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Abstract

We have constructed a 60 cm long DC–coupled *p*-side silicon microstrip detector with 50 μm pitch and beam tested it at CERN by using 50 GeV electrons. In this paper we describe the production and assembly of the ladder and present the beam test results. We obtain a signal-to-noise ratio of 10 and spatial resolution better than 13 μm over the full length of the ladder.

1 Introduction

Large scale silicon trackers used in high energy physics and space research require the ability to construct long silicon ladders with reliable performance. Long ladders have the advantage of reduced number of readout channels for a relatively large surface area. They are particularly suitable in relatively low counting rate experiments (for example at LEP [1]), where reconstruction of particle trajectories is required over large fiducial volumes with the minimal number of readout channels.

The quality of processing silicon microstrip detectors, their alignment precision and low noise front end electronics have been rapidly improving over the past few years. In this paper we describe the construction and performance of a 60 cm long silicon microstrip ladder.

In the first part of this paper we describe the production and assembly of the ladder, thereafter results of the beam tests are presented, including the signal-to-noise ratio as a function of readout length, the probability for spurious hits and the spatial resolution of the ladder.

2 Production and Assembly of the 60 cm Long Silicon Ladder

The 60 cm long detector ladder was constructed of 10 individual simple single-sided DC coupled silicon strip detectors. The front (or junction) side of each detector consisted of 641 p^+ diode strips of a length of 60.0 mm. The strip pitch was 50 μm giving an active detector width of 32.0 mm. The active area was surrounded by a 50 μm wide p^+ guard ring. The distance from the strips to the guard ring was 100 μm. The overall chip dimensions after cutting were 61.460 mm × 33.460 mm. The back (or ohmic side) consisted of a uniform n^+ layer to ensure good electrical contact for biasing and to provide break down protection.

The silicon strip detectors were processed at the Technical Research Center of Finland (VTT Electronics). The starting material was $\langle 111 \rangle$ oriented high purity n type silicon with resistivity above 6 kΩcm. The process started with the growth of the field oxide, which was followed by the first masking step of the oxide etching. A semiautomatic contact printer was employed for the mask exposure. After the oxide patterning the front side p^+ type strip doping was done with boron ion implantation and the back side n^+ doping with phosphorus ion implantation. The implantations were activated in an oxidacing ambient. The contact holes were opened with maskless oxide etching. Finally the aluminium layers were sputtered on both sides of the wafers and the front side aluminium was patterned with the second mask step. Before the construction of the ladder visual and static electrical tests were performed on the individual strip detectors to ensure their quality. Detectors with less than 1% either visually defected strips or strips with leakage current above 2 nA were accepted. The full depletion voltage was generally 35 V and break down voltage > 100 V.

Ten accepted detectors were aligned (4 μm precision) and glued together with a hybrid board and Viking readout chips onto a carbon fibre–foam–carbon fibre support bar by the L3 group at Geneva. Because of the great length of the detector ladder the wire bond connections between the detectors and to the readout chips could not be done with a conventional wedge bonder. A fully automatic K&S 1470 wedge bonder with a rotating bonding head was used. All strips of the first two detectors closest to the hybrid board were bonded together and to the five Viking chips. 512 strips of the following two detectors were read out and 384 of the two following them. In this way one Viking chip only was connected to all ten detectors. The bonding scheme is shown on Figure 1. This special way of bonding the detectors made it possible to study the signal to noise ratio as a function of strip length.

3 Beam Test Results

The detector was tested in the X3 beam of the SPS at CERN using 50 GeV electrons. A beam reference system consisting of eight silicon sensors (2 cm × 2 cm) and four scintillation counters was used to trigger the events and reconstruct the track of the particle. The eight silicon sensors provided spatial resolution of about 4 μm and signal-to-noise ratio of about 65. Figure 2 presents schematically the beam reference system. A detailed description of front-end electronics, beam reference system, data acquisition system and on-line software can be found in [2].

The beam test setup allowed also to test the ladder at various angles with respect to the incident beam. Assuming the beam direction to coincide with the z-axis and the strips to be parallel to the x-axis if the ladder is perpendicular to the beam we have defined a right-handed coordinate system presented on Figure 3. The ladder could be rotated around the y-axis (angle θ) whereas the strips remained parallel to the xz-plane. The shorter dimension of the ladder was parallel to the y-axis.

3.1 Collected Charge And Signal-To-Noise Ratio

For each trigger the raw pulse-height data (ADC-counts) from all the channels of the reference and tested detectors was recorded. The pulse-height from each individual strip was assumed to have contributions from three factors: the signal, common mode and pedestal level. Pedestals, common mode and noise were calculated in the off-line analysis of the data.

The common mode is an overall DC level and it is common for all channels of a single readout chip. In this analysis the common mode was defined as the median of the pulse-heights over all the active channels of a readout chip.

The pedestal level reflects fluctuations in channel characteristics, being unique for each channel. The pedestals for the channels were determined using the pedestal events, which were triggered between the beam spills and did not contain any tracks.

The noise level of a channel was defined as the RMS of the signal from the pedestal events.

The charge deposited in the silicon after a passage of a particle is usually divided over several strips (from 1 to 4), resulting in the formation of clusters (groups of channels). A particle hit is then reconstructed by grouping the neighbouring channels.

We have used the following clustering algorithm. A signal was considered as a hit, if it was found to be more than 4σ above the noise level of the channel, after the common mode and the pedestal level had been subtracted from the raw pulse-height data. Thereafter, if the signal in the neighbouring channel(s) was found to be more than 2σ above the noise level, the corresponding channel was included in the cluster. The collected charge was defined as the sum of signals of the channels belonging to a cluster. The signal-to-noise ratio for the cluster was then calculated using the definition:

$$\left(\frac{S}{N}\right)_{\text{cluster}} = \frac{\sum q_i}{\frac{1}{N_{\text{cl}}}\sum \sigma_i},$$

where q_i is the signal of channel i, σ_i is the average noise for channel i, N_{cl} is the number of channels per cluster and the summing is carried out over the channels belonging to one cluster.

Before reconstructing the hits all noisy channels (having noise greater than twice the average noise of the corresponding readout chip) were removed from the analysis. The cluster multiplicity distribution for the 60 cm long ladder is presented in Figure 4.

One of the main goals of the beam test was to test the ability to assemble and read out long silicon microstrip ladders with adequate signal-to-noise ratio. Therefore we have concentrated our attention to the readout chips which have 6, 8 or 10 sensors bonded. The corresponding readout length values are 36 cm, 48 cm and 60 cm respectively.

The amount of collected charge is approximately same for the readout lengths of 36 and 48 cm, whereas for 60 cm the corresponding value appears to be slightly smaller. The average noise per channel depends on the readout length, being larger for longer strips. These results are presented on Figure 5. During the measurements the center of the incident beam was at a distance of 29 cm from the readout end of the detector. We have also studied the average noise and collected charge as a function of the incident beam position, but no dependence was observed.

The signal-to-noise distribution of the clusters for readout length of 60 cm is presented on Figure 6. The overlaid fit is a Gaussian convoluted Landau, the peak value of the distribution lies at $S/N \approx 10$.

We have also estimated the efficiency of the active areas of the ladder. The efficiency was determined by requiring a reconstructed hit on the ladder in a window of $\pm 500\ \mu$m from the expected position. The expected position was determined by linear track fitting using the 8 reference sensors, see Section 3.3. The results are summarized in Table 1.

Readout length (cm)	Efficiency	Active area (%)
36	0.98	96
48	0.93	88
60	0.98	84

Table 1: Efficiency and active area of the 60 cm ladder.

We have studied the amount of collected charge as a function of the tilt angle θ, see Figure 3. The shorter dimension of the ladder was parallel to the y-axis, the ladder was rotated around the y-axis, data was taken at θ values 0°, 10°, 20°, 30° and 45°. The results are presented on Figure 7.

3.2 Spurious Hits

The detected hits which do not correspond to the passage of a particle through silicon, but are due to noise are called spurious hits. If the statistical fluctuations of signal of a channel are Gaussian then by applying a 4σ cut for a hit, the probability for a spurious hit is $3.2 \cdot 10^{-5}$. However, if the fluctuations are not a Gaussian, but have long significant tails, the probability for a spurious hit will increase.

We have measured the probability for a spurious hit for the 60 cm silicon ladder by looking at "empty events", i.e. events, where there are no particles. Applying the 4σ cut quoted above we estimate the probability for a spurious hit to be $(5.2 \pm 0.8) \cdot 10^{-5}$. The obtained result is close to the statistical prediction, showing the noise of the channels being nearly Gaussian, therefore the spurious hits do not constitute a problem for long silicon ladders.

3.3 Resolution

After the clusters of channels have been found one needs to find the impact point of the particle. For one-strip clusters the hit position was defined as the position of the strip. For clusters of 3 or more strips we have used the center-of-gravity weighted by the signal of the channel. For two-strip clusters we have used the non-linear η algorithm. The quantity η was defined as

$$\eta = \frac{S_r}{S_l + S_r},$$

where S_r and S_l are the signals in the left and right strip of the cluster. For a given η_0 value the impact position y was then calculated according to:

$$y = y_0 + P_s \int_0^{\eta_0} \frac{dN}{d\eta}(\eta)_n d\eta,$$

where y_0 is the position of the left strip of the cluster, P_s is the strip pitch and $dN/d\eta(\eta)_n$ is the normalized $dN/d\eta(\eta)$ distribution.

A linear straight line fit was thereafter performed to the 4 reference y-sensors (the 60 cm ladder is measuring the local y-coordinate, see Figure 2). The distribution of residuals $(y - y_{fit})$ is presented on Figure 8. The distribution of residuals was fitted with a Gaussian, which gave $\sigma_{res} = 14.0\ \mu$m.

The σ_{res} however includes the effect of multiple scattering in the detector planes and also the additional smearing due to the error of the predicted position, δy_{fit}.

These effects were studied by Monte Carlo, the angular distribution of multiple scattering in the detector planes was simulated according to a Gaussian given in [3]. Taking into account the geometry of the beam test setup, the overall contribution of these two effects was found to be 6.0 μm. The intrinsic resolution of the 60 cm long silicon microstrip ladder was found to be $(12.6 \pm 0.4)\ \mu$m , the error quoted is statistical only.

We have used another independent method to study the spatial resolution of the ladder. The resolution was estimated using a planar line fit (*SiR* [4]) in which the statistical fluctuation of the hit positions (in the 4 anchor detectors and in the tested detector) around the line is modelled by a sum of Gaussian noise and Gaussian scattering process. The scattering process did not have any free parameters. The scale of the noise in each detector was determined by trial and error, using the visual level plots of *SiR*, leading to the estimate $(10.5 \pm 1.0)\ \mu$m . A special feature of *SiR* is that the result is not affected by single scatter tails, ghost tracks, or electronic noise that give too bad (or too good) fits. The rate of bad fits, ignored in the estimation was 12%. *SiR* estimate of resolution is meaningful only if equivalent description of the scattering process is used in the tracking algorithm of the analysis program.

4 Conclusions

A DC-coupled 60 cm single sided silicon microstrip ladder, was manufactured and beam tested. Over the full length the signal-to-noise ratio was 10 and the spatial resolution better than 13 μm with 50 μm strip pitch. The customized silicon processing methods, assembly and readout electronics indicate that large numbers of such long ladders could be manufactured reliably and in a cost effective manner.

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[2] W. Braunschweig, et al., Beam Test Results On Si And GaAs Microstrip Detectors With Length Up To 64 cm, to be published in NIM A.

[3] Review of Particle Properties, Physical Review **D50**, 1173 (1994).

[4] P. Laurikainen, *SiR* — Robust Visual Inference of Tracking Detector Resolution from Beam Test Data, to be published in HU SEFT–RD series.

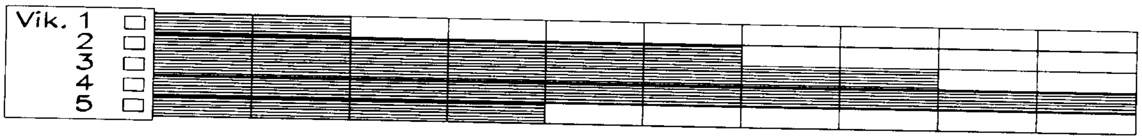

Figure 1: The bonding scheme of the 60 cm ladder. Dark areas correspond to the bonded strips.

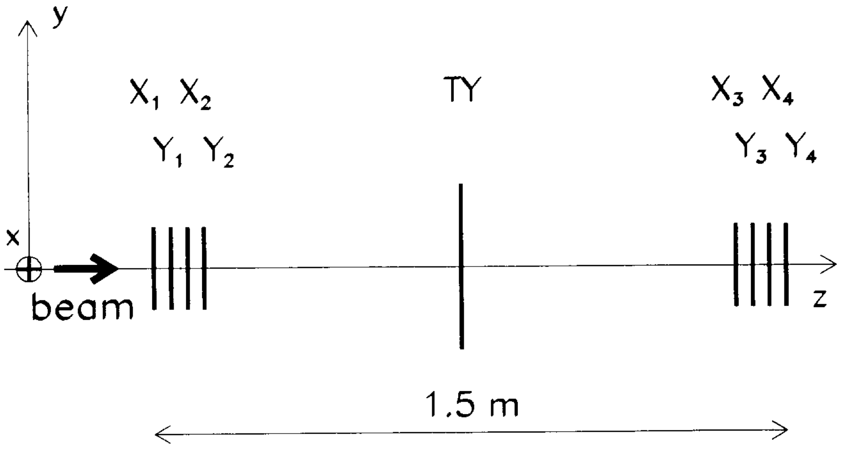

Figure 2: The beam reference system. $X_1, Y_1, \ldots$ are the reference sensors measuring x and y coordinates respectively, TY is the tested 60 cm ladder. The scintillation counters are not shown on this figure.

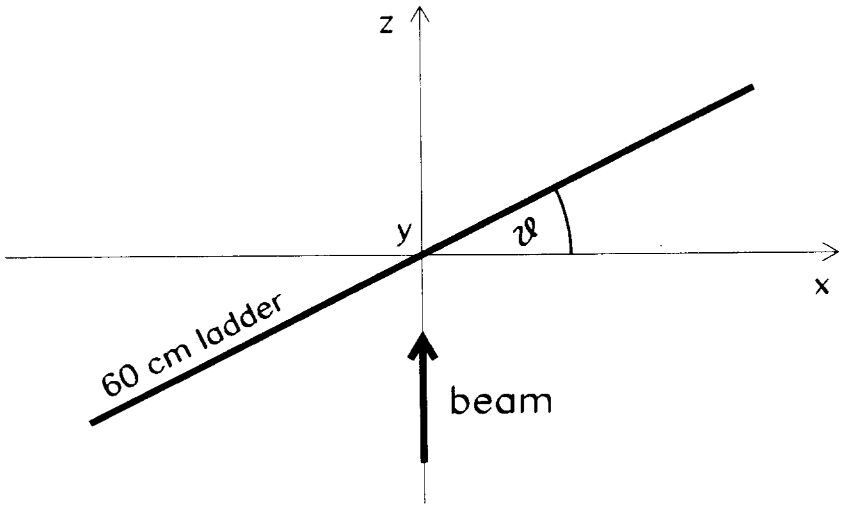

Figure 3: The beam test setup. The shorter dimension of the 60 cm ladder is parallel to the y-axis.

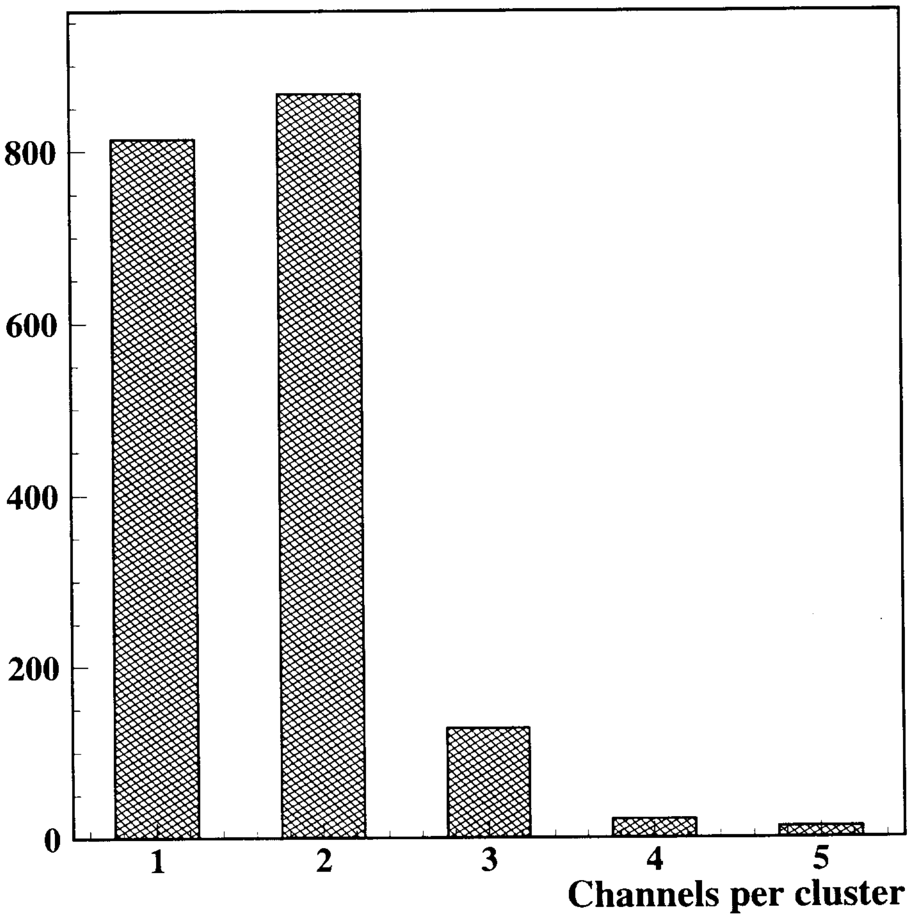

Figure 4: Cluster multiplicity distribution for the 60 cm long ladder.

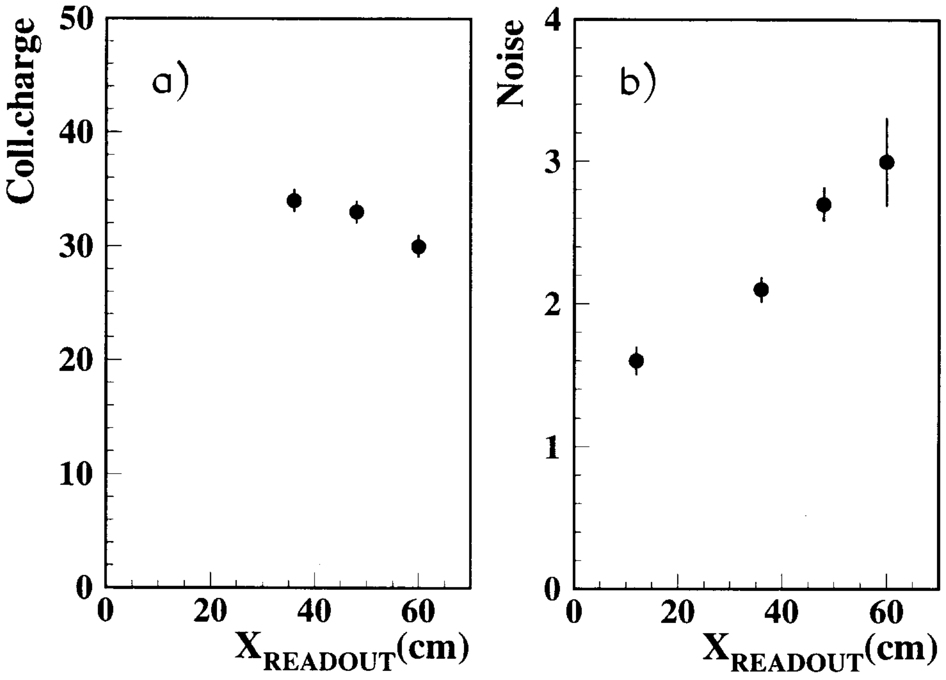

Figure 5: The collected charge (a) and noise (b) as a function of readout length. The collected charge and noise are measured in ADC-counts.

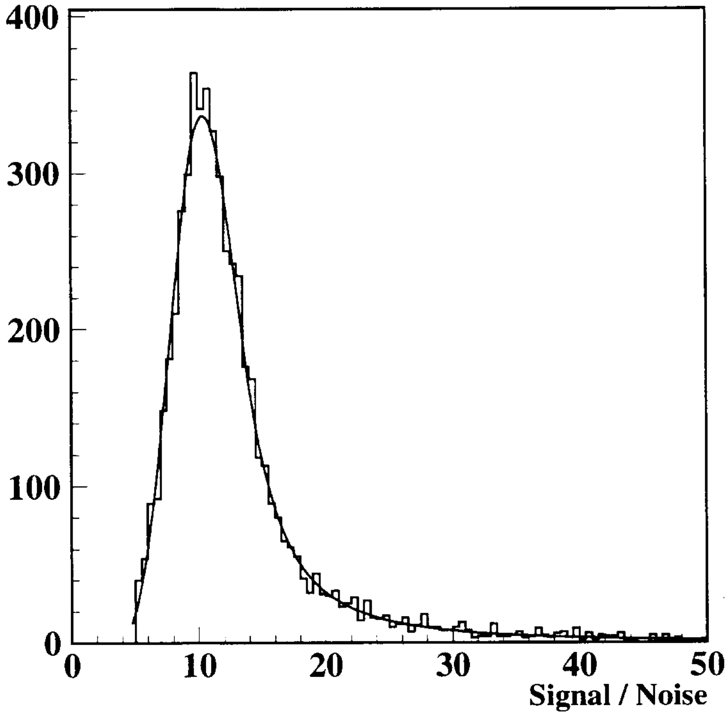

Figure 6: The signal-to-noise distribution for the 60 cm readout length.

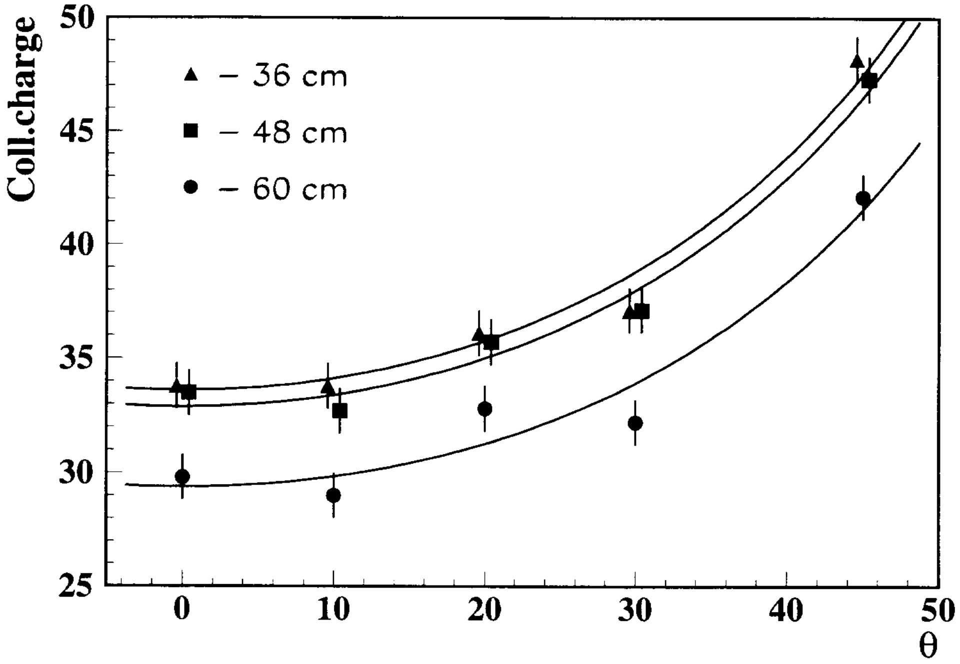

Figure 7: The collected charge as a function of the tilt angle θ for various readout lengths. The overlaid fit is $Q_0/\cos\theta$.

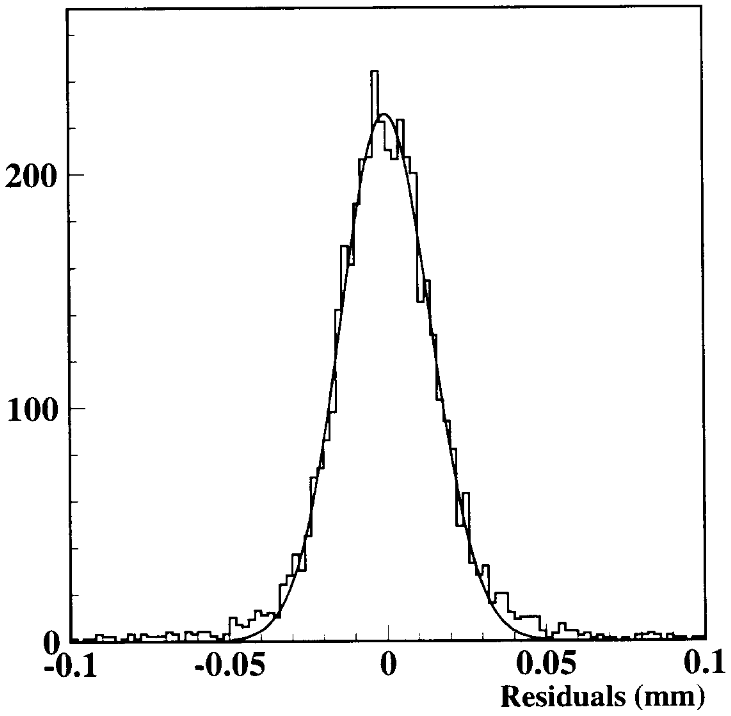

Figure 8: The distribution of residuals for the 60 cm ladder determined from the linear straight line fit.