Test beam results of Silicon Drift Detector prototypes for the ALICE experiment

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We report preliminary beam test results of linear Silicon Drift Detector prototypes for the ALICE experiment. Linearity, resolution, charge transport and collection, and efficiency have been studied using a minimum ionizing particle beam for a very large area detector prototype read out with the OLA preamplifier/shaper and for another detector read out using a new transimpedance amplifier with a non linear response.

1. INTRODUCTION

The feasibility of Silicon Drift Detectors (SDD) has been demonstrated during the eighties by E. Gatti, P. Rehak and collaborators [1–5]. These detectors are able to localize without ambiguity the crossing points of a high number of particles with good spatial resolution. Moreover, the fact that one coordinate is extracted from the drift time of the electrons generated by the crossing particle enables to read out the detector with a rather small number of electronic channels. For these reasons SDDs have been chosen to equip various relativistic heavy ion experiments (CERES/NA45, WA98, STAR, ALICE).

In particular, SDDs will be used for the two middle layers of the Inner Tracking System (ITS) of the ALICE experiment [6], where a very high track density is present. The good energy resolution of semiconductor detectors will also be exploited for low momentum particle identification. The use of more than 200 large area SDDs in ALICE, requires the assessment of large-scale production in industry with good reliability. As part of this program, originally carried out by the INFN DSI collaboration [7] and now within the ALICE collaboration, prototypes of very large area linear silicon drift detectors have been produced and tested [8].

We performed a beam test of the first large area prototype during summer 1997 at CERN using a PS 3\,GeV/c pion secondary beam. The results of this experiment concerning efficiency, charge collection and linearity are reported in detail in [9]. In order to estimate the spatial resolution of the detector without multiple scattering alteration, we performed a second test at the SPS with a higher momentum particle beam (375\,GeV/c). Moreover, during the SPS run, we tested a second detector equipped with a new front-end amplifier.
2. DETECTOR DESCRIPTION AND ASSOCIATED FRONT-END ELECTRONICS

The detectors were fabricated by Canberra Semiconductors N.V. (Belgium) on Neutron Transmutation Doped (NTD) 5" silicon wafers with a resistivity of 3 kΩ · cm.

The largest area prototype has approximately the dimensions required for the ALICE experiment (6.75 × 8 cm$^2$). It has a linear symmetry dividing the detector into two halves with opposite drift direction. On each one the maximum drift length is 33 mm and the drifting charges are collected by an array of 384 200 µm pitch anodes implanted on one surface of the detector, conventionally called n-side (the opposite one is referred as p-side). The electric drift field is produced by 265 120 µm pitch cathode strips implanted on both surfaces and polarized using an internal voltage divider. A more detailed description can be found in [8].

The wafers of the large area SDDs have also various test structures and smaller SDDs. One of these “satellite” SDD has been tested during the SPS beam, and the results are also reported here. It consists of only one drift region with a maximum drift path of 16 mm and 50 read out anodes with a 200 µm pitch.

192 anodes of the large area detector were connected to 6 very low noise 32-channel OLA front-end chip [10]. Each channel features a charge sensitive preamplifier, a semi-Gaussian shaper and a symmetrical line driver. The circuit sensitivity is 30 mV/fC, the shaper peaking time is 55 ns for a δ-like input signal. The equivalent noise charge (ENC) was measured to be ~ 230 e− at 0 detector capacitance.

The small prototype was read out with a new transimpedance amplifier [11] developed in order to increase the dynamic range, keeping good sensitivity for minimum ionizing particles, and to reduce the power consumption. The main feature of this amplifier is a non-linear response obtained by exploiting for the first stage feedback the quadratic $I − V$ curve of a MOS transistor [12].

3. EXPERIMENTAL DETAILS

We have performed beam tests at CERN at the PS and SPS facilities using minimum ionizing protons and pions with momentum 3 GeV/c [9] and 375 GeV/c respectively. In both cases, the experimental setup was quite similar. The SDDs were placed directly on the beam trajectory. The beam was defocused in order to obtain a large spot (1.5 × 2.0 cm$^2$ FWHM). Two 50 µm-pitch micro-strip telescopes, placed both upstream and downstream with respect to the SDDs, were dedicated to the track reconstruction. The beam trigger was given by the coincidence of two couples of scintillating counters placed at both ends of the setup. As the telescope active area (10 × 10 cm$^2$ at the PS and 20 × 20 cm$^2$ at the SPS) and the beam spot size were smaller than the SDDs these were mounted on a micrometric XY-table.

The front-end chip output signals were sent through a 3 m long 50 Ω coaxial cable to a voltage amplifier whose task was to drive a 34 m long twisted pair cable up to the counting room. Then, the signal was digitized using the DL350 flash ADC system [13]. All FADC channels were driven together by a sampling clock that could be programmed to be 100, 50 or 25 MHz or externally controlled. A compression of the input signal could be enabled in order to expand the 8 bit FADC resolution to a dynamic range equivalent to 10 bits. This feature was activated only for the channels corresponding to the OLA chip. Each channel has a 256 bytes ring memory, able to record the signal up to a 5.1 µs duration at 50 MHz sampling frequency. The DL350 FADC system is equipped with a programmable zero-suppression module that compares the FADC memory contents, channel by channel, with a given threshold. A programmable fraction of non zero suppressed event was recorded.

The data acquisition system (DAQ), based on VME and CAMAC, was connected via Local Area Network (LAN) to a HP715 workstation for run control, monitoring and data recording [14].
4. RESULTS

The cluster finding algorithm and related information are described in detail in [9]. The time coordinate is obtained by calculating the centroid of the cumulated signal measured on all anodes affected by the cluster. The coordinate perpendicular to the drift field is reconstructed by calculating the centroid of the charge distribution along the anode axis.

4.1. Linearity and resolution along the drift direction

The purpose of the integrated voltage divider is to produce a uniform drift field in the middle plane of the detector in order to carry the electrons from the crossing point of the particle to the collection anodes. These electrons drift with an average velocity proportional to the drift field and related to the mobility parameter $\mu$:

$$v = \mu E$$  \hspace{1cm} (1)

Figure 1 represents the behaviour of the drift time of the electron clouds in the SDD as a function of their drift distance deduced with the micro-strip telescopes, for three values of the drift field.

Figure 1. Drift time measured by the large area SDD versus drift distance for three electric field values.

Figure 2. a) Scatter plot: distribution of the residuals of cluster centroids from the ideal linearity curve along the drift axis versus drift distance. Close circles: systematic non linearity obtained by averaging the residuals over slices of drift distance. b) Distribution of the residuals integrated over the drift distance.

In order to test the full drift path of the detector, we have cumulated data taken at different SDD positions. We observe a linear shape. From the slope of these distributions, we get the average drift velocities: $4.00 \pm 0.02 \, \mu m/\mu s$, $6.10 \pm 0.03 \, \mu m/\mu s$ and $8.12 \pm 0.01 \, \mu m/\mu s$ for $300 \, V/cm$, $460 \, V/cm$ and $650 \, V/cm$ drift fields respectively. The two curves corresponding to the lowest electric fields were obtained with data taken at the PS whereas the third was taken with SPS data. Multiple scattering is mainly responsible for the widths of the distributions for the PS data (pions of $3 \, GeV/c$). At the higher SPS...
momentum (375 GeV/c), multiple scattering becomes negligible with respect to the intrinsic resolution of SDDs.

In Figure 2a we show a scatter plot of the deviation from the ideal linearity curve versus the drift distance for the highest drift field. Since the mobility is sensitive to temperature, the drift velocity has been measured separately for data taken at different positions of the detector. The deviations can be attributed to two effects: systematic deviations due to the quality of the voltage divider (represented by the close circles) and resolution. We can see that except for the first two points close to the collection zone, where the electric field is not uniform, the systematic deviations are very small: less than ±15 μm peak to peak.

By fitting the distribution of residuals to the straight line defined by the micro-strip hits (Figure 2b), we deduce that along the drift direction the resolution of the detector is $\sigma = 39 \, \mu m$. This value is quite close to the design value requested for the ALICE experiment [6].

We have performed the same analysis for the small SDD prototype. We stress that since the drift path is smaller, we could test it completely without moving the detector and then consider a unique drift velocity. We chose a quite low electric field of 345 V/cm in order to have comparable maximum drift time with respect to the large area detector. Figure 3a represents the drift time of the electron cloud versus the drift distance for data taken at the SPS. By applying a linear fit, we obtained the drift velocity $v = 4.63 \pm 0.01 \, \mu m/\text{ns}$.

Figure 3b shows deviations from linearity. We see again the influence of non uniform drift field in the collection region. The deviation of the last point can be attributed to the fact that in the region of the high voltage strip, the electric field becomes non uniform due to boundary effects. Except for these particular regions, the systematic non linearity does not exceed ±10 μm. From the fit of the distribution of the residuals we obtained (Figure 3c) an excellent resolution of $\sigma = 29 \, \mu m$.

4.2. Linearity and resolution along the anode direction

Figure 4a represents the distribution of cluster coordinate along the anode direction versus the corresponding coordinate given by the telescopes for data measured with the large area pro-
Figure 4. a) Distribution of the anode axis coordinate of the large area SDD cluster centroids versus the reference corresponding coordinate measured by micro-strip telescopes. b) Distribution of the residuals of the cluster centroids from the ideal linearity curve along the anode axis versus the reference coordinate. c) Integrated distribution of the residuals.

Figure 5. a) Distribution of the anode axis coordinate of the cluster centroids measured by the small SDD prototype versus the reference corresponding coordinate measured by the micro-strip telescopes. b) Distribution of the residuals of the cluster centroids from the ideal linearity curve along the anode axis versus the reference coordinate. c) Integrated distribution of the residuals from ideal linearity curve. d) Integrated distribution of the residuals corrected for systematic non-linearity.
gain variations between electronic channels. The misalignment of some micro-strip planes could also be responsible for this effect. However, the \( \sigma = 42 \mu m \) resolution obtained from the Gaussian fit of the residuals distribution, given in Figure 4c, remains good even without any correction for this distortion.

The results from a similar study on the small detector are presented in Figure 5. In this case only eight anodes were read out. Figure 5a represents the distribution of SDD cluster coordinates along the anode direction versus the corresponding coordinate measured with the microstrip telescope. To observe the linearity deviation shown in Figure 5b, we removed peripheral clusters in order to avoid distortions due to their biased centroid evaluation caused by their incomplete detection. Again we observe systematic non linearity mostly smaller than \( \pm 50 \mu m \). Figures 5c and 5d show the distributions of the residuals respectively obtained without and with the correction of the systematic deviations. It can be seen that the resolution improves significantly from \( \sigma = 46 \mu m \) to \( \sigma = 33 \mu m \).

4.3. Signal amplitude and efficiency

Under the effect of diffusion, the charge cloud can freely increase along the drift (constant electric field) and the anode (no electric field) directions but is confined in the central plane of the detector by the parabolic electric field present along the thickness direction of the wafer [5]. The two dimensional charge density in the wafer plane can be expressed as a function of position \( \vec{r} \) and time \( t \):

\[
\rho(\vec{r}, t) = \frac{q}{2\pi\sigma^2(t)} \cdot \exp\left(-\frac{(\vec{r} - \vec{r}_0(t))^2}{2\sigma^2(t)}\right)
\]

The cluster centroid \( \vec{r}_0 \) drifts with velocity \( \vec{v} \) from the crossing point \( \vec{r}_0 \) of the particle as \( \vec{r}_0(t) = \vec{r}_0 + \vec{v} \cdot t \), \( q \) is the charge generated by the particle. The characteristic width of the cloud \( \sigma(t) \) depends on the diffusion constant \( D \)

\[
\sigma(t) = \sqrt{D \cdot t + \sigma_0^2}
\]

where \( \sigma_0 \) represents the initial size of the cloud. Thus the maximum of the density distribution is

\[
\rho_{\text{max}} = \frac{q}{2\pi(D \cdot t + \sigma_0^2)}
\]

It can be shown that, in first approximation, the maximum amplitude of the measured signal also follows such a hyperbolic law [9].

![Figure 6. Cluster amplitude distribution versus drift distance measured with the large area detector for different drift fields.](image)
In Figure 6, we represent, for the three considered drift fields, the distributions of cluster amplitude versus drift distance. The maximum drift times are respectively 8.2 μs, 5.4 μs and 4.1 μs for $E = 300 \text{V/cm}$, $E = 460 \text{V/cm}$ and $E = 650 \text{V/cm}$. As expected, it can be seen that for every drift field the amplitude decreases with drift distance, i.e. drift time. The band with constant low amplitude corresponds to the noise. For the smallest field (largest maximum drift time), the signal amplitude can become lower than the upper limit of the noise band and clusters can be lost when a noise threshold is applied. When the electric field increases, the maximum drift time decreases, and then the diffusion effect becomes smaller. As a consequence, the signal amplitude is well separated from the noise up to the maximum drift path. In the case of $E = 460 \text{V/cm}$ the cluster finding efficiency is already 100% up to 25 mm drift path, and all particles can be detected for the highest field.

5. CONCLUSION

We have presented test beam results of two SDD prototypes obtained with minimum ionizing particles. One of these detectors has a very long drift path (33 mm). For both of them we have obtained very encouraging results concerning the linearity and resolution. The level of noise allows us to reach 100% of single cluster finding efficiency without strong demands on the electric drift field.

We wish to thank F. Piuz and P. Martinengo from CERN for the use of the micro-strip telescope and for their assistance during data taking. R. Hernández wishes to thank Conacyt from Mexico and ICTP from Trieste (Italy) for financial support.

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