CERN-PPE/94-26

March 24, 1994

30 34 14

One Micron Spatial Resolution with Silicon Strip Detectors

J. Straver¹, O. Toker^{1,4}, P. Weilhammer¹
C. Colledani², W. Dulinski², R. Turchetta²
L. Bosisio³

Abstract

We have tested two $25\mu\text{m}$ pitch DC-coupled p-side silicon micro-strip detectors with low noise VIKING readout, in a 100GeV π^- beam at CERN. Two independent analyses, using the same data set, obtained the following results: The signal to single channel noise ratio was 71 to 1 (75 to 1), and the spatial resolution was measured to be $\sigma = 1.25\mu\text{m}$ ($\sigma = 1.30\mu\text{m}$) for tracks perpendicular to the surface.

1 CERN Geneva

2 LEPSI Strasbourg

3 Universita di Trieste and INFN Trieste

4 Now at Universita Degli Studi di Perugia and INFN-Sezione di Perugia

1 Introduction

A major tool for heavy flavour decay studies in high energy physics is the micro-vertex detector equipped with silicon micro-strip detectors. The most important parameter for silicon strip detectors, in this application, is the spatial resolution. Since the appearance of modern high precision silicon detectors, almost 13 years ago [1], continuous attempts have been made to improve the spatial resolution and to reach the optimal value of about $1\mu m$, where physical limitations from ionization mechanisms could be expected. The best achievements during this period reflect the progress in detector technology, and especially, the progress in low noise electronics, helped by an intensive development of dedicated multi channel high density VLSI readout chips. Table 1 lists some milestones of spatial resolution set over the last years.

Table 1: Milestones of spatial resolution achieved with silicon micro-strip detectors since 1980.

Year	Reference	Strip/pixel pitch [μm]	Readout pitch [μm]	S/N	Spatial resolution [μm]	Comments
1983	[2]	20	60	33	4.5	Discrete electronics
		20	120		7.0	
1986	[3]	25	25	14	2.6	Discrete electronics
1990	[4]	10	10	15	2.5	Discrete electronics
1990	[5]	p-side: 25	50	28	2.9	AC double-sided double-metal detector with VLSI readout
		n-side: 35	35	13	6.5	
1992	[6]	x: 20	35	55	2.2	Monolithic pixel detector
		y: 20	125		15	

In case of an analog readout system the spatial resolution of micro-strip detectors depends on the following parameters:

- 1 Readout pitch
- 2 The presence of intermediate strips (not connected to readout)
- 3 Signal over Noise ratio (S/N)¹
- 4 Charge carrier diffusion

In this paper we report results on spatial resolution obtained with a silicon strip detector with a $25\mu m$ pitch. The detector had DC-coupled strips and was read out with a new low noise front-end readout chip (VIKING [7]). A spatial resolution in the order of $1\mu m$ has been achieved.

¹ S/N is ultimately limited by the quality of the front-end readout electronics.

2 Detector and VLSI readout electronics

The high precision detector employed for this measurement has been produced by Centre Suisse d'Electronique et Microtechnique (CSEM) Neuchatel, using technology developed for the ALEPH micro-vertex detector [9]. It is a double-sided DC-coupled detector with strip and readout pitch of $25\mu\text{m}$ on the p-side, which was the only side equipped with electronics during this test. The p+ implant width is $6\mu\text{m}$, the strip length is 12mm , and the total number of strips is 512. The mean value of the leakage current per strip is 0.02nA , for a substrate thickness of $300\mu\text{m}$ and a total depletion voltage of 40V . The implant strips are aluminized, in order to reduce the series resistance and to make the connection to the readout electronics possible. To match the readout chip pitch density of $50\mu\text{m}$, the bonding pads for the even and odd detector strips are put on opposite sides of the detector, see figure 1.

The VIKING frontend is a 128 channel VLSI CMOS chip. Each channel contains a charge amplifier, followed by a CR-RC shaper (set at $2\mu\text{s}$ peaking time), and a sample-and-hold circuit. The output information is serialized using a shift register and multiplexer. The noise performance of the VIKING has been measured to be [7, 10, 11]:

$$ENC = 135e^- + 13 * C_{tot}e^- \quad (1)$$

C_{tot} is the total detector capacitance seen by the input of the amplifier. Because of the extremely low leakage current of the detector diodes, the simple DC connection to the preamplifier input allows biasing of the detector via the feedback resistor, without unbalancing the working point of the preamplifier.

Figure 1: Schematic picture of detector-VIKING connection. The four VIKING readout chips are placed left and right of the detector and their bond-pads are aligned.

To equip the 512 strips on each of the two high precision detectors, four VIKING chips assembled on two ceramic hybrids are necessary (see figure 1). The thick-film hybrid provides steering signal lines, power supply decoupling capacitors, and also mechanical support as well as heat sinking. The single detector module is completed by a repeater card, with an input-output interface to the long cable (40m), connecting the beam area and the counting room.

3 Beam test setup and data acquisition

Position resolution measurement of the high precision silicon detectors has been done in a $100\text{GeV}/c$ π^- beam at CERN, using a telescope of eight reference detectors. The reference detectors are single-sided, AC-coupled, $3 \times 6\text{cm}^2$ silicon detectors with an implant/readout pitch of $25/50\mu\text{m}$, equipped with MX3 [12] frontend electronics. They are arranged in 4 X - Y pairs, and each pair is connected to one readout processor (SIROCCO). The precision of the individual reference detectors is $\sim 6.5\mu\text{m}$, which results in an extrapolation error of $\sim 3.5\mu\text{m}$, a factor of 3 more than the expected value for the high precision detector. In order to overcome this difficulty, the two high precision detectors were placed closely together in the middle of the telescope with their strips parallel, see figure 2. All detectors are mechanically mounted on a granite/steel optical bench. A trigger is provided by a pair of $1 \times 1\text{cm}^2$ scintillators.

Figure 2: The beam telescope with 8 single-sided reference detectors (4 x and 4 y) and two high precision detectors.

The VME/OS9 based DAQ system [13] provides the clock signals for both the MX3 chips of the reference detectors, and the VIKING readout chips of the high precision detectors. Using a coincidence of a the capture cycle of the MX3 chips and a scintillator trigger, the VIKING chips are triggered and the event is read in the VME-SIROCCO buffers. The system is controlled by a VME Eurocom 6 processor. All raw data is written to EXABYTE tape for detailed off-line analyses, and a subset of the data is analyzed online, to provide monitoring.

4 Offline Analysis

Introduction

Two completely independent analyses have been performed on the same data set, at LEPSI/Strasbourg and at CERN. Both analyses followed the same procedure for charge and position calculations with small differences in the cluster definition, but the alignment of the telescope detectors was done with completely different methods. Here the method used at CERN is explained in detail and some remarks are made about the method followed at LEPSI.

Cluster Calculation

Since the raw information of all detector strips for every event is written on tape, the strip-noise, pedestals, common-mode correction and finally the pulse heights are fully calculated offline. The noise and pedestal are continuously updated using digital filtering techniques [14], and the common mode base-line shift is calculated for each event separately.

Due to the special strip-chip connections on the high precision detectors, care had to be taken for the common mode calculations, since this has to be determined on a number of consecutive channels on the readout chip, while for the charge cluster search the detector strips have to be mapped in a consecutive order.

The cluster search method works in three steps. First all strips are scanned to find strips with a signal higher than $4 \times \sigma_{noise,i}$ ($\sigma_{noise,i}$ = single strip noise level of strip i). If such channels are found then all neighboring strips with a signal above $2 \times \sigma_{noise,i}$ are added to form a cluster, and finally the summed signal of all strips in the cluster has to be above $6 \times \sigma_{noise,i}$. This procedure is continued until all strips of all detectors have been scanned. Strips too close to the detector edges (5 strips) are not included in the cluster search.

For the method followed at LEPSI the respective cuts used in the cluster search were 3, 1 and $6 \times \sigma_{noise,i}$, and the minimal cluster charge cut was set at $S/N = 40$.

Position Calculation

Once the clusters are defined the particle impact positions are calculated using a non linear interpolation algorithm. This algorithm is used for charge cluster widths ≥ 2 . Single strip clusters are less than 0.1% of all events. In this algorithm it is assumed that the beam irradiation distribution is uniform for each individual set of two strips, and that the charge is collected by only two strips. For clusters with more than two strips the two strips with the highest pulse height are used. A quantity η is defined as follows:

$$\eta \equiv \frac{PH_r}{PH_l + PH_r} \quad (2)$$

Where $PH_{l,r}$ is the pulse height of the left,right strip in a cluster. The average impact position x for a given η value can be obtained in the following way:

$$x = P, \int_0^\eta \frac{dN}{d\eta}(\eta)_n d\eta + X_0 \quad (3)$$

Where P = strip pitch, $dN/d\eta(\eta)_n$ = the normalized $dN/d\eta(\eta)$ distribution, and X_0 = absolute position of the left strip in the cluster.

The experimental distribution of $dN/d\eta$ for tracks perpendicular to the plane of the high precision detector, and the normalized interstrip position calculated with formula 3, are shown in figure 3.

Alignment

The offline software alignment is done in three steps.

The first step is the alignment of the telescope reference detectors, for which only those tracks with hits in all x and y detectors are used. In this procedure it is assumed that the outer detectors for the x and y coordinates are already aligned. Then the two x and y detectors in between the outer detectors are shifted and rotated in an iterative process until

Figure 3: The experimental η distribution of the high precision detector (left), and the normalized interstrip position (based on the distribution on the left) as function of η (right).

the residues of the impact positions are minimal. The analysis at LEPSI used a weighted least square fit method for the alignment without iterative steps and without any assumption on detector positions [14].

The second step repeats this process for the two high precision detectors, requiring a hit in at least one of them, and using an unweighted least-square line fit through the reference detectors for the residue calculations. After this step the optimal position of the high precision detectors along the beam line (z coordinate) is determined by searching for the residual distribution with a minimal variance as function of z .

In the third step one of the two high precision detectors is used as a reference detector and the second one is re-aligned using a weighted line fit (the same iterative process), such that the residues are minimized. After this the residues are corrected for small and slow detector shifts in the time domain, which are due to temperature changes during the runs.

In all steps χ^2 cuts are applied on the line fits and $3 \times \sigma$ cuts on the residue distributions except for the final residue distribution of the high precision detectors. In this final line fit all events are accepted. The LEPSI method did not use $3 \times \sigma$ cuts on the residue distributions.

5 Results

Data has been taken only with a normally incident beam, and the results presented here are measured at only one bias voltage setting of 60V. Measurements were done at three different settings of T_{hold} ² [7] for the VIKING chip ($T_{hold} = 1000ns, 1300ns$ and $1600ns$).

Only the results of the analysis performed at CERN are shown. The results of both analyses are in total agreement with each other.

Noise, Cluster charge distribution and Signal/Noise

Figure 4 shows a typical plot of the common mode corrected noise as function of the detector strip numbers, measured with $T_{hold} = 1600ns$. This plot shows that the noise variations are dominated by detector effects because neighboring channels come from different VIKING

² T_{hold} is the waiting time for data capture after the trigger has arrived.

Figure 4: Noise levels as function of strip position for a high precision detector, measured with $T_{hold} = 1600ns$.

Figure 5: a) Noise distribution and b) cluster charge Landau distribution with gaussian fit on a part of the distributions. Both distributions were measured with the same high precision detector and with $T_{hold} = 1600ns$.

chips. The noise distribution for all channels of the same high precision detector is shown in figure 5a, together with a gaussian fit. This fit gives a too high estimate of the noise spread due to the systematic effects seen in figure 4.

The Landau shaped cluster charge distribution of this detector is shown in figure 5b. A partial gaussian fit to the peak of this distribution yields the peak value for the cluster charge. The peak values for noise, *mip* signal and S/N (calculated on event to event basis) for all three measurements are listed in table 2. It should be noted that the average S/N values in different parts of the detector vary from $S/N = 67$ to $S/N = 97$, see figure 4.

The LEPSI analysis gives an average S/N value of 75 to 1.

Table 2: Results on noise average, signal and S/N peak values for both high precision detectors. Units are in ADC counts

T_{hold}	Noise	Signal	S/N
1000ns	4.37	261.5	60.9
1000ns	3.04	207.2	68.6
1300ns	4.40	276.2	62.9
1300ns	3.06	214.0	71.0
1600ns	4.42	274.7	62.9
1600ns	3.06	212.8	70.8

Shape of the charge distributions

The projection³ of the shape of the charge distributions on the detector strips can also be derived from the $dN/d\eta$ distributions using the following formula [8]:

$$f(x) = \frac{1}{P, dN/d\eta(x)_n} \quad (4)$$

Where $f(x)$ is a normalized function describing the projected charge distribution shape. This method is sensitive to noise in the η distribution and therefore the tails of the spatial distribution cannot be determined. Only detectors with readout on every strip can be used to determine the cluster shape.

Figure 6: Cluster charge projected spatial distribution, measured with $V_{depl} = 60V$, and $T_{hold} = 1600ns$.

Figure 6 shows the cluster charge spatial distribution measured with one of the high precision detectors. The FWHM of the distribution is $13\mu m$ (at $V_{depl.} = 60V$), showing that charge interpolation can improve the ‘digital’ spatial resolution of $25\mu m/\sqrt{12} = 7.2\mu m$. This shows that with the VIKING readout electronics, the charge, which by diffusion is collected on a neighboring strip, can be detected even if the particle impinges within $\pm 1\mu m$ of the

³Notice that the real physical charge distribution has a cylindrical geometry.

center of a strip ($S/N \geq 70$). This method implicitly does not allow to get information on the charge diffusion beyond $\pm 12.5\mu m$ from the particle impact point.

Spatial resolution and cluster shapes

Only the two measurements with T_{hold} values giving the best S/N ratio were analyzed, and the results, corrected for line fit errors and multiple scattering, are listed in table 3. The corrections for the line fit errors are about equal to the measured resolutions because one high precision detector was in the line fit, and the corrections for multiple scattering were around $0.4\mu m$ due to the small distance between the high precision detectors of about $2.5cm$. The best overall result is $\sigma = 1.25\mu m$, measured with $T_{hold} = 1600ns$.

Table 3: Results on the spatial resolution in μm , corrected for line fit errors and multiple scattering. The different columns indicate the effects of cluster width, relative signal level and position in between two strips as function of η (η cut 1: $0.25 < \eta < 0.75$, η cut 2: $0.0 < \eta < 0.25$ and $0.75 < \eta < 1.0$).

T_{hold}	All clusters	2 strip clusters	3 strip clusters	S/N 40 – 90	S/N 90 – 150	η cut 1	η cut 2
1300ns	1.38	1.19	1.63	1.20	1.88	0.97	1.55
1600ns	1.25	1.18	1.39	1.13	1.95	1.06	1.43

Figure 7a shows a typical residual distribution with a gaussian fit, and figure 7b shows the corresponding width of the residual distribution in different S/N slices. Figure 7b shows clearly that for high S/N values the resolution gets worse due to δ electrons.

Figure 7: a) Residual distribution, and b) the sigma of the residual distribution as function of S/N slices, measured with $T_{hold} = 1600ns$.

Figure 8 shows the corrected residual distribution as function of S/N , and demonstrates that a spatial resolution of $\sim 1\mu m$ is obtained for tracks with overall low ionization, which implies the production of only few δ electrons with high energies.

Figure 8: The residual distribution width as function of S/N from figure 7b, here corrected for line fit errors and multiple scattering errors.

6 Conclusions and prospects

The results of two independent analyses, on the same data set, show that an overall S/N of 71 (75) and an spatial resolution of $1.25(1.3)\mu m$ are obtained for perpendicular incident minimum ionizing particles under beam test conditions.

The data suggests that the spatial resolution can be further improved. There are several possible options for improvement. Detectors could be improved by reducing the strip pitch, and/or adding intermediate strips. Decreasing the detector thickness will reduce the coulomb scattering and the fraction of δ electrons, but it will also reduce the signal. Attempts are made at present to further improve the readout electronics.

References

- [1] J. Kemmer; Fabrication of Low Noise Silicon Radiation Detectors by the Planar Process; NIM A226(1984)499–502
- [2] B. Hyams et al.; A Silicon Counter Telescope to Study Short-Lived Particles in High-Energy Hadronic Interactions; NIM A205(1983)99–105
- [3] P. Weilhammer; Proceedings of the Workshop on New Solid State Devices for High-Energy Physics; Berkeley; 1987
- [4] F. Antinori et al.; Results on a 10 Micron Pitch Detector with Individual Strip Readout; NIM A288(1990)82–87
- [5] R. Brenner et al.; Measurement of the Spatial Resolution of Double-Sided Double-Metal AC-Coupled Silicon Microstrip Detectors; NIM A326(1993)189–197
- [6] W. Snoeys et al.; First Beam Test Results from a Monolithic Silicon Pixel Detector; NIM A326(1993)145–149
- [7] P. Aspell et al.; CMOS Low Noise Monolithic Frontend for *Si*-Strip Detector Readout; NIM A315(1992)425–429
- [8] E. Belau et al.; Charge Collection in Silicon Strip Detectors; NIM A214(1983)253–260
- [9] G. Batignani et al.; Development and Performance of Double-Sided Silicon Strip Detectors; NIM A310(1991)160–164
- [10] E. Nygard et al.; CMOS Low Noise Amplifier for Microstrip Readout Design and Results; NIM A301(1991)506–516
- [11] O. Toker et al.; VIKING a CMOS Low Noise Monolithic 128 Channel Frontend for *Si*-Strip Detector Readout; CERN-PPE/93–191
Submitted to Nucl. Instr. and Meth. A
- [12] J. Stanton and N. Kurtz; RAL–89–028 Rutherford Appleton Laboratory
- [13] C. Colledani et al.; High Resolution Beam Telescope; CRN–LEPSI note
To be published
- [14] R. Turchetta; Ph.D. Thesis; N. 1019; Strasbourg, France (1991)