Results from beam tests of large area silicon drift detectors

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Abstract

Silicon drift detectors with an active area of 7.0 × 7.5 cm\textsuperscript{2} will equip the two middle layers of the Inner Tracking System of the ALICE experiment. The performance of several prototypes was studied during beam tests carried out at the CERN SPS facility. In this paper, the results obtained from the data taken during August 2000 will be presented. The spatial resolution was studied in the case of tracks perpendicular to the detector and in the case of inclined tracks. Results on the signal analysis and of the double-track resolution are also shown.

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1. Introduction

The two middle layers of the Inner Tracking System (ITS) of the ALICE experiment [1] will be equipped with Silicon Drift Detectors (SDDs) [2–4], which offer the high granularity required by the high particle density predicted in heavy-ion reactions and provide the energy-loss measurement needed for particle identification. Various prototypes have been tested with particles since 1997 at the CERN PS and SPS in dedicated beam tests, to evaluate the detector performance in actual experimental conditions. The results discussed in this paper were obtained from the
analysis of the beam test data taken at the SPS during August 2000. In Sections 2 and 3, the experimental details and the first steps of the analysis procedure are described. The study of the detector spatial resolution for perpendicular and inclined tracks and the two-track resolution are discussed in Section 4.

2. Experimental details

2.1. The detectors

During the August 2000 beam test, one prototype (named ALICE-D2) with characteristics close to those of the final design for ALICE [5] was tested. The detector, produced by Canberra Semiconductors on a 300 μm thick 500 Neutron Transmutation Doped (NTD) wafer with a resistivity of 3 KΩ cm, has an active area of 7.02 × 7.53 cm². The active area is split into two adjacent 35 mm long drift regions, each equipped with 256 collecting anodes (294 μm pitch) and with integrated voltage dividers which deplete the detector and generate the drift field [5]. Since the drift velocity is very sensitive to the detector temperature variation (v ∝ T⁻².⁴) the monitoring of this quantity is performed by means of three rows of 33 implanted point-like MOS charge injectors [6,7]. Besides the D2 prototype, two prototypes from a previous design, named D1B (with only small differences with respect to the final one), were used to provide extra tracking information, whereas the main aim of the test was to study the performance of the D2 prototype.

2.2. Beam test setup

The beam test setup presents the same basic geometrical structure of the beam tests performed since 1997 [8]. The detectors under test were placed on the beam line within a telescope made of silicon strip detectors, which was used for the track reconstruction. The telescope consisted of five pairs of single-sided silicon strip detectors with alternating orientations (x, y). Each microstrip detector covered an area of about 20 × 20 mm², with the strip pitch of 50 μm. The telescope was aligned with two pairs of scintillating counters, placed at both ends of the setup. The coincidence of a signal in all the counters was used as beam trigger. The overlapping region between each pair of scintillators covered an area of about 20 × 20 mm². Since the SDD area was larger than the beam spot and the coverage of the scintillating counters, the SDDs were mounted on a micrometric XY-table in order to perform position scans. For the study of the two-track resolution, a 9 mm thick iron target was placed upstream at a distance of 8 cm from the D2 prototype. The test was performed using a pion beam at 140 GeV/c.

2.3. Readout electronics

The readout electronics included the OLA [9] front-end chip, specifically designed for SDDs, a voltage amplifier/driver and a Flash A/D converter (FADC). OLA is a 32-channel low-noise, bipolar VLSI chip. Each OLA channel consists of a charge-sensitive preamplifier, a semi-Gaussian shaping amplifier and a symmetrical line driver. The peaking time is 55 ns for a δ-like input signal and the Equivalent Noise Charge in laboratory conditions was measured to be ≈230e⁻ at zero detector capacitance. The OLA was followed by a voltage amplifier, originally developed for gas drift chambers [10], driving a 30 m long twisted-pair cable connected to the flash-ADC which sampled the signal at 40 MHz. The FADC system was the DL350 [11], developed by Laben and Struck. It is based on 8-bit resolution FADC chips having an input circuitry that expands the dynamic range to 10 bits with a non-linear transfer function.

2.4. Data sets

Most of the data (3.2M events) were taken with single tracks with perpendicular incidence on the SDD. For reason of geometrical acceptance and acquisition speed, it was chosen to connect 72 anodes from each detector to the FADCs. Whereas for the D1B detectors the same group of 72 anodes was maintained for all data-taking, the connections to the D2 detector were changed
during the position scans in order to ensure that the performance of the complete half-detector could be measured. The nominal drift field was 667 V/cm for the ALICE-D2 detector and for one D1B, and 583 V/cm for the other D1B prototype.

Some data (600k events) were also taken with inclined tracks in the plane formed by the SDD anode axis and the SDD normal axis. In ALICE, the maximum value possible for the angle between the beam axis and SDD normal axis is 45° for primary tracks. The inclination angles chosen for the test were 22.5 and 36°, since the mechanical support did not allow larger angles. Another set of data (800k events) were taken with the target in order to collect multitracks events to study the double-track separation capabilities of the SDD.

3. Corrections

3.1. Correction for doping inhomogeneities

Since 1999, systematic errors in the determination of the particle impact point position were observed [12] and attributed to inhomogeneities of the dopant concentration. In SDDs, doping inhomogeneities affect the performance of the detector, since they induce variations in the potential distribution causing a parasitic electric field. The component of the parasitic electric field parallel to the drift direction locally changes the drift velocity and causes systematic errors in the measurement of the coordinate along the drift axis. The component of the parasitic electric field perpendicular to the drift direction induces deviations of the electron trajectories leading to systematic errors in the anode coordinate. To obtain an optimal resolution, it is necessary to correct the measured coordinates for these systematic deviations. For the ALICE-D2 prototype, it was possible to map the systematic deviations along both the drift and the anode directions for the full half-detector tested. In Fig. 1, the systematic deviations of the measured anodic coordinate (top) and of the measured drift coordinate (bottom) with respect to the reference position given by the microstrip telescope is represented as a function of the anode coordinate (x) and the drift distance (y). The value of the systematic deviation for each bin of the histogram, corresponding to an area of $0.5 \times 0.3 \text{mm}^2$, was obtained by considering the centroid of the residual distribution between the SDD and the reference coordinates. The empty areas in Fig. 1(a) correspond to noisy or non-working channels and were not taken into account during the analysis. In Fig. 1(b), the horizontal line at a drift distance of $\approx 17 \text{mm}$, corresponding to a sharp change of the residual distribution for all the anodes is due to a short-circuit between two adjacent biasing cathodes at that drift distance. The circular structures centered on the middle of the SDD are attributed to the radial dependence of the dopant concentration fluctuations [13]. The systematic deviations reach values up to 400 μm. In Fig. 2, as an example, a projection on the y-axis of the previous histograms, representing the systematic deviations as a function of the drift distance for a slice around the anode no. 147 ($x = 44 \text{ mm}$), is shown for both the coordinates. This anode corresponds to the first anode closest to the central region after the group of the discarded channels mentioned above.

These maps were used in the analysis to correct the coordinates measured by the SDD and thus optimise their spatial precision. From the values of the systematic deviations, it is possible to estimate the values of the components of the parasitic electric field. It can be demonstrated that the components of the parasitic electric field parallel and perpendicular to the drift direction can be expressed by

$$E_{\parallel} = E_{\text{drift}} \frac{d\Delta y/dy}{1 - d\Delta y/dy}$$

$$E_{\perp} = E_{\text{drift}} \frac{d\Delta x/dy}{1 - d\Delta y/dy}$$

where $d\Delta y/dy$ and $d\Delta x/dy$ represent, respectively, the derivatives of the systematic deviations along the drift direction and along the anode direction with respect to the drift coordinate. $E_{\text{drift}}$ represents the drift field generated by the biasing cathodes. The maps shown in Fig. 3 were obtained with $E_{\text{drift}} = 667 \text{ V/cm}$. In Fig. 3(b), the effect of the short-circuit at the drift distance of 17 mm is clearly visible. In Fig. 4, a projection on the y-axis...
3.2. Correction for temperature variations

Silicon drift detectors are very sensitive to temperature fluctuations, which induce carrier mobility, and therefore drift velocity, variations of about 1%/K at room temperature. In the ALICE SDDs, the current flowing through the integrated voltage divider causes heat dissipation, creating temperature gradients in the sensitive region of the detector. Variations of the ambient temperature during operation also affect the temperature of the detector and thus the drift velocity. To monitor the drift velocity variations, the ALICE SDDs are equipped with MOS charge injectors [6,7]. For the analysis presented in this paper, the drift velocity variations caused by temperature fluctuations were corrected using the reference position given by the microstrip telescope.

4. Results

4.1. Cluster size

The electron cloud generated by an ionizing particle in the SDD undergoes a diffusion while drifting to the collection anodes. After the digitisation of the anode signals, the cloud is
represented by a two-dimensional set of amplitude values, called a “cluster”. A measurement of the cluster size was performed in both the anode and the drift directions. The time evolution of the amplifier output signal results from the convolution of the anodic current and the time response of the amplifier. The anodic current shape is, to a good approximation, similar to the electron collection time distribution. The nominal value of the OLA shaping time is 55 ns for a zero input capacitance, but it was larger and not precisely known in our experimental conditions, since the detector capacitance, expected to be about 300 fF [9], was not measured. This uncertainty did not allow the precise determination of the size of the electron cloud along the drift axis. However, since the shaping time of the OLA was constant during all the data taking and of the same order of magnitude of the anodic signal duration, a qualitative comparison of this duration is possible by calculating the r.m.s. cluster size along the drift direction, that is the r.m.s. of the anode signals along the time axis. Fig. 5 shows the distribution of the r.m.s. of the signal as a function of the drift time for the various values of the incident angle.

Calculating the ratios between the most probable value (m.p.v.) of the signal r.m.s. distribution at 0° and at different inclination angles, no significant difference is observed, confirming the independence of the cluster size along the drift axis from the inclination angle. Fig. 6 shows the relative amounts of clusters collected by one, two or three anodes as a function of the drift time for inclination angles of 0°, 22.5° and 36°. The number of clusters collected by more than three anodes is less than 1%. As expected, the number of multi-anode clusters increases with the inclination angle of the tracks. The number of single-anode clusters in the anode region decreases with the inclination angle changing from 11% of the total number of clusters for 0° to 4% for 36°. The number of three-anode clusters increases with the drift time and the inclination angle from 20% for 0° to 41% for 36° of the total amount of clusters.

4.2. Charge

Since the OLA amplifier has a linear response, for each channel the integral of the output signal is expected to be proportional to the charge collected.
by the anode. Under the condition that the threshold is sufficiently low compared to the maximum amplitude of the signal, that the signal has no undershoot, and that the sampling period is small enough compared to the signal shaping time, the sum of the linearized amplitudes of the cluster is proportional to the total collected charge. In the following, this sum will be called charge. In Fig. 7 (top) the most probable value (m.p.v.) of the cluster charge versus the drift distance are shown for the perpendicular tracks and inclined tracks for each group of the analysed runs. As one can notice, the collected charge decreases as a function of the drift distance. A charge collection inefficiency was already observed in this detector on the test bench in the laboratory. The necessity to understand the origin of the phenomenon was one of the reasons to choose this detector for the beam test. The reason for the collection inefficiency is attributed to electron trapping centres in the bulk silicon, introduced by impurities during detector fabrication. A cross-check with the data from the production cycle allowed to pin down the reason for the contamination and correct the problem in the subsequent detector production.

The ratio between the m.p.v. for perpendicular tracks and the m.p.v. for the inclined tracks has, apart from the experimental fluctuations, a constant value versus the drift time consistent with the value of the cosine of the inclination angle, that corresponds to the increase in the track length in silicon. The obtained value for the ratio is $0.805 \pm 0.011$ for the inclination angle of $36^\circ$ and $0.917 \pm 0.009$ for the angle of $22.5^\circ$. Due to this increase in the cluster size along the anode axis, an improvement of the resolution along the anode axis when the angle increases is expected.

Fig. 3. Maps of the components of the parasitic electric field, caused by dopant concentration fluctuations of the silicon wafer, perpendicular (a) and parallel (b) to the drift direction. The values of the field are given by the grey scale in V/cm and are represented as a function of the anode coordinate ($x$) and the drift distance ($y$).
4.3. Position resolution

The detector position resolution was evaluated considering the difference between the cluster position measured by the SDD and the impact point coordinate reconstructed with the microstrip telescope. The resolution is defined as the r.m.s. of the residual distribution. The data were corrected for the doping inhomogeneities and, for the resolution along the drift axis, for the temperature variations. For the data taken with perpendicular tracks, all the anodes of a half-detector were read out and the resolution in different regions, along both the anode and the drift direction, was studied. For the analysis of two-track resolution and for the data with inclined tracks a smaller region was studied.

4.3.1. Perpendicular tracks

The resolution along both the drift axis and the anode axis was evaluated on eight separate regions of 32 anodes each. Fig. 8(a) shows the results obtained for the resolution along the drift axis, after the corrections for the doping inhomogeneities and the temperature variations. The black circles represent the average of the values of the resolution obtained in the separate regions. The grey area represents the difference of the values of the resolution in the different regions. The limits are given by the worst and the best values. The average value of the resolution is \( \sim 35 \mu m \). Fig. 8(b) shows the spatial resolution along the anode axis. At short drift distances, the resolution is affected by the intrinsic uncertainty due to the charge cloud being smaller than the anode pitch. At a drift distance of \( \approx 15 \) mm, the average r.m.s. of the residual distribution reaches its minimum value of \( \approx 15 \mu m \). At the longest drift distances, the resolution deteriorates with respect to the minimum value because of the reduction of the signal-to-noise ratio \( S/N \) due to the signal spreading over more anodes due to diffusion and the charge loss. \( S/N \) can be defined approximately as \( Q/(\sigma \sqrt{n}) \) where \( Q \) is the integral of the signal (proportional to the charge), \( \sigma \) is the noise r.m.s. and \( n \) is the average number of anodes which collect the signal. The difference in \( S/N \) between zero and the maximum drift distance
can be estimated:
\[
k = \frac{(1 - \alpha)Q_0/(\sigma\sqrt{2.5})}{Q_0/(\sigma\sqrt{1.1})} = (1 - \alpha)\sqrt{1.1}/2.5 = 0.4
\]
where \(\alpha\) represents the charge loss and \(\sigma\) the noise r.m.s. This value corresponds to a variation of \(S/N\) of about 60%.

The average resolution is of the order of \(\sim 25\,\mu m\). The differences in the values of the resolution for the different regions are due to different gain stability of the electronic channels. The regions with worse resolution correspond to electronic channels which have the gain less stable in time than the others.

4.3.2. Spatial resolution with inclined tracks

The spatial resolution with inclined tracks is presented only along the anode axis, where an improvement, with respect to the one with perpendicular tracks, is expected. A modest improvement of the spatial resolution along the drift direction is expected from the higher value of the \(S/N\) ratio. However, the \(S/N\) variation obtained by changing the incidence angle by an angle \(\theta\) with respect to the perpendicular is \(1/\cos \theta\) which is about 20% for an angle of 35°. In Fig. 8(a), we can see that a variation of \(S/N\) up to 60% produce a change of just 6\(\mu m\) on the resolution. On the other hand, simulations made in the AliRoot framework, the ALICE simulation tool, have also indicated that a negligible influence is expected by increasing the \(S/N\) ratio of 20% [14]. In Fig. 9, the comparison between the spatial resolution at 0° and at different inclination angles as a function of the drift distance is shown. Fig. 9(a) shows the comparison between the measured resolution for perpendicular tracks and for the
inclination of 22.5° in the SDD region between anodes 0 and 60. The comparison between the resolution for perpendicular tracks and for the inclination of 36° is illustrated in Fig. 9(b), for the SDD region between anodes 60 and 110. It can be observed that in the vicinity of the SDD anodes, the values of the anodic resolution for inclined tracks become better with respect to those for perpendicular tracks. This behaviour is caused by the decrease of the fraction of narrow clusters in the inclined track events. For longer drift distances, the values of the resolution are very similar to those for perpendicular tracks. Except at short drift distances, the average value of the resolution is better than 30 μm.

Fig. 6. Percentage of the events in which a cluster is collected by one, two or three anodes as a function of the drift time for inclination angles of 0° (a), 22.5° (b) and 36° (c).
4.3.3. Two track resolution

The double-track resolution was studied for the D2 detector. The detector was positioned at a distance of 8 cm from the iron target and a specific selection of data were applied. The events with two and only two tracks of the secondary particles, reliably reconstructed by the rear microstrip telescope, were selected. A minimisation procedure using the single track data were applied for the separation of the overlapping SDD clusters. Both of these reconstructed tracks had to pass through the SDD area selected for the analysis. If the SDD reconstructed exactly two hits within a compatible distance from the tracks, the event was counted as resolved. If there was only one SDD reconstructed hit, the event was unresolved. Otherwise, the event was discarded due to inefficiency of the analysis procedure. The fraction of resolved two-track events as a function of distance between tracks is shown in Fig. 10. The 50% point, where half of the track pairs are resolved, is reached after a separation value of 450 μm, while 90% is reached at 800 μm.

5. Conclusions

An extensive study of the performance of a silicon drift detector with characteristics close to the final SDD designed for the ALICE experiment was carried out using the OLA front-end ASIC. The characteristics of the detector were studied in
the case of perpendicular tracks and with inclined tracks. The analysis showed the presence of systematic effects due to doping inhomogeneities, which affect the measurement of the coordinates leading to systematic deviations up to 400 µm. Applying a correction for this effect, the average values of the spatial resolution in the case of perpendicular tracks are \(~25\) µm along the anode axis and \(~35\) µm along the drift axis. As expected, a significant improvement of the resolution along the anode axis was observed for the data taken with inclined tracks for small drift distances (\(<10\) mm). The double-track resolution was also measured and an average value of \(450\) µm was obtained.

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