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Beam test results of pixelated silicon sensors for the charge identification of cosmic rays

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Abstract: Silicon sensors with 64 pixels of 1 cm^2 area and 500 μm micron thickness were developed as building blocks of a large array for the charge identification of cosmic-ray nuclei in balloon-borne or space-based experiments. A small telescope of sensors was exposed to pion and proton beams, interacting in a target, at CERN. Experimental results on the performance of the sensors are reported.

Introduction

A direct measurement of the elemental composition of charged radiation from space, requires the identification of individual chemical species in the cosmic-ray (CR) flux and the determination of their energy. In contrast with ground based experiments, where the identity of the incoming particle is inferred on a statistical basis and with large systematic uncertainties (via parametric models of atmospheric showers), modern instruments floating on balloons or orbiting around the Earth, can identify the incoming particle on an event-by-event basis. While earlier instruments could resolve groups of elements (e.g. the CNO group) and, only in some cases, could reach the single-element discrimination on a limited mass interval, a new generation of experiments are pushing the available detector technology to achieve the identification of single elements over the whole interval from proton to Iron and above. At energies higher than 1 or 2 GeV, where the time-of-flight (TOF) technique is no longer effective, or in instruments with no magnetic analysis of momentum, cosmic-ray particle identification is typically achieved via an accurate measurement of the electric charge Z of the incoming (fully ionized) nucleus. Silicon sensors, provide an excellent charge discrimination, taking advantage of the saturated specific ionization for relativistic particles on the Fermi plateau and its Z^2 dependence. This technique has been applied successfully by space-borne instruments as AMS [1] and PAMELA [2] and by balloon experiments as ATIC [3] and, more recently, CREAM [4].
Direct measurements of cosmic-ray fluxes at high energy are statistics limited as a consequence of the steeply falling energy spectrum and of the collection power of the instrument, which is severely constrained by its weight and size. Therefore, the effective exposure becomes an important factor and it is one of the main limitations of present balloon-borne experiments, with a typical flight duration of a few weeks, to be compared with 3 to 5 years for space-borne payloads. In both cases, the geometric factor of the instrument should be as large as possible and this leads to the development of large arrays of silicon sensors for CR composition studies [5], where a seamless sensitive area is achieved by a suitable mechanical arrangement of partially overlapping sensors. Pixelated sensors offer the advantage of an easier pattern recognition task, as compared with silicon strip devices that are affected by ambiguities in the pairing of coordinates measured on orthogonal planes.
An important issue is also the specification of the front-end electronics [6, 7] that should have a sufficiently low noise figure to allow for the identification of Z=1 particles, with a S/N larger than 5,

while providing, at the same time, a dynamic range of at least 10^3 MIP, in order to identify nuclei up to Iron and above. As per the choice of the pixel size, the tradeoff is between detector noise (smaller pixels imply a lower detector capacitance, hence less noise) and the total number of readout channels (power, cost and system complexity).

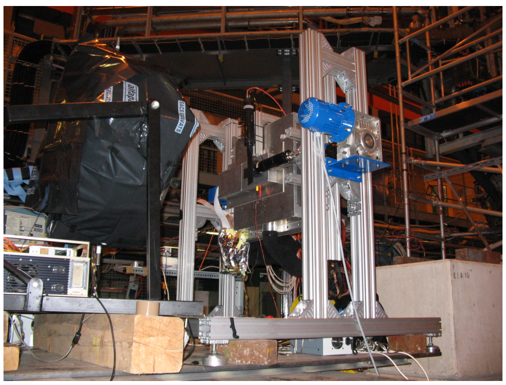
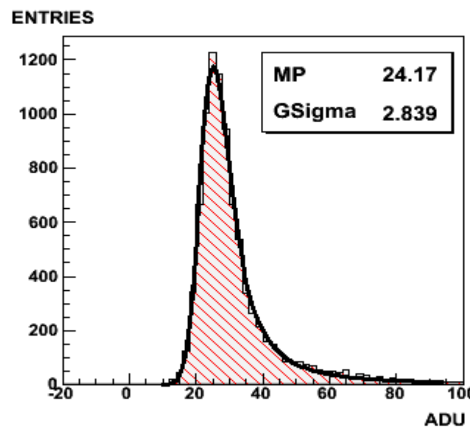


Figure 1: Beam test layout. The silicon telescope is mounted on a rotating fixture (visible on the right end side of the picture) preceded by a prototype of the NUCLEON instrument (on the left), wrapped into a light-tight black shroud.

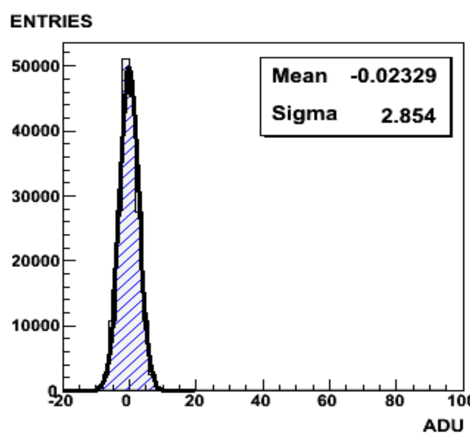
In this paper, we report on the performance of a small telescope of large area silicon sensors, equipped with low-noise, low-power, large dynamic range front-end electronics, during a beam test at CERN in November 2006.

The silicon sensors

The silicon sensors used during the test were PIN diodes with 8×8 pixels. The active pixel area was 1cm^2. The sensor was developed from a 6 inches wafer of thickness 500 μm. A larger thickness (with respect to the standard 300 - 380 μm) was chosen to increase the S/N, while keeping the depletion voltage within a safe value for operation in space. This was achieved by requiring a wafer resistivity larger than 10000 Ω·cm.
The characterization of the sensor and its performance with atmospheric muons is discussed in previous papers [8, 9]. The front-end electronics was based on a 64 channels board equipped with two



(a)



(b)

Figure 2: (a) Pulse height distribution from one sensor with beam muons. The Landau distribution for a single MIP has its most probable value close to 24 ADC counts; (b) pedestal distribution from the same run.

ASICs of the VA family (HDR14.2), optimized for positive polarity and with a linear response within 2.5 % up to input charges of about 6.5 pC. The average RMS channel noise of the board was around 0.8 fC [7].

The silicon sensors beam test

A small two-layered telescope was tested at CERN on November 2006 on the H2 beam line (Fig. 1). It was mounted on the entrance window of a 16 radiation lengths calorimeter prototype and triggered by the coincidence of two scintillator counters. The readout of 512 channels (including the calorimeter's) was carried out by a VME board interfaced to a PC via a 30 m long optical fiber. The response of the sensors was first checked using beam muon triggers. A correction was applied to the raw data to subtract the contribution due to correlated noise among the 32 electronics channels of the same ASIC. Different versions of a "Common-Mode-Correction" (CMC) algorithm were tested, where the reference channels for a measurement of the common noise, on an event-by-event basis, were chosen among those pixel located outside the beam area. The pulse height distribution for muon triggers is shown in Fig. 2(a) where the Landau distribution of the single MIP has its most probable value (MPV) close to 24 ADC counts and is well separated from the pedestal with $\sigma \sim 3$ (Fig. 2(b)). The most probable signal-to-noise ratio was around 8.

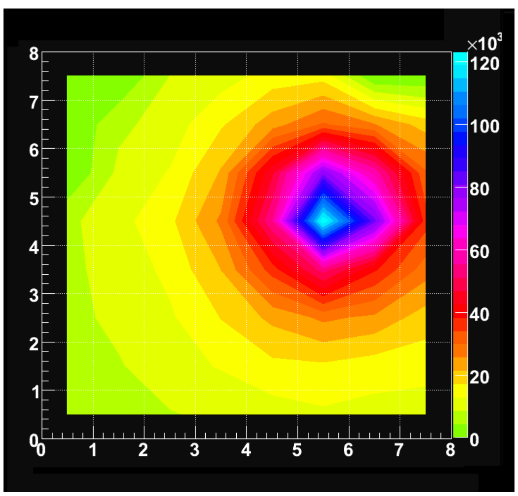


Figure 3: Two-dimensional cross-section of the beam as reconstructed by the silicon telescope during pion runs.

At the beam test, while a fraction of the data was taken with no material in front, during most of the runs the telescope was preceded by a prototype of the NUCLEON instrument[10]. The latter was comprised of multiple layers of silicon sensors and thin scintillators (with minimal contributions to the total material budget and negligible interaction probability for a beam particle), a carbon target of about 20 g/cm^2 and gamma-converters for a total of 3 additional radiation lengths of tungsten.

During pion runs at 300 GeV beam energy, multiparticle production resulted in more than one charged particle impinging on the same pixel at a distance of approximately 70 cm from the target. The beam profile is well visible in the spatial distribution of secondary particles hitting the telescope (Fig. 3).

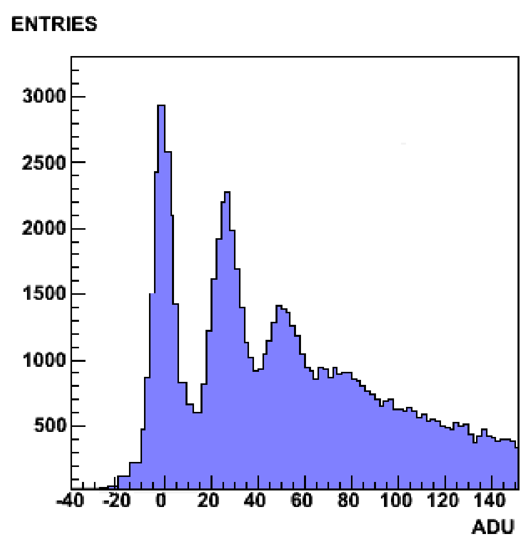


Figure 4: Pulse height distribution of one sensor in the second layer during pion runs.

The pulse height distribution of events (raw data) recorded in the second layer (Fig. 4), shows a clear peak close to 24 ADC counts, that corresponds to

Z = 1 minimum ionizing particles. A second peak, close to twice the previous value, is also visible. This was due to the cases when two secondary charged pions were impinging on the same pixel.

Conclusions

Beam test data confirmed the excellent performance of silicon sensors and related front-end electronics that were developed as building blocks of a large silicon array to provide charge identification of ultra-relativistic cosmic ray nuclei.

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