The PAMELA Si-W electromagnetic calorimeter

Luca Pacher

INFN and University of Turin

Final presentation for Calorimetry in Particle Physics Experiments
Outline

- the PAMELA experiment, introduction and motivations
- the PAMELA detector
- the Si-W electromagnetic calorimeter
- front-end electronics
- calibrations and performance
- some physics results
**Physics goals**

- a really nice acronym, not so appealing the full name...
  - a Payload for Antimatter-Matter Exploration and Light Nuclei Astrophysics

- very large Italian component (INFN) inside the PAMELA collaboration!

- PAMELA is a space *satellite* experiment!

- mainly designed for direct measurements of *primary cosmic rays antiparticles* (antiprotons and positrons) in the cosmic radiation over a wide energy range (100 MeV to ~ TeV)
  - precise measurements of *positrons* and *antiprotons* energy spectra
  - study of the cosmic ray *electrons* energy spectrum up to ~TeV

- search for evidence of light *anti-nuclei*, in particular anti-helium
  - measurement of the $\bar{\text{He}}$/He ratio with a sensitivity of $\sim 10^{-7}$

- search for evidence of *dark matter*

- *solar physics* studies
- the detector is hosted on-board the Russian *Resource-DK1* earth-observation satellite installed inside a pressurized container attached to the satellite itself
- placed in orbit on 15 June, 2006
- 350-600 km from the Earth surface, Sun synchronous
The PAMELA detector

- **TOF systems**
  - 3 planes of plastic scintillators + PMT
  - L1 trigger

- **anti-coincidence systems**
  - plastic scintillators + PMT
  - fake-triggers rejection

- **electromagnetic calorimeter**

- **spectrometer**
  - Si strip + magnet (0.43 T)
  - 6 planes of double-sided silicon μstrip
  - charge sign, rigidity (momentum/charge), $dE/dx$

- **neutron detector**
  - 36 $^3$He gas counters
  - high energy electron/hadron discrimination

1.3 m height, 470 kg total mass, 335 W power consumption
Calorimetry - requirements

- high granularity, radiation hardness (~25 kRad), low power consumption, compact size, mechanical reliability
- energy measurements, particle identification, shower spatial development
  - total energy deposited + energy distribution along the shower itself
  - reconstruction of showers spatial development, both in the longitudinal and transverse directions
- identification of cosmic-ray antiprotons from a huge electron background and positrons from a huge background of protons with high efficiency and high rejection power
  - the calorimeter must be able to separate electrons from hadrons at a level ~10^5
- extraction of the $\bar{p}$ signal
  - electron background ~5x10^3 times the antiproton component at 1 GeV, decreasing to ~10^2 at 10 GeV
  - ~90% efficiency
  - $e^-$ rejection power ~10^-4
- extraction of the $e^+$ signal
  - proton background ~10^3 times the positrons component at 1 GeV, increasing to 5x10^3 at 10 GeV
  - ~70% efficiency
  - $p$ rejection power ~10^-5
The Si-W sampling calorimeter

- 3x3 silicon matrices, 8cm x 8cm each one
- 24cm x 24cm total sensitive area
- each matrix is segmented into 32 read-out strips (2.4 mm pitch)
- each strip is bonded to the corresponding strip on the other two matrices in the same row/column, forming 24 cm long read-out strips
- strips of two consecutive layers are orthogonal, providing two-dimensional spatial information

- 44 single-sided silicon sensor planes, 380 μm thickness
- 22 plates of tungsten absorber, 0.26 cm thickness corresponding to 0.74 radiation lengths
- total depth of 16.3 radiation lengths and ~0.6 nuclear interaction lengths
- 24 x 24 x 18 cm$^3$ total sensitive volume, 110 kg total mass (including electronics and cables), 75 W power
- experimental vibration and shock tests successfully performed before the launch in space
Fron-End electronics

- each tungsten plate is sandwiched between 2 PCBs containing the silicon detector and the associated read-out electronics
- signals are read-out by a full-custom VLSI front-end chip specifically designed for the PAMELA calorimeter
  - the use of an ASIC allows a considerable weight saving, low power and compact design with respect to discrete preamplifiers used in previous balloon experiments

  - 2 μm mixed A/D CMOS technology
  - standard read-out chain (folded cascode CSA + CR-RC shaper + T/H + circuit + output MUX + buffer)
  - 16 read-out channels/chip x 6 chip/module x 44 modules = 4224 read-out channels
  - self-trigger system and input calibration circuit also integrated on the chip

- on each detector board the 6 CR-1.4P outputs are connected to a commercial 16-bit **ADC** (AD977A)
- 4 **DSPs** (ADSP2187) + one **FPGA** (Altera A54SX72) for reading, data processing and controls
- adopted also for the PAMELA Transition Radiation Detector (TRD)
More technicalities...

- **Front-End chip**
  - large detector capacitance, ~180 pF
  - 5 mV/ MIP gain (~1mV/ fC, with 1 MIP ~ 5 fC for 380 μm thick silicon)
  - 1 μs peaking time
  - high dynamic range, the linearity is conserved up to 1400 MIPs
  - low power consumption, less than 6 mW/channel → ~100 mW/chip
  - good noise performance, ENC ~2700 e- RMS (no input capacitance) + 4.7 e- RMS/pF (noise slope)
  - 30 kHz counting rate
  - self-trigger threshold ≥ 30 MIPs

- **ADC (AD977A)**
  - 5 μs conversion time
  - 60 mW power consumption
  - serial digital output

---

Measured linear range
(one single channel)
Self-trigger configuration

- A self-trigger system has been implemented in the calorimeter read-out electronics to measure very high-energy electrons (from ~300 GeV to more than 1 TeV) in the cosmic radiation.

- These events are quite rare in comparison with the nominal event rate of PAMELA.
  - A reasonable statistics can be achieved by increasing the geometrical acceptance.
  - The overall acceptance of the detector is determined by the spectrometer one and reaches ~21 cm$^2$sr.
  - With a modified trigger constraint, the overall acceptance becomes ~600 cm$^2$sr.

- The CR-1.4P chip includes a trigger-switch option in order to work both with an external trigger (standalone mode) and with a modified trigger requirement (self-trigger mode).
Test beam calibrations (1)

- Calibration data have been obtained in test beams at CERN SPS, 2002-2004.
- Runs with electrons, hadrons (protons, pions, etc.) and muons with different beam energies.
- The calorimeter capabilities has been evaluated both using data from test beams at CERN and MC simulations.
Test beam calibrations (2)

- 50 GeV electrons
- 50 GeV pions
- 150 GeV muons
- ADC pedestal due to noise and random triggers
- detector response to different charged particles

- signal distribution of one strip from MIP data
- 100 GeV hadron beam
- S/N ~ 5

Pedestal:
Gaussian Fit
Mean: 5206.9
Sigma: 7.2

Signal:
Landau Fit
Peak: 5243

ADC pedestal due to noise and random triggers

100 GeV hadron beam
S/N ~ 5
Test beam calibrations

ADC pedestal due to noise and random triggers

Detector response to different electrons beam energies.
**Test beam calibrations (4)**

- Calibration curve with electron test beam
- Linear response, no saturation
- 1 GeV = 4.2 x 640 ADC channels

- Number of hit strips vs total energy for proton and electrons test beams, 200 GeV
- Good separation between protons and electrons!
- Efficiency ~95%, with a rejection factor ~3x10^4
Energy resolution

- simulated energy resolution (GEANT4)
- stochastic term coefficient $a \sim 18\%$

- measured energy resolution with electrons test beam
- stochastic term coefficient $a \sim 29\%$
- constant term coefficient $c \sim 3\%$
- noise term $b/E$ not included in the fit
On-fly status and calibration

- The stability of the instrumentation is monitored by means of a set of external temperature, voltage and gain sensors and by looking at data taken every orbit during the calibration procedure.
- On-fly calibrations are done every ~90 minutes.

- In the example, monitored temperature of the calorimeter external box as a function of time (2 orbits around the Earth, ~3 hours).
- The temperature is stable at ~30°C, no variations from the average value can be noticed.
- No differences have been noticed also respect to the position of the satellite to the Sun.
Particle identification

- $dE/dx$ measurements provided by the calorimeter and the tracker can be used to identify the incident radiation
- the **rigidity** (momentum divided by charge) is measured by the magnetic spectrometer
Particle selection

- protons and electrons dominate the charged component of the cosmic radiation
  - *positrons* must be identified from a background of protons
  - *antiprotons* must be identified from a background of electrons

- electrons must be selected with high efficiency and small hadron contamination

- a complex set of *specific variables* is used to separate electromagnetic and hadronic showers in the calorimeter
  - shower starting point
  - longitudinal and transverse profiles
  - topological development of the shower
  - fraction of energy deposited along a track
  - etc...
e$^+$ selection example

An example of positron selection on a sample of events using a full set of variables and cuts to reject hadrons

**Fraction of energy** released along track in the calorimeter as given by the tracker for positive and negative particles

- dominant e$^-$ contribution (~50% energy lost)
- The positron component is completely overwhelmed by protons

Positron selection cuts have been applied

- non interacting particles disappear
- the positron distribution appears
Non interacting 18 GeV $p$ event

x-view

y-view
92 GeV/c $e^+$ event
84 GeV/c $p$ event

x-view

y-view
14.7 GeV/c Z=8 event
Some physics results

- preliminary results presented in August 2008 at ICHEP (Philadelphia)
- data show an excess of positrons in the 10-60 GeV range
  - maybe a sign of dark matter annihilation processes?
- no excess of antiprotons has been observed
  - inconsistent with theoretical predictions from most models of dark matter sources
  - positron and antiproton excesses should be correlated
- other measurements obtained for albedo particles (secondary particles produced by cosmic rays interacting with the Earth’s atmosphere that are scattered upward), light nuclei fluxes, etc.
Antiproton-to-proton flux ratio measured by the PAMELA experiment and compared with other contemporary measurements (left plot) and various theoretical predictions (right plot).

- excellent agreement both with data from other experiments and theoretical models!
- the flux ratio smoothly increases with the energy up to 10 GeV and then levels off
- electrons in the antiproton sample can be easily rejected by applying conditions on the calorimeter shower topology
- selection efficiencies studied using both simulated protons and antiprotons and proton samples from flight data
- systematic uncertainties are less than a few % of the signal, significantly lower than the statistical ones
Positron fraction measured by the PAMELA and compared with other contemporary measurements and with a theoretical prediction for dark matter and astrophysical primary production.

- at low energies PAMELA data are lower than most of the other measurements
- above 10 GeV the ratio increases significantly with the energy → positron excess
- is there any theoretical physicist among you?
Conclusions

- I didn't know the existence of a silicon calorimeter before this course/presentation!

- the main scientific goal of the experiment is a precise measurement or cosmic-ray antiproton and positron energy spectra

- the PAMELA calorimeter has been extensively tested with particle beams, mechanical tests and simulations before the launch on space

- PAMELA is continuously collecting data since its launch, 5 years of data taking ~18 TB of data!

- the whole calorimeter has been stable since the integration of the detector at ground and no changes in the detector performance could be noticed since the launch of the Resurs-DK1 satellite

- apologize but I have to attend another PhD course (11.00-13.00) ...
The PAMELA collaboration, *The Electromagnetic Imaging Calorimeter of PAMELA*

The PAMELA collaboration, *Performance of the PAMELA Si-W calorimeter in space*

The PAMELA collaboration, *A Silicon-Tungsten Calorimeter for PAMELA*

Adams et al., *The CR-1 chip: custom VLSI circuitry for cosmic rays*

E. Mocchiuti, *The PAMELA Electromagnetic Calorimeter: Flight Status*

R. Sparvoli and V. Malvezzi, *Measurements of Cosmic Rays Fluxes with PAMELA*

The PAMELA collaboration, *Results from PAMELA*

The PAMELA collaboration, *PAMELA and electrons*

O. Adriani, *PAMELA main results after 5 years of data taking*