The Anticoincidence Shield of the PAMELA Satellite Experiment

SILVIO ORSI

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Silvio Orsi

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Cover illustration: detail of an anticounter scintillator during assembly in the laboratory. The LED glued to the scintillator and the micro-coaxial signal cable are visible on the right.

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Abstract

The PAMELA space experiment is scheduled for launch towards the end of 2004 on-board a Russian Resurs DK1 satellite, orbiting Earth at an altitude of 300–600 km. The main scientific goal is a study of the antimatter component of the cosmic radiation. The semipolar orbit ($70.4^\circ$) allows PAMELA to investigate a wide range of energies for antiprotons (80 MeV–190 GeV) and positrons (50 MeV–270 GeV). Three years of data taking will provide unprecedented statistics in this energy range and will set the upper limit for the ratio $\bar{\text{He}}/\text{He}$ below $10^{-7}$. PAMELA is built around a permanent magnet silicon spectrometer, surrounded by a plastic scintillator anticoincidence shield built at KTH. The anticounter scintillators are used to aid in the rejection of background from particles not cleanly entering the acceptance of the tracker. Information from the anticounter system will be included as a veto in a second level trigger, to exclude the acquisition of events generated by false triggers.

An LED-based monitoring system has been developed for the anticounter system. The LEDs mimic the light signal produced in the scintillator by an ionising particle. This allows the functionality of the AC system to be verified in-orbit. The development and testing of the monitoring system are presented and comparisons have been made with independent radioactive source-based calibration methods. The anticounter system has also been extensively tested with cosmic rays and particle beams. Most of these tests have been performed with the anticounters integrated with the other PAMELA subdetectors in a flight-like configuration.

Key words: astrophysics, particle physics, antimatter, organic scintillators.
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Appendix A Acronyms

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Trying is the first step towards failure.

Homer Simpson

All causes shall give way: I am in blood
Stepp’d in so far, that, should I wade no more,
Returning were as tedious as go o’er.
Strange things I have in head, that will come to hand,
Which must be acted, ere they may be scann’d.

Macbeth, Act III, Scene IV
Introduction

Outline of the Thesis

This thesis describes the anticoincidence shield of the PAMELA experiment, with emphasis especially on the design of a LED based monitoring system. The performance of the overall anticounter system has been tested in the laboratory and with beam particles. Analysis of recent beam test data are presented and compared to previous results.

Chapter 1 provides an overview of cosmic rays, from production in space to detection on Earth. A description of their composition and propagation is given, with particular focus on the antimatter component and possible signatures arising from the annihilation of heavy supersymmetric particles in the antimatter spectra. The content of the chapter summarises part of the references [1, 2, 3].

The PAMELA experiment, the scientific objectives and the payload configuration are described in chapter 2 [4, 5]. The construction and purpose of all the subdetectors is illustrated. The data acquisition system is briefly described, followed by the environmental conditions (thermal, radiation and mechanical), which are needed to describe the qualification tests.

Chapter 3 presents a description of the anticoincidence system. The detector properties are illustrated together with the performance of the read out system. Qualification tests of single components (LEDs and ADCs) are presented.

Chapter 4 contains a detailed description of the LED based monitoring system. The design and the realisation are illustrated. Radiation sources are used to calibrate the detectors and to interpret the LED results. A comparison with measurements obtained with cosmic muons is consistent with the results obtained with the sources. The AC calibration procedure is described.

Chapter 5 contains an analysis of test beam data (CERN, September 2003). This is a standalone analysis of the anticoincidence data, with focus on the performance of the AC electronics and detectors. Backscattering studies are also presented, with comparisons to previous beam test data (October 2001). A discussion on the second level trigger is presented, introducing for the first time all AC detectors in the analysis.

Finally, chapter 6 contains conclusions and the outlook for future work.
The Author’s Contribution

When I joined the group of Particle and Astroparticle Physics at the Royal Institute of Technology in 2000, I was starting my diploma work at CERN on the ATLAS data acquisition system. Later, from September 2001, my doctoral studies have been mainly dedicated to the satellite based experiment PAMELA. My work on PAMELA includes hardware development, qualification tests and beam test data analysis.

During the first months of work I was involved mainly in the assembling of the flight model of the anticounter detectors and in preliminary efficiency measurements with cosmic rays. I took part in the design and review of the electronic read-out board. My work on the electronic data acquisition system included DSP programming (C and assembler) for the flight electronics and VHDL programming during the development phase of the read-out electronics.

My main involvement in the PAMELA project has been in the realisation of an LED based monitoring system to perform calibration in space (chapter 4). I have also performed qualification tests on electronic components for the read-out system. On three occasions between 2001 and 2003 I took actively part in beam tests at CERN. The analysis of data from the September 2003 beam test is described in chapter 5.

I have been several times in the INFN laboratories in Rome, for a total period of more than two months, for software studies, for testing the detectors, the electronics and to integrate the AC detectors in the final flight configuration.

The work presented here is partially described in the following publications, of which I am coauthor:


Besides PAMELA, during my doctoral studies I have been involved in a new project devoted to the study of cosmic showers in the atmosphere, SEASA (Stockholm Educational Air Shower Array, [6]). The aim of SEASA is to bring high school students closer to the world of astroparticle physics. This project is described in:

Chapter 1

Cosmic Rays

The study of cosmic rays allows processes covering the energy range \( \sim 10^6 \) eV up to \( \sim 10^{20} \) eV to be studied. This is an enormous advantage in comparison with accelerator-based particle physics, which provide much more accurate measurements, but currently reach energies ‘only’ up to \( \sim 10^{13} \) eV. The Large Hadron Collider (LHC) at CERN will collide protons at a centre of mass energy of 14 TeV, which, in the hot Big Bang scenario, corresponds to the conditions of the Universe a fraction of a second after the Big Bang. Until more powerful accelerators are available, information on earlier cosmological times (higher energies) have to come from astrophysical observations.

Astroparticle physics is a fertile field of research also in the energy range covered by accelerators. The search for antiprotons and positrons from neutralino decays is an example (section 1.4).

1.1 A Brief History of Cosmic Rays

Since its birth, astrophysics has always been closely related to particle physics. The discovery of new particles in the years around 1900 grew at a rate following closely the great improvements in the development of particle detectors. At the birth of particle physics (~ 1900) with the discovery of the electron, it was believed that the radiation measured on ground was emitted by the Earth’s surface. This view changed in 1912, when cosmic rays were discovered by the Austrian physicist Victor Hess through manned balloon ascents, making use of an electroscope. He showed that the intensity of ionising radiation was decreasing up to 1500 m from ground, but increasing continuously after that. Further measurements (Kolhörster, 1914) confirmed Hess’ data and increased the balloon flight range up to 9 km. It was only in 1926 that Millikan, at first skeptical of Hess’ work, used for the first time the expression ‘cosmic rays’. Millikan showed also that the atmosphere does not produce cosmic rays but acts only as a calorimeter. Primary cosmic rays interact
with atoms in the atmosphere and produce secondary particles, which may in turn interact with other atoms and give rise to a multitude of other particles (a ‘cosmic ray air shower’).

In 1929 the invention of the ‘Geiger-Müller’ detector enabled single cosmic rays to be detected. With Geiger-Müller detectors, Bothe and Kolhörster studied the atmospheric attenuation and concluded that the radiation is corpuscular (through coincidence measurements) and that these particles at sea level would have to be very energetic ($10^9$–$10^{10}$ eV) due to their long range observed. The observation of single particle tracks became possible in the 1930s, after the discovery of cloud chambers. In 1932 C. Anderson discovered the positron, predicted theoretically by P. Dirac in 1929. The positron and the muon, discovered in 1936, were the first in a series of subatomic particles discovered as a result of cosmic ray research. These discoveries gave birth to the science of elementary particle physics. In 1947 C. Powell and G. Occhialini observed Yukawa’s pion, and soon after the K meson was discovered, followed by several other particles ($\Lambda, \Sigma, \Xi$), all heavier than the nucleons. Improved measurements of particle masses and lifetimes made classification of the discovered particles possible, which was realised in the quark theory by M. Gell–Mann and G. Zweig in 1963. Particle physicists used cosmic rays for their research until the advent of particle accelerators, which, in the 1950s, took over the detailed investigations of elementary particles under much more controlled conditions.

The cosmic ray spectrum is today known with good precision (figure 1.1) up to $10^{19}$ eV. The differential energy spectrum can be represented by a power law function, with varying spectral index depending on the energy region. At low energies it is dominated by solar modulation (section 1.6). At higher energies, below $\sim 10^{15}$ eV (the “knee” of the spectrum), the spectral index is about $-2.7$, and drops to $-3$ for higher energies, until $\sim 5 \cdot 10^{18}$ eV (the “ankle”), where it becomes $-2.8$. While particles with energies below the “knee” can be directly measured with balloon flights or in space, observations of the highest part of the spectrum requires large ground-based detectors, as described in section 1.2, and provide an indirect measure of the primary particle.

### 1.2 Detecting Cosmic Rays

**In space**

The primary component of cosmic rays is better studied with a satellite, in order to reduce to zero the residual atmosphere, therefore minimizing the probability of measuring secondary particles, created by the interaction of primary cosmic rays with atmospheric atoms. The effect of solar modulation affects the low energy part of the spectrum. All the particles are stable or long-lived and consist mainly of protons ($\sim 90\%$), alpha particles ($\sim 9\%$), electrons ($\sim 1\%$). Other nuclei,
antiprotons and positrons are also present, in smaller quantities, and studied by ad hoc experiments, requiring a very powerful particle identification.

**In the atmosphere**

In the top level of the atmosphere the secondary cosmic ray flux is small compared with the primary component. With increasing atmospheric depth, i.e. with decreasing altitude, the secondary flux becomes more and more significant. New particles are produced via hadronic and electromagnetic interactions. The main interaction chain involves the production of pions, that decay into muons and neutrinos ($\pi^\pm \rightarrow \mu^\pm + \nu/\bar{\nu}$) and into high-energy gammas ($\pi^0 \rightarrow \gamma + \gamma$). Part of the muons decay into $e^\pm$ before detection.

Depending on the geographical location, the experiment would measure a softer (high latitude, close to the poles) or harder (equatorial regions) spectrum.
Chapter 1. Cosmic Rays

On the Earth surface

At high energies the primary particle flux of figure 1.1 becomes so small (less than one particle per km$^2$ per year at $E \sim 10^{20}$ eV) to make direct detection of such energetic particles very rare. Such data would be useless, since no calorimeter could contain a shower, and no spectrometer could measure the curvature radius. Furthermore, no primary particle (except neutrinos) would reach the Earth without interacting with the atmosphere. Therefore, very large ground based detectors are used to measure secondary particles produced by the interaction of the primary particle with the atmosphere. One ultra high energy (UHE) primary cosmic ray is able to create a cosmic shower of millions of particles at ground level, over an area of several square kilometres.

A higher limit on the cosmic ray energy is imposed by the Greisen-Zatsepin-Kuzmin cut-off ($\sim t \cdot 10^{19}$ eV) [7]. Particles with energy above this limit interact with the CMBR and lose energy. The energy reduced below the GZK limit, therefore no cosmic ray with energy larger than $\sim 7 \cdot 10^{19}$ eV should be observed. Several ground based experiments have detected events with energy around the GZK cut-off using ground arrays [8, 9] and N$_2$ fluorescence in the atmosphere [10]. Experiments are in good agreement with the theory, except for AGASA, which has measured events above the GZK limit [11]. New hybrid fluorescence and large array detectors are now under development (Auger [12]). Hybrid detectors will provide a cross-calibration between the two techniques.

1.3 Composition and Origin of Cosmic Rays

The composition of cosmic rays depends on the energy range considered. The composition of cosmic rays for energies up to $\sim 10^{19}$ eV is compatible with a production of the nuclei in supernovae and with a successive acceleration via the Fermi mechanism. Active Galactic Nuclei (AGN) are the most likely objects responsible for the acceleration of particles above $10^{18}$ eV.

1.4 Antimatter in Cosmic Rays

After the theoretical prediction of antimatter by Dirac and the experimental results that confirmed the existence of the positron, it was believed that the universe must consist of both matter and antimatter in equal amounts. This assumption was motivated by basic symmetry principles and on studies on Big Bang cosmology. In the late 1950s, the amount of antimatter in our galaxy was calculated to be less than one part in a hundred million. If there were an isolated system of antimatter in the universe, free from interaction with ordinary matter, no earth-bound observation could distinguish its true content. So, even if nothing was visible, the possibility of extragalactic antimatter was wide open. In the following years, motivated by basic symmetry principles, it was believed that the Universe must consist of both matter
and antimatter in equal amounts. Primary antinuclei have never been observed in space.

The known antimatter component of cosmic rays consists of antiprotons and positron. The observed \( \bar{p} \) spectrum indicates that antiprotons are produced by collisions of cosmic ray nuclei with the interstellar gas. These antiprotons are called 'interstellar secondary antiprotons'. Positrons are produced through pair production \( (\gamma \rightarrow e^+e^-) \) and through a multitude of reactions that involve the creation of pions \( (\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm) \). Upper limits on the presence of antihelium, the most stable of any possibly existing antinuclei, have been imposed by experiments to be \( \sim 10^{-6} \) (\( \text{He}/\text{He} \) ratio). If any antihelium is discovered, it could have been produced either during primordial nucleosynthesis, together with all the other nuclei we see, or via nuclear fusion reactions between antinuclei. In order to demonstrate that somewhere in space there is an “antistar”, anticarbon nuclei \( (\overline{C}) \) have to be discovered, since \( \overline{C} \) could not have been produced in primordial nucleosynthesis. Both hypotheses are still very speculative, since no strong sign of antimatter–matter annihilation (for instance 511 keV photons from \( e^+e^- \) annihilation) is visible in the \( \gamma \)–component of cosmic rays. Nasa’s orbiting Compton Gamma Ray Observatory (CGRO) spacecraft detected an unexpected cloud of antimatter in the Milky Way Galaxy (figure 1.3). This is partially explained by ESA’s space probe INTEGRAL, which resolved about 100 individual \( \gamma \) sources towards the centre of the galaxy [13]. The mistery surrounding the positron abundancy is not totally solved and needs to be investigated further.

Signatures of relic particles, diluted during the inflationary era, may be observable in the cosmic ray spectra (e.g. [3]). Among massive particles predicted by supersymmetric theories, neutralinos are Majorana particles \( (\chi = \chi) \) predicted to leave a signature in the spectra of \( \gamma \)'s, \( \nu \), \( \bar{p} \) and \( e^+ \) (figure 1.2). Several experiments include in their scientific objectives the search for neutralino signature as distortions in the cosmic ray spectra components: \( \gamma \)'s (GLAST), \( \bar{p} \) and \( e^+ \) (PAMELA, Bess, HEAT, AMS, etc) and \( \nu \) (Amanda, Ice Cube).
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Chapter 1. Cosmic Rays

Figure 1.3. Positron emission from the Milky Way. The figure represents a survey in 511 keV $\gamma$ from our galaxy. The brightest spot corresponds to the centre of the galaxy and the horizontal distribution to the galactic plane seen from Earth. The bright region above the galactic centre is still a puzzle for astrophysicists.

1.5 Propagation Models

The mean free path for antiprotons in interstellar space is larger than typical galactic distances. This makes the determination of the antiproton energy spectrum essential for understanding the propagation of cosmic rays and for validating different propagation models. Light nuclei and $\bar{p}$ are produced through different mechanisms and (for instance, nuclei are produced by spallation and $\bar{p}$ mainly by cosmic ray protons) and depend on the propagation of protons and heavier nuclei, which might have a different model of propagation. Compared to hadrons, electrons and positrons lose a large fraction of their energy through radiation losses. The inverse Compton scattering with the CMBR limits the distance $e^−/e^+$ can travel, making them the only cosmic ray particles whose flux on the top of the atmosphere is totally galactic.

The propagation of cosmic rays in space can be described by a transport equation, which takes into account diffusive and convective terms, energy loss in the galaxy and escape from the galaxy. Two models are most frequently used to describe cosmic ray propagation.

The diffusive halo model is based on the assumption that the sources of cosmic rays are uniformly distributed in the galaxy disk, which is surrounded by a halo. Cosmic rays diffuse throughout the disk and the halo and escape freely from the boundary of the halo into intergalactic space. A simplified version of this model is the leaky box model. Cosmic rays have constant probability per unit time to escape at each encounter with the boundary. This allows the diffusion term to be ignored and leads to a simplified solution. The leaky box model is plausible for particles of secondary origin (for instance $\bar{p}$ and $e^+$) since the cosmic ray protons and nuclei interact with the interstellar gas uniformly.
1.6 Solar Modulation

The trajectory of a charged particle in space is affected by magnetic fields. The strongest magnetic fields are present in the vicinity of massive stellar objects such as black holes and AGN. Even smaller objects (like our Sun) have a magnetic field, whose effects extend for several astronomical units. Hot plasma ejected from the solar corona can reach our planet travelling at velocities $v \approx 300 - 500 \text{ km s}^{-1}$, creating electromagnetic storms in the atmosphere during the periods of stronger solar activity. Satellites, airplanes and telecommunication systems are all affected by such storms. The magnetic field of the Sun changes polarity every 11 years, and its intensity has thus an 11 year period (figure 1.4). The number of sunspots is an observational parameter used to monitor the solar activity, which varies with the same period of 11 years. Another parameter used to monitor the cosmic ray flux on Earth is the neutron flux on ground [14, 15, 17]. Neutrons are created at the top of the atmosphere, moderated in the atmosphere and detected at ground level by a net of neutron monitoring stations put into operations in the 50’s.

A strong solar magnetic field $\mathbf{B}$ (high solar activity) affects the motion of charged cosmic rays also in the vicinity of the Earth, preventing them penetrating the atmosphere and reaching the surface, much more than a weak $\mathbf{B}$ (low solar activity).
Chapter 1. Cosmic Rays

Figure 1.5. Cosmic ray proton flux at several solar activity levels between 1997 and 2000 measured by BESS [18]. The plotted data is the ratio of the proton fluxes to the proton flux at BESS-98. Ratio of the Climax neutron intensity data at BESS flight date are also shown to the right.

The effects due to the variation of the solar magnetic field are known as solar modulation, which can be summarized as an anti-correlation between solar activity and cosmic ray flux. The effect is significant in the low region of the cosmic rays spectrum and becomes negligible for high energies (above \( \sim 10 \) GeV).

An experiment running during a period of ‘solar maximum’ measures a harder spectrum, and will have better statistics at high energies than an analogous experiment taking data in conjunction with a ‘solar minimum’ (figure 1.5).
Chapter 2

The PAMELA Experiment

PAMELA is a satellite based experiment scheduled for launch towards the end of 2004 from the Baikonur cosmodrome. It will be hosted on-board a Russian Resurs DK1 satellite and orbit the Earth at an altitude of 300–600 km. PAMELA (a ‘Payload for Antimatter–Matter Exploration and Light-nuclei Astrophysics’) is being built within the WiZard collaboration [20] and is a natural progression from the balloon flights performed during the past 15 years (MASS, TS93 and CAPRICE). It is part of the Russian Italian Mission (RIM) framework, which has generated the successful Sil-Eye I and II [21] and NINA [22] space experiments.

2.1 Scientific Objectives

The main scientific goal of the experiment is a study of the antimatter component of the cosmic radiation. The semipolar orbit (70.4° inclination) allows PAMELA to investigate a wide range of energies for antiprotons (80 MeV–190 GeV) and positrons (50 MeV–270 GeV). Three years of data taking will provide unprecedented

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<td>80 MeV - 700 GeV</td>
</tr>
<tr>
<td>antiprotons</td>
<td>$&gt;3 \times 10^4$</td>
<td>80 MeV - 190 GeV</td>
</tr>
<tr>
<td>electrons</td>
<td>$6 \times 10^6$</td>
<td>50 MeV - 2 TeV</td>
</tr>
<tr>
<td>positrons</td>
<td>$&gt;3 \times 10^5$</td>
<td>50 MeV - 270 GeV</td>
</tr>
<tr>
<td>He nuclei</td>
<td>$4 \times 10^7$</td>
<td>$\leq 700$ GeV/n</td>
</tr>
<tr>
<td>Be nuclei</td>
<td>$4 \times 10^4$</td>
<td>80 MeV - 700 GeV/n</td>
</tr>
<tr>
<td>C nuclei</td>
<td>$4 \times 10^5$</td>
<td>80 MeV - 700 GeV/n</td>
</tr>
<tr>
<td>$^4$He limit (90% c.l.)</td>
<td>$7 \times 10^{-8}$</td>
<td>80 MeV - 30 GeV/n</td>
</tr>
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</table>
Chapter 2. The PAMELA Experiment

Figure 2.1. PAMELA antiproton flux expectations after three years of data taking. The figure includes present data and PAMELA expectations in case of exotic contributions, with signal coming from the decay of a heavy neutralino, with mass 964 GeV [23]. Present data and PAMELA expectations are plotted with error bars.

Figure 2.2. PAMELA expectations after 3 years of data taking. The positron fraction ($e^+/e^+ + e^-$) is plotted for existing and future experiments, with signal coming from the decay of a neutralino with mass 336 GeV [24].
2.1. Scientific Objectives

![Figure 2.3. Present experimental limits for the He/He ratio. The expectations foreseen for future experiments are shown with dotted lines: BESS, PAMELA (after 3 years of data taking) and AMS. From [25].](image)

statistics in this energy range and will set the upper limit for the ratio He/He below $10^{-7}$ (figure 2.3). PAMELA will also perform a measurement of light nuclei (H → C) in the energy range 100 MeV/n up to 700 GeV/n. The expected number of events for each particle type and the energy range are listed in table 2.1. Figures 2.1 and 2.2 show a summary of the current status of antiproton and positron flux measurements. The present limits are 50 GeV for antiprotons and 30 GeV for positrons. The majority of the data available comes from balloon-borne experiments, with the exception of AMS-01, that was flying on the Space Shuttle in 1998. In both figures the dotted lines (with a maximum around $E \sim 10$ GeV) show a possible distortion to the spectrum expected from neutralino annihilation or decay. The other lines indicate expectations from secondary production models [26].

Beyond the primary objectives listed above, PAMELA can be used to address issues related to the solar-terrestrial environment (above 50 MeV) such as solar particle events (isotopic composition of H and He, e$^-$ and, for the first time, e$^+$ spectrum) and composition and temporal dependence of the trapped and albedo particle component [27]. There are additional objectives [28] involving Jovian protons [27] and the modulation of galactic cosmic rays in the heliosphere [4].
Chapter 2. The PAMELA Experiment

2.2 The Launcher and the Host Satellite

The launch of PAMELA is scheduled for the end of 2004 on-board a Resurs-DK1 Russian satellite. The carrier rocket is a SOYUZ 2 (the same kind of launcher used in manned missions) that will lift off from the Baikonur Cosmodrome (Kazakhstan). The Resurs-DK1 satellite is designed to transmit prompt data on sea surface status, ice coverage, meteorological conditions in Earth polar regions and information for Earth natural resources study. The satellite will take high resolution images of the Earth surface. For this reason, a large amount of hard disk space (> 100 GB) will be available on the satellite. The satellite, orbiting at an altitude between 300 and 600 km, will be continuously oriented towards the Earth in order to fulfill this program of Earth surface observation. The PAMELA experiment will be housed in a pressurised and temperature controlled container installed on the upward side of the satellite. The satellite is shown in figure 2.4, together with PAMELA in its egg-shaped container.

The satellite has a total mass of ~ 10 tonnes and an average power consumption of 2000 W. PAMELA (figure 2.6) is 1.2 m high, weights ~ 450 kg (750 kg with its container) and consumes ~ 450 W. Solar panels and batteries will supply
2.2. The Launcher and the Host Satellite

Figure 2.5. The PAMELA trigger rate is evaluated over an orbital period. The dotted curve is an estimation of the total trigger rate, while the lower curve shows only the ‘good’ triggers. The trigger rate is strongly dependent on the orbital position, reaching its minimum in equatorial regions. The sharp increase in the trigger rate towards the right of the plot is due to the SAA.

Figure 2.6. The PAMELA experiment.
Chapter 2. The PAMELA Experiment

Figure 2.7. An antiproton and a positron enter PAMELA through its acceptance. Particle identification is done using information from the TRD (signal present only for the positron), the tracker (the bending radius identifies the electric charge), the calorimeter (see figure 2.14) and the ToF (energy loss in the scintillator). Showers not contained in the calorimeter may deposit energy in S4 and in the neutron detector. In the trajectory curvatures in the magnet cavity are exaggerated for illustrative purposes. Particles entering cleanly the PAMELA acceptance present no activity in the AC system.

data from the satellite will be downlinked at every orbital passage above the ground stations in Russia. The semi-polar orbit (70.4° inclination) is elliptical with a height between 300 and 600 km. PAMELA will traverse both the inner and outer radiation belts when it approaches the polar regions as well as the South Atlantic Anomaly (SAA). In the SAA the particle flux will increase dramatically due to low energy particles trapped in the Earth’s magnetic field. An estimation of the PAMELA trigger rate is provided in figure 2.5.

2.3 PAMELA Payload Configuration

The PAMELA experiment consists of several subdetectors, each providing an independent measurement of the incident particles. The combination of detectors allows the energy and rigidity (≈momentum/charge) of the particle are measured, as well as the sign and absolute value of its charge, its mass and type (hadron
or lepton). The subdetectors provide redundant information in order to evaluate systematic errors present in the measurements.

Figure 2.6 provides a schematic overview of the PAMELA experiment and shows the location of the subdetectors described in sections 2.3.1-2.3.7. PAMELA is built around a permanent magnet spectrometer (tracker) equipped with double-sided silicon detectors. The tracker is surrounded by an anticoincidence system which can be used to reject particles not cleanly entering PAMELA acceptance. Above the tracker, the transition radiation detector (TRD) is used to identify leptons and hadrons and is made up of straw-tube detectors interleaved with carbon fiber radiators. Below the tracker is placed the electromagnetic calorimeter, whose main aim is the energy measurement of electrons and positrons. Another important calorimeter task is particle identification. Electromagnetic and hadronic showers develop differently in the calorimeter, allowing identification through shower analysis (figure 2.14 provides a visual example of antiproton and electron interaction in the calorimeter). The calorimeter consists of silicon strip detectors interleaved with
Chapter 2. The PAMELA Experiment

The Time of Flight System (ToF) consists of three groups of scintillators (S1-S3), placed respectively above the TRD (S1), above the tracker (S2) and below it (S3). It measures the velocity of the incident particles, rejecting albedo (up-going) particles, and acts as the main PAMELA trigger by coincidence of energy deposits in the scintillators. In order to increase PAMELA geometrical acceptance at energies above 300 GeV, a self-trigger feature is implemented in the calorimeter. In self-trigger mode, calorimeter data is saved when a total energy larger than 300 GeV is deposited in the calorimeter (details in section 2.3.4). The ToF is not involved in the calorimeter self-trigger measurement.

The S4 scintillator and the neutron detector are placed below the calorimeter and measure highly energetic events not contained in the calorimeter.

A visual representation of particle interactions in the PAMELA experiment is shown in figure 2.7, which shows a comparison between a positron and an antiproton event. Figure 2.8 shows PAMELA during integration in the clean room in Rome.

2.3.1 Time of Flight

The Time of Flight (ToF) system is composed of three planes of scintillator detectors. The first plane (S1) is located above the TRD, the second plane (S2) between the TRD and the tracker and the third plane (S3) beneath the tracker. Each detection layer consists of two independent and segmented layers of organic plastic scintillators (Bicron BC-404), read out by multiple PMTs (Hamamatsu R5900U) for redundancy and rough trajectory estimate. The overall sensitive area of the three planes is: 330 × 408 mm$^2$ (S1), 150 × 180 mm$^2$ (S2), 150 × 180 mm$^2$ (S3). The layers of S1 and S3 are 7 mm thick, while those of S2 are 5 mm thick. Both ends of each scintillator paddle are glued to a one-piece adiabatic UV-transparent plexiglas light guide. The PMTs are mechanically coupled to the light guide by means of optical pads. Figure 2.9 offers a schematic view of the ToF detectors.

The ToF system has to provide a fast signal for triggering the data acquisition of the whole experiment. Furthermore, it measures the flight time of particles crossing its planes, providing a measure of the velocity $\beta$. The segmented design allows a preliminary measurement of the trajectory, to correctly evaluate the velocity. This timing resolution enables also the rejection of albedo particles, i.e. particles entering the acceptance from the bottom (calorimeter side) and exiting from the top (TRD side). The timing resolution is about 111 ps, to be compared to a flight time of 2.7 ns (3.7 ns) for a 1 GeV/c electron (proton). The measurement of the energy loss $dE/dx$ in the scintillators allows the determination of the absolute value of the charge of the incident particle and provides a discrimination between protons (antiprotons) and electrons (positrons) up to $\sim$ 1.5 GeV/c.
2.3. The Transition Radiation Detector

The Transition Radiation Detector (TRD) [30], with a mass of 58 kg, is a velocity measurement system based on the detection of transition radiation emitted by ultra-relativistic particles. It ensures a rejection of the order of 20 against electrons in the identification of antiprotons as well as against protons in the identification of positrons. The detector, located between the ToF scintillators S1 and S2, consists of 9 sensitive layers of straw tube modules (figure 2.10) interleaved with carbon fiber radiators. The straws are 280 mm long, have a diameter of 4 mm and are made of 30 µm thin Kapton foil. The radiators are cushions of carbon fiber, whose density of 60 g/l has been considered suitable to optimise the radiation yield based on Monte Carlo simulations and previous experience. The TRD is composed of 5 detection planes consisting of 4 straw tube modules each, placed above 4 planes with
Figure 2.10. Detail of a module assembly of the transition radiation detector. The 280 mm long straw tubes are clearly visible. From [31].

3 modules each. This gives a total of 32 modules, i.e. 1024 straw tubes, for a total height of the detector of 270 mm. The tubes are filled with a 80% Xe / 20% CO$_2$ gas mixture, and operated at a high voltage of 1400 V. The total height of the detector is 270 mm. A total storage of 1500 ℓ of gas mixture will guarantee a TRD lifetime in space of at least 3 years. The TRD dead time is of 0.9 ms and the maximum counting rate is about 105 Hz.

A charge integration technique has been chosen to measure the transition radiation, based on results from particle beam tests. At CERN pion and electron beams have been used to study the detector particle identification capability. The results are summarized in figure 2.11 where a 5% π contamination for a 90% electron efficiency is shown using the beam test data [32].

2.3.3 Magnetic Spectrometer (Tracker)

The silicon tracker, with a mass of 5 kg, is installed inside the magnet (figure 2.12) and allows the measurement of the momentum vector and the charge sign of the traversing charged particle with rigidity (= momentum / electric charge) up to 700 GV/c [33].

The tracker is composed of 18 ladders of double-sided, double-metal, AC coupled Si detectors arranged on 6 planes inside the permanent magnet. The detectors have a surface area of $70.0 \times 53.3 \text{ mm}^2$ and a thickness of 300 μm; each side is divided into 1024 strips, with an implantation pitch of 25 μm on the junction side and of 67 μm on the ohmic side. The readout pitch is 50 μm on both sides. The measured spatial resolution is 4 μm on the junction side, corresponding to the magnet bending side, and 15 μm for the ohmic side. Particles trajectories are bent in the magnet cavity and from the bending radius it is possible to evaluate the rigidity (momentum/charge) of the particle. The Maximum Detectable Rigidity
2.3. PAMELA Payload Configuration

(MDR) is defined as the upper limit of the measurable rigidity interval, where the measurement error (due to the limited spatial resolution of the tracking system) is equal to 100%. For the PAMELA spectrometer, $MDR \approx 700 \text{ GV/c}$. With decreasing deflection the relative error in the deflection measurement increases, so it becomes more and more likely that high-energy positively-charged particles may be assigned the wrong bending direction. This phenomenon is known as spillover and will result in misidentification of a number of high-energy protons as antiprotons (and positrons as electrons). Since protons are $10^4$–$10^5$ times more abundant than antiprotons, this sets a high energy limit for antiproton measurements.

The silicon tracker is able to measure the absolute charge of particles up to $Z=6$ (carbon). The maximum counting rate of a single tracker counter is of the order of $10^5 \text{ s}^{-1}$ and the dead time (event reading and handling) introduced by the whole instrument is 1.1 ms (which corresponds to the PAMELA dead time, being the largest).

The Permanent Magnet, with a total mass of 115 kg, is divided in five modules (figure 2.12), each 81 mm high, interleaving six frames 8 mm high in which silicon sensors are placed. The total height of the spectrometer is 445 mm, with an inner rectangular cavity of $161 \times 131 \text{ mm}^2$ corresponding to a geometrical factor of about

Figure 2.11. The TRD performance. Pion contamination is shown as function of the electron efficiency. At 90% electron efficiency the $\pi$ contamination is 5%.
26

Chapter 2. The PAMELA Experiment

Figure 2.12. Detail of the magnetic spectrometer. (a) Modules of the flight model of the magnet are mounted on the baseplate. Total dimensions: (13.2 × 16.2 cm² × 44.5 cm high. Geometrical factor: 20.5 cm²·sr. (b) One module is filled with magnetic material (Nd-B-Fe). From [33].

20.5 cm²·sr. This number is referred to as the ‘acceptance’ of the PAMELA experiment. The magnetic material used is the sintered Nd-Fe-B with a large residual magnetic induction (1.3 T). The average field inside the magnet is 0.4 T, with a good homogeneity. A detailed 3-dimensional mapping of the residual field outside the magnet has been done [34, 35] to study the effect of magnetic field on the photomultiplier tubes (PMTs) of the anticounter and Time of Flight (ToF) systems. The residual field at the anticounter PMT locations is always less than 5 mT (Earth magnetic field at the surface: \( \sim 50 \mu T \)).

2.3.4 Electromagnetic Calorimeter

The PAMELA calorimeter [36] (figure 2.13) is mounted below the baseplate, upon which the tracker is mounted. The main purpose of the calorimeter, besides the energy measurements of electrons and positrons, is to help separate \( e^+ \) from \( p \) and \( e^- \) from \( \bar{p} \). The spatial development of showers allows to distinguish between electromagnetic showers, hadronic showers and non-interacting particles (figure 2.14). The rejection power for electrons (in the antiprotons sample) and protons (in the positrons sample) is greater than \( 10^4 \) with an efficiency of 90%. The energy resolution for high energy electrons is better than 10%. An example of particle identification is shown in figure 2.15.

The PAMELA imaging calorimeter is a sampling calorimeter made of 22 silicon sensor planes interleaved with tungsten absorber plates, each 2.6 mm thick. The total thickness corresponds to 16.3 radiation lengths (\( X_0 \)), i.e. about 0.6 interaction lengths. Each tungsten plane (absorber) is sandwiched between two layers of silicon sensor planes (detector). The instrument is designed with high segmentation, both
in the longitudinal (Z) and in the transversal (X and Y) directions. Each sensitive layer contains an array of $3 \times 3$ ministrip Silicon sensors, $380 \mu m$ thick, each with an area of $8 \times 8 \text{cm}^2$ and strip pitch of 2.4 mm. Each of the 32 strips of a detector is connected to those belonging to the corresponding strips of the two detectors in the same row (or column), forming 24 cm long strips. The total sensitive area is $24 \times 24 \text{cm}^2$ and the total number of channels is 4416. The granularity, along with the energy resolution of the silicon detectors, allows an accurate topological reconstruction of the shower development.

A spacequalified aluminium alloy was chosen for the design, since it allowed to have a light, robust and cheap solution. The basic unit is called a 'detection plane' and consists of an absorber plate, the two matrices of silicon sensors and two multi-layer printed circuit boards (for X and Y views), supporting the silicon detectors and the front-end electronics. Two such detection planes form a 'detection module'. All modules are independent and fully extractable, like drawers, from the mainframe. There are 22 tungsten plates, which correspond to 11 detection modules, for a total calorimeter mass of 110 kg.

The calorimeter also has a hardware-implemented self-trigger functionality, which allows it to record electrons from 300 GeV to more than 1 TeV with a geometrical factor of $\sim 600 \text{cm}^2\text{sr}$ (to be compared to PAMELA acceptance: $20.5 \text{cm}^2\text{sr}$). A self-triggered event is recorded if the particle enters one of the first 4 calorimeter planes and traverse at least 10 radiation lengths ($X_0$). Simulation studies have shown a self-triggering efficiency $>99\%$ for electrons above 300 GeV.

### 2.3.5 The AC System

The anticoincidence (AC) system [38] consists of 4 scintillators covering the sides of the magnet (CAS) and one larger scintillator (CAT) covering the top of the magnet,
Chapter 2. The PAMELA Experiment

Figure 2.14. Visual representation of energy deposition in the calorimeter for a 10 GeV antiproton event (left) and a 10 GeV electron (right) event. The arrows represent the direction and the hit location of the incident particle. The bars are proportional to the deposited energy in each channel.

Figure 2.15. The number of calorimeter strips hit plotted versus the total detected energy provides an efficient particle identification. The figure shows the separation between 100 GeV/c electrons and pions with data from the 2000 beam test at CERN SPS [37].
2.3. PAMELA Payload Configuration

2.3.6 The Second AC System

An additional anticounter system was designed during 2003 and produced with the aim of covering the four lateral sides of the volume occupied by the TRD. This will allow the detection of all the particles traversing the TRD volume from the sides. The design of the new four detectors (named CARD – AC Reserve Detectors) is very similar to that of the CAS detectors. Figure 2.17 shows a comparison between CARD and CAS detectors. At the time of writing this thesis, it has not been decided if these detectors will be used in flight.

The read-out electronics is an identical copy of the board used for the read-out of the CAS/CAT detectors. The CARD detectors have been extensively used in the qualification tests of the electronics (section 3.5).

2.3.7 S4 and the Neutron Detector

The S4 bottom scintillator [39] is located just under the calorimeter and has the main task to detect showers not fully contained in the calorimeter. The detector
has a sensitive area of $480 \times 480 \text{ mm}^2$, a thickness of 10 mm and is read out by 6 PMTs. A deposited energy larger than 10 mips in S4 in coincidence with the main PAMELA trigger is the mark for the neutron detector to read out the data from its counters.

The neutron detector, placed under the S4 scintillator, has been added to the PAMELA instrument to expand the energy range of the recorded primary protons and electrons up to $10^{11}-10^{13}$ eV. It consists of 36 $^3\text{He}$ counters enveloped by a polyethylene moderator. The neutron detector will also provide a proton rejection factor of about 1000, which will play an important roll when the calorimeter is in self-trigger configuration (section 2.3.4).

### 2.3.8 The Data Acquisition System

The CPU of the experiment (PSCU: PAMELA Storage and Processing Unit [41]) is based on a ERC-32 architecture (a sparc v7 implementation) running a RTEMS real-time operating system. The custom-designed space qualified device has a 2 Gbyte mass memory and is controlled by the satellite via a 1553 bus. Data acquisition from the detectors is performed via a 2 Mbyte/s interface. Download to satellite memory is handled by a 16 Mbyte/s bus. Figure 2.18 contains a diagram of the on-board DAQ system. The acquisition system is dimensioned to handle the maximum data volume generated by PAMELA (up to 20 GB/day). When a trigger is detected, the subdetectors are read out. The operation is handled by an Intermediate Data Acquisition System (IDAQ), which sequentially requests information from each of the subdetectors. Data is then ‘down-loaded’ into the satellite on-board memory and stored prior to be ‘down-linked’ to Earth. Downlinked data will be received by downlink stations in Russia, which will receive data at a transmission rate of 150 Mbit/s. Two downlink ‘windows’ of about 10 minutes will be
2.4 Particle Identification

The possibility of making redundant measurements of the incident particles with different subdetectors enables efficiency determination for the subdetectors using flight data. A summary of the main detector properties described above (sections 2.3.1–2.3.7) is shown in table 2.2.
Table 2.2. Particle Identification is obtained through (redundant) measurements. The quantities measured by each detector are summarised in the table, as well as the main detection properties of each detector. All the detectors are described in sections 2.3.1–2.3.7.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Measured quantities</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>ToF</td>
<td>particle velocity</td>
<td>– provides trigger</td>
</tr>
<tr>
<td></td>
<td>energy loss ((dE/dx))</td>
<td>– albedo particle rejection</td>
</tr>
<tr>
<td>Tracker</td>
<td>trajectory curvature</td>
<td>– multi-track events rejection</td>
</tr>
<tr>
<td></td>
<td>energy loss ((dE/dx))</td>
<td>– charge (sign) measurement</td>
</tr>
<tr>
<td>CALO</td>
<td>energy ((e^-/e^+))</td>
<td>– rigidity ((\tilde{p}/\text{charge})) measurement</td>
</tr>
<tr>
<td>TRD</td>
<td>lepton/hadron discrimination</td>
<td>– discriminates between electromagnetic/hadronic interactions and non-interacting particles</td>
</tr>
<tr>
<td>AC</td>
<td>out-of-acceptance particles</td>
<td>– rejection of multiple tracks (via a rough tracking)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– signal present (absent) for (e^-/e^+) (p/\bar{p})</td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td>– helps rejecting false triggers but backscattering studies are needed</td>
</tr>
<tr>
<td>Neutron det.</td>
<td></td>
<td>– detects showers not fully contained in the calorimeter</td>
</tr>
</tbody>
</table>

2.5 The Second Level Trigger

Figure 2.19 provides a schematic view of simulated events with activity in the anticounter detectors (false triggers and backscattering events). A particle enters PAMELA from the side and interacts in the magnet producing secondaries which give coincidental energy deposits in the ToF scintillators producing a trigger. Such false triggers can be suppressed making use of a second level trigger, which contains information from the anticounter system. A problem arises at high energies, since particles backscattered from the calorimeter can enter the anticounters even though the trigger particle passes cleanly through PAMELA’s acceptance. This undesirable loss of good events is usually referred to as ‘self-veto’. Studies of the backscattered particles have been realised using data from a CERN SPS testbeam (2002) [44]. The agreement between simulated and experimental backscattering data is good. A second level trigger would be enabled from Earth through uplinked commands if the PAMELA data volume is significantly larger than expected. This trigger could be formed by asking for coincidental energy deposits in the ToF scintillators (the standard trigger) and also that there is no activity in the anticounter system. The inclusion of calorimeter information in the second level trigger would ensure that


2.6 Mechanical and Thermal Conditions

The PAMELA detectors are designed to resist to extreme environmental conditions. On Earth, PAMELA will be transported for thousands of kilometers on truck and train, therefore it will be subject to prolonged mechanical vibrations and extreme thermal conditions. The vibrations with the largest amplitude are expected to be those present during launch. Therefore tests with random vibration spectra have been realised for the AC system [45] (to test for instance the PMT-scintillator coupling) and for the other subdetectors, to search for resonance frequencies. A final combined vibration test of the assembled experiment will be performed during the summer 2004.

2.7 Radiation Environment

In space, radiation [46] can affect the performance of the electronics. The particle flux in space has been simulated [47] and the Total Ionising Dose absorbed by PAMELA during its foreseen lifetime (3 years) is evaluated to be $\simeq 10$ Gy. Solar particles count for about 50% in this estimate, and the remaining 50% is due to galactic particles and to particles trapped by the radiation belts PAMELA will

*Figure 2.19. Backscattering studies. Simulated events showing (a) a 'good' trigger: a particle passing cleanly through the acceptance without inducing a signal in the AC detectors, (b) a 'false' trigger: a particle entering PAMELA from the side and whose backscattering is recognised as a trigger, (c) a particle goes cleanly through the acceptance and generates backscattering and signal in the AC detectors. From [43, 44].*
traverse during its flight (inner and outer radiation belts, and in particular the South Atlantic Anomaly – SAA).

Space radiation will produce two classes of effects on the microelectronic devices mounted on PAMELA:

- long-term effects, due to the prolonged exposition to radiation, as measured by the Total Ionising Dose (energy released per mass unit of the target, measured in Gy)

- events caused by the passage of a single, ionising particle (Single Event Effects, SEE). In particular, Single Event Upsets (SEU) and Latch-ups (SEL) have been considered in the choice of the components. A SEU is an unplanned change of state in a memory cell of a digital electronic device. Even if it is not destructive, it can lead to corruption or loss of information. In the case of a SEL, the deposited charge can open a low-resistance conduction channel inside the device, connecting its power supply to ground. If no current-limiting mechanism is implemented, the device can suffer permanent damage.

All the electronic components for all subdetectors have undergone radiation tests with a total dose of at least 5 krad. Single Event Upsets (SEU) and Latch-ups (SEL) have been studied at heavy-ion beam accelerators.

### 2.8 PAMELA Operational Modes

Two operational modes are foreseen for the operation of PAMELA in space. The experiment will be in ‘Physics Mode’ for a large fraction of the time. The main PAMELA trigger is activated and a trigger signal is sent to all detectors when a coincidence of energy deposits is measured in the ToF scintillators S1, S2 and S3. After each trigger, data from all detectors is read out sequentially by the IDAQ, and stored on mass memory on the satellite. The second level trigger may replace the main PAMELA trigger upon uplink command from ground.

Once per orbit, on the ascending mode, physics data acquisition is stopped and PAMELA is set to ‘Calibration Mode’. The detectors are calibrated sequentially and independently (exception: section 4.7.1). The calibration procedure for most detectors foresees the usage of random triggers (i.e. trigger signal generated by a pulse generator, not related to physical particles traversing the experiment) to assess noise levels in the detectors. The AC calibration will be described further in chapter 4.
Chapter 3

The Anticoincidence System

The PAMELA experiment is equipped with an anticoincidence (AC) shield to help reject particles not cleanly entering the acceptance of the experiment. The AC system consists of five plastic scintillators; four of them (CAS) cover the sides of the magnet and one (CAT) covers the top of the magnet, and has a rectangular hole in correspondence with the tracker acceptance.

3.1 Purpose

The first level trigger in PAMELA is defined by the coincidental deposit of energy in the three time-of-flight (ToF) planes S1, S2 and S3. Most of these triggers will be ‘false triggers’ (figure 2.5), i.e. events with particles not cleanly entering the acceptance of the experiment, but generating secondary particles through an interaction with the mechanical structure of the experiment or the satellite. These secondary particles eventually deposit coincidental energy in the ToF scintillators and are erroneously interpreted as ‘good triggers’ by the first level trigger. The AC shields will help identify ‘false-trigger’ events and reject them during off-line data analysis. Some of the ‘good-triggers’, i.e. events characterised by one particle cleanly entering PAMELA’s acceptance, may induce a signal into one or more of the AC scintillators due to backscattering. Studies to discriminate backscattering events from false triggers have been done with testbeam data (section 5.3.2). Information from the AC detectors is planned to be implemented in a second level trigger, to reduce online the number of false triggers, and may be activated by an uplink command from ground.

3.2 Particle Interactions in the Anticounters

Plastic scintillators are characterised by very fast response times. Plastics are often used for detection of charged particles. The density and atomic number are
Chapter 3. The Anticoincidence System

Figure 3.1. Energy loss rate \( \frac{dE}{dx} \) in various materials. For all practical purposes \( \frac{dE}{dx} \) in a given material is a function only of \( \beta \). From [53].

rather low, which makes the material not very well suited for efficient gamma ray detection. Compton scattering dominates over a large energy interval, therefore the energy deposited in the scintillator will not correspond to the photon total energy, but is a function of the scattering angle between the incoming and the outgoing photons. The energy deposited via Compton scattering is lower than a maximum energy \( E_{max} \), which is referred to as the ‘Compton edge’:

\[
E_{max} = h\nu \cdot \frac{2\gamma}{(1 + 2\gamma)},
\]

where \( \gamma = h\nu/m_e c^2 \), and \( h\nu \) is the incoming photon energy.

This property affects the calibration procedure with a radioactive source described in section 4.2.1, but is not relevant for operations in space. The AC system is aimed to the detection of ionising particles entering PAMELA from the sides, but is not designed to detect photons. The AC detectors have to detect all minimum ionising particles (mips), i.e. the minimum energy loss in figure 3.1, which corresponds to the minimum deposited energy in the Bethe-Bloch formula:

\[
-\frac{dE}{dx} = 2\pi N_o r_o^2 m_e c^2 Z z^2 \beta \left[ \ln \left( \frac{2m_e c^2v^2W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]
\]
3.3 The AC Detectors

The AC detectors consist of sheets of 8 mm thick plastic scintillators read out by photo-multiplier tubes (PMTs). The scintillating material is a Bicron BC-448M cross-linked polymer, characterised by fast response time (≈ 1.5 ns), robustness, good radiation resistance and in particular good temperature stability. The PMTs used in the design are small-form-factor R5900U tubes, manufactured by Hamamatsu. They are light (26 g), small (30 × 30 × 27 mm$^2$), have high gain ($10^6$) and a fast rise time (1.5 ns). The optical coupling between PMTs and scintillators

where: $2\pi N_a \rho^2 m_e c^2 = 0.1535$ MeV cm$^2$/g; $\rho$, $Z$ and $A$ are the density, atomic number and atomic weight of the absorbing material; $z$ and $\beta = v/c$ ($\gamma = (1 - \beta^{-1/2})$) are the atomic number and velocity of the incident particle; $W_{max}$ is the maximum energy transfer in a single collision; $\delta$ and $C$ are respectively shell and density corrections.

The linear term describes the behaviour of the energy loss at low energies, while the logarithmic is responsible of the relativistic rise (figure 3.1 and [48], [49]).

Charged particles emit electromagnetic radiation in the electric field of a nucleus (Bremsstrahlung). Since this process is related to the scattering, it is related to the mass of the incident particle and is significant for light particles like electrons and positrons. The radiation length of a material is defined as the distance over which the electron energy is reduced by a factor $1/e$ due to radiation loss only.

### Figure 3.2

CAD drawing of the anticounter detectors CAT. An exploded view of the detector close to two PMTs is shown on the right. From [44].
Figure 3.3. CAD drawing of the anticounter detectors CAS. The detector is shown exploded in all its components. The PMT holder (containing 2 PMTs) is shown in the up-right corner. From [44].

is maintained by means of 7 mm thick optical pads (BC-634A, manufactured by Bicron [50]), slightly compressed, to provide also good resistance to vibrations during launch. The spectral matching between scintillators and PMTs will be shown in chapter 4 (figure 4.9). The scintillators are wrapped in layers of UV–reflecting Tyvek to maximize the light collection, and then in opaque Tedlar for light proofing. The light proofing simplifies tests on ground but will not be required for operation in space. The wrapped scintillators are then mounted into custom made aluminium containers designed to protect them from mechanical stresses and light leakage. These boxes also act as PMT holders to ensure a good scintillator–PMT coupling and provide means to attach the counters to the structure of PAMELA.

Each CAS scintillator is read out by two PMTs for redundancy. The two PMTs facing the same CAS scintillator have very different quantum efficiency (QE), in order to compensate PMTs with lower QE with others with higher QE. Due to its irregular geometry, the CAT scintillator is read out by eight PMTs. This number is the result of studies on the CAT sensitive surface, which may be divided in four sections. Each CAT section is read out by two PMTs with different quantum efficiency. For redundancy each section is read out by two PMTs. Figure 3.2 (3.3) shows a drawing of the detector CAT (CAS), with an exploded view of the region close to two PMTs.

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1 The Quantum Efficiency (QE) of a PMT is defined as the ratio between the number of electrons emitted by the photocathode (photoelectrons) to the number of incident photons.
3.4 The Read-Out System

The PMT operating voltage is fixed to 800 V. A high voltage divider is located directly behind each PMT. LEDs are glued to all scintillators and are used to monitor the detector performance during the flight. The LED-based monitoring system is described in detail in chapter 4.

3.4 The Read-Out System

The 16 PMTs are connected to the read out board (figure 3.4). The board consists of an analog section, which handles the PMT pulses, and a digital section.

The latter section contains a programmable logic device (FPGA) that has the task to communicate with the IDAQ (section 2.3.8) and to handle the AC operation. As shown in figure 3.4, this action is performed independently on each channel comparing (with a discriminator) the user-defined threshold voltage (converted by the DAC) with the integrated PMT pulse. The integrator is needed since both scintillator and PMT have very fast response time. The discriminator registers an event as a ‘hit’ if the output voltage from the integrator is larger than the DAC voltage (user-defined). This means that the AC system does not store information on the deposited energy, but only binary information whether the deposited energy is larger than a pre-set discriminator value. The discriminator threshold is set on each channel to register all minimum ionising particles (mips). The FPGA reads continuously the discriminator output and stores the data in memory, in the form of a ‘shift register’, with a time resolution of 80 ns. When a trigger arrives (from the IDAQ) to the FPGA, the shift register is ‘frozen’, i.e. is not updated until the data is sent to the IDAQ.

Shift register data consist of hit-information in the AC detectors in a time-window of 1.28 µs around each trigger, divided in 16 80 ns-wide bins. The time
Chapter 3. The Anticoincidence System

of 1.28 µs has been chosen to allow the calorimeter to read out self-trigger events, which takes few hundreds of ns (section 2.3.4).

Partial hit information is included in the ‘hitmap’, which is a 16-bit word containing the hit-information on each channel in the 1.28 µs (without time segmentation: for each channel this is a logical OR between all the time windows). The ‘hitmap’ is provided in order to get a faster read-out of AC data in preliminary analysis and for the implementation of the second level trigger. Sixteen counters are implemented in the FPGA and measure the total number of ‘hits’ in each channel. The counters run independently from the trigger (therefore are called ‘free running counters’), and measure the total number of hits between consecutive triggers. Eight coincidence counters are also implemented as the logical OR of 4 couples of channels. The information gathered from the coincidence counters is used to monitor the cross correlation between contemporaneous hits in distinct channels.

The FPGA (Actel, A54SX72A, described further in [51]) was chosen after radiation tolerance comparison with a QuickLogic device [47]. The Actel chip is a programmable-once device and has 72000 gates. A second programmable chip is present on the board (ADSP-2187L, Analog Devices, [52]) and will be used only during the detector monitoring procedure (chapter 4).

Aside the shift register handling, the FPGA has other tasks to perform. The most important are:

- handle the alarm line, which informs the IDAQ that there is a problem on the AC board;
- handle the alarm bits (a single alarm bit cause the alarm line to activate): temperatures (read out every 0.5 s via an ADC), regulators (which prevent SEU and latch-up from damaging the board), DSP (error during the monitoring procedure) and CRC (IDAQ–AC data transmission error). The 16 alarm bits form the ‘status word’, which is included in the physics event, to locate the cause of the alarm.
- handle the 16 counters (and the 8 coincidence counters) used for monitoring the stability of the system;
- start the monitoring procedure.

3.5 Qualification Tests

The detectors have undergone several tests in order to verify their performance and their resistance to the extreme conditions required for the PAMELA space experiment. Several irradiation tests have been performed on the electronic components. Irradiation tests of the analog to digital converters (ADC) and LEDs with a $^{60}$Co source are included in this thesis, in section 3.5.1. Other tests performed are described for example in [47].
3.5. Qualification Tests

Thermal tests have been performed on the electronic board and on the detectors [51]. Tests with random vibration spectra have been realised for the AC system [45], to test for instance the PMT–scintillator coupling. Efficiency measurements with cosmic muons have been realised in the laboratory. Further investigations on AC efficiency are described in [51].

3.5.1 Irradiation Tests

The components on-board PAMELA are expected to absorb a dose equivalent to 10 Gy during PAMELA’s lifetime. Most of the components of the AC front end electronics (FPGA and DSP included) have been tested on dedicated ion-beams by other members of the collaboration [47]. Radiation tests on the ADC (used for temperature monitoring on the AC board) have been performed in Stockholm (Department of nuclear chemistry, KTH) with a $^{60}$Co radioactive source in 2001. The setup is shown in figure 3.5. During the test a known input voltage was delivered to the ADC, and the digital ADC output interpreted by a read-out system, built for the test. Measurements were taken continuously, in order to analyse the ADC’s behaviour as a function of the absorbed dose. A known analog signal is sent every 12ms to the ADC through a 2m-long ribbon cable. The same cable was used for communication between the ADC and an Altera FPGA (Flex20k) located
Figure 3.6. The input–output relationship before irradiation is shown here. The plot is linear, and a constant offset of \(\sim 30\) mV is present in all data. The units on both axes are expressed in binary units (the full scale for an 8-bit ADC corresponds to 256 binary units).

Two ADC chips were irradiated at a constant rate of \(\sim 300\) Gy/h until their input–output relation differed from linearity. At a total dose of \(\sim 300\) Gy both ADCs showed a sudden and significant decrease in their performance. The difference of input and output voltage is plotted for one of the ADCs in figure 3.7 as a function of the absorbed dose, in the range 0–60 krad. After absorbing a dose of 10 Gy (expected on flight), the ADCs did not show any change in their behaviour.

The radiation resistance of the LEDs to be mounted on the flight model of the AC detectors to monitor the AC detectors’ performance during flight (chapter 4)
3.5. Qualification Tests

Figure 3.7. Irradiated ADC: (deviation from linearity) vs dose. The spread around the average is also shown. The units on the y-axis are expressed in binary units (the full scale for an 8-bit ADC corresponds to 256 binary units).

Figure 3.8. LED relative output versus absorbed dose. Five identical LEDs have been tested.
was also tested. The devices under test were five low intensity LEDs\(^2\). The test took place in 2002 in Stockholm with the same \(^{60}\)Co radioactive source used to test the ADCs. The device under test (DUT) was composed of the mentioned LEDs attached to a $3 \times 3 \times 3$ cm\(^3\) plastic scintillator read out by a PMT (Hamamatsu R5900U). The DUT was irradiated and, at regular intervals, extracted from the \(^{60}\)Co box in order to measure the LED performance at several absorbed doses. At the total dose of $\sim 250$ Gy, the LEDs showed a decrease of the light output by $\sim 8\%$ (figure 3.8). Assuming a linear in the LED light output, after three years of space operation, the performance of the LED will be reduced by radiation by a factor lower than 0.3\%.

\(^2\)Red LED: Everlight Electronics Co.LTD. (model no 15-21VRC).
Chapter 4

The Monitoring System

Every detector has characteristics that may change during its lifetime. Several issues affect the efficiency of the PAMELA anticounter system: vibrations during transport and launch may affect the coupling between PMTs and the scintillator; in orbit, radiation will eventually increase the scintillator opacity; PMTs' efficiency might decrease with their age; variations in temperature affect the coupling between PMT and scintillator and may modify the characteristics of the electronic components. The detector characteristics need to be studied before flight, in the laboratory. At a later stage, any variation from the previously measured characteristics must be assessed during the flight. The stability of the system can be studied during the physics data acquisition, but a detailed monitoring of the system requires the modification of several parameters (for instance, the discriminator thresholds) from their default values. For this purpose, once per orbit, on the ascending node, the data acquisition is stopped to study the response of the detector when these parameters are modified. During these stops PAMELA leaves the “physics mode” and enters the “calibration mode” (see section 2.8).

This chapter contains a description of the LED-based monitoring system for the PAMELA anticoincidence shields. The feasibility studies and subsequent measurements show that the monitoring system is able to identify variations of the AC system characteristics. The original anticounter system (CAS and CAT) was delivered for integration before the final read-out electronics was available. Some of the results included in this chapter make therefore use of the CARD detectors (section 2.3.6), delivered to Rome in December 2003.

4.1 Calibration and Monitoring

An interaction between an ionising particle and an organic scintillator provides an ionisation (thus a light output) proportional to the energy deposited in the scintillator, according to the Bethe–Bloch formula (equation 3.2). The deposited energy
Chapter 4. The Monitoring System

is often measured in mip, i.e. the energy released by a minimum ionising particle in the detector (see section 3.2). A mip corresponds to the minimum in the Bethe–Bloch formula, shown in figure 3.1. For the AC scintillators, 1 mip is approximately 1.6 MeV\(^1\). A photomultiplier tube (PMT) collects the light generated in the scintillator and converts it into a current pulse. The measured output voltage from the integrator (section 3.4) can be associated to the deposited energy scale through a calibration procedure provided the outputs for two known energies are known and the relation voltage–energy is linear. In the laboratory, radioactive sources are often used to calibrate the energy scale of scintillators. The PAMELA AC scintillators have been studied in the laboratory with \(^{22}\)Na and \(^{137}\)Cs radioactive sources.

Once the relation between deposited energy and measured current (often a voltage) is measured, for simplicity, it is obtained, it has to be monitored regularly during flight operation to detect any change in the detector’s characteristics. No radioactive sources are allowed on-board PAMELA, so an alternative solution to detect any deviation in the detector characteristics has been developed. The system is based on LEDs (Light Emitting Diodes), which emit short pulses of light into the scintillator, detected then by a PMT. Since the PMT output from an LED flash resembles, but is not, the output from the interaction with a ionising particle, it is inappropriate to describe the procedure as calibration. The main difference between the two types of PMT pulses resides in the light flash that reaches the photodiode. An ionising particle deposits energy in the scintillator, which releases this energy in the form of blue light (\(\lambda \approx 440\) nm for PAMELA AC scintillators, see figure 4.9), detected at the PMT. On the contrary, an LED transmits photons into the scintillator, which will be detected by the PMT. A change in the detector system will modify the measured signal from the PMT, which can be compensated by a user action (see section 4.5).

It should be noted that the LEDs provide an indirect measurement of the properties of the system. For this reason the expression “Calibration” has been sometimes replaced by “Monitoring”. Given the strong analogy between the two notions, several expressions involving the term calibration, such as “calibration curves” (see next section), are used throughout the chapter also to describe the LED system. The context should clarify whether they refer to a proper calibration with ionising particles or to a monitoring procedure with LED flashes.

4.2 Calibration Curves

Every ionising particle passing through a scintillator releases an amount of energy depending on the type of particle, its initial energy and the angle of incidence. As explained in chapter 3, the PAMELA anticounters store hit information for those events that release an energy larger than the preset discriminator thresholds. The

\(^1\)The PAMELA anticounters are 8 mm thick and have a density of 1.03 g/cm\(^3\). A minimum ionising particle traversing a scintillator with a 90° angle (i.e. vertically) deposits therefore \(\sim 1.6\) MeV (1 mip) in the scintillator [53].
4.2. Calibration Curves

FPGA sets the discriminator voltage through an 8 bit DAC (256 steps: \(2^8 = 256\)). This threshold is the limit between the detected pulses (hits) and the pulses too small to be detected, as illustrated in section 3.4.

Assume we have a flux of particles through the detector from a radioactive source. We can reasonably assume that the particle flux is constant, if measured over a time much smaller than the half life of the radioactive source, and long enough to reduce the statistical errors. A measurement is performed for each threshold value over a fixed constant time interval, set by a count gate in the electronics. With this assumption, the number of particles giving a signal above the threshold as function of the threshold level results in a monotonically non-increasing curve\(^2\). The calibration curve obtained is thus an integral energy spectrum.

The count rate in each detector is measured making use of the free running counters implemented in the AC read-out electronics (see section 3.4). The threshold is incremented with regular steps from zero to its maximum value, keeping constant the acquisition time for each step.

Figure 4.1 shows the typical integral spectrum obtained with a radioactive source placed on a CARD scintillator. The solid (dashed) line shows a \(^{137}\text{Cs}\) (\(^{22}\text{Na}\)) source. For reference, the measured spectrum when no source is present on the detector is shown (dotted line). At low discriminator thresholds, the hit rate grows rapidly due to electronic noise.

The shape of each calibration curve depends on the chosen source of light in the scintillator. In the following pages three different kinds of calibration curves are illustrated and compared. Ionising radiation (radioactive sources and cosmic muons) and LED flashes have been tested for calibration of the PAMELA anticoincidence scintillators. Section 4.4.3 is devoted to a more detailed analysis of the AC calibration curves obtained with LEDs. The LED pulses are calibrated with the radioactive sources. Results obtained from comparison of the various methods are consistent with expectations.

4.2.1 Calibration Curves with a Radioactive Source

When a radioactive source is placed on a scintillator, the count rate in the corresponding PMT is increased in the energy region corresponding to the source emission peak(s). The sources used during the tests were \(^{22}\text{Na}\) (55 kBq) and \(^{137}\text{Cs}\) (370 kBq). The \(^{22}\text{Na}\) spectrum is characterised by a \(\gamma\)-emission peak at \(E = 1.275\) MeV (branching ratio: 10\%) and by positron emission (90\%). The positron is converted by annihilation with an electron in the aluminium cover into two 511 keV \(\gamma\)'s. One of the two emitted gamma rays may then be detected in the scintillator. The \(^{137}\text{Cs}\) emits monoenergetic \(\gamma\)'s with energy 662 keV.

The photons interact with the AC plastic scintillator material mainly via Compton scattering (section 3.2). The \(^{137}\text{Cs}\) spectrum presents the typical 'Compton

\(^2\)The curve is generally decreasing, but strictly speaking it is non-increasing, since there might be plateaus, where the curve has zero derivative. This behaviour is barely visible for curves generated with radioactive sources, but will become evident when LEDs are used (see figure 4.16).
Chapter 4. The Monitoring System

edge' at 478 keV (formula 3.1), but the photopeak is not visible in the measurements. Analogously, the $^{22}\text{Na}$ source presents two Compton edges at 341 keV and 1060 keV, corresponding respectively to the 511 keV and 1.275 MeV $\gamma$'s. Figure 4.1 shows the integral spectra for $^{137}\text{Cs}$ (solid line) and $^{22}\text{Na}$ (dash-dotted line) measured with a CARD detector. The Compton edges are best seen after differentiating the spectra. Figure 4.2 shows the differential spectra for all CARD detectors. The differentiation was obtained by subtracting consecutive elements of the integral spectrum and rebinning the data. The Compton edges in the figure are broadened by the finite resolution of the detector (plastic scintillators are not designed to detect $\gamma$'s, unless enriched in heavy atoms like Pb). Figure 4.3 shows the differential spectrum of the same $^{22}\text{Na}$ source, measured with a CsI crystal, read out by PIN diodes, for comparison. The CsI crystal resolves better the structure of the $^{22}\text{Na}$ source (photopeaks and Compton edge) thanks to the better energy resolution. Much less energy ($\sim 6.2$ eV) is needed to produce a photon in a CsI crystal than in a plastic scintillator ($\sim 100$ eV). The energy resolution is given by the statistical variation in the number of produced photons: $\Delta E/E \propto \Delta N/N$.

The Compton edges seen on each channel through the analysis of figure 4.2 are used to evaluate for all channels the discriminator voltage values that correspond to the deposit of 1 mip in the scintillator. This is realised in two consecutive steps. First, a linear fit of the spectra around the Compton edge$^3$ sets the DAC voltage

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$^3$The fit is linear in a log–log scale (figure 4.2), and is performed over a voltage range just smaller than the voltage corresponding to the Compton edge.
Figure 4.2. Radioactive Source differential spectra for CARD1-4. See description in the text.
Figure 4.3. The (differential) spectrum of the $^{22}\text{Na}$ radioactive source is measured with a CsI crystal, read out by PIN diodes [54]. The crystal is being used for qualification tests of the calorimeter for the GLAST experiment [55, 56].

value corresponding to the Compton edge energy. This procedure is performed on all channels making use of the $^{137}\text{Cs}$ source. The second step consists now in calculating the voltage corresponding to 1 mip, which becomes:

$$1 \text{ mip} (V) = CE \cdot \frac{1.6 \text{ MeV}}{478 \text{ keV}} \simeq 3.3 \cdot CE$$  \hspace{1cm} (4.1)$$

where $CE$ is the Compton edge expressed in Volts.

The procedure is repeated for all the channels and the results are shown in table 4.1. The same procedure is applied to the $^{22}\text{Na}$ spectra. The $^{22}\text{Na}$ Compton edges are difficult to define with good accuracy, because the statistical errors are large due to the strength of the source. For this reason the conclusions are drawn only from $^{137}\text{Cs}$ studies and $^{22}\text{Na}$ studies are only used as a cross-check. For example, CARD1-A shows the $^{137}\text{Cs}$ Compton edge at 0.35 V (which identifies 1 mip as 1.17 V) and the $^{22}\text{Na}$ Compton edges at 0.27 V (1 mip=1.16 V) and 0.80 V (1 mip=1.20 V).

4.2.2 Calibration Curves with Cosmic Muons

An experimental setup to detect cosmic muons was arranged in the laboratory primarily in order to test the trigger system. The read-out set-up approximates well the trigger handling system during operations in space. The data obtained were
Table 4.1. The CARD detectors are calibrated with $^{137}$Cs following the procedure described in the text (equation 4.1). The DAC voltage corresponding to the Compton edge (a mip) is shown in the second (third) column.

<table>
<thead>
<tr>
<th>Detector CARD</th>
<th>Compton edge (V)</th>
<th>Calculated mip (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-A</td>
<td>0.35</td>
<td>1.17</td>
</tr>
<tr>
<td>1-B</td>
<td>0.28</td>
<td>0.94</td>
</tr>
<tr>
<td>2-A</td>
<td>0.32</td>
<td>1.07</td>
</tr>
<tr>
<td>2-B</td>
<td>0.39</td>
<td>1.31</td>
</tr>
<tr>
<td>3-A</td>
<td>0.30</td>
<td>1.00</td>
</tr>
<tr>
<td>3-B</td>
<td>0.32</td>
<td>1.07</td>
</tr>
<tr>
<td>4-A</td>
<td>0.18</td>
<td>0.60</td>
</tr>
<tr>
<td>4-B</td>
<td>0.40</td>
<td>1.34</td>
</tr>
</tbody>
</table>

also used to cross-check the results obtained with radioactive sources. Table 4.1 shows that 1 mip corresponds to voltages out of range (i.e. >1 V) in the majority of CARD channels. It will therefore be impossible to reconstruct the spectra on all channels making use of cosmic muons without changing the experimental set-up.

Figure 4.4 shows the experimental setup used to take calibration curves with cosmic muons. The four CARD scintillators are placed in a vertical stack. Two PMTs facing the two outer scintillators are used as external trigger. Their coincidence signal is directed, through NIM logic and a TTL/LVDS converter\(^4\), to the AC trigger line. The other 6 PMTs are directly connected to the AC board and are read-out every time a trigger signal is detected (i.e. a particle traverses the scintillator pile).

The discriminator level on the trigger scintillators is set to accept all minimum ionising particle events and to ignore events with low deposited energy. The DAC thresholds on the six channels under test are varied from zero to the maximum voltage (1 V). Differently from the calibration with a radioactive source described above, this setup allows a fixed number of triggers to be recorded for each DAC step. This number was set to 1000, as compromise between a relatively short data taking time ($\approx$ 12 hours) and good statistics. This is in strong analogy to the LED-based monitoring system, described in the next section. The recorded number of triggers on each channel is shown in figure 4.5a as a function of the DAC threshold. At low thresholds almost all the triggers are detected, producing a ‘high-level’ plateau, while, with increasing voltage thresholds, the fraction of detected particles decreases, and eventually reaches zero (‘low-level’ plateau). The curve represents the integral spectrum of deposited energy in the scintillator. The derivative of this function leads to the differential spectrum of figure 4.5b.

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\(^4\)LVDS (Low Voltage Differential Signals) are often used in long transmission lines instead of TTL (Transistor Transistor Logic) for their good noise rejection and for the low power consumption. LVDS are used widely in PAMELA for communication between subsystems.
Figure 4.4. Test setup for cosmic muon detection. When a muon interacts with the scintillators 1 and 4, the coincidence of two PMTs (C, dotted lines) provides a trigger (T) for the PAMELA read-out electronics. The other 6 PMTs are read out (B, solid lines) by the AC electronic board. After each trigger, the data is automatically read out by a computer (PC, right of the figure), in the form of a “physics event”.

An estimation of the errors involved in the spectrum reconstruction is provided here. Assume $\bar{N}$ triggers are collected at a given threshold. The probability $p_i$ of detection may be estimated as the number of detected triggers $N_i$ divided by the total number of triggers $\bar{N}$. At each DAC step, the distribution is thus binomial, with parameter $p_i$ and standard deviation:

$$\sigma_i = \sqrt{\bar{N} p_i (1 - p_i)}.$$  \hfill (4.2)

The statistical errors in the measurement of $N_i$ are:

$$N_i \pm \sigma_i = N_i \pm \sqrt{N_i \cdot (1 - \frac{N_i}{\bar{N}})}$$  \hfill (4.3)

and are represented in figures 4.5a and 4.5b. The relative errors $\sigma_i/N_i$ are shown in figure 4.6. The experimental setup includes a small ($\simeq 1\%$) inefficiency; a fraction of the particles giving rise to a trigger do not necessarily go through the detectors 2 and 3 of figure 4.4. The fraction of these particles is estimated from the undetected triggers at low thresholds (about 1%). This effect lowers the integral spectrum by about 1%. The distribution is therefore binomial only in first approximation, and the deviation is more evident in the lower part of the spectrum of figure 4.6. The scatter of the measured points is much less than the calculated standard deviation. The plotted errors are thus an over-estimation of the real error bars in the low part of the spectrum, while are consistent with the real spread in the data for higher energies.

The solid line in figure 4.5b is obtained fitting the data obtained with CARD1-A with a Landau distribution. A Moyal parametrisation [57] of the Landau distribution is used in the fit. The Moyal parametrisation is an analytical approximation.
4.2. Calibration Curves

Figure 4.5. Calibration curves obtained with cosmic muons. (a) The integral spectrum shown with error bars. The statistical errors are small, since 1000 events per DAC value were collected (see figure 4.6). The systematic errors are estimated to depend only on the inefficiencies of the experimental setup for the test. A study of the lower part of the (integral) spectrum shows that about 1% of the events are not detected. The setup is not optimised for efficiency measurements. The differential spectrum is shown in (b). See section 4.2.2 and figure 4.6 for details of the error calculation. The plots represented here have been obtained using CARD4-A.

Figure 4.6. Error estimation for calibration with cosmic muons. The statistical errors shown here are calculated assuming binomial distributions with parameters $p_i$ (equation 4.2). The solid line represents the errors shown in figure 4.5 (1000 events per DAC step). The two other lines are chosen for illustrative purposes and show different statistics in the acquisition: 100 events per DAC step (dashdot) and 10000 (dashed).
which reproduces the Landau curve in the vicinity of the peak. This analytical description is known to be too low in the tail, but this does not affect the description provided here since most of the tail is out of range in the data and in figure 4.5. The maximum of the fitting line occurs at 0.65 V and corresponds to 1 mip. The error bars are purely statistical. Systematic errors due to muon traversing the detectors not vertically (therefore traversing more scintillating material and depositing more energy) are estimated to be of the order of 5%. The results confirm within statistical and systematic errors the $^{137}$Cs studies, which led to a mip value of 0.60 V for CARD4-A (table 4.1).

4.3 Existing Experiments Using LED Monitoring Systems

In the field of particle physics, most of the experiments around the world make use of LEDs to monitor scintillators. The LED-based systems are mostly used to increase calibration statistics, especially for large experiments, which would require very intense radioactive sources in order to get large statistics in calibration data. Among the experiments present in the literature, two have been of particular interest in the realisation of the PAMELA anticounter monitoring system:

- The Primakoff Experiment at Jefferson Lab (PrimEx) [58, 59] is designed to measure with high precision the width of the decay channel $\pi^0 \rightarrow \gamma\gamma$. The central part of the calorimeter consists of 1200 PbWO$_4$ crystal modules, that need periodic energy calibration based on a photon beam. The process is time consuming and can not be done often. An optical monitoring system [60] is used between beam calibrations as a relative calibration. Bright blue LED pulses, 8 ns each, simulate the scintillation response of the lead tungsten crystal. The stability of the system is very good, since the light pulse variation during one measurement is only 0.2% in average, and no noticeable degradation was observed over a period of six months.

- During Run II of the Tevatron, the D-zero [61] muon scintillation counters make use of an LED Pulser System [62], to speed up the calibration and fine tuning of the system used during Run I, which made use of cosmic muons and muon beams. Aim of the LED Pulser System is to imitate a muon passing through the counter, thus the voltage thresholds are accordingly set for each channel.

4.4 Monitoring with LEDs

The monitoring system for the PAMELA anticounters is designed to check the response of the anticounters to a known input. Given the impossibility of using
4.4. Monitoring with LEDs

Figure 4.7. LED based monitoring system (detail of LED mounted on CAS scintillator).

radioactive sources, as described earlier in this chapter, the chosen monitoring system is based on LEDs. Each scintillator has an LED glued on it (figure 4.7), and the micro-coaxial cable connected to the LED comes out from a hole drilled in the aluminium case (figure 4.8). The LED is placed far away from the PMT, in order to provide a long path for the photons to reach the PMT, which increases the sensitivity to opacity.

The output amplitude is set by the choice of the LED. Small form factor LEDs were chosen, to simplify the assembling work and to reduce the weight to a minimum. The LEDs are diodes conducting current (thus emitting light) only when the voltage exceeds a minimum operating voltage, typically around 2 V. Each LED has a minimum non-zero light output, which in most of the cases was too high to resemble a mip. This issue was solved making use of red low intensity LEDs. The emitted wavelength (640 nm, red part of the visible spectrum) does not match the scintillator quantum efficiency (∼ 430 nm, blue, figure 4.9) or the peak photocathode sensitivity, reducing further the number of photons converted into photoelectrons. In order to fine tune the intensity of the light pulses emitted by each LED, each LED transmission line contains a series resistor, to make the pulse from each PMT resemble a mip output.

Each LED emits short light pulses, whose shape and timescale have to be as similar as possible to mip-generated pulses. In the case where an ionising particle interacts with an organic scintillator, the response is very fast (less than 10 ns). Dispersion in the scintillator stretches the light pulse reaching the photocathode, then the photomultiplier tube stretches slightly the signal. The typical time scale is less than 50 ns.

In order to keep the electronic design as simple as possible, the monitoring system makes use of the same electronic system used for physics operation. The Actel FPGA is used to drive the LEDs, as shown in the set-up described in figure 4.11. When the FPGA is set to ‘calibration mode’, the program running on the DSP
starts flashing the LEDs and taking calibration curves.

One of the problems encountered during early tests was the impossibility of exactly reproduce mip-like pulses from each channel. This is due to the fact that each scintillator is read out by two PMTs, with different quantum efficiencies (section 3.3, but only one LED is present on each CAS (and CARD) scintillator. For CAS, each LED flash creates a light pulse in the scintillator, which corresponds to almost the same amount of photons on the photocathodes of the two PMTs, since they have the same sensitive area and their geometrical position differs by only 3 cm. The different PMT amplification factor is the cause of the two different PMT outputs. The above description applies also to CAT, with the main difference that CAT is read out by 8 PMTs, and 2 LEDs are present.

4.4.1 LED Pulse Amplitude

It was mentioned in the previous section that the amplitude was first set choosing the correct LED (wavelength, intensity; see figure 4.12), then fine tuned with the series resistors placed between the transmitter (Actel FPGA) and the LED. The overall setup is schematically represented in figure 4.11. The relevant LED properties are taken from the datasheet [63] and are shown in figure 4.10. Tests performed with 4 LEDs with different characteristics glued on the engineering model of a side anticounter (CAS) provided the results plotted in figure 4.12. The most suitable
4.4. Monitoring with LEDs

Figure 4.9. Scintillator light yield and PMT quantum efficiency. From [64, 44]

Figure 4.10. a) LED emission spectrum; b) LED output temperature dependence. From [63].
LED is a low emission red LED\textsuperscript{5}. Its voltage range is within the requirements, and its output is the less sensitive to input voltage variations.

Once the LED is chosen, the pulse amplitude and width have to be set. Tests with a pulse generator were performed in order to test the PMT response as function of the input LED voltage for pulse length in the range 10–80 ns (figure 4.13). Pulse amplitudes between 20 and 40 ns were investigated further making use of an Altera FPGA as transmitter and eventually 25 ns pulses (obtained with the 40 MHz clock already present on the AC read-out board) were chosen for the final design.

On the AC electronic board, the pulse amplitude is tuned by the insertion of a series resistor between the FPGA (transmitter, with constant voltage, equal to 3.3 V) and the LED (figure 4.11). The voltage across the LED as function of the resistor value is evaluated from the LED (non linear) impedance and it is shown in figure 4.14. Several resistors in the range 51–110 Ω have been tested on each channel. The resistor is then chosen independently for each LED. For each LED, the final value of the series resistor is then chosen analysing the spectra of an LED-based calibration curve (section 4.4.3). The chosen resistor values are indicated in table 4.2.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{CAS} & \textbf{LED} & \textbf{R (Ω)} & \textbf{ΔV (V)} & \textbf{I (mA)} \\
\hline
CAS1 & 82 & 1.86 & 17.6 \\
CAS2 & 51 & 2.03 & 24.9 \\
CAS3 & 51 & 2.03 & 24.9 \\
CAS4 & 56 & 2.00 & 23.3 \\
\hline
\textbf{CAT} & \textbf{LED} & \textbf{R (Ω)} & \textbf{ΔV (V)} & \textbf{I (mA)} \\
\hline
CAT1 & 56 & 2.00 & 23.3 \\
CAT2 & 56 & 2.00 & 23.3 \\
\hline
\textbf{CARD} & \textbf{LED} & \textbf{R (Ω)} & \textbf{ΔV (V)} & \textbf{I (mA)} \\
\hline
CARD1 & 110 & 1.77 & 13.9 \\
CARD2 & 110 & 1.77 & 13.9 \\
CARD3 & 110 & 1.77 & 13.9 \\
CARD4 & 110 & 1.77 & 13.9 \\
\hline
\end{tabular}
\caption{Choice of the series resistors.}
\end{table}

4.4.2 LED-System Qualification Tests

Operating conditions will vary during the flight, inducing changes in the monitoring system. For this reason stability tests of the system have been performed in the

\textsuperscript{5}Technical LED details: Everlight Electronics Co., Ltd. Model No: 15-21VRC/TR8. Emitted wavelength: 640 nm; low luminous intensity (9 mcd). From [63].
4.4. Monitoring with LEDs

Figure 4.11. LED based monitoring system: set-up.

Figure 4.12. Output from the PMT as function of the input voltage to the LED. The 40 ns long pulses to the LED come from a pulse generator. The device under test is the engineering model of a side anticounter (its main difference compared to the flight model is the thickness: 1 cm, compared with the 8 mm thick flight model of CAS and CAT). The 5 different curves correspond to LEDs with different wavelength and intensity (see the legend in the figure). The output corresponding to the chosen LED (VRC) is shown as a bold line. Its voltage range is within the requirements and its behaviour as function of the input voltage is flatter than the other LEDs tested, which ensures small output variations in case of any (small) variation in the input voltage.
laboratory in Stockholm, to study the response of the detectors to known inputs.

Temperature tests

The output variations of the LED system due to room temperature variations have been studied. Figure 4.10a (LED datasheet) shows that the LED light yield can vary up to about 10% in the temperature range of interest, which explains the preliminary results obtained in the laboratory.

The PAMELA flight model will undergo temperature cycle tests in Russia before launch, which will provide detailed LED-based monitoring data over a wide temperature range. Previous thermal cycle tests (20°C–60°C) of the AC electronics performed in the laboratory in Stockholm were aimed at assessing the temperature dependence of the FPGA. The electronic board was the only part of the AC system in the oven. Continuous data taking during the test did not show any change in the LED data. Any change in the LED data in the planned thermal tests in Russia will therefore be solely due to the LED/detector system. During flight, LED data will be analysed offline, and temperature effects will be taken into consideration in the analysis.

Radiation effects

Radiation damages to LEDs have been evaluated after irradiation with γ-rays and are analysed in details in section 3.5.1, together with the radiation tests performed
4.4. Monitoring with LEDs

The qualification tests on the LED system described until here were performed with the CAS and CAT detectors, which were delivered to Rome for integration with the other subdetectors before the final version of the AC read-out system was available. For this reason the CARD detectors were used in the tests of the LED system described from this point. The similar geometry for the other detectors makes this solution reasonable.

Figure 4.16 shows the integral (top 8 plots) and differential (lower 8 plots) LED-based spectra for the 4 CARD detectors. As described in section 4.2, the spectra...
are taken varying the discriminator threshold from 0 to 1 V through 256 steps. The differential spectrum is evaluated from subtracting consecutive elements of the integral spectrum. The differential spectrum is limited (all the pulses are below a certain discriminator threshold) and almost symmetric. No binning has been used to obtain this figure. On the x-axis, the discriminator level is shown in Volts in all plots. Table 4.3 shows the voltages correspondent to 1 mip (obtained from the Compton edge of $^{137}$Cs) and the mean value of the LED distribution. The standard deviation is also shown.

The singles rate from cosmic particles in a PAMELA AC scintillator at sea level is small enough (above electronic noise, the rate is below 100 Hz) to reduce the probability of one random coincidence in the time window $t_{gate}$ to less than 1%. The cosmic contribution to the number of hits during the LED calibration procedure is therefore neglected.

### 4.4.4 Statistical Deviations in Calibration Curves

During each LED calibration procedure, the number of light flashes in each bunch is fixed. The statistical errors can be estimated with the same procedure described for muon detection (section 4.2.2), and are therefore typical of a binomial distribution. The results, shown in figure 4.17, should be compared with the muon spectra encountered earlier (figure 4.5). Even if no rebinning has been applied to the plot, the error bars in the integral spectrum are barely visible in the figure, since they are too small. The differential spectrum is obtained by subtracting consecutive
Figure 4.16. Calibration curves obtained with the LED-based monitoring system and the CARD detectors. See text for details.
Table 4.3. For each CARD detector, the $^{137}$Cs Compton edge (CE) is used to calculate the value of 1 mip. This is compared to the mean of the LED differential spectrum. The standard deviation of the LED distribution ($\sigma$) is shown in the last column.

<table>
<thead>
<tr>
<th>Detector CARD</th>
<th>$^{137}$Cs CE (V)</th>
<th>Calculated mip (V)</th>
<th>LED mean (V)</th>
<th>LED $\sigma$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-A</td>
<td>0.35</td>
<td>1.17</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>1-B</td>
<td>0.28</td>
<td>0.94</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>2-A</td>
<td>0.32</td>
<td>1.07</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>2-B</td>
<td>0.39</td>
<td>1.31</td>
<td>0.21</td>
<td>0.04</td>
</tr>
<tr>
<td>3-A</td>
<td>0.30</td>
<td>1.00</td>
<td>0.18</td>
<td>0.03</td>
</tr>
<tr>
<td>3-B</td>
<td>0.32</td>
<td>1.07</td>
<td>0.23</td>
<td>0.06</td>
</tr>
<tr>
<td>4-A</td>
<td>0.18</td>
<td>0.60</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>4-B</td>
<td>0.40</td>
<td>1.34</td>
<td>0.23</td>
<td>0.05</td>
</tr>
</tbody>
</table>

elements of the integral spectrum. The errors are thus doubled in this procedure: they are plotted in figure 4.17b, still without rebinning the data. It is here assumed that the errors in successive bins are uncorrelated.

![Integral Spectrum](image-a)

![Differential Spectrum](image-b)

Figure 4.17. LED-generated integral (a) and differential (b) spectrum with statistical error bars. Detector CARD3-A.

4.5 LED Monitoring: Conclusions

An LED monitoring system has been designed, implemented and tested. In the design phase, the Compton edge from a $^{137}$Cs source is used for a pre-flight calibra-
tion of the CARD detectors. The same procedure will be performed on the CAS and CAT detectors in Rome in the next months. The LED pulse properties are adjusted to allow the energy scale around the Compton edge position to be monitored in flight. The AC discriminator voltages will be set during physics operation to correspond to $\sim 0.5$ mips. These studies, performed with radioactive sources and cosmic muons, show the relation between various spectra ($^{137}$Cs, cosmic muons and LEDs), reported in figure 4.18.

The monitoring procedure provides large statistics (statistical errors $\sim 1\%$) in a short time ($\sim 1.4$ s). This makes the LED system invaluable for stability studies of the AC system. In orbit the LED system will be the main monitoring system, given the impossibility of calibrating the detectors with a radioactive source.

The main goal of the LED system is to detect and quantify any variation in the AC detectors performance. If any variation occurs, it would be detected as a change in the LED-induced spectrum, and the voltage corresponding to 1 mip is recalculated according to the new measures.

The system will be studied after launch, since vibration may potentially change the PMT–scintillator coupling. This would be seen as a change in the peak position or a broadening of the peak after launch. Changes occurring at a later stage will lead to a redefinition of the relation between the discriminator threshold scale and the deposited energy scale.

**Figure 4.18.** Comparison between LED, $^{137}$Cs and muon differential spectra. The $x$-axis is common to all data. The $y$-axis is linear for LEDs and muons, logarithmic for $^{137}$Cs.
4.6 Application: Magnetic Field Effects

The magnet that surrounds the tracking system could potentially modify the output of all the PMTs present in the PAMELA detectors. In the PMTs, the electron trajectories between consecutive dynodes are finely tuned to reach an amplification of $\sim 10^6$. A strong magnetic field may modify these trajectories and reduce the PMT amplification. Detailed calculations of the field strength at the PMT positions have been done [34] according to the distribution of materials in the detectors. The residual field $\vec{B}_f$ the AC PMTs have to sustain is less than 0.5 mT along any of the three spatial directions parallel to the PMT edges (Earth’s magnetic field: 50 $\mu$T). The magnet is covered with ferromagnetic screens. Since the satellite is steered by a magnetic system, many efforts were dedicated to ensure that the residual dipole field was minimised.

Tests on the modified AC system output in the presence of the residual magnetic field have been done after the integration of the AC detectors in flight configuration in the clean room at INFN, Rome (figure 4.19). Calibration curves obtained with the detectors mounted in flight configuration were compared with analogous curves taken with the detectors far away from the magnet. The curves were taken in the same environmental conditions (except for the magnetic field), separated by few minutes. The magnetic field effects were confirmed to be negligible, as expected from figure 4.20. The results confirm that the AC PMTs do not require further magnetic shielding.
4.7 Complementary Monitoring Procedures

The LED monitoring system will be able to detect and quantify any change in the detector properties. In order to reach the highest possible level of redundancy in the monitoring and calibration process, other modes of calibration based on cosmic rays have been studied. The main goal of a secondary calibration system is to extract as much new information as possible without dedicating more time to the calibration.

The next section provides a description of an alternative monitoring procedure, that will be performed in conjunction with the LED based monitoring procedure during calibration runs. Section 4.7.2 describes other means of monitoring the performance of the detector during flight using physics data.

4.7.1 Counting Rate (with Random Trigger)

The calorimeter and tracker are calibrated with ‘random triggers’. These triggers are called “random”, even if their frequency is fixed, since they are not in coincidence with a particle traversing PAMELA. Random triggers are used to measure the pedestal of these detectors. These triggers will be directed also to the anti-counter system, where they will be used to assess the rate of accidental hits in the AC system. The rate may increase if, for example, a PMT becomes noisy. The random trigger acquisition will be performed after the LED monitoring procedure, during each calibration, with the discriminator thresholds set to the levels used...
in physics acquisition. For every incoming trigger, the DSP reads and saves into memory the content of the shift register. Data is then analysed offline on Earth.

4.7.2 System Stability

The stability of the system is monitored through the calibration procedures described in the previous sections. Another invaluable mean of checking the system for changes comes from the offline analysis of physics data. The counters implemented in the FPGA design are the most important instrument to monitor the singles rates as a function of orbital position during physics operation. Other variables should be monitored during the lifetime of the experiment. The large statistics should allow a prompt discovery of variations in the hit position and length in the shift register, a presence of double hits in specific positions in the SR (see results from beam test studies in chapter 5).

4.8 The Calibration System

The PAMELA apparatus will enter calibration mode (see section 2.8 for an overview of operational modes) once every orbit, at the ascending node. Each subdetector is calibrated according to a procedure decided by the group responsible for the detector. All the detectors are calibrated one after the other.

The AC system is the first subdetector to be calibrated. The procedure consists of two consecutive analysis, the first based on LEDs (section 4.4.3) and the second on random triggers (section 4.7.1). During the first phase (LEDs), the monitoring system makes use of the free running counters present in the read-out electronics. The counters are activated and measure the number of pulses above the threshold level for a time \( t_{\text{gate}} \). During flight, it is planned to perform calibrations for all PAMELA detectors when approaching equatorial regions. This means that the radiation level in the environment is low during calibration, which ensures that the probability of random coincidence of particles is small. The expected particle rate for a plane scintillator with a sensitive area \( A = 0.25 \text{ m}^2 \) is \( \sim 30 \text{ Hz} \). This comes from an estimation of singles rate in the space region where PAMELA will operate [65]. In the time window \( t_{\text{gate}} \), in average a number of particles \( N_p < 0.1 \) would be present. Out of 6220 pulses, less than 0.1 are expected to come from cosmic particles. The LED monitoring procedure can thus be considered not to be affected by coincidences with cosmic particles.

The calibration procedure is handled by the DSP, in conjunction with the FPGA. The FPGA handles the communication link with the IDAQ, sends at the beginning of the calibration the ‘start’ command to the DSP, and sends the pulses to LEDs, when the DSP sends the appropriate command to the FPGA. The calibration data is stored in the DSP data memory and is read at the end of calibration.

The time needed for the LED based monitoring procedure of the AC system is less than 2 seconds. The largest contribution to time needed for the LED procedure
4.8. The Calibration System

is represented by the time needed to send the LED pulses. The remaining time is used for data transmission between the PSCU and the AC board (LVDS link at $\sim 5$ MHz) and between DSP and FPGA on the AC board (TTL logic at 40 MHz). The monitoring procedure based on random triggers takes $\sim 30$ s to be completed, but since it is performed in parallel with the calorimeter (and tracker) calibration, it does not need any extra time.
Chapter 5

Tests with Particle Beams

The response of all of the PAMELA subdetectors has been studied on a yearly basis between 2000 and 2003. First subdetectors were tested stand-alone, but later tests were performed with PAMELA in a flight configuration.

During the spring and summer of 2003, the tracker system, two layers of the time of flight scintillators (S2 and S3, see section 2.3.1), the calorimeter, the anticounter system, the neutron detector and the S4 scintillator were mounted in their flight configuration in the clean room of the INFN Wizard Group, in Rome. A few months later, in September 2003, all these detectors were tested in a beam line at the SPS accelerator at CERN. The anticounter (AC) detectors flight model was first tested with beam particles in June 2002. Previous tests had been done with the engineering model of the anticounter scintillators. The beam test that took place in September 2003 was the first occasion to test the final electronic AC read-out system. Until the 2002 beam test, temporary electronic boards had been used. See table 5.1 for details of all PAMELA testbeams.

The performance of the anticounter system during the September 2003 beam test is investigated in this chapter with an independent analysis, which does not make use of data from other detectors. A combined analysis using the AC data together with data from other detectors will be presented in [51]. Results from previous beam tests for the PAMELA anticounter system are discussed in [66, 67, 44].

5.1 The SPS Particle Beam

The test took place in the North Experimental Area (H2 beamline) of the SPS secondary beamline, at the CERN Prévessin site. Primary protons with momentum up to 400 GeV/c are extracted from the SPS and directed to the experimental areas. These protons are made to collide with targets, placed along the beam line.
Table 5.1. PAMELA beam tests. The engineering model (EM) of the AC data acquisition system (DAQ) was based on Altera FPGAs (Flex or Apex) in the test-beams until 2002. The flight model (FM) DAQ was based on the final Actel FPGA, mounted in a socket. The other detectors listed are the calorimeter (CALO), tracker (TRK), transition radiation detector (TRD), ToF (S2-S3), S4 and neutron detector (ND). The engineering model of the power converter (DC/DC) was used during the September 2003 beam test. A star (*) indicates the flight model of the detector was used.

<table>
<thead>
<tr>
<th>Date</th>
<th>Beam</th>
<th>AC Detectors</th>
<th>AC DAQ</th>
<th>Other Detectors Detectors</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2000</td>
<td>PS</td>
<td>pre-EM, 1/4 CAT+1CAS (standalone)</td>
<td>pre-EM, Flex-based</td>
<td>CALO, TRK, TRD</td>
<td></td>
</tr>
<tr>
<td>7/2000</td>
<td>SPS</td>
<td>EM v.1, CAT+1CAS (standalone)</td>
<td>pre-EM, Flex-based</td>
<td>CALO, TRK, TRD, S4</td>
<td>[44]</td>
</tr>
<tr>
<td>10/2001</td>
<td>SPS</td>
<td>EM, CAT+1CAS (standalone)</td>
<td>EM, Apex-based</td>
<td>CALO</td>
<td>[44]</td>
</tr>
<tr>
<td>6/2002</td>
<td>SPS</td>
<td>FM CAT+4CAS (mounted)</td>
<td>EM, Apex-based</td>
<td>TRK*, CALO*</td>
<td>[66], [67]</td>
</tr>
<tr>
<td>7/2002</td>
<td>PS</td>
<td>not present</td>
<td>not present</td>
<td>TRD, CALO*</td>
<td>[67]</td>
</tr>
<tr>
<td>9/2003</td>
<td>SPS</td>
<td>FM CAT+4CAS (mounted in Rome)</td>
<td>FM (socket), EM DC/DC</td>
<td>TRK*, CALO*, S2-S3* (no read-out), S4*, ND*</td>
<td>This work, [67], [51]</td>
</tr>
</tbody>
</table>

The resulting secondary particle beams consist of (depending on the target chosen) hadrons, electrons and muons of momenta between 10 and 400 GeV/c [68, 69].

To test the PAMELA response to particles with known characteristics (type, energy and position), electrons with energies between 20 and 180 GeV and protons between 40 and 150 GeV have been used. Lower energies were not possible, since the particle rate on PAMELA was too low. The experimental area and the beam conditions are discussed further in [70], [71] and [72].

The primary particle beam was available for tests for 6 days, 4 of which were primarily dedicated to LHC experiments to verify the electronics and detector designs under realistic LHC operating conditions. This meant that the proton beam coming from the SPS had a 25 ns bunch structure, which reproduces the beam configuration at the LHC (figure 5.1).
5.2 PAMELA Configuration at the Beam Test

At the test, the detectors present were: the electromagnetic calorimeter, the tracker, the anticounter system, the Time of Flight (ToF) detectors, the neutron detector and the S4 scintillator. All of these detectors were already mounted in flight configuration and had been shipped from the INFN laboratory in Rome to Geneva for the test. Due to delays in the flight read-out system, the ToF scintillators were physically present but not powered. An external trigger system was therefore needed for PAMELA. Four scintillators placed in the beam line generated the trigger signal for all the detectors and for the data acquisition system. Two small finger-shaped scintillators, slightly overlapping, provide a coincidence signal and two larger scintillators (with a hole over the overlap of the “fingers”) form an anti-coincidence signal. The first two scintillators define the hit location, and the latter two reduce the inevitable halo that surrounds the beam.

PAMELA arrived from Rome on-board a truck, in a large vessel, that provided it with a protected environment and protected it from vibrations. Figure 5.2 shows a photo of PAMELA in the beam area, when the vessel had just been opened. The bottom half of the (white) vessel is clearly visible in the lower part of the photo. Above it, there is the baseplate to which the calorimeter and the tracker are connected, and which is also used to lift PAMELA with the crane. Above the plate, the anticounter detectors are visible, surrounded by the read-out and high-
voltage cables. Once placed in position in the beam line, PAMELA is covered by a plastic box (approximately $1.5 \times 1.5 \times 2 \text{ m}^3$), as shown in figure 5.3. An air conditioning system removes the heat generated by the power supply units and read-out electronics present inside the box. The temperature and humidity in the box were therefore constant during the whole duration of the tests. During flight operations, there will be a liquid cooling system for this purpose. Part of a (still unconnected) cooling pipe is visible in figure 5.2, just above the baseplate (centre-left).

Inside the box, PAMELA is mounted on a custom-built support and rotated in order to align the acceptance with the beam line. The beam can be directed into different positions in the tracker cavity by moving PAMELA. The support allows variations of the tilt angles $\alpha$ and $\beta$ as well as horizontal translations. The plane hosting the whole structure may be shifted vertically. Figure 5.4 provides a definition of the coordinates system used to describe the PAMELA positions.
A frontal view of PAMELA in the beam line is provided in figure 5.5, which shows a drawing of CAT and an expanded view of the 4 CAS detectors. The CAS detectors have been enlarged and displaced from CAT, that would otherwise cover most of them in such a view of PAMELA.

5.2.1 The Read-Out System

The PAMELA space-qualified CPU (PSCU, section 2.3.8) was still under development in Rome when the beam test took place. An alternative, PC-based data acquisition system was therefore used to acquire data during the beam test. The system consisted of a National Instrument card (NI PCI-6534, data rate up to 80 MB/s) mounted in a PC with Windows 2000 operating system. A known but thought to be benign bug in the AC read-out system (the FPGA did not answer the request for event data in about 2% of the cases) provoked continuous crashes in the data acquisition system. This was due to a problem with the time-out handling and meant that a standalone read-out system for the anticounter detectors had to be built. The system was set up in less than two days, losing about 24 hours of
beam time for the anticounter system. Once the system was set up, the AC standalone read-out system and the PAMELA read-out system ran independently, but the events could be matched later, thanks to the trigger counters stored in both AC and tracker data. This allows a combined data analysis even if the AC system registered a data loss of $\sim 2\%$. The data loss depends on the fact that, when the AC board fails in sending data, the acquisition system waits for a time equal to the preset time-out and does not register the following event(s).

5.3 Results

In this section the results from the analysis of testbeam data are presented. The results are divided into ‘performance of the electronics’, which includes shift register studies, a stability study of the temperature sensors and an analysis of the status word. Later, previous backscattering studies are reviewed and the dependance of backscattered particles versus the beam type and energy is analysed. An analysis of the AC detector efficiency follows.

5.3.1 Performance of the AC Electronics

The test beam was the first opportunity to test the flight model electronics design in realistic conditions. The electronics board was placed with boards from other subdetectors in a custom-built crate attached to PAMELA’s baseplate. The electronics
5.3. Results

Figure 5.5. CAT in the beam (front view). The 8 PMTs facing CAT are shown and named according to the convention adopted for the CAS detectors. Each CAS detector is schematically represented with two rectangles; one represents the scintillator and the other the case containing the 2 PMTs (for details on CAS, see figure 3.3).

was therefore exposed to the possibility of Single Event Effects (SEE, section 2.7). The stability of the electronics to a large number of triggers was studied.

Shift Register Stability

The shift register (SR) is designed to contain all the hits due to backscattered particles in the centre. Figures 5.6–5.9 show the counts in each SR bin for all 16 channels for electrons (20 GeV and 180 GeV) and protons (40 GeV and 150 GeV). The shift registers work properly and are stable, since the majority of the hits are always in the central 3 bits. Furthermore, CAT4-B shows a peculiar double-peak, visible as an anomaly in figures 5.6–5.9. Investigations led to the discovery of a broken soldering and a missing ground connection on this channel. Table 5.2 confirms that the second peak for CAT4-B is dependent on the main peak and is therefore consistent with the ‘ringing’ on the electronic transmission line due to the broken soldering.

The difference between CAS and CAT detectors consists in a ‘tail’ of hits detected after the trigger (up to ~ 500 ns delay). This tail, present in the CAS detectors for proton and electron runs, is less pronounced (absent) on CAT for
Figure 5.6. Position of hits in shift register for electrons at $E = 20$ GeV. The $x$-axis shows the 16 bins in the shift register (left: times before the trigger). The $y$-axis represents the number of counts, with a logarithmic $y$-scale. Triggered events: $\sim 10^4$.

Figure 5.7. Position of hits in shift register for electrons at $E = 180$ GeV. Logarithmic $y$-scale. Triggered events: $\sim 10^4$. 
5.3. Results

Figure 5.8. Position of hits in shift register for protons at $E = 40$ GeV. Logarithmic $y$-scale. Triggered events: $\sim 10^4$.

Figure 5.9. Position of hits in shift register for protons at $E = 150$ GeV. Logarithmic $y$-scale. Triggered events: $\sim 10^4$. 
Table 5.2. A summary of the hit position in the shift register (SR). ‘Centred’ refers to bits 7-9, ‘off-centre’ refers to bits 1-6 or 10-16 and ‘off-only’ refers to off-centre hits with no centred activity. All results are shown in % and normalised to the ‘centred’ activity. Beam: electrons (20 GeV and 180 GeV) and protons (40 GeV and 150 GeV). Most of the off-centre hits do not have a counterpart in the SR centre, i.e. these events are not directly related to the particles triggered by PAMELA. The different behaviour of CAT4-B is discussed on page 77.

<table>
<thead>
<tr>
<th>CAS</th>
<th>1-A</th>
<th>1-B</th>
<th>2-A</th>
<th>2-B</th>
<th>3-A</th>
<th>3-B</th>
<th>4-A</th>
<th>4-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>off-centre</td>
<td>3.54</td>
<td>2.75</td>
<td>3.33</td>
<td>2.64</td>
<td>4.33</td>
<td>3.79</td>
<td>2.24</td>
<td>2.65</td>
</tr>
<tr>
<td>off only</td>
<td>3.54</td>
<td>2.52</td>
<td>3.33</td>
<td>2.64</td>
<td>4.11</td>
<td>3.37</td>
<td>2.24</td>
<td>2.48</td>
</tr>
<tr>
<td>CAT</td>
<td>1-A</td>
<td>1-B</td>
<td>2-A</td>
<td>2-B</td>
<td>3-A</td>
<td>3-B</td>
<td>4-A</td>
<td>4-B</td>
</tr>
<tr>
<td>off-centre</td>
<td>1.09</td>
<td>1.77</td>
<td>0.89</td>
<td>0.62</td>
<td>1.37</td>
<td>1.19</td>
<td>0.95</td>
<td>23.40</td>
</tr>
<tr>
<td>off only</td>
<td>1.09</td>
<td>1.26</td>
<td>0.76</td>
<td>0.46</td>
<td>1.21</td>
<td>1.19</td>
<td>0.79</td>
<td>0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAS</th>
<th>1-A</th>
<th>1-B</th>
<th>2-A</th>
<th>2-B</th>
<th>3-A</th>
<th>3-B</th>
<th>4-A</th>
<th>4-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>off-centre</td>
<td>1.82</td>
<td>1.90</td>
<td>2.22</td>
<td>1.87</td>
<td>2.24</td>
<td>1.99</td>
<td>2.42</td>
<td>2.41</td>
</tr>
<tr>
<td>off only</td>
<td>1.55</td>
<td>1.70</td>
<td>1.61</td>
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proton (electron) runs, and may be explained by ‘delayed backscattering’. Particles interacting in the calorimeter may interact with the infrastructures present in the beam area (mostly concrete and metal) and give rise to low energy photons. These photons may reach the CAS detectors, producing the measured tail. The length of the tail is consistent with photons generated in infrastructures distant few tens of meters from PAMELA. The effects is not present on CAT because CAT is covered by the magnet, and is therefore shielded from scattered photons. Another explanation of the existance of a tail is related to the feature of the 25 ns pulsed beam, described in section 5.1 and illustrated in figure 5.1. If the trigger system registers a particle in one of the first bunches, the particles present in the following bunches can be recorded by the anticounter detectors. These hits may be due backscattered particles or to direct hits, depending on the beam focus quality and external trigger system efficiency. The observation of several double tracks in the magnet spectrometer during the beam test strengthens this hypothesis, but does not explain the difference between CAS and CAT behaviour. The ‘delayed backscattering’ hypothesis is thus preferred.

The higher ‘off-centre’ activity in the proton runs may be due to coincidental hits by other protons in the same bunch ‘train’ (1.2µs, figure 5.1). This hypothesis is supported by the large number of particles per spill in proton runs compared to the electron runs [75]. The different behaviour between electron and proton runs may also be a reflection that in the hadronic interactions pions and muons are produced, which are more likely to reach the AC detectors.

The same data is summarised in table 5.2, which shows that in the majority of the events ‘off-centred’ hits do not have a counterpart in the central bins. This implies that the tail is dominated by single entries. Figure 5.10 shows the number of cluster in the shift register for electrons at 180 GeV. Similar results are seen at other energies. The width of the clusters is shown in figure 5.11. The large majority of the events present only one cluster, where the cluster is mostly one bin wide (80 ns). No events were measured with more than 2 clusters or with clusters longer than 2 bins (CAT4-B excluded).

**Temperature Measurements**

Four temperature sensors are placed on the AC read-out board. They are glued respectively to: ground plane (T1), Actel (T2, not mounted during the beam test), DSP (T3), PCB surface (T4). The AC temperature monitoring system must be very stable to avoid generating false alarms but reliably send an alarm if the temperature rises above a certain value.

During the whole test, PAMELA was in a temperature controlled environment, which allowed a stability test of the AC temperature system to be performed. Figure 5.12 shows the three temperatures (T2 is not plotted). They are constant, within two bits. The temperatures are saved as 8-bit words, and have a precision of 2° C. Assuming the real temperature inside the box is constant, the AC temperature
Figure 5.10. Histogram over the number of clusters (x-axis) in shift register (SR). Beam: electrons (180 GeV). Triggered events: $\sim 10^4$. Logarithmic y-scale.

Figure 5.11. Cluster width. Beam: electrons (180 GeV). Triggered events: $\sim 10^4$. Logarithmic y-scale.
monitoring has a precision better than 5°C, as expected. No transient errors in the ADC components were therefore seen (see section 3.5.1).

![Graphs of T1, T3, and T4 temperatures](image)

**Figure 5.12.** Three temperature sensors, mounted on the anticounter read-out board, provide a monitoring of the temperature in the PAMELA electronic crate during the beam test data acquisition. The x-axis shows the full ADC range (0-255 in binary units).

### Status Word

The status word (section 3.4) contains information on alarms generated by the AC read-out system and has therefore to work reliably in space. The beam test was a good occasion to test the reliability and stability of the status word over a long period of time in space-like conditions. The CRC bit could not be tested properly because of the problem in the data acquisition system described in section 5.2.1. After the first ‘no-answer’ event, the bit indicated an error until a reset command was sent, i.e. until the end of the run.

The other 15 bits of the status word worked properly during the beam test and never showed any alarm.

### 5.3.2 Backscattering Studies

The first level trigger in PAMELA is a coincidental deposit of energy in the 3 layers of the Time of Flight system. Monte Carlo simulations [44] have shown that the majority of triggers in space are expected to be “false” triggers, i.e. where the coincidental energy deposits in the ToF scintillators do not arise from the passage of a particle through the acceptance of PAMELA. For example, a particle can enter PAMELA from the side of the tracker (through one of the CAS anticounters) and interact in the magnet, with the secondary particles produced fulfilling the trigger criteria. A second level trigger has therefore been studied, with the insertion of the anticounter detectors in the trigger system. A problem arises when “good” events, i.e. passing cleanly through the tracker cavity, are rejected because of particles...
Figure 5.13. Backscattering ratio versus energy for electrons (circles) and protons (triangles). Each plot corresponds to an electronic channel (PMT). The 8 plots on the left (right) describe CAS (CAT) response. The data points correspond to the same hit point \((s, h)\) constant, figure 5.4). Events per run: \(10^4\) for electrons, \(5 \cdot 10^4\) for protons.

backscattered from the calorimeter through one of the AC scintillators. A good event would be discarded due to this “self-veto”. It is thus important to evaluate the backscattering as function of the incident particle. The backscattering ratio (events with AC activity due to backscattering / total events, usually in \(\%\)) is often used analysing beam test data. Studies of previous test beam data and simulations have been performed [44] with the engineering model of the AC system using data from the 2001 testbeam. The main aim of the analysis presented here is to compare results from previous beam tests with the data from the 2003 beam test. The comparison is very interesting because the mechanical configuration is now final. In previous studies PAMELA was not integrated. The anticounters were therefore positioned at an appropriate distance from the calorimeter with the expected orientation. There was no material between the calorimeter and the anticounters, in stark contrast to the integrated configuration (magnet present). In the future simulations will be done to finalise the analysis of the data presented here.
The dependance of the backscattering ratio on particle type and energy has been evaluated for selected runs. Figure 5.13 shows, for each channel, the backscattering ratio for electrons in the energy range 20-180 GeV and for protons in the energy range 40-150 GeV. CAS shows a stronger energy dependance than CAT, which is confirmed by comparison with the 2001 data (experimental and simulated). The backscattering studies using data from the 2001 beam test ([44], p.54) make use only of one CAS detector. Furthermore, as mentioned earlier, the absence of the magnet during the 2001 beam test reflects in a larger backscattering ratio, especially at high energy. This is visible in figure 5.14, which shows data from backscattering in each CAS detector with electron beams from both beam tests. A hit in a CAS detector is defined as an event with activity in at least one of the two PMTs facing the scintillator. The 4 CAS detectors show a systematic difference in the backscattering ratio, due to the position of the beam, displaced from the geometrical centre of PAMELA acceptance. The data from the 2001 beam test, shown for reference, contains simulated and experimental data, which overlap almost completely (agreement within 0.6 σ for all the considered electron runs). Data from CAT was not implemented in the analysis of the 2001 beam test because the beam halo was too wide and the number of hits on CAT too large.

Figure 5.15 shows the backscattering ratio for electron and proton runs as function of the beam energy in CAS and CAT, where by definition a backscattering event in CAS (CAT) is an event with activity in at least one of the 8 CAS (CAT) PMTs. The AC total backscattering ratio is also shown (events with activity in at least one of 16 PMTs / total events). The backscattering ratios for CAS and CAT plotted in figure 5.15 are much higher than the values plotted in figure 5.13 (single PMTs) at all energies. This implies that in most of the backscattering events only one AC detector is hit.

Studies on the multiplicity of CAS detector signals have been done using beam test data. Figure 5.16 shows the activity in the CAS detectors summarised in number of CAS hit for several electron and proton runs at several energies. It is interesting to notice that backscattering events with particles entering correctly PAMELA acceptance are likely to show a signal only in one CAS detector (the distribution is energy and particle dependent), while particles interacting with the magnet from the sides have a higher probability of producing a signal in two or more CAS detectors. This feature will be investigated further in the near future for the development of the second level trigger.

During almost all runs, the discriminator thresholds were constant, with the value set by the studies with the radioactive sources (section 4.2.1) and cosmic rays (section 4.2.2 and [51]). This value corresponded the ~ 0.5 mip for all channels. Finally, a few runs have been done with increased threshold voltage (twice and 4 times the value chosen for physics operation). A decrease of the backscattering ratio when the threshold is set to 1 mip or more indicates that many particles traversing the detector are indeed mip, and that there are few multi-particle events. This behaviour is typical of CAS, while the backscattering ratio on CAT is nearly independent of the threshold (figure 5.17). Assuming the backscattered particles are
Figure 5.14. Backscattering ratio versus energy for the four CAS detectors (logic OR between the two PMTs facing the same detector) for electron beams. The results from the 2001 beam test [44] are shown (dotted lines); experimental and simulated data overlap almost completely.

Figure 5.15. Backscattering ratio versus energy for electrons and protons. The plot is the cumulative response for CAS, CAT (dotted lines) and total (solid), for electrons and protons (see legend).
5.3. Results

Figure 5.16. The number of CAS detectors giving a signal at the same time. The figure shows the fraction of events with 1, 2, 3 or 4 CAS detectors hit, and is normalised to the number of events with activity in CAS. The data refers to electrons in the energy range 40–180 GeV (circles) and protons (triangles) with energies 40–150 GeV entering the PAMELA acceptance. Data with a proton beam hitting the magnet ($\alpha = 0^\circ$, $\beta = -5^\circ$) is also shown (diamonds), where the four data sets refer to a hit on the magnet top side through CAT (solid line), on the magnet lateral side through CAS3 (dash-dot 30 GeV, dashed 100 GeV), magnet inside through S1 (dotted).
minimum ionising particles, the explanation probably lie in the event multiplicity, i.e. in the number of detected particles in the CAT scintillator in each backscattering event.

5.4 Efficiency Studies

Among the runs dedicated to the anticounter detectors, one consisted of directing the beam (5000 protons with energy 100 GeV) onto CAT, at the location shown in figure 5.18. Only one run of this kind was possible during the beam test. The light distribution inside the CAT scintillator has been studied. The fraction of the detected hits in each PMT facing CAT is shown in the same figure, normalised to the PMT with the highest hit count (CAT3-B). As expected, the PMTs that face directly the hit position have a much higher count rate than those on the opposite site of CAT. The other PMTs register most of the events too, which adds redundancy in case the primary 2 PMTs fail.

As already discussed in chapter 3, a “hit” in a CAS detector is defined as the logical OR between the two PMTs. Most of the times the two PMTs fire at the same time, while rarely only one fires. Figure 5.19a shows for each CAS the logical expressions: A AND B, A AND \overline{B}, B AND \overline{A}. All the expressions are normalised to the number of hits (A OR B). Normalised in this way, the first expression can be seen as the relative efficiency for a CAS detector.
5.4. Efficiency Studies

Figure 5.18. Light distribution on CAT PMTs with beam hitting CAT.

Figure 5.19. Relative efficiency estimation for CAS. a) For each CAS, the main bar (left) represents the total number of hits in both PMTs. The remaining two bars represent the number of hits in one PMT only (channels A and B, for each CAS detector). b) Histogram over the number of PMTs firing for each event. The data is normalised to the total number of events in each anticounter detector. The plots are obtained with a beam of electrons with energy 20 GeV.
For CAT it is not possible to define in the same way an efficiency, so the number of PMTs firing at the same time is used instead (figure 5.19b). Both plots of figure 5.19 have been obtained with an electron beam with energy 20 GeV.

5.5 Conclusions

This chapter describes the analysis of AC data from the September 2003 beam test at the CERN SPS, the first test in a beam line of the flight model of the AC detectors. The studies described in this chapter are aimed at the assessment of the AC read-out system performance during prolonged data acquisition runs in 'space-like' configuration. The overall behaviour of the system was reliable. Specific issues were tested positively: the most important are the stability of the temperature monitoring system, the reliability of the status word handling and the stability of the shift register.

The presented description of backscattering studies provides a method to identify backscattering events from 'false triggers', based on the multiplicity of the hits in the AC detectors. This result is important for the implementation of the second level trigger. Simulation studies are needed to confirm the experimental results.

Finally, efficiency studies for CAS and CAT detectors are presented, and the read-out redundancy is discussed.
Chapter 6

Conclusions

PAMELA is a space experiment devoted mainly to the study of the antimatter component of the cosmic radiation. Measurements performed across a wide range of energies for antiprotons (80 MeV–190 GeV) and positrons (50 MeV–270 GeV), partially unexplored at present, will resolve issues about cosmic ray production and propagation. If any primary component in the antimatter flux is found, it may be an indication of physics beyond the Standard Model of particle physics.

PAMELA consists of a magnetic spectrometer, an electromagnetic calorimeter, a transition radiation detector and a time of flight system. The spectrometer is surrounded by an anticounter shield, realised with plastic scintillators and read out by photomultiplier tubes. The anticounter system has been developed at KTH and tested in the laboratory and with beam particles. The aim of the anticounter system is to reject particles not cleanly entering the PAMELA acceptance but still giving rise to a trigger signal (‘false triggers’). A signal can also be produced in the anticounter system even if a particle passes cleanly through the acceptance of the experiment due to particles backscattered from the calorimeter. A comparison with previous backscattering studies ([44]) is presented. This study is the first with PAMELA fully integrated and showed that previous studies overestimated the amount of backscattering. A potential method to distinguish between false triggers and backscattering events is also presented and will be developed further with simulations in the future.

Beam test data was analysed to assess the AC read-out system performance during prolonged data acquisition runs in a ‘space-like’ configuration. The overall behaviour of the system was reliable. Specific issues were tested positively: for example, the stability of the temperature monitoring system, the reliability of the status word handling and the stability of the shift register.

An LED monitoring system has been designed, implemented and tested. In the design phase, a radioactive source and cosmic ray muons are used for a pre-flight calibration of the detectors. The monitoring procedure provides large statistics, which makes the LED system invaluable for stability studies of the AC system. In
orbit the LED system will be the main monitoring system, given the impossibility of calibrating the detectors with a radioactive source. A complementary monitoring procedure will make use of random triggers to assess the rate of accidental hits in the AC system. During physics mode, the counters implemented in the AC data acquisition system will monitor the singles rate as a function of orbital position.

The integration of the detectors is in a final stage now in the clean room in the INFN laboratory in Rome. In the next months the experiment will be delivered to Russia for integration with the Resurs satellite. The launch is scheduled towards the end of 2004 from the Baikonur cosmodrome.
Appendix A

Acronyms

List of the most used acronyms encountered in the thesis:

AC : AntiCoincidence  
ADC : Analog to Digital Converter  
CARD : AntiCounters Reserve Detectors  
CAS : Side AntiCounters  
CAT : Top AntiCounter  
CRC : Cyclic Redundancy Check  
CERN : European laboratory for particle physics (Geneva)  
: Centre Européen de Recherche Nucléaire  
DAC : Digital to Analog Converter  
DSP : Digital Signal Processing  
FPGA : Field Programmable Gate Array  
KTH : Kungl Tekniska Högskola (Royal Institute of Technology)  
IDaq : Intermediate Data Acquisition  
INFN : Istituto Nazionale di Fisica Nucleare  
: (Italian Institute for Nuclear Research)  
LED : Light Emitting Diode  
LHC : Large Hadron Collider  
LVDS : Low Voltage Differential Signal  
mip : minimum ionising particle  
PAMELA : A Payload for Antimatter Matter Exploration and Light nuclei Astrophysics  
PCB : Printed Circuit Board  
PMT : Photo Multiplier Tube  
QE : Quantum Efficiency  
PS : Proton Synchrotron  
PSCU : Processing and Storage Central Unit (space qualified PAMELA CPU)
SAA : South Atlantic Anomaly
SEE : Single Event Effect
SEL : Single Event Latch-up
SEU : Single Event Upset
SPS : Super Proton Synchrotron
SR : Shift Register
TRD : Transition Radiation Detector
TTL : Transistor Transistor Logic
Acknowledgments

This work could not have been possible without the help of many people.

First of all, I want to thank my supervisor Doc. Mark Pearce for his invaluable help during the time I spent at KTH. He has always been active and propositive and very helpful in the laboratory. I am grateful to him for proof-reading N times my thesis, without getting lost in my Italian constructions. His main corrections and suggestions concerned anyway the contents, which was not due to my brilliant English... I must thank him also because he became used to my “quarto d’ora accademico” without complaning (too much).

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Whoever invented the old saying that ‘you known a person only after you have spent one week together on a boat in the open sea’ had apparently never been to a beam test. I was present at three beam tests at CERN and every time I was surprised that unbearable schedules and technical difficulties never led to fights (seen on boats, though). On the contrary, I enjoyed the company of the colleagues that made the work in the control room more pleasant.

Thanks to the people of the PAMELA collaboration for their help in answering my questions. In particular, many thanks go to the colleagues in Rome, for their warm hospitality during my visits in the past two years.

I am proud to thank my friends from the volleyball team “Alla talar Italienska” and the football team “Ingen Aning” for reminding once more me during the past year that there is more than physics in life.
I can not end without mentioning all the friends that have always been close to me. Those here in Sweden, and especially the few that live on the other side of the ‘Norrbotten’ and that I still manage to be in touch daily or weekly with.

Finally, a special thank goes to my family for constant support and comprehension.
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