A high resolution silicon beam telescope

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Abstract

We describe the design and present the performances of a charged particle telescope used for high resolution silicon pixel developments. A telescope made of 4 x and 4 y single-sided silicon microstrip layers was built, providing an r.m.s. position resolution of 1 μm for high energy charged particles. A signal over noise ratio of 130 was achieved with minimum ionizing particles.

Key words: Silicon, microstrips, position resolution
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1 Introduction

Modern high position resolution detectors for particle physics experiments require tools to measure their performances and properties with beams of test particles. The coordinates and directions of impinging particles have to be determined with a much higher precision than those of the detector under investigation or its typical size and granularity. For instance, the CMS vertex pixel detector will determine track coordinates with an r.m.s. resolution of about 15 μm [1]. The technology to achieve precisions of the order of 1 μm is available [2–4] and high resolution charged particle telescopes have been constructed [5].

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We have built a charged particle telescope capable of detecting incoming high energy charged particles with an r.m.s. resolution of 1 μm, which we briefly describe in this paper.

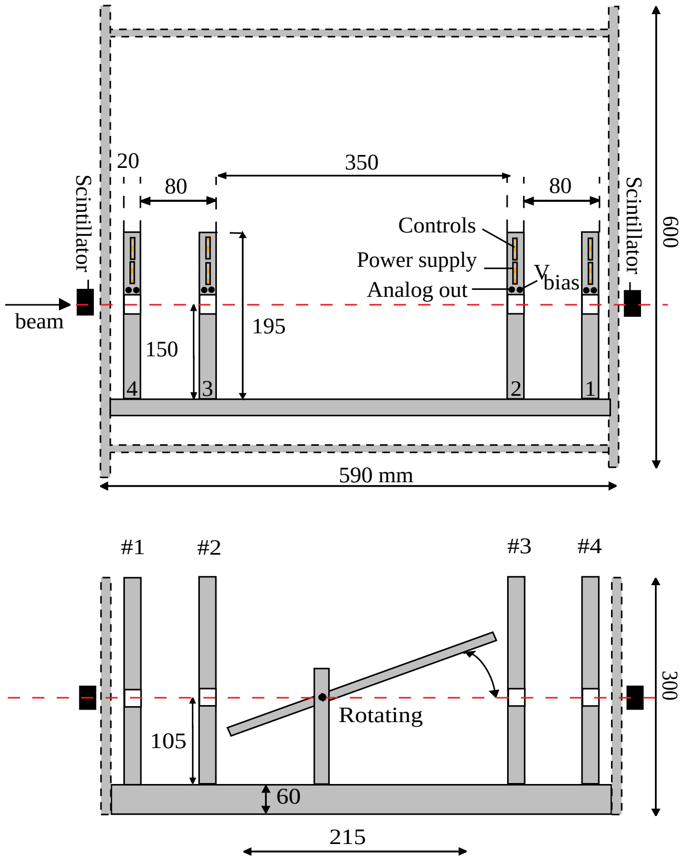

Fig. 1. Top and side views of the telescope. Dimensions are given in mm.

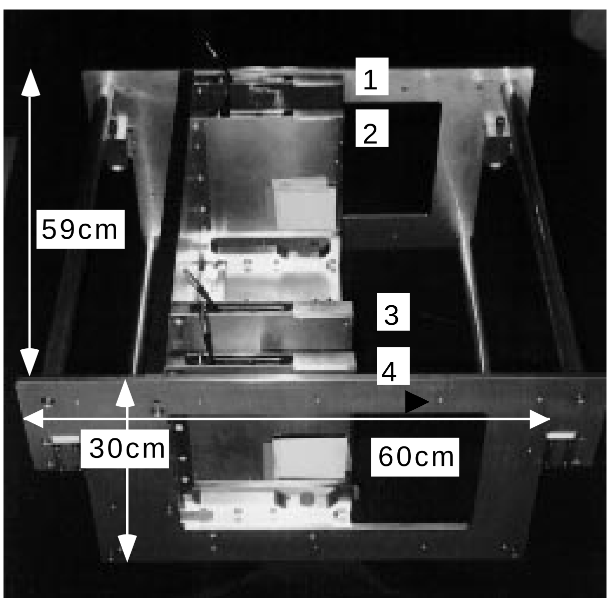

Fig. 2. Photograph of the beam telescope.

2 Mechanical assembly

A sketch of the beam telescope is shown in fig. 1 and photographs are presented in fig. 2. The telescope consists of 8 single sided silicon microstrip detectors grouped in 4 modules, each containing a pair of detectors mounted orthogonally to each other and providing the x- and y-coordinates of the passing charged particles. A space of 35 cm is left between the third and fourth module to accommodate the device to be tested, which can be mounted on a rotating support. Two scintillation counters or, alternatively silicon diodes, at the telescope entrance and exit provide the necessary trigger for the readout electronics. The aluminium support structure and modules frames have been machined in the mechanical workshop of the Physik-Institut, achieving an *absolute* precision of 10 μm in the detector coordinates. The dimensions of the frame are $590 \times 600 \times 305$ mm^3 and the weight of the telescope is about 17 kg. The device can therefore be easily transported from the laboratory to the beam areas. A three dimensional view of the mechanical assembly for one module is shown in fig. 3.

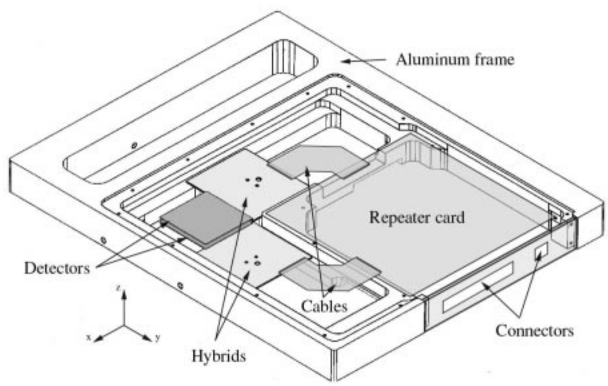

Fig. 3. Three-dimensional view of the open telescope module without electronics, showing the detectors, the hybrids and the space for cables and repeater card (see also fig. 2).

The eight identical single sided silicon microstrip detectors were manufactured by SINTEF (Oslo). They are made of n-type silicon with p^+ implants on the strip side and an n^+ ohmic contact on the back side. The active surface of a detector is 32×32 mm^2 and the thickness is 300 μm. The pitch of the 10 μm wide strips is 25 μm, but only every second strip is connected (AC coupled) to the readout electronics. The intermediate strips are left floating. This leads to 640 readout strips for each detector, hence a total of 5120 channels. A structure of six guard rings controls the bias voltage at the edge and removes surface currents. The x- and y-detectors in each module are separated by 3 mm. Aluminum protective foils of 100 μm thickness provide the entrance and exit windows of each module. The operating temperature is 300 K. The total power consumption, including frontend and line driver electronics, amounts to 12 W. Cooling is achieved with heat sinks in ambient air.

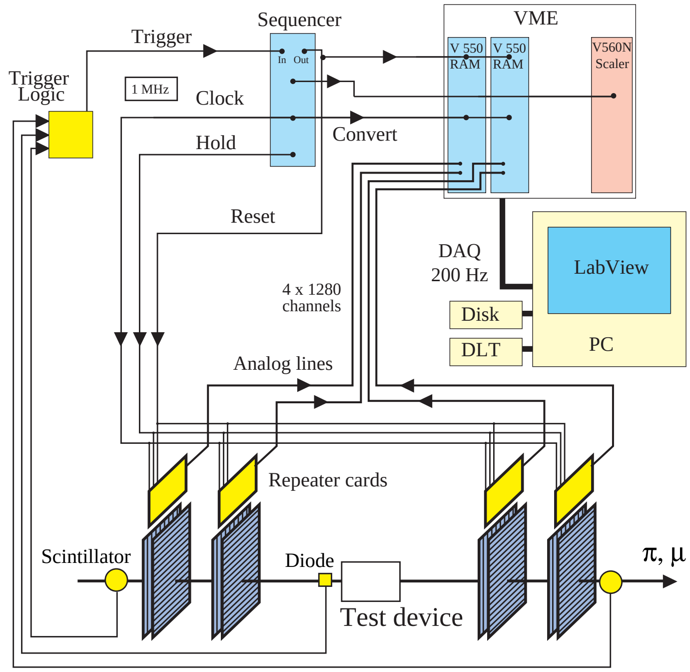

Fig. 4. Diagram of the readout system.

The bias voltage (54 V for full depletion) is provided by an array of 9V batteries. The typical leakage current was measured to be 100 nA/detector. For 300 μm thick silicon, the most probable energy loss for minimum ionizing charged particles is 85 keV which corresponds to the production of 24,000 electron-hole pairs.

Figure 4 shows the block diagram of the system and readout electronics, including the VME based data acquisition system. The front end electronics for one detector is provided by 5 VLSI chips (VA2 128 channels preamplifiers from IDE-AS, Oslo). These preamplifiers are widely used for silicon detectors in high energy physics [6]. They include charge sensitive amplifiers, semigaussian shapers, analog storage and signal multiplexing. The chips are mounted on ceramic hybrids (see fig. 3) which are aligned and fixed by screws on the aluminium frame. The heat dissipation to the frame is improved by a heat conducting paste. The integrated charges of the 1280 x- and y-strips in each module are read out sequentially at a rate of 1 MHz, controlled by the external sequencer which accepts the trigger signal and provides the hold, the clock and the reset signals to the hybrids, via custom made repeater cards [7]. The four modules are processed in parallel and the four signal streams are then fed through 110 Ω twisted pair cables into two CAEN V550 RAMS flash ADCs (maximum conversion time 200 ns/channel). The pedestals are subtracted and read out zero unsuppressed. The data acquisition is controlled by a PC running Labview and data are stored on disk. The typical maximum data acquisition rate is 200 Hz.

Figure 5 shows a typical signal from one detector, generated by a minimum ionizing electron (< 3.5 MeV) from a ^{106}Ru radioactive β-source, measured in single channel mode. The peaking time is set to 2.3 μs, yielding the optimum signal over noise ratio.

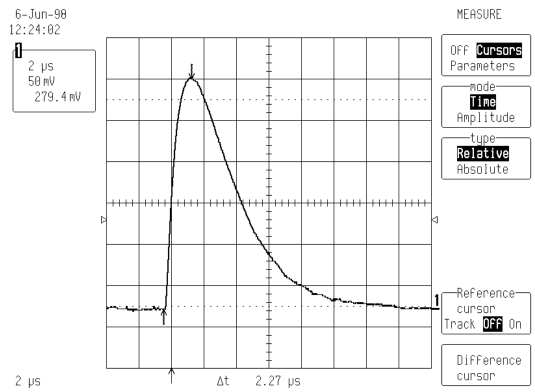

Fig. 5. Signal generated on one strip by a minimum ionizing electron after preamplification and shaping in the VA2 chip.

3 Results

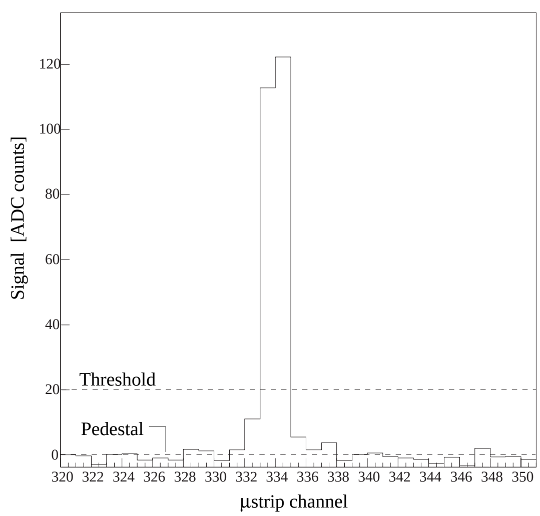

Fig. 6. Signal amplitude as a function of strip number for a typical event in one of the detectors. The pedestal has already been subtracted. The offline threshold to find clusters was 20 ADC counts.

The telescope was tested in the X5 beam line at the CERN SPS with 100 GeV/c muons. A high momentum beam was chosen to minimize multiple scattering. The typical incoming rates were 10^4 muons per pulse (duration 2.4 s). The two scintillators provided the trigger. We collected events with several bias voltages between 36 and 63 V. The number of adjacent strips firing in each plane (cluster size) was mostly 2 (82%), while 15% of the clusters contained single strips and only 3 % contained three adjacent strips. Figure 6 shows a typical event with two adjacent strips firing above threshold. The typical Landau distribution of the energy loss is plotted in fig. 7a for events with cluster sizes of two.

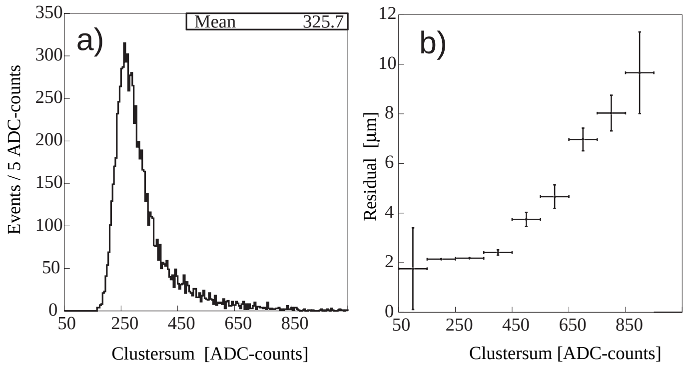

Fig. 7. a): Distribution of energy loss from 100 GeV/c muons in one of the 300 μm thick detectors (bias voltage 45 V); b): r.m.s residual as a function of total energy deposit (see text) .

The signal over noise ratio was derived by dividing the most probable pulse height after pedestal subtraction (260 ADC counts at 45 V, see fig. 7a) by the r.m.s. noise. The noise ($\sigma \simeq 2$ ADC counts) was calculated by fitting the distribution of pedestal fluctuations with gaussian functions for strips without signal. A signal over noise ratio of 128 (131) was obtained for a bias voltage of 36 (45) V. The best signal over noise ratio of 133 was reached at 54 V or above, at which voltages the detectors were fully depleted. Such a high signal over noise ratio is achieved thanks to the long integration time, the good quality of the sensors and the very low noise readout chips.

We collected a few 10^4 events on tape and applied the following data selection criteria. The threshold was set to 20 ADC counts (fig. 6), i.e. at the level of 10 σ above noise. Events with only one cluster in every plane and with cluster size two were retained for further analysis. Events with large energy deposits stem from δ electrons and spoil the position resolution. This is illustrated in fig. 7b which shows the r.m.s width of the residual distribution, i.e. the distribution of the difference between measured hit in one detector and the predicted hit from the other three (the procedure is described below) as a function of energy deposit. Events with a total energy deposit of more than 400 ADC counts were therefore discarded for the next step. At 63 V these cuts left about 15% of the events from the original data sample, which were kept for further analysis.

For a traversing charged particle leaving a signal on one strip only, the coordinate is given by the strip number and the spatial resolution is determined by the pitch Δ= 50 μm, divided by $\sqrt{12}$ ($\sim$ 14 μm). These single hits are, however, suppressed due to the intermediate floating strips. The hit coordinates can then be determined more accurately by using the energy deposits shared among adjacent readout strips. The charge Q is deposited on two adjacent strips (left L and right R) and the fraction of charge deposited in the left strip is

$$\eta = \frac{Q(L)}{Q(R) + Q(L)}. \tag{1}$$

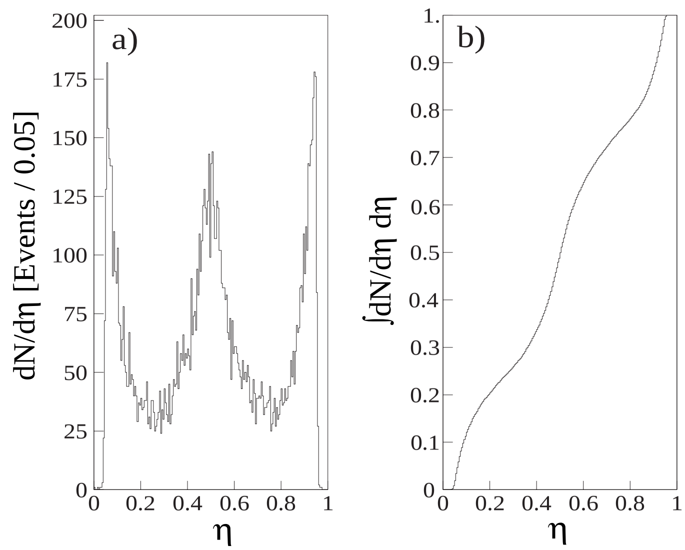

Fig. 8. η-distribution a) and its integral b). In b) the η-distribution is normalized to unity.

Figure 8a shows the η distribution $dN/d\eta$ for one of the detectors. The peak at η=0.5 stems from charge collected by the floating intermediate strip, inducing signals of equal magnitudes on the neighbouring left and right readout strips. For a given passing particle, the impact point x between the two strips can be obtained [8] by integrating the *normalized* η distribution up to the measured value of η (fig. 8b):

$$x = \Delta \int_0^{\eta} \frac{dN}{d\eta} d\eta, \tag{2}$$

where

$$\int_0^1 \frac{dN}{d\eta} d\eta = 1, \tag{3}$$

and the pitch $\Delta = 50\ \mu$m. This leads to the (position dependent) resolution

$$\sigma_x = \Delta \frac{dN}{d\eta} \sigma_\eta. \tag{4}$$

The resolution σ_η depends on η, the charge collected and the noise. Resolutions an order of magnitude better than Δ can be achieved. For instance, we obtained $\sigma_x = 13$ μm for the 125 μm wide prototype pixel detector of CMS [10].

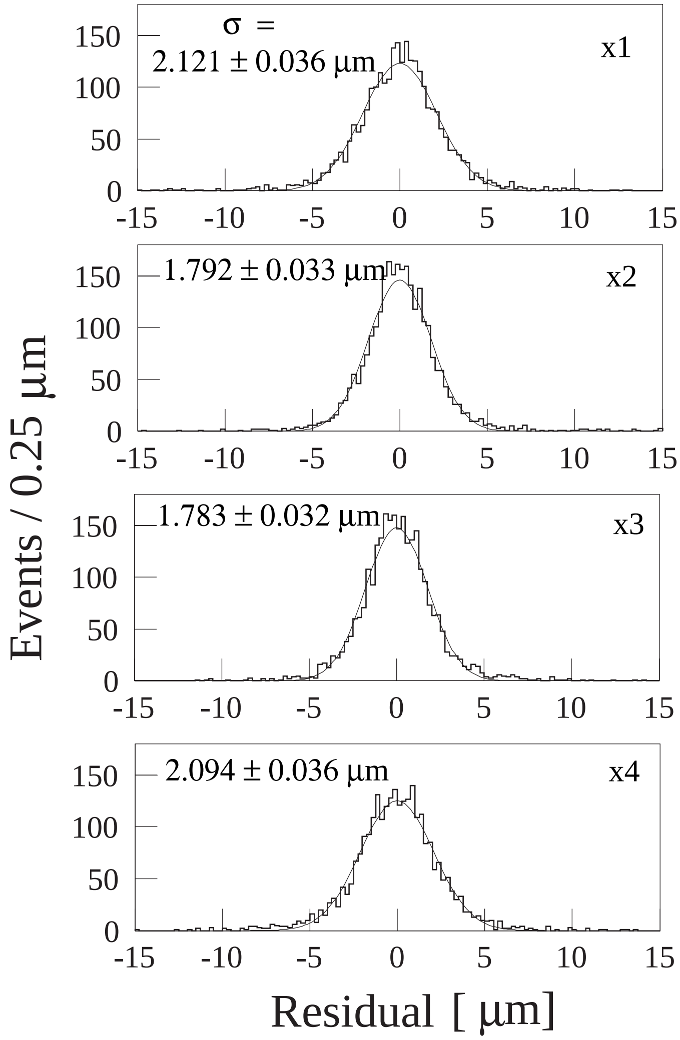

Fig. 9. Residuals for the four x-detectors. The bias voltage was 63 V. The curves are fitted normal distributions. The muon beam enters the telescope into layer $x1$.

The 4 x- and 4 y-layers were first aligned by software using passing high energy muon tracks. The accurate location of each layer was determined by fitting straight tracks through the other three layers and calculating the deviations (residuals) of the expected coordinates from the measured ones. In the software alignment procedure the detectors were allowed to move and rotate in the plane transverse to the beam axis. The resolutions were derived by histogramming the residuals. They are shown in fig. 9 for the four x-layers. The y-residuals are similar. All resolutions are typically $\sigma = 2$ μm, which implies that the contribution from multiple scattering is small. Multiple scattering was calculated by Monte-Carlo simulation for 100 GeV minimum ionizing particles. Its contribution was indeed only $\sigma = 0.7$ μm for particles traversing the whole telescope, to be quadratically added to the intrinsic resolution of 2 μm.

We can finally estimate the resolution on a test device at the center of the telescope. Assuming that all detectors have the same resolution of about 2 μm (fig. 9) and neglecting the short distance between the two first and the two last modules, one finds the final resolution

$$\sigma_f \simeq \sigma/2 = 1\ \mu\text{m}. \tag{5}$$

This kind of resolution is suitable for measuring the position resolution of high energy physics detectors. For instance, using this telescope and cosmic rays, a resolution of 24 μm was obtained for the 140 μm wide detector strips of the ATHENA antihydrogen experiment [9].

This precision also allowed us to scan CMS pixel prototype detectors in small steps to investigate the charge drift in a strong magnetic field of 3 T [10,11]. In the high rate environment of LHC, radiation damage can strongly alter the properties of silicon detectors. In particular, the high dose reduces the achievable depletion thickness. We have measured with our telescope the depletion thickness of an irradiated pixel detector prototype for the CMS experiment. The detector was irradiated with a flux of 6×10^{14} pions/cm^2 at the Paul-Scherrer Institute (PSI). We then determined at the SPS test beam the cluster sizes generated by high energy charged particles traversing the 300 μm thin sensor layer at grazing angles of about 8°, thus with tracks nearly parallel to the sensor surface [12]. The Lorentz angle, under which the electron cloud drifts towards the anode in a strong magnetic field, was measured as a function of ionization depths. For an irradiated detector this angle appears to be reduced near the detector surface [13].

4 Acknowledgements

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