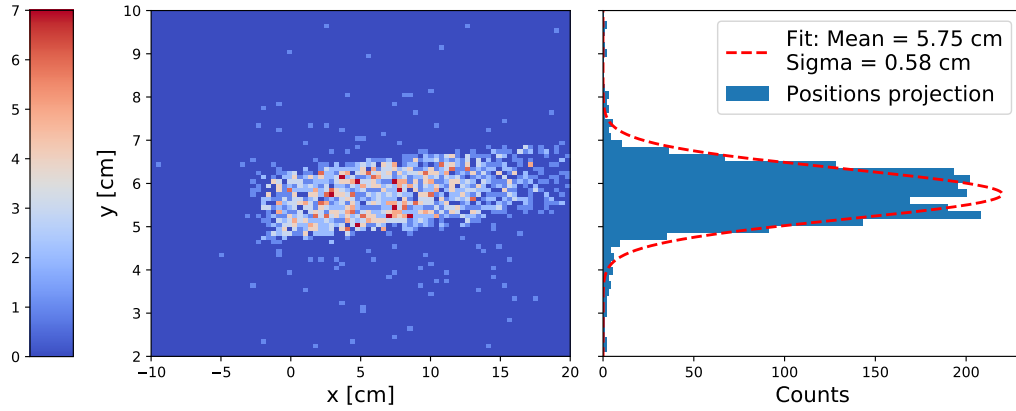


FIGURE 4.9: 2D tracks distribution of a single bar and its y projection. In red, the gaussian fit to estimate the center and the width of the distribution. The width was used in the analysis to calculate the coordinates rotation angle to align the bar with respect to the BCs.

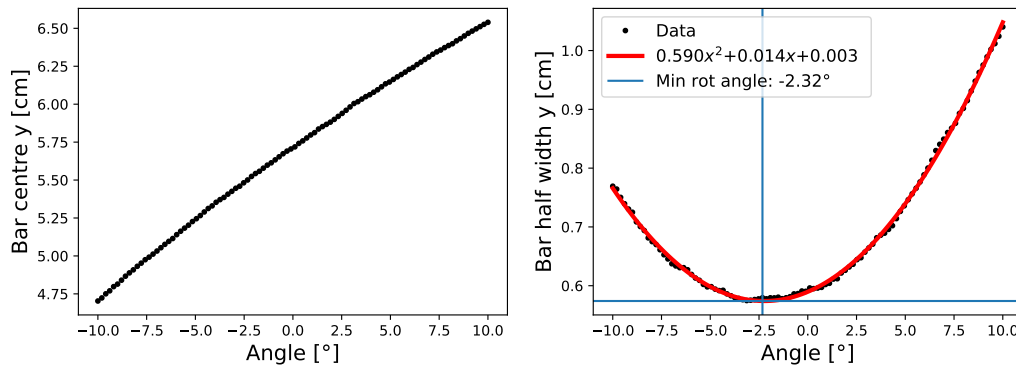


FIGURE 4.10: Y projection center and width as a function of the coordinates rotation angle. The red line is the fitted curve to estimate the angle that minimizes the width.

noise signal was detected instead of a particle. To determine the average signal produced by the MIPs in the region of interest, a fit with a gaussian function of the MIP peak was performed and the most probable value was estimated, along with its error. In Figure 4.13 the MIP peaks of the two bars and the fit with the gaussian function are shown. The errors on the points considered for the fit were calculated as the square-root of the entries in every bin.

The most probable value and its error extracted from the fit were computed for 6 different distances between the corresponding region of interest and the SiPM. The different regions considered for the analysis along the entire length of

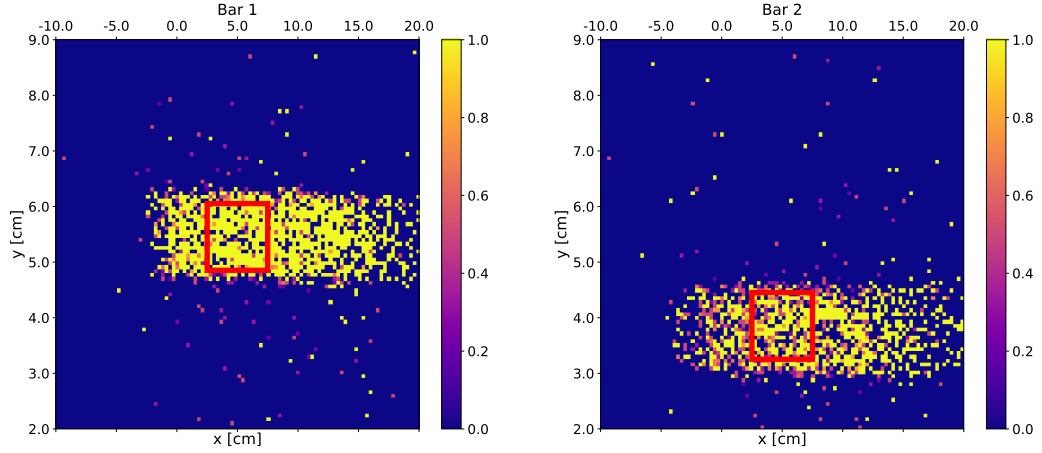


FIGURE 4.11: Efficiency map of the two bars in the bar length scan. In red, the selected region of interest for the analysis.

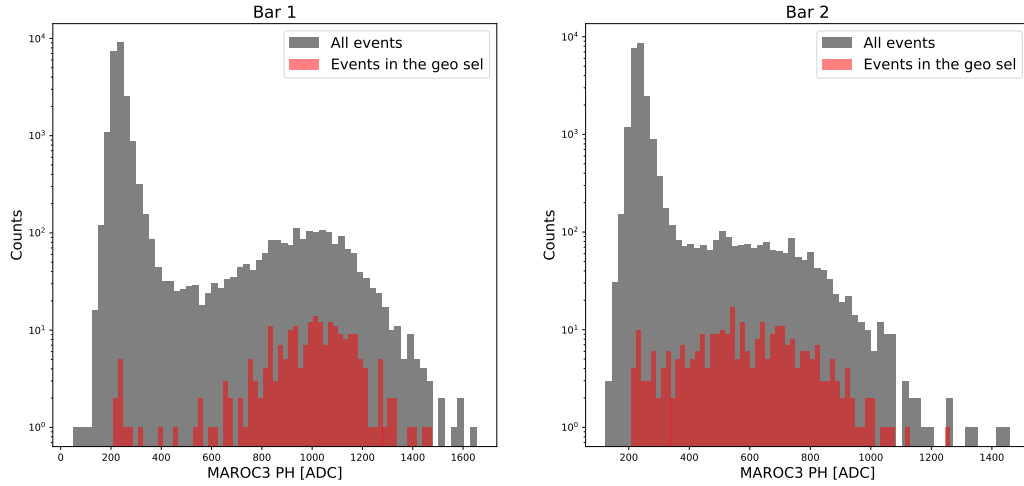


FIGURE 4.12: PH spectra of the two bars in one data run of the bar length scan. In gray, the raw PH without any selection; in red, the PH after the selection of the cosmic rays tracks within the region of interest.

the bars are shown in Figure 4.14. The result is shown in Figure 4.15, where the MIP signals are normalized to the first position, i.e. the one closest to the SiPM. The error bars on the percentages were calculated using the error propagation formula [116], while the ones on the distances allow to consider the width in the x direction of the geometrical cuts and were taken as the half of the width absolute value.

These results show a decrease in the MIP signal of about 30%-40% along the

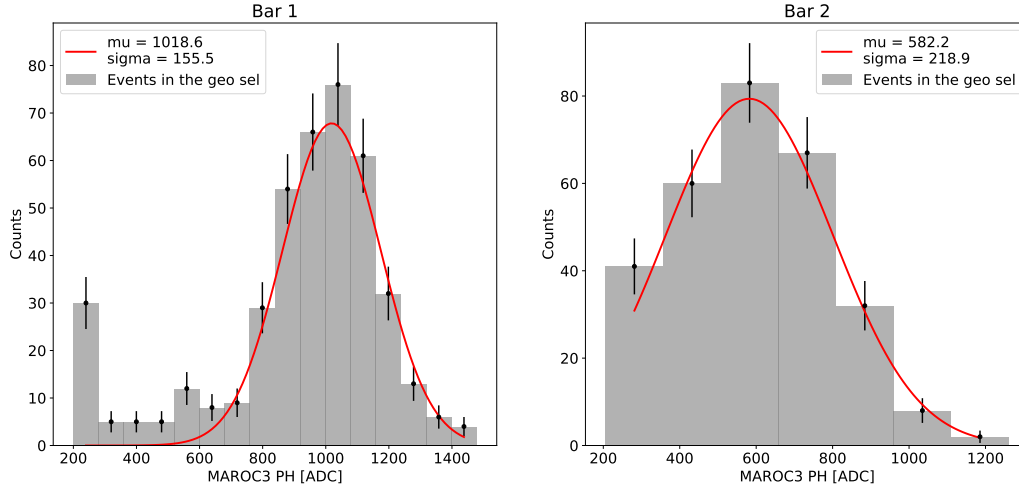


FIGURE 4.13: MIP peaks of the two bars with the gaussian fit in the preliminary tests for the estimation of the MIP signal as a function of the distance between the hit position and the SiPM.

length of the bar, which is mainly due to the non-uniformity of the glue distribution inside the bar and the light attenuation along the fibers. This phenomenon causes a broadening of the MIP signal in the PH spectra of each bar in the final version of the detector. This problem may be solved reading out the fibers from both sides of the bars, on the other hand increasing the number of channels and the cost for the photodetectors and the electronics. However, as can be seen in Figure 4.16, all the MIP peaks are well discriminated from the noise for all the acquired distances. In addition, it has to be taken into account that these measurements were acquired with two test bars (not the ones used in the final version of the detector) readout by two old model SiPMs, which do not feature high performances, as the ones chosen for the DANTE detector.

In conclusion, these tests, performed in the so-called *worst-case scenario*, allowed to estimate the light attenuation inside the bar-fiber system, obtaining a result (Figure 4.15), in accordance with the one found in literature.

4.2 The SiPMs characterization

The second preliminary tests were focused on the characterization of the ASD RGB1S-P SiPMs and their front-end electronics (presented in Chapter 3).

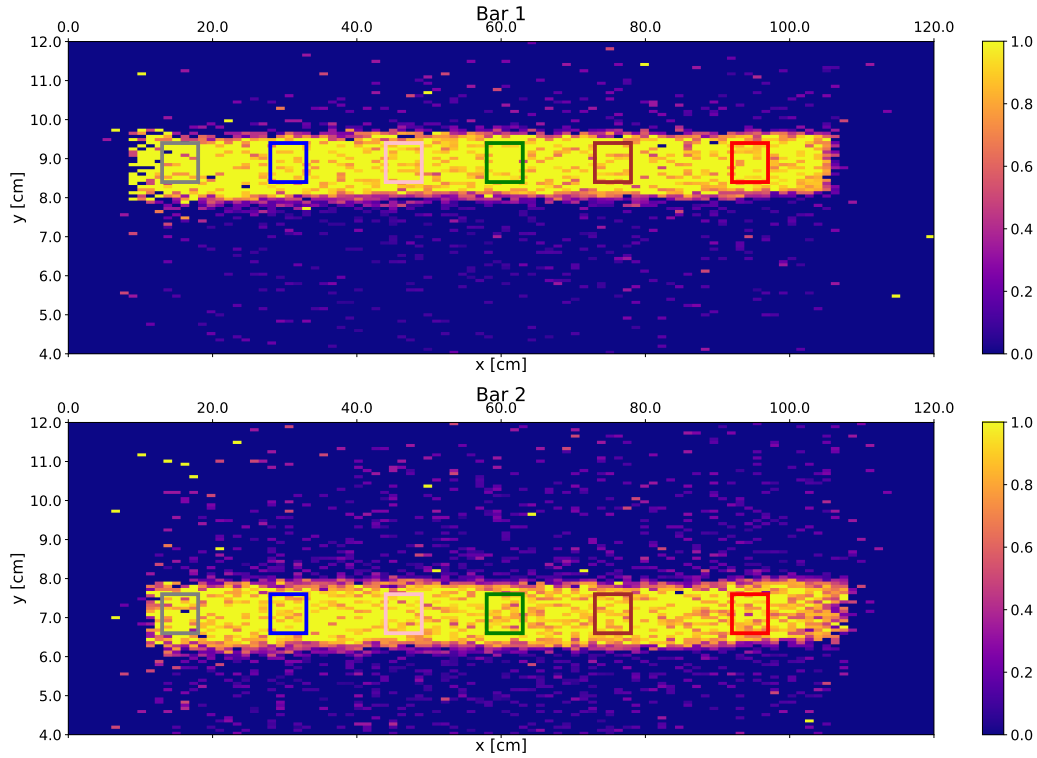


FIGURE 4.14: Bars efficiency maps and the 6 regions of interest for the bar length scan. The x coordinates represent the distances in cm from the SiPM.

4.2.1 The SiPM boards tests and IV curves

To verify the correct operation of all the 40 SiPM boards, they were switched on one at a time with a ± 5 V power supply and their 12 output channels were connected to an oscilloscope.

First, the I-V curve of the board was acquired. Since the SiPM bias voltage is given in common to the 12 board channels, it was not possible to measure the I-V curve of a single SiPM, so the curves presented here are the ones of the board. This measurement is useful to investigate if the SiPMs are biased in the right way and if one or more draw an excessive current from the supply. The I-V curve was obtained applying a variable bias voltage to the boards and measuring the current flowing across a $1\text{ k}\Omega$ resistor in series with the SiPMs. The results for every tested board are presented in Figure 4.17a. In Figure 4.17b an example of the I-V curves of 6 boards is shown with more points taken at higher bias voltages.

The I-V curves allow to estimate the over voltage that has to be applied to the board to bias correctly the SiPMs. In fact the breakdown voltage of the

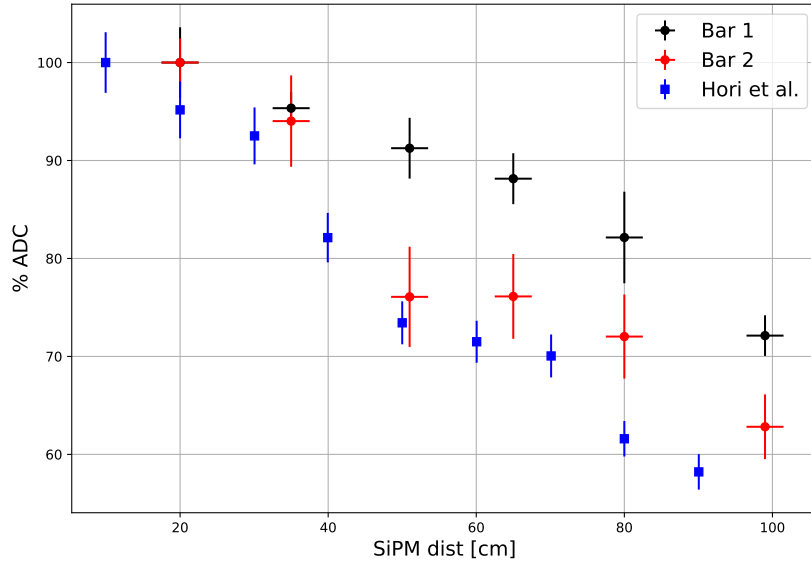


FIGURE 4.15: MIP signal as a function of the distance between the region of interest and the SiPM for the two bars in the preliminary tests. The values are normalized to the first position, i.e. the one closest to the SiPM. The errors on the distances represent half of the width along the x direction of the region of interest. A comparison with the data from Hori *et al.* [117], taken with the same bar-fiber system, is presented.

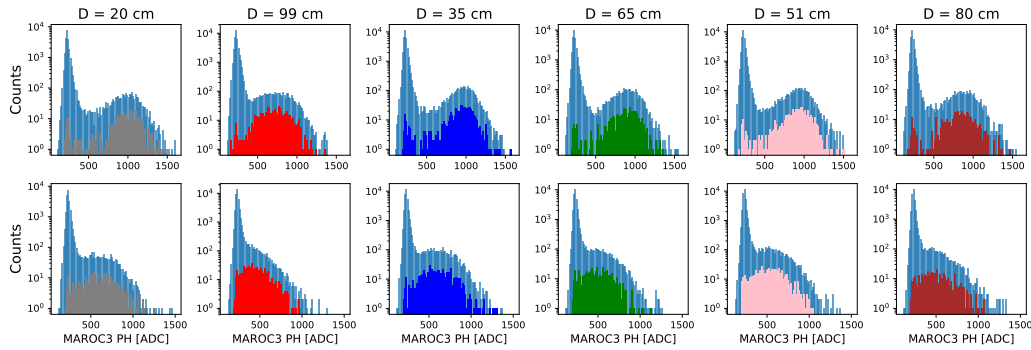


FIGURE 4.16: PHs of the two bars for the 6 steps of the bar length scan. In light blue the PHs without any selection; the colored histograms are the PHs after the selection of the tracks within the region of interest. The distances between the selected region and the SiPM are indicated above the histograms.

boards can be identified around 29 V, i.e. the bias voltage for which the current is different from 0, but the breakdown voltage of a single SiPM is 27 V as reported in the datasheet.

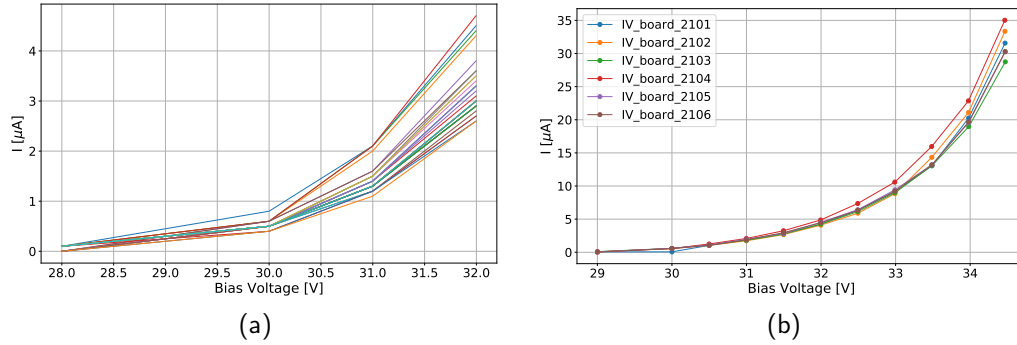


FIGURE 4.17: (a) I-V curves of all the SiPM boards; (b) I-V curves of 6 boards with more points at higher bias voltages.

4.2.2 The SiPM dark counts analysis

A random triggered waveform was acquired to investigate the dark noise main characteristics of the ASD RGB1S-P SiPMs, such as: the Dark Count Rate (DCR), the Optical Cross-Talk (OCT) probability and the PhotoElectron (Pe) spectrum. The dark counts were measured acquiring a 10 ms waveform of the signal of a single SiPM darkened in a dedicated box at a temperature of $\sim 26^\circ\text{C}$, readout by a CAEN DT5730 digitizer with a sampling rate of 2 MS/s and a range of 14 bit. Eight waveforms were acquired for eight different bias voltages from 29.5 V up to 33 V.

The analysis procedure measured the amplitude and the time of the peaks of a signal, such as the one shown in Figure 4.18. The algorithm can be summarized as follows:

- the baseline value of the waveform is calculated as the average value of its first 1000 points and subtracted to shift the waveform to zero;
- the shifted waveform is smoothed by a first order low-pass filter with a cutoff frequency of 50 MHz, to reduce the high frequency electronics noise;
- the derivative of the filtered waveform is calculated and a threshold value is applied to discriminate the signal from the baseline fluctuations;
- the algorithm finds the time at which the derivative goes below the threshold and the time at which it crosses the first time the zero value;
- the peak amplitude is computed as the integral of the derivative between the two times found in the previous point.

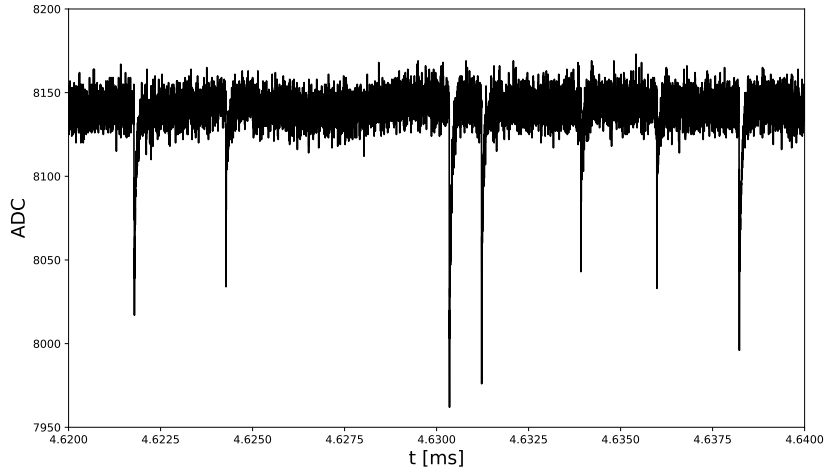


FIGURE 4.18: 200 μs snapshot of the raw waveform acquired in the dark noise measurement of a SiPM biased at 31 V.

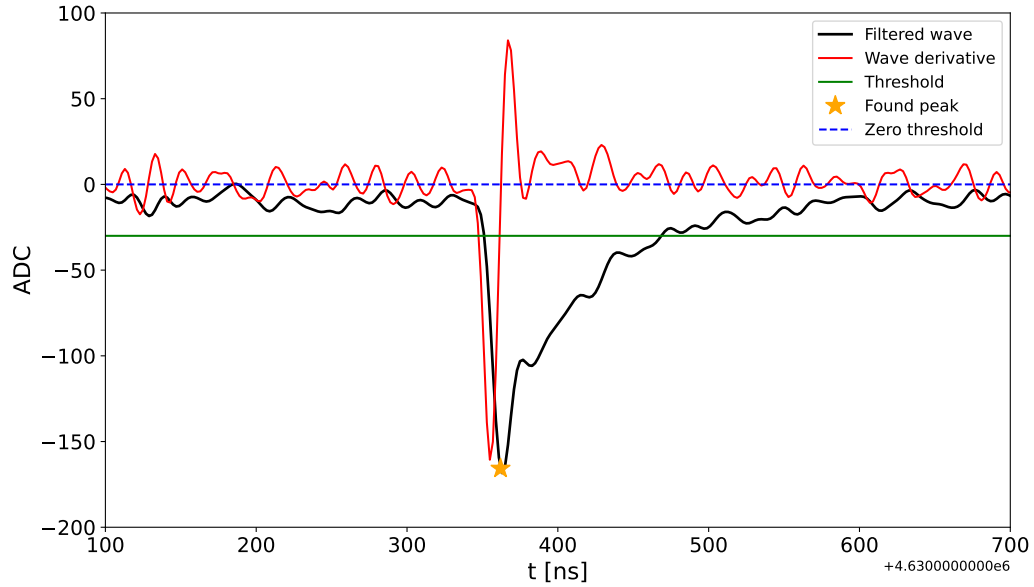


FIGURE 4.19: Example of the peak finder algorithm result on a waveform of a SiPM biased at 31 V.

An example of a signal and the result of the algorithm is shown in Figure 4.19. In addition, this method measures the distance in time between two subsequent peaks as the difference of their peak times. The distribution of these time intervals for one data set is shown in Figure 4.20. Since the dark counts follow a poissonian probability distribution in time, their rate has been estimated by fit-

ting the time distribution with an exponential function, whose decay constant is precisely the rate. The DCR for all the bias voltages is presented in Figure 4.21. These measurements are in agreement with the ones of the SiPM datasheet that were taken at a temperature of $\sim 20^\circ\text{C}$; taking into account that (Chapter 3) the DCR doubles every $\sim 10^\circ\text{C}$, the measured DCR has increased of a factor ~ 1.5 as expected.

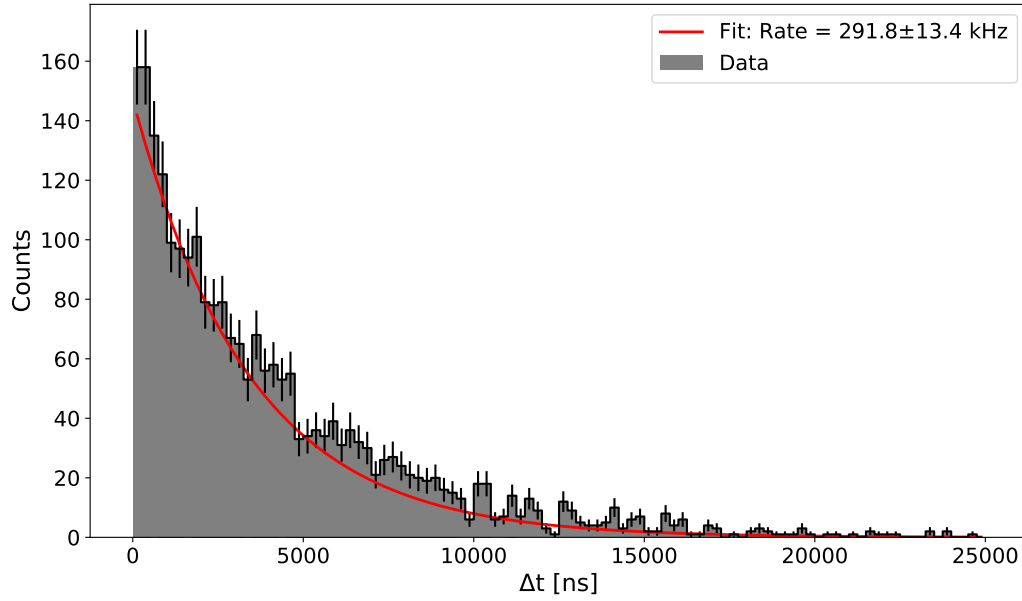


FIGURE 4.20: Time intervals distribution of the dark noise events of a SiPM biased at 31 V. In red the exponential fit to estimate the Dark Count Rate (DCR).

In Figure 4.22 the histogram of the peaks amplitudes (PH) in ADC counts of the waveform acquired with a bias of 31 V is shown. The peaks in this spectrum correspond to the signal produced respectively by one, two, etc. triggered cells in the SiPM itself. The single photoelectron signal is due to the thermal induced dark noise, while the signal at a higher PH is due to the OCT between the SiPM cells, that triggers more than one cell thus producing a noise event corresponding to two, three or more photoelectrons. The first three peaks were fitted with a gaussian function to estimate their mean (μ) and sigma (σ) (the colored lines in Figure 4.22) that are plotted as a function of the corresponding number of photoelectrons to calibrate the SiPM. The calibration coefficients were calculated with a linear regression of the mean PHs as a function of the number of Pes, as presented in the inset in Figure 4.22. The calibration of the PH in number of photoelectrons will be used in Section 4.3.

Since the input signal range of the digitizer was set to $[0, 2]$ V, the PHs of the single photoelectron peaks for every bias voltage were converted in their

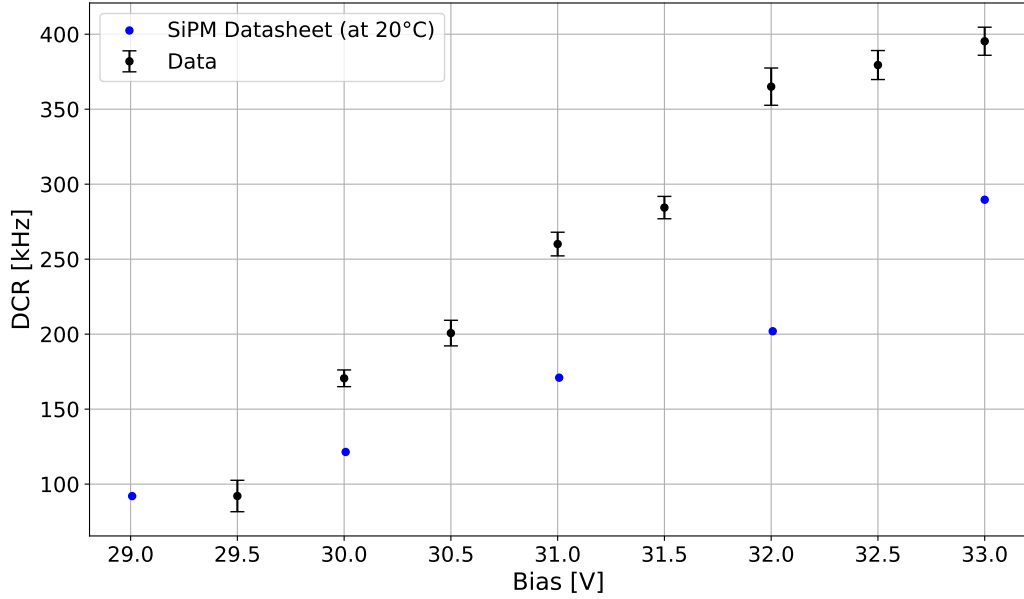


FIGURE 4.21: Dark Count Rate at different bias voltages at $\sim 26^\circ\text{C}$. The DCRs from the ASD RGB1S-P SiPM datasheet are also shown. Note that the two datasets were acquired at two different temperatures.

corresponding values in mV and plotted as a function of the bias. The result is shown in Figure 4.23. The data show a linear trend, as verified by the unity of the R^2 for the calculated linear fit.

The Optical Cross-Talk probability was estimated as suggested in [118], i.e. as the following:

$$p_{OCT} = \frac{\#(\geq 2 \text{ p.e.})}{\#(\geq 1 \text{ p.e.})} \quad (4.3)$$

where $\#(\geq 1 \text{ p.e.})$ and $\#(\geq 2 \text{ p.e.})$ are the number of noise events with a PH greater than the signal of 1 and 2 photoelectrons respectively. The OCT probability computed for different bias voltages is shown in Figure 4.24. The greater the bias, the more the OCT effects occur, so the larger the dark noise. This has to be taken into account, when choosing the bias voltage of the SiPMs in the detector, to maintain a good signal to noise ratio.

All the noise effects of a SiPM are well visible in Figure 4.25, where the correlation between the PH and the time interval is shown. Comparing it with the plot shown in Figure 3.15 in Chapter 3, it is possible to identify the delayed cross-talk events and the afterpulses, that cannot be discriminated in the pure PH spectrum. In this plot, these effects are enhanced due to the high bias voltage applied to the SiPM for this measurement.

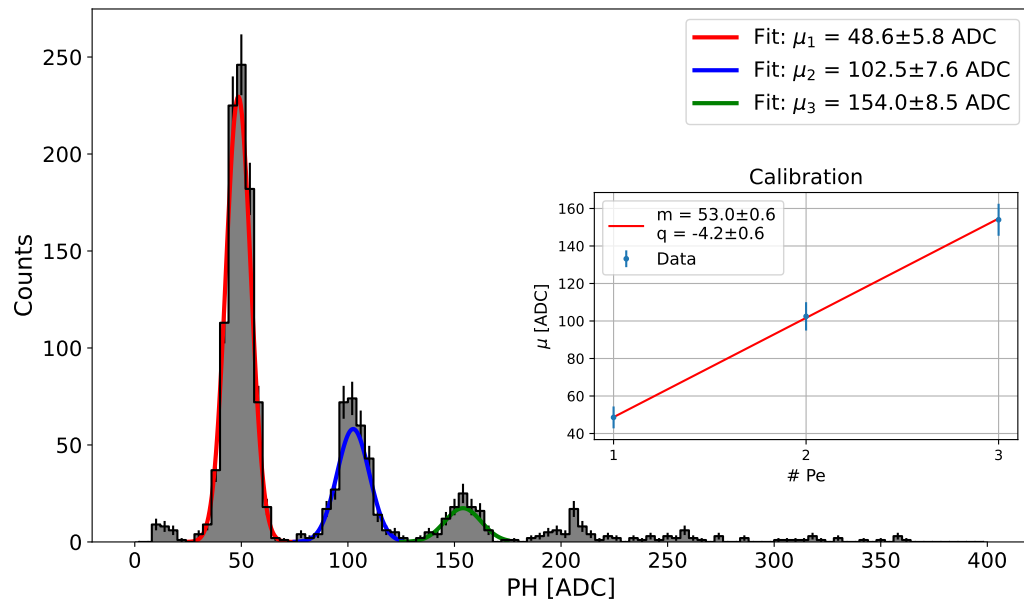


FIGURE 4.22: Dark noise PH in ADC of a SiPM biased at 31 V. The colored lines are the gaussian fits of the peak in the spectrum. In the inset, the calibration of the mean value of the PH in number of photoelectrons is shown.

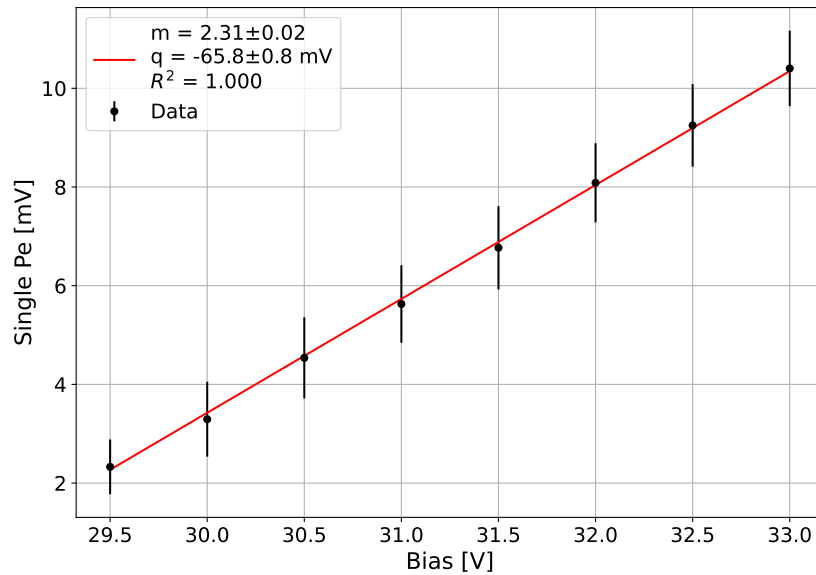


FIGURE 4.23: Single photoelectron signal in mV as a function of the SiPM bias voltage. In red, the linear fit of the data.

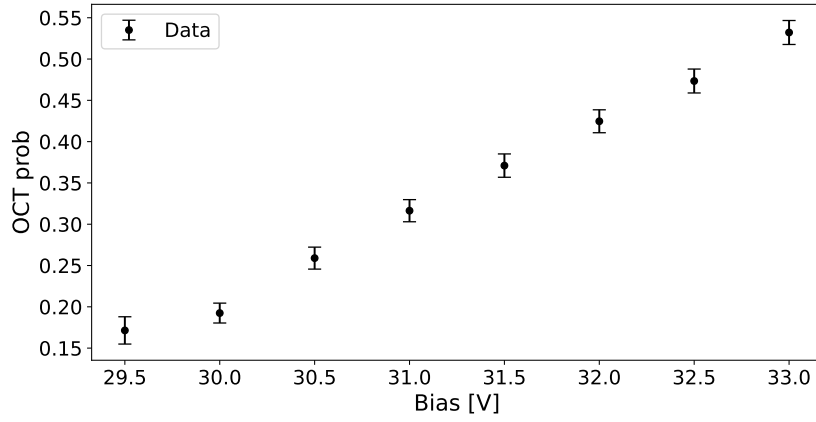


FIGURE 4.24: OCT probability as a function of the SiPM bias voltage.

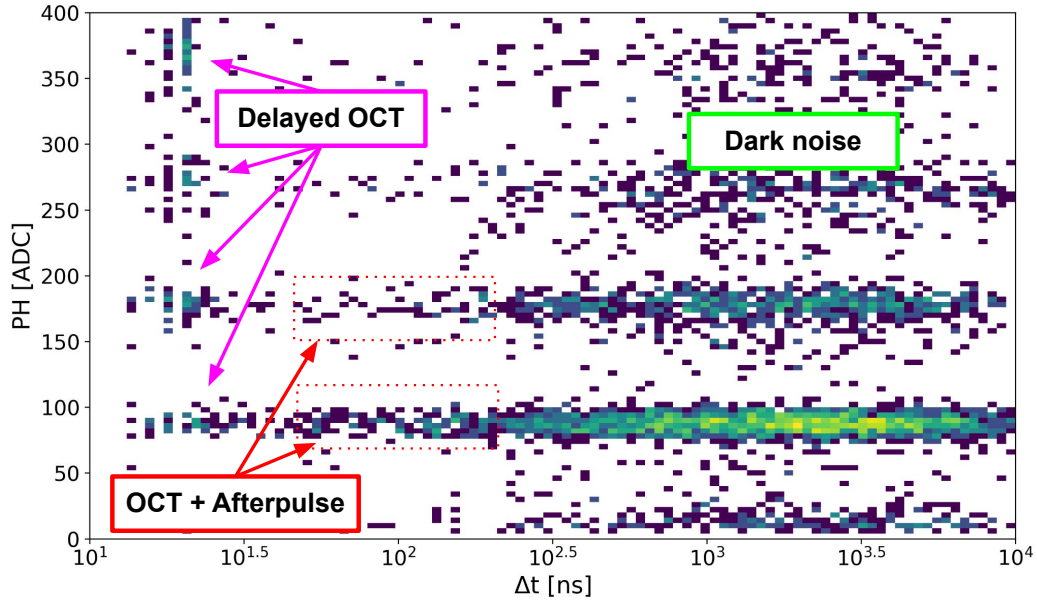


FIGURE 4.25: Correlation between the dark noise PH and the time interval between subsequent events in the dark noise for a 33 V biased SiPM. The cross-talk events and the afterpulses are enhanced by the high bias voltage applied to the SiPM.

4.3 The MIP Photoelectrons measurement

To measure the number of photoelectrons corresponding to a signal produced by a MIP inside the scintillator bar, the waveforms of the SiPM biased at 31 V coupled to the bar under test were acquired by a CAEN DT5730 digitizer (the

same one used for the dark noise measurement). The acquisition window had a 1024 ns length and was sampled at 500 MS/s. The input signal range was set to $[0, 2]$ V. In Figure 4.26 the superposition of 50100 waveforms is shown. In this plot, the region corresponding to a signal around 1700 ADC (the more populated apart from the noise one) corresponds to the average signal of a MIP in the bar.

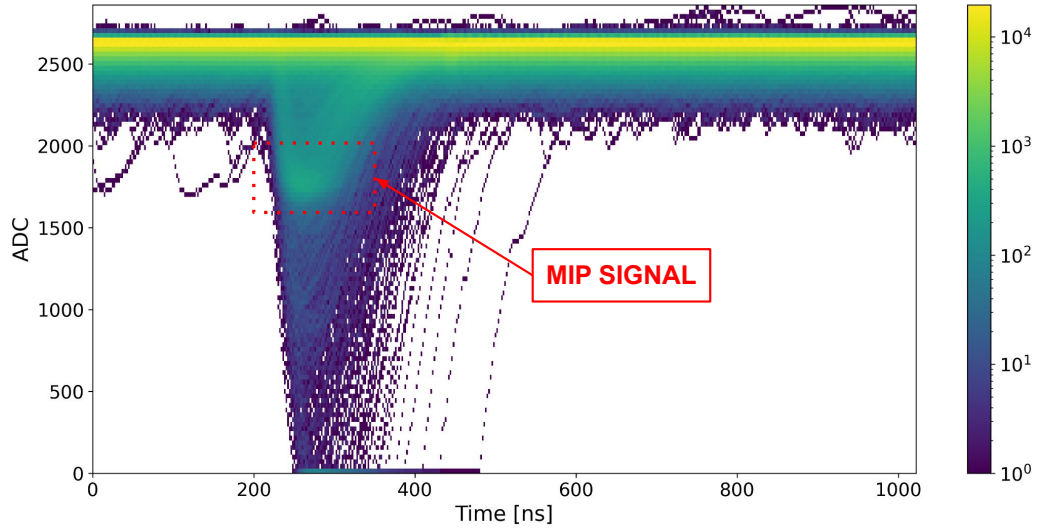


FIGURE 4.26: Superposition of all the acquired waveforms of a SiPM coupled to a scintillating bar.

The amplitudes of the signals were calculated using the algorithm explained in Section 4.2.2 and the found PH spectrum is shown in Figure 4.27, where the peak corresponding to the average signal produced by a MIP is well visible. This peak was fitted with a gaussian function and the mean value was estimated. Although the expected shape of the peak should be a Landau curve, the choice of using a gaussian curve was due to the necessity of fitting also the lower PH falling edge to better estimate the maximum. This edge did not present a Landau shape due to the noise at low PH, which could not be filtered because of the poor statistics. Using the SiPM ADC-photoelectrons calibration described in Section 4.2.2, the number of photoelectrons, corresponding to the MIP signal, was found to be 16 ± 1 . This result is shown in Figure 4.28.

This measurement was performed using one of the "good" bars of the X3 plane. Thus, it can be considered a good estimate of the fired cells in the SiPMs when a MIP crosses the detector. Of course, a worse fiber-SiPM coupling, a damage in the bar or in the fiber or a non-uniformity of the response of the SiPM may lead to a smaller number of photoelectrons and then a smaller signal to noise ratio.

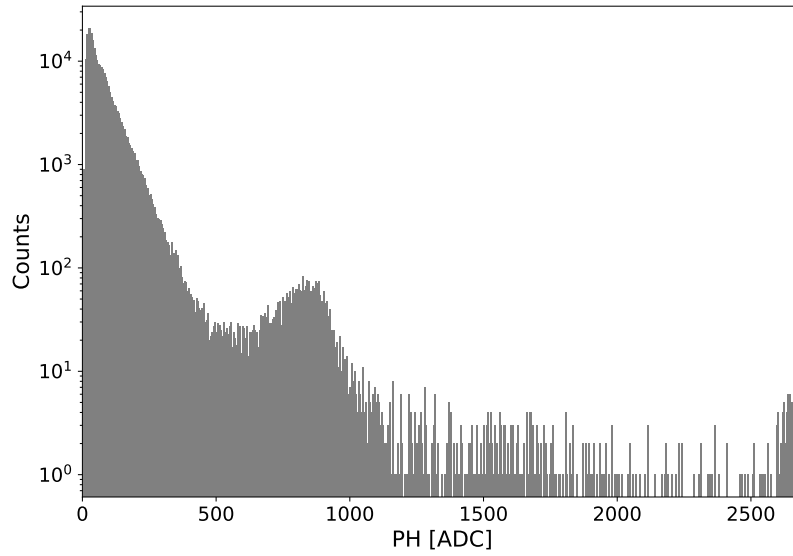


FIGURE 4.27: PH spectrum of a SiPM coupled with a scintillating bar. The peak corresponding to the average signal produced by a MIP in the bar is well visible around ~ 900 ADC.

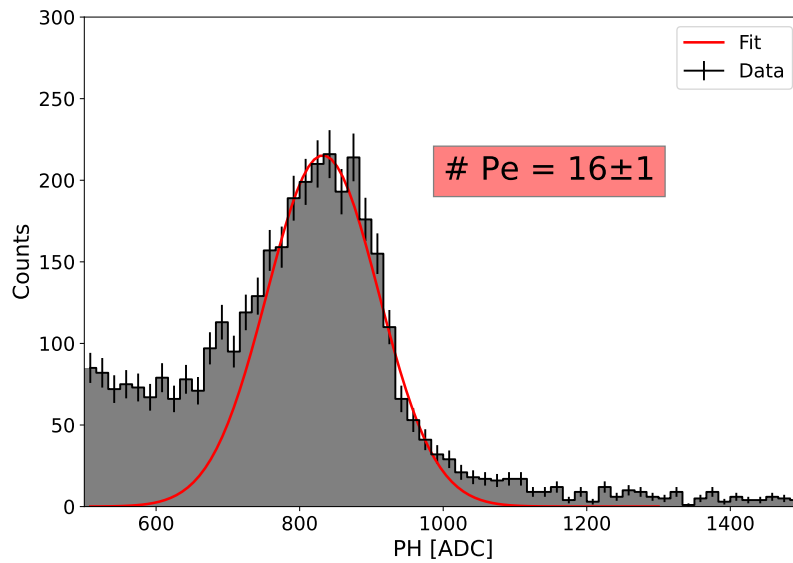


FIGURE 4.28: Fit of the MIP signal in ADC and conversion of its average value in number of photoelectrons.

Chapter 5, will present the analysis and the results of four of the planes of the DANTE detector, concentrating on the efficiency and the spatial resolution measurements.

CHAPTER 5

The detector characterization

The commissioning of four planes of the DANTE detectors was performed in the second half of 2021 and in the first months of 2022 in the INSULAB laboratory with cosmic rays. With two slightly different experimental setups, the efficiency of the scintillating bars and of the entire planes and the corresponding spatial resolution for each plane have been measured. In this chapter, the experimental setups, the data analysis procedures and the obtained results are presented. As in Chapter 4, the data analysis was performed using the numpy, matplotlib, scipy.optimize and lmfit Python3 packages.

5.1 The planes efficiency measurement

5.1.1 The experimental setup

The first measurement performed with four complete detector planes allowed to estimate their efficiency, evaluated both on a bar by bar basis and for each whole plane.

The efficiency measurement requires to reconstruct the cosmic ray particles with high resolution detectors; the experimental setup (Figure 5.1) was made as follows:

- two scintillator detectors [119] for the trigger, each one made of ten 19 cm long and 1.9 cm wide extruded bars readout by P30CW5 PMTs, operating in coincidence;

- four silicon microstrip detectors in a XY configuration for the cosmic rays tracking. Each detector plane consists of 4 $410\ \mu\text{m}$ thick microstrip detectors, for a total active area of $\sim 18 \times 18\ \text{cm}^2$, with a readout pitch of $456\ \mu\text{m}$ (1 floating strip scheme). The spatial resolution of the detector is $60\ \mu\text{m}$. The single XY module is called BARCA and it is visible in Figure 5.2. In the middle of the silicon layer there is a 2 mm wide non-sensitive region. These detectors were developed in the framework of the "Fisica in barca" project in 2007¹;
- 4 planes of the DANTE detector, named X3, Y3, X4 and Y4.

For this measurement, the planes were studied separately in different runs and, as in Section 4.1, the Data AcQuisition saved the xy coordinates measured by the silicon detectors in cm in a DST file only for single cluster events in both the BARCA detectors, together with the Pulse Heights (PH) of the 64 channels of the MAROC3 ASIC of the FEB of the single plane under test. The choice of acquiring singularly the planes instead of all of them together, at this stage of the commissioning, was done to monitor the power consumption and the behaviour of the SiPMs FEBs and the MAROC3 board for the single plane. The power consumptions of all the boards and the bias are reported in Table 5.1.

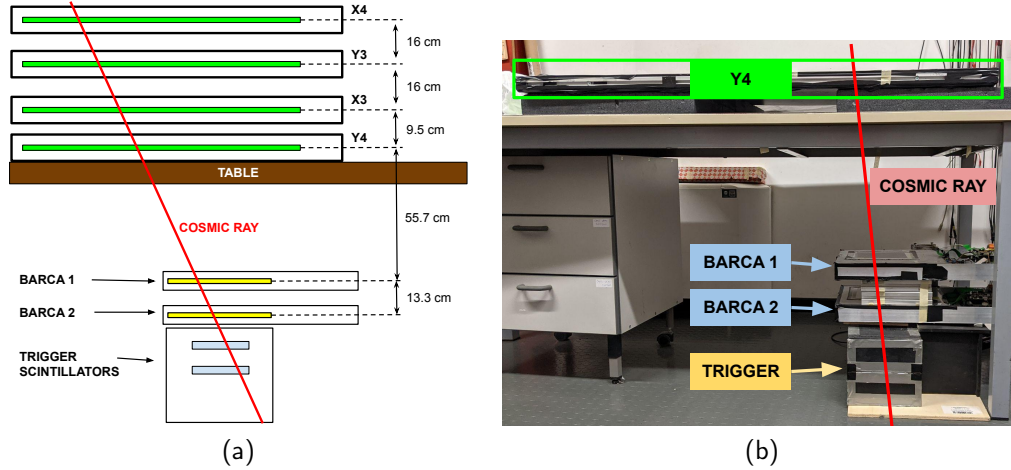


FIGURE 5.1: (a) Scheme of the experimental setup for the efficiency measurement. The distances between the detectors are shown; (b) picture of the experimental setup. In the picture, only the Y4 plane was mounted and shown.

The planes under test were placed with the bars aligned along the x coordinate of the silicon detectors and at a distance large enough to have the possible largest

¹<http://fisicainbarca.ts.infn.it/> (accessed on March 2, 2022)

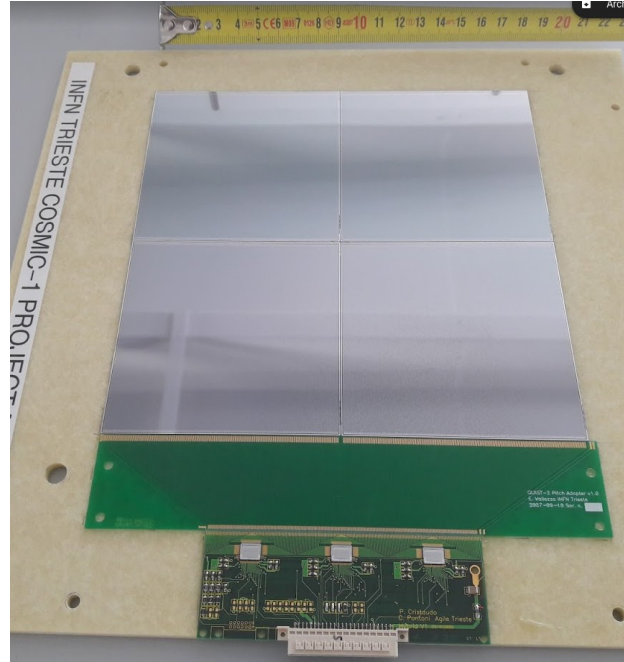


FIGURE 5.2: Picture of the inside of the BARCA silicon detector: a single side silicon layer is visible, while the one with the strips in the other direction is placed below. It is possible to see in the middle the 2 mm wide region of the non-sensitive area.

number of bars per plane placed inside the solid angle defined by the silicon detectors and the trigger scintillators.

5.1.2 The data analysis

To determine both the single bar and the whole detector plane efficiency the positions of the cosmic rays on the plane of the bars were reconstructed. In Figure 5.3 the 2D distributions of the x and y positions detected by the BARCA detectors are shown. In particular, it is possible to see the cross-shaped region

TABLE 5.1: Power consumption and bias of a single DANTE plane.

SiPM boards supply		MAROC3 board supply	
Power supply	Current	Power supply	Current
+5 V	625 mA	+5 V	430 mA
-5 V	570 mA		
SiPM bias voltage		31 V	

around $x \sim 9$ cm and $y \sim 9$ cm due to the 2 mm wide non-sensitive area of the silicon detectors. With the same projection technique used in Section 4.1, the hit positions of the particles that crossed the detector under test were reconstructed.

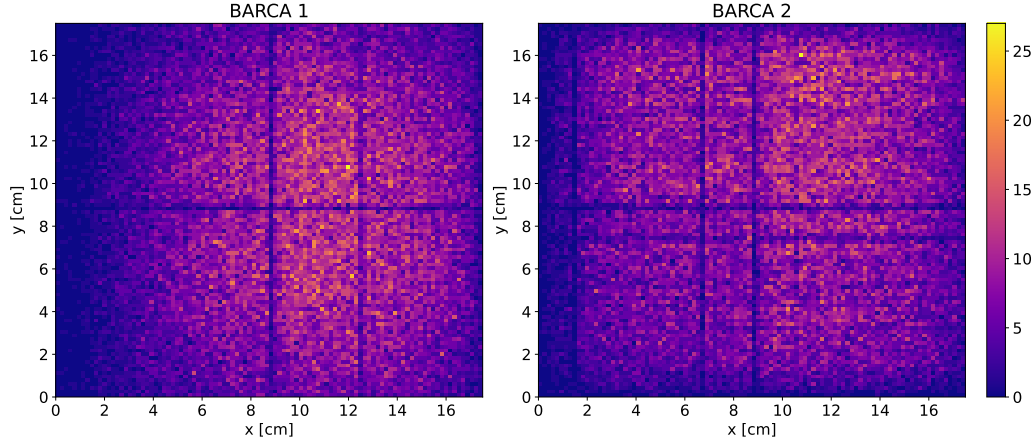


FIGURE 5.3: 2D distributions of the positions of the cosmic rays detected by the BARCA 1 & 2 silicon planes.

To identify the tracks that crossed a bar of the plane under test, the PH spectra have to be analyzed. First, every channel of the MAROC3 was coupled to its corresponding bar via 2 maps, connecting the bar number to the index on the MAROC3 board and to the index of the MAROC3 channel. Figure 5.4 presents the PH distributions of the bars of the X3 plane, superimposed and divided in five groups of 12 spectra each, corresponding to the 5 SiPM boards of the plane itself. It is possible to see that the channels with more events at large PHs are the ones of the boards placed in the center of the plane. In fact, the trigger and the silicon detectors were positioned in the middle with respect to the planes under test and approximately 10 cm from the SiPM boards in the x direction. Since the number of cosmic ray tracks with a large angle with respect to the vertical axis is small, the farthest bars from the center present a poorer statistics.

To discriminate the thermal noise events from the ones corresponding to the of a particle, a threshold was set for every bar. To do that, the *pedestal*, i.e. the signal of the electronics chain when there are no particles, was analyzed:

- 200 random triggers were acquired. The DAQ generates the triggers with a rate of 200 Hz to avoid to count real cosmic ray events during the pedestal run;
- the average PHs (*pede*) for every channel were calculated with their Root Mean Squares (RMS) as errors;

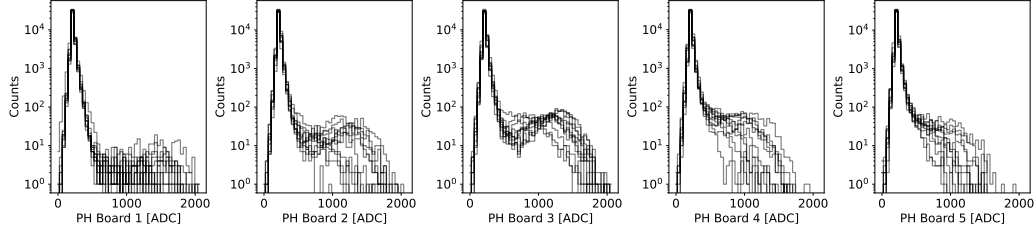


FIGURE 5.4: PH spectra of all the bars of the X3 plane. The distributions are superimposed and grouped in five plots of 12 spectra each as the five SiPM boards of the plane under test.

- the Common Mode Subtracted RMS (CMS RMS) was computed. The Common Mode for the j^{th} event is defined as:

$$CM_j = \frac{\sum_i^N (PH_{i,j} - pede_i)}{N} \quad (5.1)$$

where i runs over the N channels, $PH_{i,j}$ is the Pulse Height of the i^{th} channel for the j^{th} event and $pede_i$ is the pedestal of the i^{th} channel. For every event, the CMS pedestal PH is computed as:

$$CMS_j = PH_{i,j} - CM_j \quad (5.2)$$

and the $pede$ and RMS are re-calculated to obtain the common mode subtracted noise.

The pedestal, the RMS and the CMS RMS for the X3 plane are presented in Figure 5.5. With the calculated pedestal and RMS, the Signal to Noise Ratio (SNR) was computed for every i^{th} bar as the following:

$$SNR_i = \frac{PH_i - pede_i}{RMS_i} \quad (5.3)$$

and shown in Figure 5.6. Different thresholds were then set on the SNR values to analyze the behaviour of the efficiency as a function of the threshold itself.

In Figure 5.7 the 2D distributions of the hit positions of the cosmic rays on the Y3 bars plane are shown without and with the threshold on the SNR. In particular, in Figure 5.7b the positions for which the SNR is more than 3 for bar 31 are shown and the shape of the bar is clearly visible. Since the bars planes were not perfectly aligned with the silicon detectors, a rotation procedure of the positions, as the one used in Section 4.1, was applied. As in Section 4.1, a fiducial cut on the cosmic ray positions was defined for every bar, setting the bar width to 1.2 cm around its center in the y direction (that was found as the

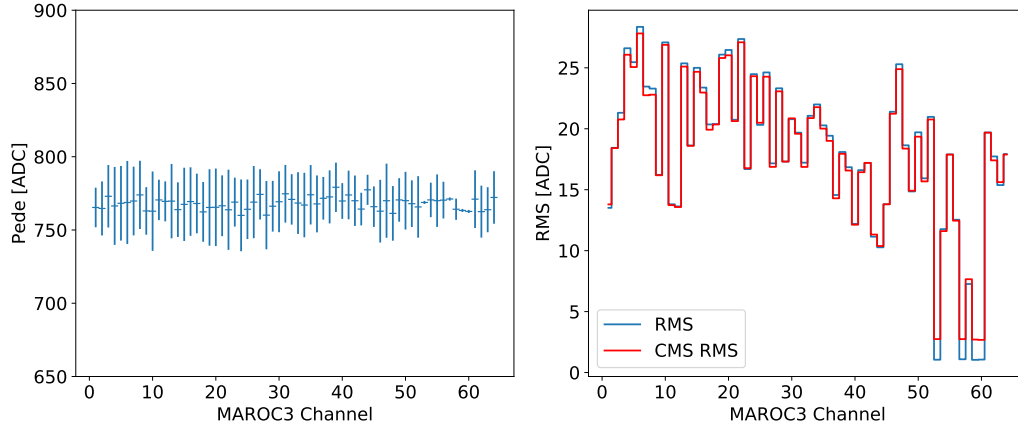


FIGURE 5.5: Pedestal, RMS and CMS RMS of the channels of the MAROC3 of the X3 plane. All the 64 MAROC3 channels were read, but only 60 of them were connected to the 60 SiPMs of the plane. This is the reason why 4 channels have a very low RMS value.

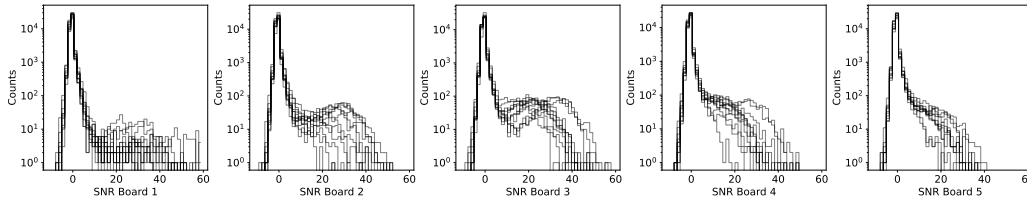


FIGURE 5.6: Signal to Noise Ratios of all the bars of the X3 plane. The SNRs are superimposed and grouped in five plots of 12 spectra each as the five SiPM boards of the plane under test.

maximum of the y projection of the 2D hits distribution) and the length as the nominal bar length (96 cm). An example of a region of interest of three bars of the Y4 plane is shown in Figure 5.8.

The efficiency was calculated as the ratio between the number of the hits in the bar fiducial area on the bars plane corresponding to the events with a SNR above threshold and the total number of hits in this fiducial area. The efficiency was computed for every bar and for the four planes under test using three different SNR thresholds: 2, 4 and 6. The result is shown in Figure 5.9.

ROC method for the best threshold evaluation

For a correct estimate of the efficiency of every bar and, in particular, the efficiency of the whole plane under test (that will be presented in the following sections), it is important to set the right threshold on the SNR. This can be

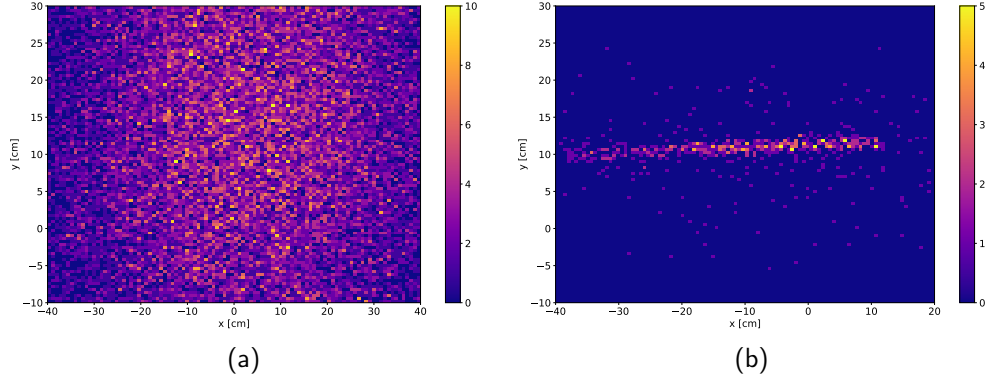


FIGURE 5.7: (a) 2D hit position distribution on the Y3 bars plane; (b) 2D hit position distribution on the Y3 bars plane with a SNR threshold = 3 for bar 31. The shape of the bar is clearly visible.

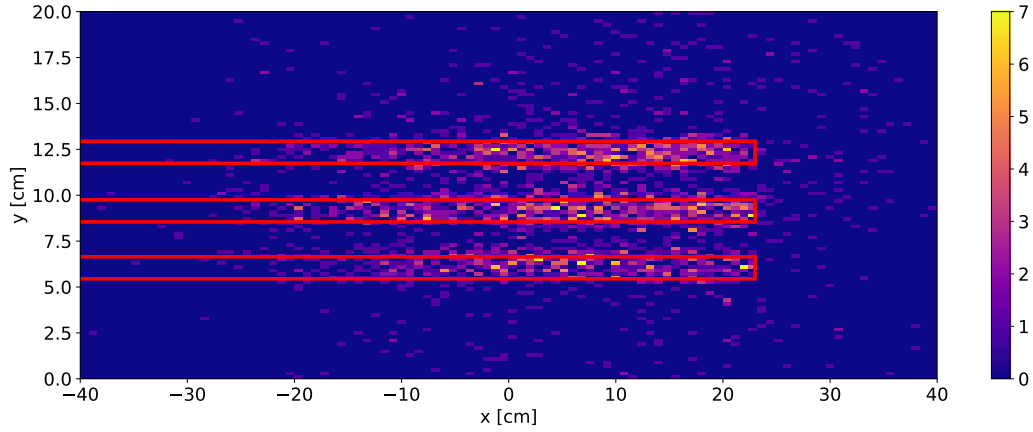


FIGURE 5.8: Regions of interest for 3 bars (23, 25 and 27) of the Y4 plane.

done by computing the True Positives Rate (TPR) and the False Positives Rate (FPR) of the events detected by the bars in the efficiency measurements. In fact, if the threshold is too low, the efficiency of the bars (TPR) assumes a high value, because several noise events are counted in the efficiency calculation, while if the threshold is too high, the efficiency is under-estimated, because some physics events are not considered. The FPR was computed as the ratio between the number of events with a SNR above the given threshold and a hit position outside the fiducial area, and the total number of events with a hit position outside the fiducial area of a given bar. This calculation was done for different SNR threshold values and the results for the TPR and FPR are shown in Figure 5.10.

From the TPR and FPR computation, the ROC (Receiver Operating Char-

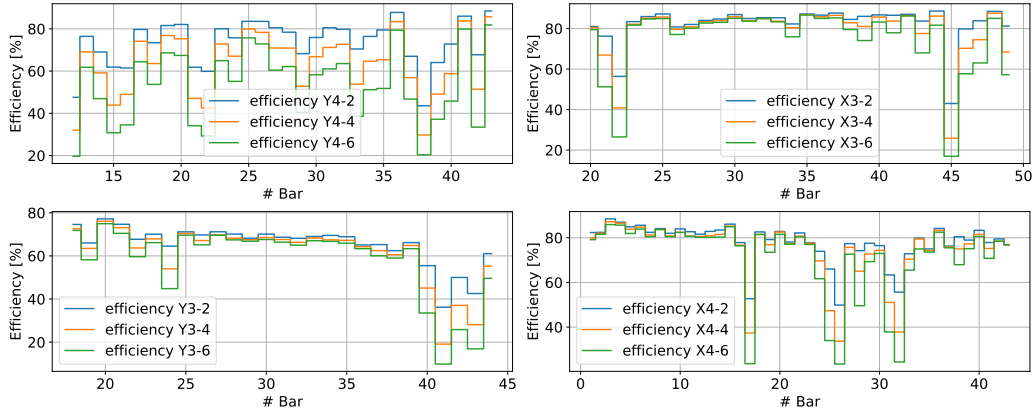


FIGURE 5.9: Efficiency of the 4 planes under test computed with 3 different threshold values (SNR 2,4 and 6).

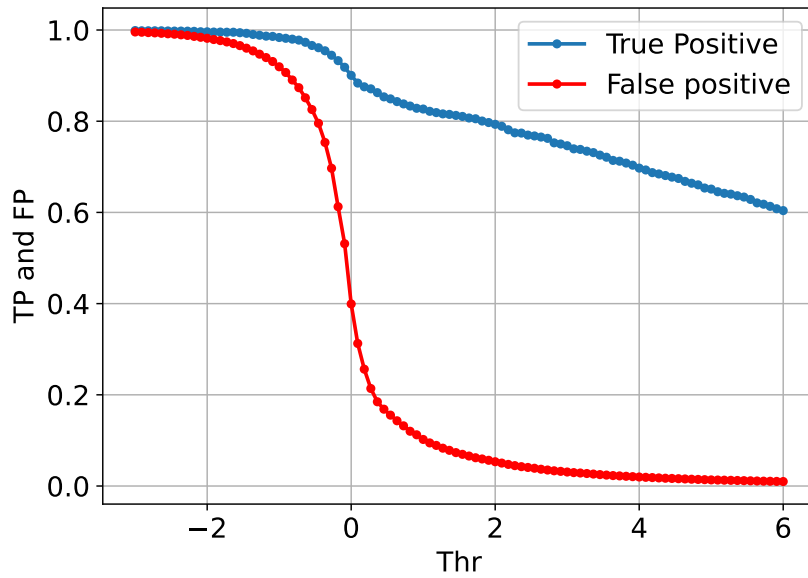


FIGURE 5.10: True Positives Rate and False Positives Rate as a function of the SNR threshold for the Y4 plane.

acteristic) curve² was built, plotting the True Positives Rate as a function of the False Negatives Rate. This curve (shown in Figure 5.11a for the Y4 plane) describes the capability of the analysis to discriminate the crossing of a particle from the noise generated events for a given SNR threshold. Moreover, it is possible to extract the best threshold for the analysis itself by computing the

²https://en.wikipedia.org/wiki/Receiver_operating_characteristic

TABLE 5.2: Best SNR threshold values for the tested planes.

Plane	Best SNR Threshold
Y4	1.7
X3	3.5
Y3	2.5
X4	3.1

Youden J statistics (or Youden index J) [120]. The J index is the distance between the ROC curve and the bisector of the TPR/FPR plane and is defined as $J = TPR - FPR$. The J index as a function of the SNR threshold for the Y4 plane is shown in Figure 5.11b. This plot allows to extract the best threshold, that is the one for which the J index is maximum. The ROC analysis was performed for all the tested planes (their ROC curves are shown in Figure 5.12) and the best thresholds are reported in Table 5.2.

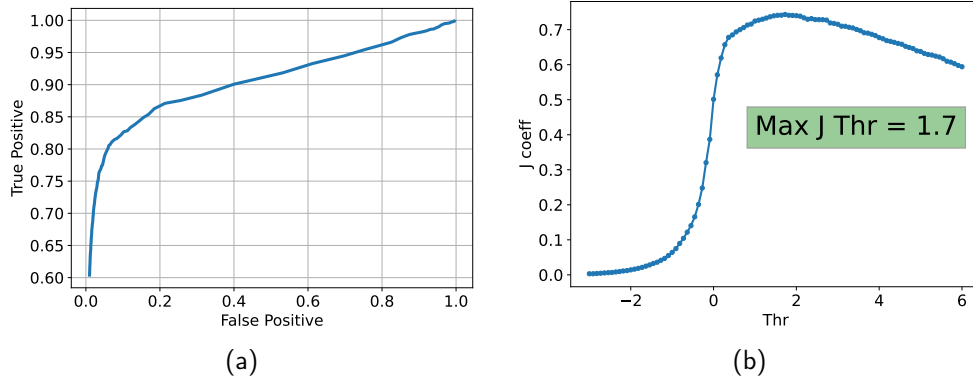


FIGURE 5.11: (a) ROC curve of the Y4 plane calculated for different SNR threshold values; (b) J index for the Y4 plane as a function of the SNR threshold. The threshold for which J is maximum is indicated.

Efficiency maximization

Due to technical reasons, the distances between the silicon detectors and the planes under test could not be measured precisely. This could have affected the estimate of the efficiency in the previous described analysis. For this reason, given the SNR thresholds found with the ROC method, the efficiency was re-computed for different silicon detectors-plane distances. Since the efficiency of some bars in a plane can be much smaller than the average efficiency of the

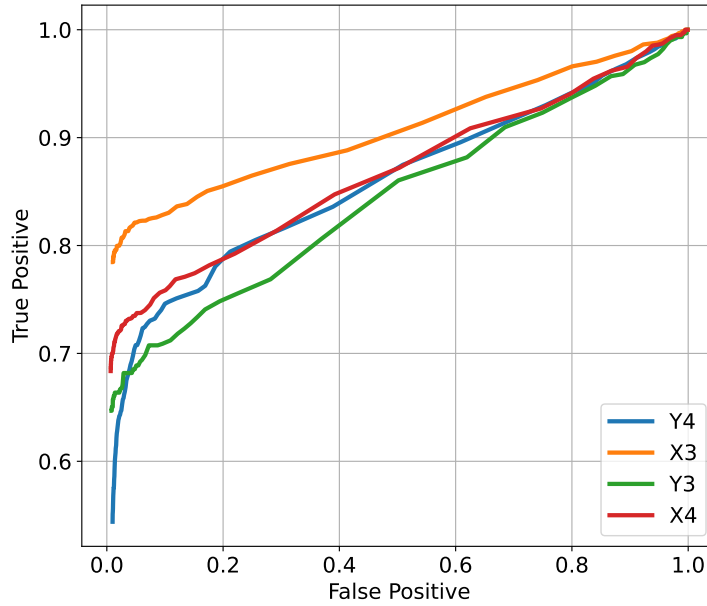


FIGURE 5.12: ROC curves of all the tested planes.

majority of the bars (as can be seen in Figure 5.9), the median of the efficiency for every plane was calculated and plotted as a function of the distances between the silicon detectors and the planes. A fit with a 2 degree polynomial function was performed to find the distance that maximizes the efficiency. An example of the median efficiency as a function of the distances for the X3 plane is shown in Figure 5.13.

The efficiency of every plane was then re-calculated with the correct distance and is shown in Figure 5.14. The bars in the four planes feature an efficiency in the $[70, 90]\%$ range and, apart from the Y4 plane, the efficiency can be considered quite uniform along the plane axis, except for a few bars that present a very low efficiency value, due to a bad fiber-SiPM coupling.

The plane average efficiency

The efficiencies found in the previous section have been calculated for every bar in the 4 planes independently. The efficiency of a single whole plane may be larger than the one computed as the median of the single bars efficiencies. This can happen because the cosmic rays with a large incoming angle with respect to the vertical axis can cross more than one bar, so the bar with a signal above the threshold may be not the one in which the hit position was reconstructed. In the analysis presented above, it was not possible to set an angular range, like the one used in Section 4.1, due to the poor statistics, so even the tracks with

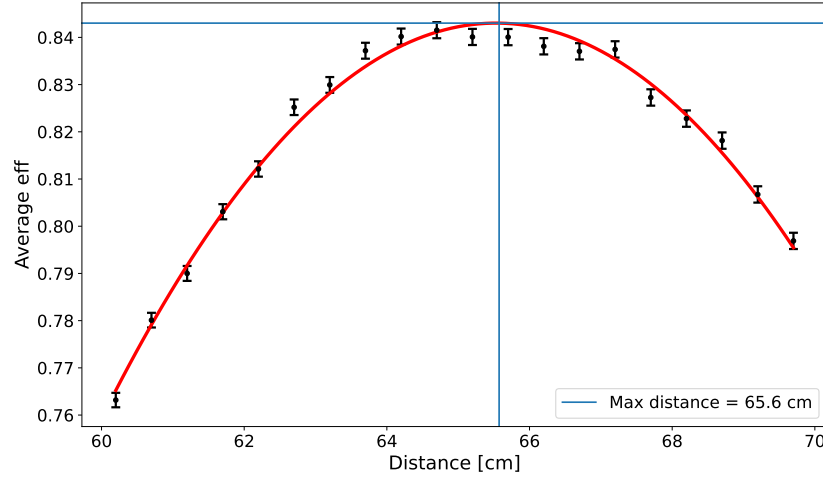


FIGURE 5.13: The median efficiency of the X3 plane as a function of the silicon detectors-plane distances. The red line is the 2 degree polynomial fit used to find the distance for which the median efficiency is maximum.

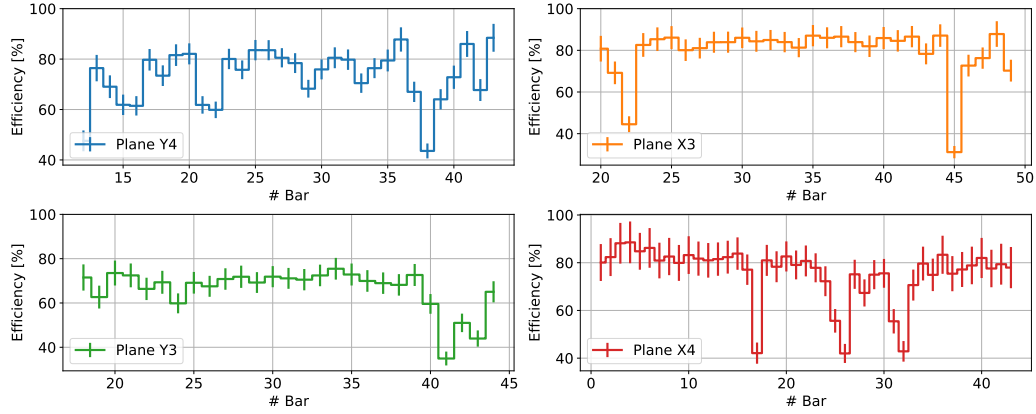


FIGURE 5.14: The efficiency of the 4 planes under test computed with the best thresholds and after the efficiency maximization.

large angles were considered.

The efficiency was then re-computed taking into account the two bars close to the one being considered. In particular, an event was considered in the efficiency calculation if it had a track inside the fiducial area of the i^{th} bar and if the corresponding signal was above the threshold in this bar or in the $(i \pm 1)^{th}$ bar, where the "or" has to be considered as exclusive (XOR). The results for the 4 planes are shown in Figure 5.15, together with the efficiencies computed before. Note that the black lines do not represent the efficiency bar by bar, but they have

to be interpreted as an average-like efficiency computed on three subsequent bars.

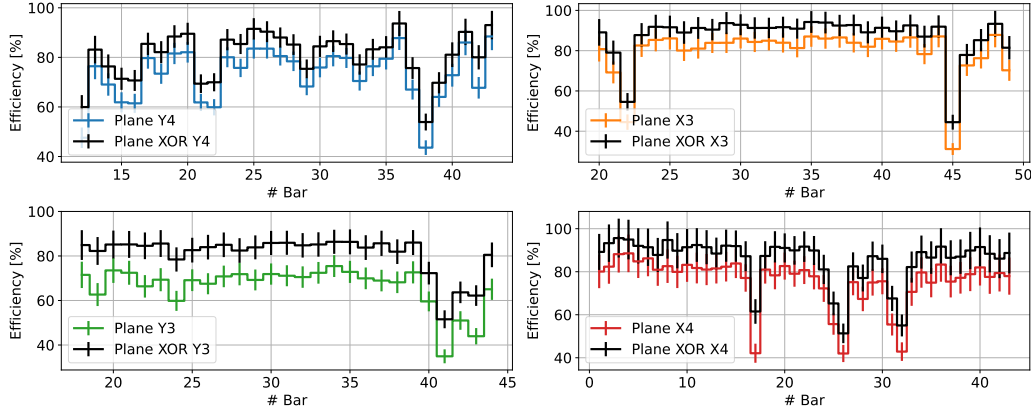


FIGURE 5.15: The efficiency of the 4 planes under test computed taking into account the two closest bars to the one considered for the efficiency calculation. The colored lines are the efficiencies calculated for all the bars considered independently. Note that the black lines represent an average-like efficiency computed on three subsequent bars.

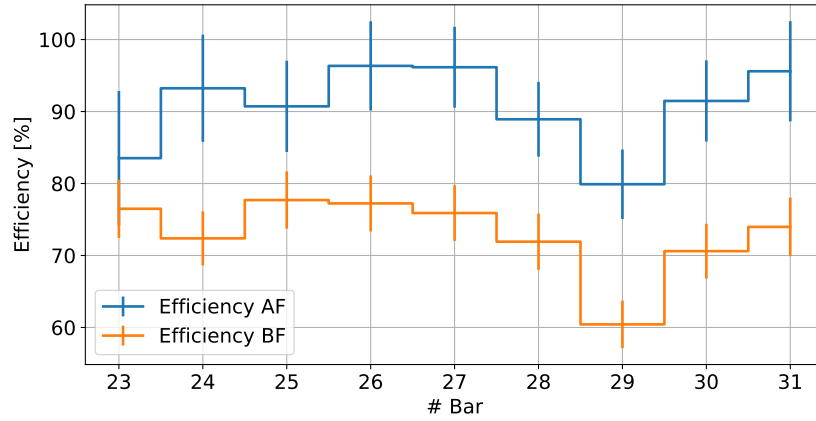
The median value of the efficiency is a good estimate of the global efficiency of the single whole plane. In Table 5.3 all the median efficiencies for the four planes are reported. The X3, Y3 and X4 planes present a good efficiency with median values between 84% and 91% and, as said before, a good uniformity along the plane axis. On the other hand, the slightly worse and non-uniform efficiency of the Y4 plane is due to an improper fiber-SiPM coupling along the whole plane. Once this plane was opened after the efficiency measurement data taking, it turned out that several SiPM boards were not in the right position and have been moved out by the pressure of the WLS fibers against the socket couplers. The mechanical support was then reinforced and the optical coupling checked and corrected where necessary. The comparison between the efficiencies of the bars from the 23rd to the 31st before (BF) and after (AF) the fixing is shown in Figure 5.16, where a very clear improvement is visible.

5.2 The spatial resolution

The spatial resolution estimates the capability of the DANTE detector to track precisely the hit positions of the detected particles. The spatial resolution measurement requires the precise reconstruction of these positions, in order to compare them with the ones detected by a more precise detector, like the silicon tracker one (spatial resolution 60 μm). The setup used for the spatial resolution

TABLE 5.3: Median efficiency for the four tested planes.

Plane	Median Efficiency
Y4	$(83.7 \pm 0.6)\%$
X3	$(91.3 \pm 1.0)\%$
Y3	$(84.6 \pm 1.1)\%$
X4	$(89.1 \pm 1.2)\%$

FIGURE 5.16: The efficiency of the Y4 plane bars from the 23rd to the 31st before (BF) and after (AF) the fixing of the mechanics and the coupling.

measurement is similar to the one presented in Section 5.1.1, but with the trigger scintillators and the BARCA detectors placed above the four DANTE planes, as shown in Figure 5.17. This setup was chosen to minimize the error on the projection on the bars planes of the hit positions detected by the silicon detectors, by reducing the distance between the BARCA detectors and the DANTE planes.

The hit position reconstruction

The reconstruction of the hit positions detected by the DANTE planes needs a cluster identification algorithm. A cluster is a group of one or more contiguous bars in which one single particle deposits energy and thus they have a SNR above threshold. In a single event, more than one cluster and more than one bar per cluster can be found in the considered plane, as shown in Figure 5.18. The developed cluster identifier algorithm for every plane proceeds as follows:

- for every event in the run, the number of the bars of a plane with a signal above the set threshold is saved, together with their SNR;

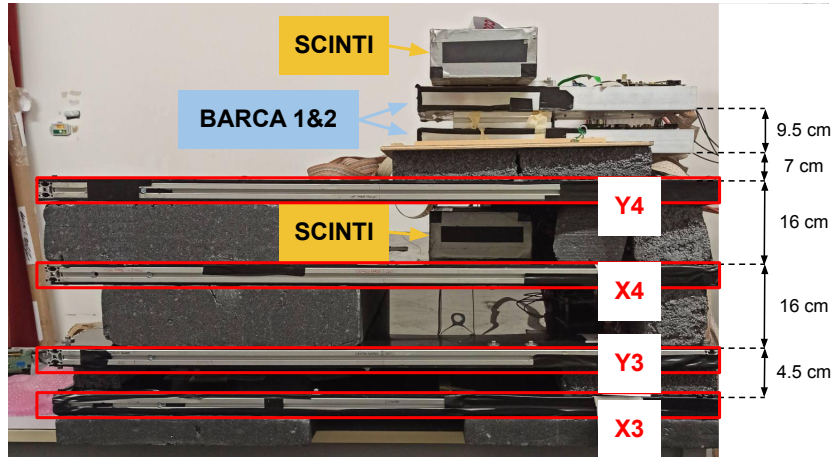


FIGURE 5.17: The experimental setup used to measure the spatial resolution of the DANTE planes. The distances in cm are shown.

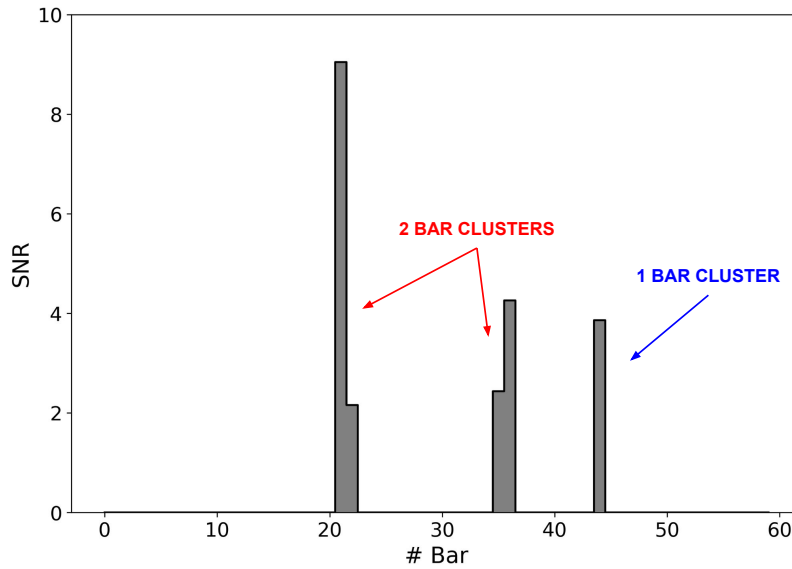


FIGURE 5.18: Example of an event in the Y4 plane. The SNR of the bars above threshold is plotted: three clusters are visible.

- if the difference between subsequent bar numbers is larger than 1, the bars are considered to belong to different clusters; if this difference is equal to 1, the two subsequent bars belong to the same cluster and the algorithm groups them labeling the found cluster for the analysis;
- the number of bars per cluster and the number of cluster per event are saved.

The positions of the clusters for every event are expressed as bar numbers; to compare them to the projections of the tracks detected by the silicon detectors, they are converted in cm (where 0 cm corresponds to the position of bar 0). For each cluster, the hit position in cm is defined as the center of gravity of the deposited signal in the bars of the cluster, as follows:

$$x \text{ [cm]} = \frac{\sum_i^{N_{Bars}} BarNumber_i \cdot SNR_i \cdot BarPitch}{\sum_i^{N_{Bars}} SNR_i} \quad (5.4)$$

where N_{Bars} is the number of bars in the cluster, $BarNumber_i$ is the number of the i^{th} bar in the cluster of the DANTE plane, SNR_i is the signal to noise ratio of the i^{th} bar in the cluster and $BarPitch$ is the bar width along the plane axis (i.e. 1.5 cm).

The resulting hit position profiles of the four planes under test and the distributions of the number of clusters and the number of bars per cluster are shown in Figure 5.19. It is possible to observe that the number of clusters and the number of bars per cluster are both peaked around 1, except for the number of clusters in the Y4 plane. This means that the threshold for the discrimination between physics and noise events may be too low, so for several triggered events the algorithm has detected more than one single cluster, because the noise has "turned on" bars not crossed by a particle. The low number of bars per cluster can be explained taking into account that the probability that the noise triggers contiguous bars in a single event is small. The prevalence of single bar clusters means that the detected particles have a small angular distribution, making them cross mostly one single bar per plane. This can be explained by considering the trigger geometry used in this measurement setup: the two trigger scintillators operating in coincidence were put far from each other, to define a small solid angle with respect to the track of the incident cosmic rays.

The spatial resolution minimization

The spatial resolution for every plane was computed using the residual technique. This method compares the projection of the tracks detected by the silicon detectors on the bars plane and the position computed with the hit position reconstruction described in the previous section.

The analysis was the following:

- the single cluster events were selected and the corresponding positions detected by the silicon detectors and by the planes of the DANTE detector were saved;
- with a projection technique like the one used in Section 4.1, the tracks detected by the BARCA detectors were reconstructed on the bars plane;

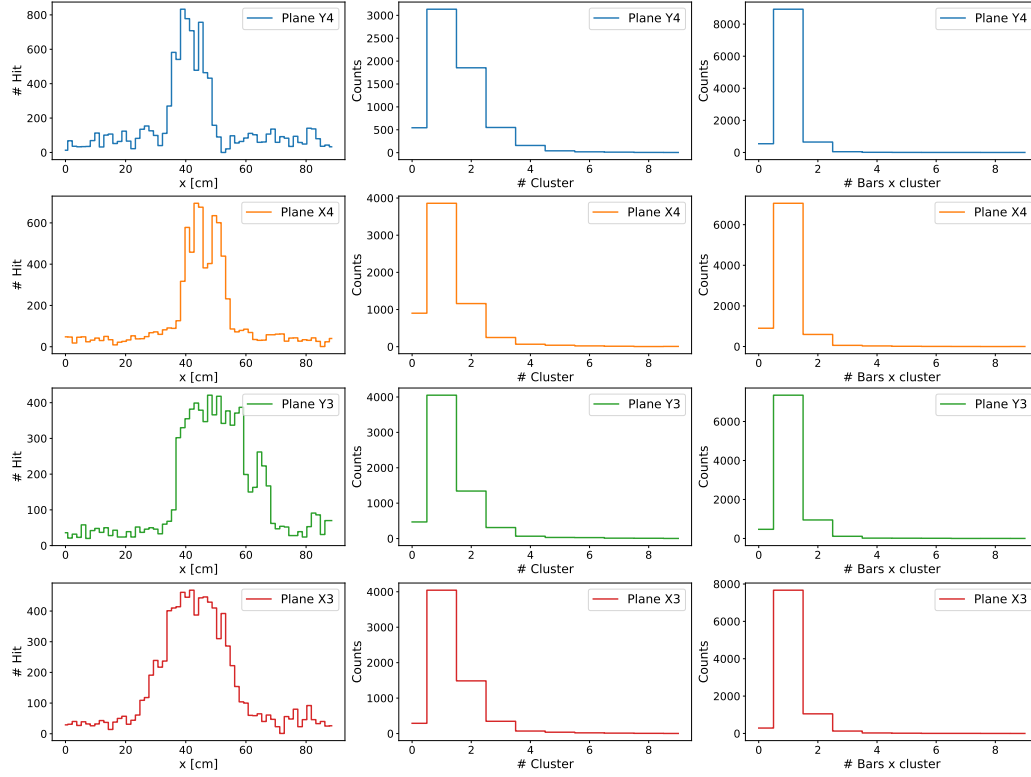


FIGURE 5.19: The results of the hit position reconstruction for the four planes under test. The hit profile with the positions in cm, the number of clusters and the number of bars per cluster are shown for every plane.

- the residuals were computed as the difference between the reconstructed positions and the ones detected by the DANTE planes;
- for each DANTE plane, the distribution of the residuals was fitted by a gaussian function to estimate its sigma;
- the spatial resolution of each plane was defined as the sigma of the gaussian fit.

Since the distance between the silicon detectors and the bars planes, used in the projection of the tracks, could not be measured precisely, the spatial resolution was re-computed for different distances and plotted as a function of the correction on the original measured distance. As can be seen in Figure 5.20, the curve presents a minimum and the spatial resolution of the considered plane was computed by fitting the data with a 2 degree polynomial function and taking its minimum. The corrections on the distances for each plane to minimize the

spatial resolution were of the order of ~ 2 cm. This value can be explained considering that the distances between the silicon detectors and the bars planes were measured from the silicon layers to the top surface of each DANTE plane. However, the bars lay some cm below the top plane cover and the spatial resolution minimization allowed to measure their vertical position precisely.

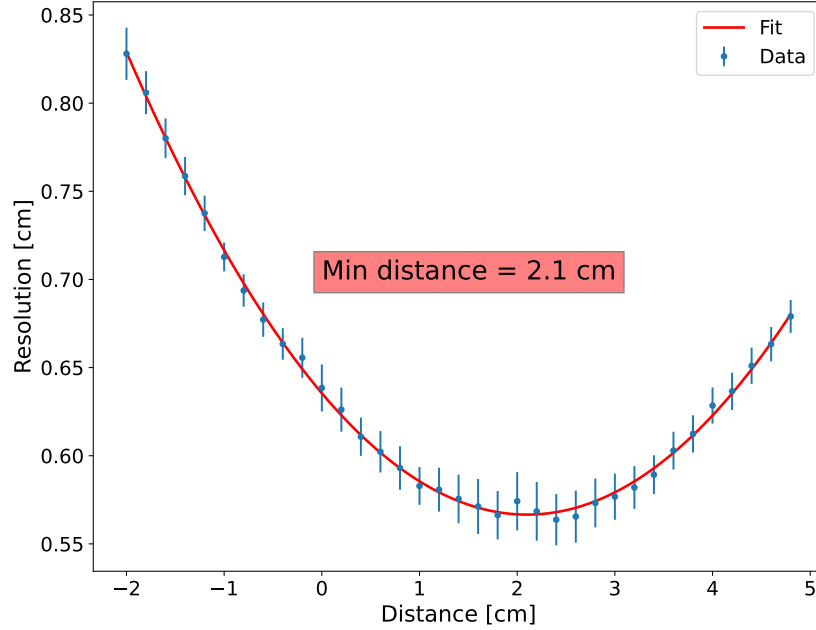


FIGURE 5.20: The spatial resolution minimization method. The spatial resolution as a function of the correction on the distance between the silicon detectors and the bars plane for the Y4 DANTE plane. In red, the 2 degree polynomial fit used to compute the distance correction corresponding to the minimum spatial resolution.

In figure 5.21 the distributions of the residuals for every plane under test are presented, together with the gaussian fit for the spatial resolution estimate.

The spatial resolutions computed for each plane are summarized in Table 5.4.

5.3 The cosmic rays self-trigger data taking

The last part of this thesis work is about the study of the behaviour of the DANTE planes in self-trigger mode. The experimental setup used for the data taking was the same as the one of Section 5.2, except for the trigger scintillators. In fact, the trigger was generated as follows:

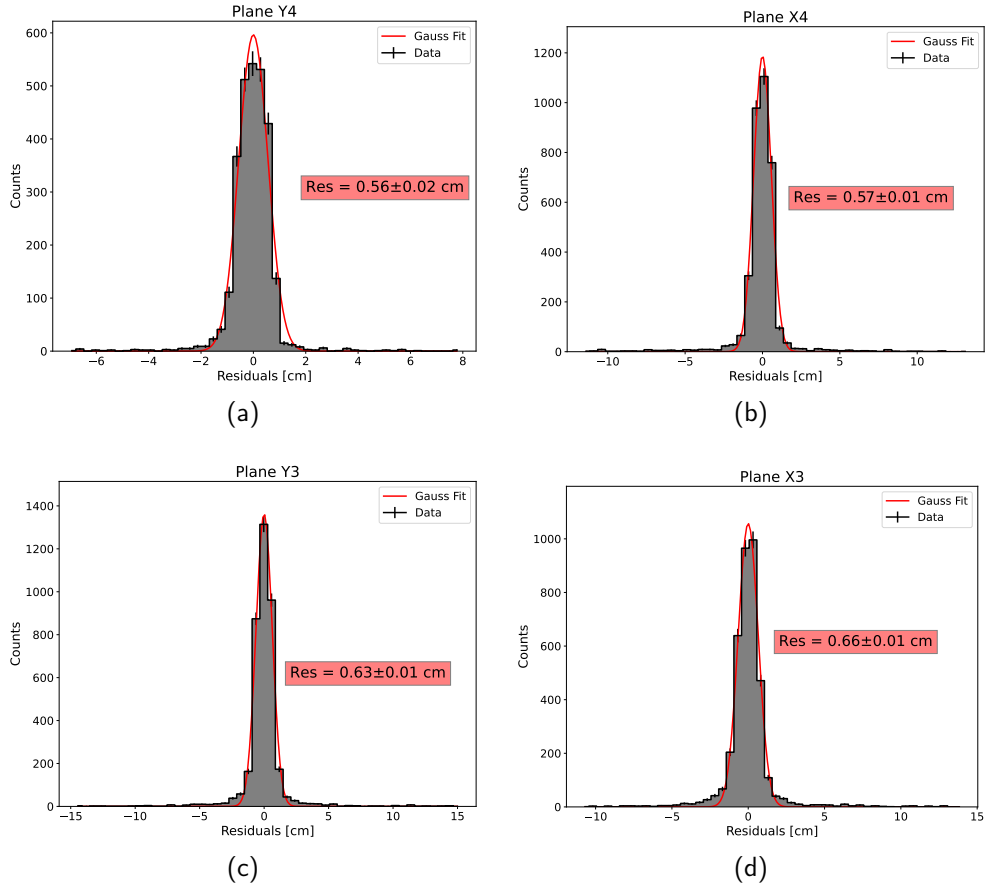


FIGURE 5.21: The residual distributions of the four tested planes. In red, the gaussian fit to estimate the spatial resolution of the planes.

- the threshold of the MAROC3 fast discriminator was set at 600 DAC for the Y4 and X3 MAROC3 boards (i.e the MAROC3 boards of the two planes chosen for the trigger);
- the OR of the 60 connected channels for each chosen plane has been computed by the FPGAs on the two MAROC3 boards and sent to the VCB board;
- the VCB computed the AND of the two OR signals and used it as the trigger signal.

This trigger logic allowed to acquire the events for which one or more particles crossed the bars of the top and the bottom planes in the setup. The silicon detectors above the planes were used to control the efficiency in the self-trigger

TABLE 5.4: Spatial resolution for the four tested planes.

Plane	Spatial Resolution
Y4	(0.56 ± 0.02) cm
X4	(0.57 ± 0.01) cm
Y3	(0.63 ± 0.01) cm
X3	(0.69 ± 0.01) cm

mode. In Figure 5.22 the PHs of the four planes are shown. In Figure 5.23 two PH spectra of channel 31 of the two triggering planes are shown. It is possible to observe the effect of the threshold: when the considered channel does not trigger, the acquisition saves the signals corresponding to a not-hit channel, i.e. the pedestal; when the considered channel has triggered, the saved signal has to be above threshold, so in the PH spectrum a peak appears. This spectrum is useful to check if the set MAROC3 discrimination threshold has been chosen in the correct way. In this case, as indicated in Figure 5.23, the threshold was set correctly in the middle between the pedestal PHs and the MIP peak, so it is possible to conclude that the threshold was chosen appropriately. Note that in the Y4 plane PH spectrum (Figure 5.23) the MIP peak cannot be clearly discriminated from the pedestal, but it stays in the long tail at large PHs.

In Figure 5.24, the hit profiles of the four modules are shown. These profiles are clearly not uniform: this can be explained taking into account that the trigger was made using the Y4 plane before the fixing of the fiber-SiPM coupling. The non-uniformities in the efficiency of this plane, shown and discussed in Section 5.1.2, affected the ability of the plane itself to trigger properly with all its bars.

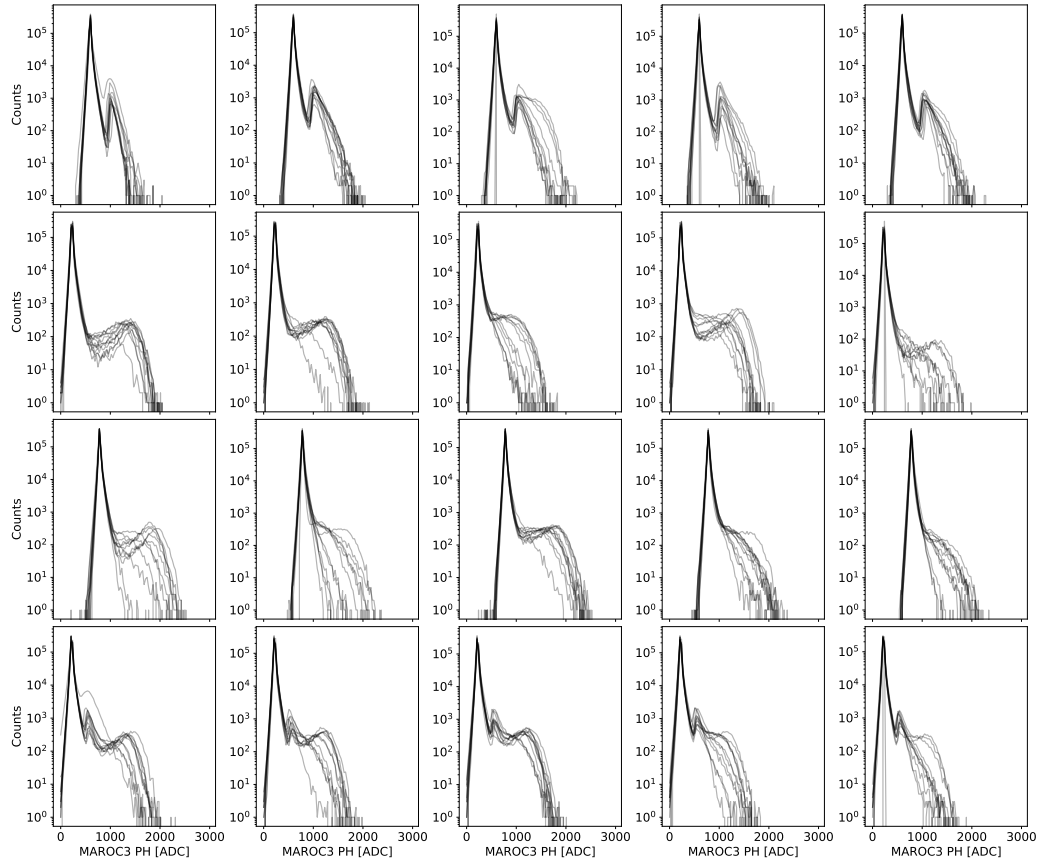


FIGURE 5.22: Pulse Height spectra of all the channels of the X3, Y3, X4, Y4 planes in self-trigger mode. The spectra are superimposed and grouped in five plots of 12 spectra each as the five SiPM boards of each plane under test

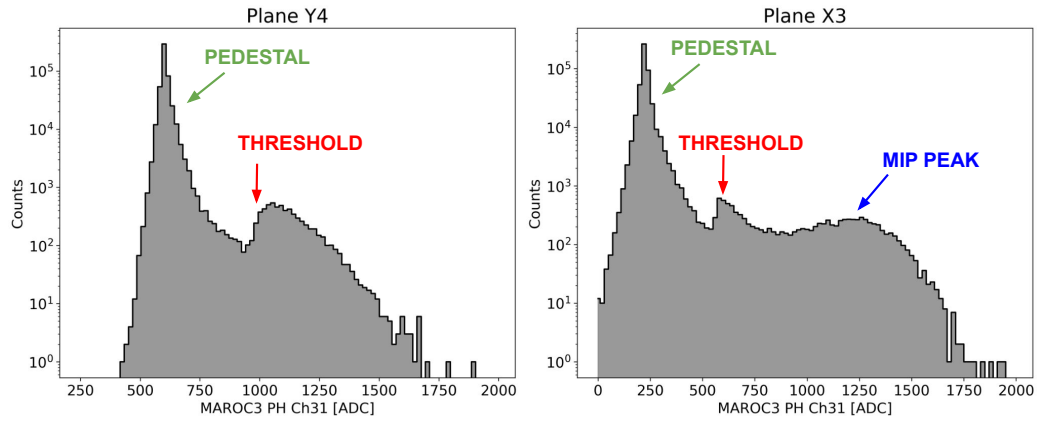


FIGURE 5.23: Pulse Height spectra of channel 31 of the X3 and Y4 planes in self-trigger mode. Note that in the Y4 one the MIP peak cannot be clearly discriminated from the pedestal, but it stays in the long tail at large PH.

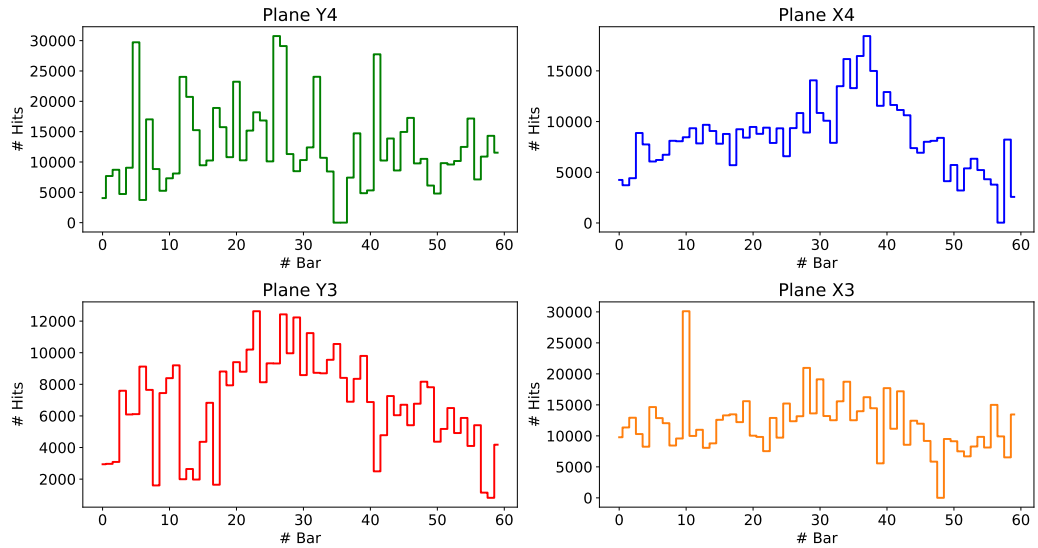


FIGURE 5.24: The hit profiles of the X3, Y3, X4, Y4 planes in self-trigger mode.

Conclusions

In this thesis work the upgrade of the ASACUSA scintillating bars tracker was presented, from the preliminary tests of the components, to the construction and the commissioning in the INSULAB laboratory with cosmic rays.

The detector, whose first version was built in 2008, was developed in the framework of the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration, based at the AD/ELENA facility at CERN. Among its experimental goals, the production of cold antihydrogen plays an important role for the study of the matter-antimatter asymmetry, via the anti-atoms hyperfine spectroscopy. The antihydrogen synthesis is a difficult task in terms of the experimental beamline: ASACUSA has developed a new model of particle trap, called cusp trap, that allows to mix slow positrons and antiprotons and produce an antihydrogen beam adequate for high precision spectroscopy measurements. The behaviour of positrons and antiprotons inside the trap can be monitored detecting the annihilation products of the interaction between the trapped antiprotons and the trap walls. In particular, it is important to track the exiting pions to reconstruct the annihilation region, so a position sensitive detector is needed.

The first versions of the detector, now called DANTE (Detector for ANnihilation Tracking Experiment), consisted of several planes of extruded scintillating bars, made of Polystyrene Dow Styron 663 W + 1% PPO + 0.03% POPOP, with a section of $1.5 \times 1.9 \text{ cm}^2$ and a length of 96 cm. The scintillating light was collected and transported by 1 mm diameter WLS (WaveLength Shifter) fibers to 64 channels Hamamatsu MAPMTs (Multi Anode PhotoMultiplier Tubes). Due to mechanical problems and difficulties in the fibers-MAPMT coupling, an upgrade of the light readout system and the bars supporting mechanics was decided. This upgrade has focused on the substitution of the MAPMTs with 1 mm^2 ASD RGB1s-P SiPMs, the design of the new SiPM front-end electronics and the new fiber coupling mechanics.

The upgrade started in the first part of 2021 with the preliminary tests on the single components of the new version of the detector and continued in the second part of the year with the assembly and the tests with cosmic rays of the first four complete planes, made of 60 scintillating bars readout by 60 SiPMs

each. In the first months of 2022, other 4 planes were assembled to complete the detector, that will be commissioned in the ASACUSA experimental area in April 2022.

The preliminary tests were dedicated to the measurement of the light yield of a bar as a function of the particle hit position on the bar itself, the characterization of the SiPMs front-end boards and of the SiPMs noise and the measurement of the number of photoelectrons corresponding to a MIP signal inside the bar. In particular, the MIP signal decreases of about 30%-40% along the bar length in the farthest position from the SiPM. This was attributed to the non-uniformity of the glue distribution inside the bar (used to couple and keep in position the WLS fiber) and to the light attenuation along the fiber. However, the results show that the Signal to Noise Ratio (SNR) does not change considerably, so, taking also into account the increase in the number of channels and the cost, a readout on both sides of the bar was not considered to solve the light attenuation problem.

The I-V curve measurements and the dark counts analysis of the SiPMs allowed to decide the proper bias voltage to be applied to the photodetectors. The chosen bias voltage was 31 V, for which the SiPMs are characterized by a DCR (Dark Count Rate) of ~ 260 kHz (in agreement with the one reported in the SiPM datasheet) and an OCT (Optical Cross Talk) probability of $\sim 32\%$. The measured number of photoelectrons corresponding to the signal of a MIP in the scintillating bar was found to be 16 ± 1 .

The commissioning tests of four planes of the DANTE detector allowed to measure the efficiency of every bar of each plane. The best efficiency measurement was obtained using the ROC (Receiver Operating Characteristic) method to choose the best threshold on the SNR to discriminate the signal from the noise for each bar. The median of the bars efficiencies was found to be in the 70%-80% range. This test was also helpful to identify the channels with a poor efficiency, mainly due to their bad fiber-SiPM coupling, for which dedicated interventions are planned. The efficiency of the plane was computed considering also the two closest bars to the expected one and evaluating the median of the efficiencies of all the bars in a plane. The efficiencies for the four planes have been found in the 84%-92% range.

The spatial resolution for each plane was estimated implementing a cluster reconstruction algorithm, to compute the hit position in cm of the cosmic rays detected by the planes, and a minimization procedure of the residuals (defined as the difference between the positions reconstructed by the silicon detectors and the ones computed with the DANTE detector). The spatial resolution of each plane has been measured in the range from ~ 0.56 cm to ~ 0.69 cm, that is comparable to the theoretical value of 0.43 cm.

In the next future, the planes are planned to be equipped with a mechanic

structure that allows to keep them in the vertical position to be placed around the cusp trap in the ASACUSA experimental area. Before the installation at CERN in April 2022, some interventions to fix and improve the coupling problems will be performed.

List of acronyms

AA	Antiproton Accumulator
AC	Antiproton Collector
AD	Antiproton Decelerator
ADC	Analog to Digital Converter
AEgIS	Antihydrogen Experiment gravity Interferometry Spectroscopy
AGS	Alternating Gradient Synchrotron
ALPHA	Antihydrogen Laser PHysics Apparatus
AMT	ASACUSA Micromegas Tracker
APD	Avalanche PhotoDiode
ASACUSA	Atomic Spectroscopy And Collisions Using Slow Antiprotons
ASIC	Application-Specific Integrated Circuit
ASTERIX	Antiproton STop ExpeRiment on Initial X-rays
ATHENA	ApparaTus for High precision Experiment on Neutral Antimatter
ATRAP	Antihydrogen TRAP
BASE	Baryon Antibaryon Symmetry Experiment
BC	Beam Chamber
CERN	Organisation Europeenne pour la Recherche Nucleaire
CMS RMS	Common Mode Subtracted RMS
DANTE	Detector for ANnihilation Tracking Experiment
DAQ	Data AcQuisition
DCR	Dark Count Rate
ELENA	Extra Low ENergy Antiproton
FBK	Fondazione Bruno Kessler
FEB	Front-End Board
FI	Field Ionizer
FIT	Field-Ionization Trap
FNAL	Fermi National Accelerator Laboratory
FPR	False Positives Rate
FPGA	Field Programmable Gate Array
GBAR	Gravitational Behaviour of Anti-Hydrogen at Rest

HfS	Hyperfine Splitting
HFS	High-Field Seeker
ICE	Initial Cooling Experiment
ISOLDE	Isotope mass Separator On-Line facility
ISR	Intersecting Storage Rings
LEAR	Low Energy Antiproton Ring
LEP	Large Electron-Positron collider
LFS	Low-Field Seeker
LHC	Large Hadron Collider
LS2	Long Shutdown 2
MAPMT	MultiAnode PhotoMultipliers Tube
MAROC	Multi Anode ReadOut Chip
MCP	Multi Channel Plate
MIP	Minimum Ionizing Particle
MRT	Multi-Ring electrode Trap
MUSASHI	Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigations
MWPC	Multi Wire Proportional Chamber
OCT	Optical Cross-Talk
OV	Over Voltage
PAW	Physics Analysis Workstation
PDE	Photon Detection Efficiency
PH	Pulse Height
PMT	PhotoMultiplier Tube
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
PUMA	antiProton Unstable Matter Annihilation
QE	Quantum Efficiency
RF	Radio Frequency
RFQD	Radio Frequency Quadrupole Decelerator
RMS	Root Mean Square
SiPM	Silicon PhotoMultiplier
SME	Standard Model Extension
SNR	Signal to Noise Ratio
SppS	Super antiproton proton Synchrotron
SPS	Super Proton Synchrotron
SPTR	Single Photon Time Resolution
TPC	Time Projection Chamber
TOF	Time Of Flight
TPR	True Positives Rate
VCB	VME Cyclone Board

VME	Versa Module Eurocard
WEP	Weak Equivalence Principle
WLS	WaveLength Shifter

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