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A HYBRID SILICON PIXEL TELESCOPE TESTED IN A HEAVY-ION EXPERIMENT

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ABSTRACT

Specific features of the Omega-Ion pixel detector are the adjustable delay with external trigger capability and the detector leakage current compensation. A row of pixels can be used for testing the electrical performance of the amplifier and comparator circuits. Detailed results of these electrical tests are presented. A telescope made of three Omega-Ion hybrid silicon pixel detectors has been successfully tested in the heavy-ion experiment WA94. Each plane consisted of a single detector with 1006 active pixels ($500\text{ }\mu\text{m} \times 75\text{ }\mu\text{m}$), each one being bump-bonded to the readout chip, and arranged in 16 columns and 63 rows respectively. With a sensitive area as small as $8000 \times 4725\text{ }\mu\text{m}^2$ several million events with at least one track originating from the sulphur-sulphur interaction have been recorded in a few hours. Results on target reconstruction, tracking accuracy and efficiency are presented.

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1. INTRODUCTION

In particle physics, particularly in high-multiplicity and high-rate environments like heavy-ion experiments and future hadron colliders, the track detectors in the inner region need a precision of $10\text{ }\mu\text{m}$ [1]. The approach using silicon microstrip detectors may satisfy this precision, but it is not a suitable solution because of the large computation time needed for resolving the ambiguities. A possible solution is to complement the microstrips with two-dimensional silicon pixel detectors: such devices present a finer segmentation and a lower noise [2]. A first effort in the development of silicon pixel detectors with adequate speed was performed in the framework of the CERN/LAA research and development program [3] and now this work continues in the CERN RD-19 program [4].

A telescope made of three new hybrid silicon pixel detectors has been tested in the heavy-ion experiment WA94 at CERN and the first results have been already presented elsewhere [5]. This Omega-Ion device combines a two-dimensionally segmented silicon detector of 1006 sensor elements arranged in 16 columns and 63 rows with a geometrically identical matrix of readout electronic circuits with active, fast pulse processing electronics in each cell.

Besides our own effort, other groups have been studying experimental pixel detectors for similar applications. In particular, should be mentioned the group at the Rutherford Appleton Laboratory which pioneered CCD-type pixel detectors [6] and a separate effort aiming at direct readout pixel detector structures [7]. At Stanford a prototype monolithic detector has been manufactured and the first results have been reported recently [8]. An SSC collaboration has worked with Hughes Aircraft on a hybrid device [9]. In the Max-Planck Institut in Munich pixel detectors with integrated amplification and charge storage are being developed [10]. At IMEC in Leuven new approaches for integration of detector and readout are under development by Vanstraelen and Dierickx [11].

In sects 2 and 3 we present a detailed functional description of the readout chain for an individual pixel element and the general architecture of the readout chip. This chip was tested electrically and the results obtained are discussed in sect. 4. The results from the beam test are described in sects 5 and 6, illustrating the performance of these detectors as well as highlighting some problems. Finally, in sect. 7 we draw some conclusions and discuss further work.

2. PIXEL ELECTRONICS

Each sensor element of the pixel detector is coupled to a complete electronics readout chain which is contained within a silicon area equal to the area of the sensor element, $75 \times 500\text{ }\mu\text{m}^2$. A block diagram of this readout chain is shown in fig. 1. It

contains a fast, charge-sensitive preamplifier (CSA), a comparator, a delay and a memory element. A signal from a sensor element is amplified by the CSA, discriminated by the comparator, delayed and gated into memory by the strobe, provided the strobe signal coincides with the delayed comparator signal.

Figure 2 shows the CSA with feedback which incorporates leakage current compensation. Transistors M1 and M3 form a folded cascode pair which provides the transconductance g_m required to transfer the input signal charge to the 7 fF feedback capacitor C_{fb} . The decay time constant of the CSA is around 1 μ s. Transistors M2 and M4 control the bias currents of the folded cascode. M6 and M7 are two diodes connected in series which fix the DC operating point of the preamplifier. M9 is a diode which clips the output of the preamplifier for large input signals avoiding any saturation phenomenon which could block the circuit over a long period of time. The detector leakage current is compensated by using M5 to subtract a DC current equal to the leakage current detected on a dummy pixel.

Figure 3 is the schematic of the latched comparator. Transistors M10 and M11 form a differential stage which is AC coupled by the capacitor C_c . This differentiates the output of the preamplifier such that the resulting current in the pair has a peaking time of around 50 ns. The cross-coupled pair M16 and M17 behaves as a bistable feedback element which switches state when the differential current output of M10, M11 exceeds the bias current of M18 which is fixed by I_{dis2} . Thus, I_{dis2} can be used to adjust the threshold of the comparator. The regenerative circuit which is made by transistors M21 to M27 senses the switching of the comparator and latches the comparator output.

The latched output of the comparator is connected to the delay element which, as shown in fig. 4, is a series of three inverters whose switching speed is controlled by currents I_{dn} and I_{dp} . The I_{dn} (and subsequently I_{dp}) can be adjusted externally enabling the delay to be varied. The final inverter is not controlled in switching speed and it is used to clean up the edges of the output signal. The output from the delay resets the comparator via an OR gate. The delay thus defines the pulse width of the signal from the comparator.

Figure 5 shows the architecture of the coincidence logic and memory element. The multiplexor, MuxA, is used to ensure that the trailing edge coming from the delay inverters after twice the delay sets the D flip-flop if it coincides with the strobe. If a falling edge is present then a 1 is clocked into the D flip-flop element. When the strobe is low, MuxB connects all the D flip-flops in one column of pixels together forming a vertical shift register which can be clocked using the *clkout* signal through MuxA. A drawback of this architecture is that the *clkout* must undergo a low-to-high transition during the strobe high phase to avoid false hits.

3. CHIP ARCHITECTURE

Figure 6 shows the architecture of the readout chip. After a strobe has been applied, each pixel which has been hit has a 1 in its D flip-flop. When read out the pixel cells form 16 parallel 64-bit long shift registers which are clocked out using a train of 64 pulses applied to the *clkout* terminal. Each column on the readout chip has 65 elements in total. The top row of pixels is not connected to the detector, but is coupled capacitively to an electrical input enabling the electrical performance of the chip to be evaluated independent of the detector bonding. This test input can be used for a functionality test prior to scribing and mounting of the chips and also during the detector operation for testing if there are no particles. An extra row of pixels at the bottom (not shown in fig. 6) serves as a row of dummy cells for detector leakage current detection and for the generation of bias currents for the column. The leakage current detected in the bottom cell of one column is mirrored to and subtracted from the input of each of the cells in that column.

A picture is taken (fig. 7) with a scanning electron microscope (SEM) of a small part of the readout chip. One recognizes the cells having each a solder bump ready for the input connection to the silicon detector chip.

4. ELECTRICAL MEASUREMENTS

As described above, all pixels in the top row are connected capacitively to an input bonding pad. The approximate value of the capacitor (calculated from the manufacturer's parameters and the drawn size) is around 30 fF. Note that in ref. [5] this capacitance was estimated at the lower value of 20 fF. The higher, but more precise estimation has forced us to scale up our original estimates of noise and threshold variation. The noise after rescaling is $\sim 90 e^-$ r.m.s. Unambiguous determination of the noise figure needs absolute measurements in terms of the electron charge. Such measurements are currently performed using photon-emitting radioactive sources.

Figure 8 shows the thresholds of one row of 16 pixels at two different values of threshold current, I_{dis1} . The pixel-to-pixel variation is around $750 e^-$ r.m.s. and appears to be of a random nature suggesting that it is due to the poor reproduction of bias currents from one pixel to the next due to geometrical uncertainties in processing. This variation is calculated to be equivalent to 15 mV r.m.s. at the input to the discriminator. As the maximum size of the current mirror transistors is limited by the size of one pixel, we do not expect to be able to improve significantly this random variation in future versions. One possible remedy would be to increase the gain of the preamplifier in order to reduce the size of the r.m.s. variations relative to a given input signal. However, it would be difficult to reduce the size of the 7 fF feedback capacitor any further.

Measurements of the time slewing of the discriminator were made on a separate chip with pixels which had only the preamplifier and discriminator and no delay or coincidence logic. This slewing measured from twice the threshold to ten times the threshold is < 15 ns and is constant for all cells.

A study was made of the strobe timing and variations as this ultimately limits the efficiency of the pixel detector device in a fixed-target application. A first observation proved that the minimum width of the strobe was around 150 ns. This was larger than expected, but it can be explained by the slewing of the strobe signal across the chip due to the large capacitances of the strobe lines. Figure 9 shows the delay between the arrival of the input test signal and the output of the delay element resulting from an input signal of $50\,000\text{ e}^-$ for two values of delay control current, I_{dn} . There appear to be two effects superimposed in this case. Firstly, there is a random effect which presumably comes from the geometrical matching problems which we encountered with the threshold non-uniformity. Secondly, there is a left-right effect in the strobe timing. A detailed examination of the chip layout reveals that the power supplies were under-dimensioned leading to a drop in voltage across the chip from left to right. As the external delay control current is applied in parallel to one diode-connected transistor per column, each of these diodes generated a slightly different I_{dn} and I_{dp} for each column. This led to the left-right variation in the delay timing.

The maximum readout frequency was measured to be 5 MHz. This was lower than simulations suggested, but it may be explained by the slowing down of the edges of the *clkout* signal due to the large capacitance of the lines.

5. BEAM TEST

During the run of the heavy-ion WA94 experiment a parasitic test of the pixel telescope has been performed in the 1.8 T magnetic field of the CERN Omega spectrometer. A sulphur beam hits a sulphur target with an intensity of 5×10^5 particles/spill and a spill length of 5.1 s every 19.2 s. The experimental set-up is sketched in fig. 10(a): three pixel detector planes were positioned downstream of the target at 204 mm, 224 mm and 235 mm distance, with their centres 11.5 mm below and 3 mm sideways of the beam axis. In such a way the largest part of the produced particles is not detected and radiation damage did not occur in this test.

Figure 10(b) shows a typical high-multiplicity event. It indicates very clearly the advantage of a true two-dimensional detector over a crossed strip approach.

A first set of runs was made under nominal bias conditions. The results as obtained on-line during the run are shown in fig. 11. Here each pixel is represented as a box

whose length is proportional to the accumulated number of hits in the pixel. As the areas of the boxes are proportional to the square of the accumulated number of hits, the differences are exaggerated by these plots. There are several points of interest. Firstly, all pixels in all planes were able to detect particles (no blank spaces) and there were only four noisy pixels which have been removed from the plot. Secondly, on all three planes there seem to be more pixels hit in the top left corner of the device and less at the opposite corner. The beam was at the top left corner of the chip and this means that the distribution of the hits could be simply due to the beam drop-off. We note here that in planes 1 and 2 the left-hand column seems to receive fewer hits than the rest. Also in plane 3 this effect is seen over the first 4 columns. This is explained later.

The aim of the next set of data taken was to look at the effect of varying the threshold of the discriminators. The bias current I_{dis2} was varied only on the plane 2 leaving planes 1 and 3 under nominal bias conditions. Figure 12 shows that the response of the detector changes only slightly over a wide range of threshold currents. This result is not surprising when one realizes that the discriminator threshold is around 6000 e^- under nominal biasing conditions while the charge deposited by a typical crossing particle is $25\,000\text{ e}^-$.

A further set of data was taken to consider the effect of varying the delay by controlling the bias current I_{dn} . This test was performed only on plane 2. Remembering the results of the electrical tests one would expect a left-right effect across the chip. In the experiment the strobe delay corresponded to the first-level trigger and was around 400 ns . The strobe width was fixed at around 400 ns . Figure 13 indicates very clearly the effect of varying the current I_{dn} . It can be seen that there exists an optimum value of I_{dn} which allows all the pixels of one chip to be sensitive. It is interesting to see that the result of $I_{\text{dn}} = 6.375\text{ }\mu\text{A}$ is almost identical to plane 1 in fig. 11 and the result of $I_{\text{dn}} = 6.875\text{ }\mu\text{A}$ is also very similar to plane 3 in fig. 11. This indicates that the values of I_{dn} were not optimized for planes 1 and 3 at the nominal biasing conditions. However, it must be said that this observation is one which only became obvious after off-line analysis.

6. DATA ANALYSIS

For this set of data the values chosen for the currents regulating the threshold (I_{dis2}) and the strobe delay (I_{dn}) are $30\text{ }\mu\text{A}$ and $8.5\text{ }\mu\text{A}$ respectively. The results presented hereafter come from 5×10^5 events which have been collected under stable, optimized conditions in 8 h. Only 4 noisy pixels have been found out of 3018 and they have been removed from the analysis which is presented in this paper. No dead pixels have been detected.

6.1 Geometrical reconstruction

Since the three detectors are not arranged in a projective way a fiducial volume has been defined in order to choose tracks which travel through the whole telescope. We select a subset of our data by requiring that all hit pixels in one event be inside a volume defined as a pyramid pointing to the target and containing the common region of the three detectors (fig. 14).

Moreover, we exclude events with hits in the regions corresponding to columns 1 to 4 in plane 3, because a mistuning of the electronic bias current I_{dn} for this plane may have caused inefficiencies. At this stage of the analysis no constraints are imposed on the hits. About 22% of the events survive this cut. The maps of the three planes representing the number of hits detected in the fiducial volume are shown in fig. 15.

Figure 16 shows the distribution of the number of hit pixels per plane and per event. Because of the very small solid angle covered by the telescope, which is placed off the beam line, the mean value of the distribution is only 1.7 hits. Only for few events the multiplicity is larger than 20 hit pixels per plane (the occupancy is always $< 5\%$). A simple topological and one-dimensional algorithm has been used to study adjacent hit pixels along z (i.e. in the same column, see fig. 17(a)). This simplification was possible because of the different granularity of the detector in the two dimensions (the pixel y -dimension is more than six times larger than the z one). We define as “cluster” a group of hit pixels which are adjacent along z and we call “cluster width” the number of hit pixels. For example, an isolated single-hit pixel is a cluster of width one. Figure 17(b) shows the cluster width distribution of our data: 79% of the clusters have a single hit, 19% have a double hit, 1.9% have a width between 3 and 10, and only 0.1% has a width larger than 10. One should keep in mind that there is a possibility of high multiplicity in the heavy-ion reactions. The mean width of our clusters is ~ 1.3 pixels. The observed percentage of double-hit events corresponds to the charge sharing expected for adjacent pixels when crossed by inclined tracks, and simply taking into account the geometry of the detector (which is 300 μm deep with a pixel pitch of 75 μm).

The fast way to reconstruct the target position is to select candidates to be single-track events for which no complicated reconstruction program is needed. The selection is simply done by choosing events with one cluster per plane. This kind of events represents $\sim 1/3$ of our sample (around 1.2×10^4 events). Since we do not have any external detector to check the relative position of our telescope planes, we have aligned these planes requiring the self-consistency of the offsets. First, we choose a clean sample of events having only a single hit per plane, then we require that the track candidate comes from the interaction region (target). Therefore, each plane is aligned by minimizing the χ^2 distribution of the trajectory fit of all track candidates. After alignment, a linear fit to the tracks has been performed in the zx plane (minimally affected by the magnetic field) using

the barycentre values of the clusters (fig. 18(a)). The distribution of the intercept between the fitted tracks and the axis $z = 0$ is given in fig. 18(b): the accumulation in the target region proves that tracks are coming from physical interactions. The tail at negative x corresponds to upstream interactions not filtered by a simple volumetric cut (some matter is indeed present on the beam line in front of the target). This distribution has been fitted assuming a gaussian shape for the target region, superimposed over a flat background. Under these assumptions the target position can be reconstructed with a σ of 1.035 cm.

6.2 Accuracy

It is now possible to evaluate the spatial accuracy of the telescope by using the same sample as for the target reconstruction. First, we define a straight line with the barycentre values of the clusters in planes 1 and 3. Then we compute the difference Δz between the barycentre value of the cluster in plane 2 and the intercept of the line with this detector. The distribution of the residual Δz is presented in fig. 19. This distribution was fitted assuming a gaussian shape. The mean value of $-33 \mu\text{m}$ represents our error on the alignment of the middle plane. The σ of $25 \mu\text{m}$ is a good estimate of our precision: it compares well with the one expected for an ideal telescope with 3 planes and $75 \mu\text{m}$ of pitch, which is calculated to be $75/(2 \times \sqrt{3}) = 22 \mu\text{m}$.

The knowledge of the tracking accuracy together with the variance of the linear fit can be used to discriminate in our sample “good” tracks candidates from the “bad” ones. In fact, we define as “good” a track with $\Delta z < 75 \mu\text{m}$ (i.e. $< 3 \sigma$) and a variance $< 10^{-4} \text{ cm}^2$ in the linear fit(*).

In such a way we select 11 808 events (around the 94% of our sample). Figures 20(a–c) show the correlations between the z -coordinates of the three planes combined two by two, while fig. 20(d) shows the z -coordinates in the middle plane versus the point where the line constructed using the z -coordinates in planes 1 and 3 intersects the middle detector. The width of the distributions can be explained by the angular spread of the particles emerging from different interaction points in the target.

6.3 Efficiency

We have studied the remaining 6% in order to understand the nature of the so-called “bad” candidates. We have subdivided this sample in two subsamples according to the value of the variance of the linear fit, which suggests a different interpretation of the data. In fig. 21 we show the same coordinate correlation plots for candidates with a very bad

(*) We call variance the sum of the squared residuals indicating the badness of fit. If the variance is $< 10^{-4} \text{ cm}^2$ all the residuals are $< 100 \mu\text{m}$. In other words we can say that the 3 points are aligned within our tracking precision. If the variance is $> 10^{-4} \text{ cm}^2$ then one point is not on a straight line.

variance of the linear fit ($> 10^{-2}$ cm) and a $\Delta z > 3 \sigma$ (300 events, around 2%). The interpretation of the data is that these are two-track events not fully contained in our fiducial volume. As sketched in fig. 22, the first track intercepts planes 2 and 3 (but not plane 1), the second only plane 1. Those candidates are false single-track events and should be removed from our sample when calculating efficiency.

The second subsample contains candidates with a variance on the linear fit in the range $10^{-4} < \text{var} < 10^{-2}$ and a $\Delta z > 3 \sigma$ (600 events, around 4%). Those events seem to be low-energy particles (like protons around 1 GeV) which present a big scattering in the middle plane. In this case, in fact, the correlation plots (fig. 23) show a good correlation between planes 1 and 2 and between planes 2 and 3, but a missing correlation between planes 1 and 3 because of the large scattering angle. The fraction of events found is consistent with the analytical evaluation of the probability that a proton of 1 GeV energy has a scattering in the middle plane leading to a deviation of 100 μm or more.

The efficiency is the probability that a track traversing a pixel detector will actually be detected. An estimate of the efficiency for plane 2 was made by applying a similar criterion as for “good” candidates, i.e. one cluster in planes 1 and 3, and no requirement for the middle plane. Moreover, a candidate is accepted if the straight line defined by these two coordinates intercepts the beam axis in the target region as previously defined. This requirement is very important for the sample without hits in the middle plane, in order to strengthen the definition of a real “track”. Figure 24(a) shows a distribution of this beam axis intercept (in the target region), to be compared with fig. 24(b), where an enlarged view of the corresponding distribution taken from fig. 18(b) is shown. The two shapes, the centre and the width values are very similar (even if the number of entries is quite different) and this reinforces our confidence in the criterion adopted to define the sample. If we call “ N_{empty} ” the number of events in the sample with no hits in the middle plane and “ N_{full} ” the number of events in the sample with one cluster per plane, the efficiency for the middle plane is defined as

$$\text{Efficiency} = \frac{N_{\text{full}}}{N_{\text{full}} + N_{\text{empty}}} = 99.2\% .$$

7. CONCLUSIONS

In a complicated device like this first operational hybrid silicon pixel detector, with active signal processing, it is essential to provide means for electrical testing. The electrical test results have been correlated with the results from the beam particle test. Even though the detector worked satisfactorily, a few problems were revealed in this way. In particular, power supply and bias distribution must be implemented carefully. Equally, the ultimate timing accuracy of the circuit is determined by careful line driver design.

This evaluation has enabled us to design the improved version F-Omega-Ion which will be used in the near future. However, the beam test results indicate that even this present version is a very useful detector for the high-multiplicity environment. A larger array, still using this first D-Omega-Ion chip, is now under construction in order to study the practical aspects of assembly, yield and reliability.

For the first time a telescope made of three hybrid silicon pixel detectors was tested successfully in a fixed-target experimental environment. It was possible to develop a very simple and fast pattern recognition, without ambiguities in space, for the study of single and multitrack events. The test has shown the good position accuracy of the pixel detector, which was $25\text{ }\mu\text{m}$ in the direction of the $75\text{ }\mu\text{m}$ pitch. The efficiency was measured to be 99.2%.

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FIGURE CAPTIONS

- Fig. 1** Block diagram of the pixel readout circuit D-Omega-Ion.
- Fig. 2** (a) Partial schematic of the charge sensitive amplifier (CSA).
(b) Overall schematic of the CSA including biasing and leakage current compensation circuits.
- Fig. 3** Schematic diagram of the comparator in the pixel cell. I_{dis1} and I_{dis2} are externally adjustable current sources which control the threshold.
- Fig. 4** Schematic of the inverter delay line which is adjustable via the I_{dn} and I_{dp} currents.
- Fig. 5** The coincidence logic and the memory, which becomes part of the output shift register upon readout.
- Fig. 6** Block diagram of the readout chip architecture.
- Fig. 7** Scanning electronic microscope (SEM) photograph of a few cells of the readout chip with solder bumps already prepared.
- Fig. 8** The distribution of thresholds of the 16 pixels in the electrical test row at two values of the current I_{dis1} , 44 μA (left) and 30 μA (right). The current I_{dis2} was kept constant at 30 μA .
- Fig. 9** The distribution of the binary signal delay for the row of test pixels at two settings of the adjustable current I_{dn} .
- Fig. 10** (a) Sketch of the experimental set-up.
(b) Reconstruction of a “good” high-multiplicity hit on three pixel planes in the Omega spectrometer.
- Fig. 11** Diagrams representing the number of hits detected during a run in the Omega experiment for each pixel cell in three successive 63×16 cell detectors, planes 1, 2 and 3. The beam passed perpendicular to the detectors ~ 10 mm above the top left corner.
- Fig. 12** Same as fig. 11, but only the middle plane 2 is shown for two different settings of the threshold: (a) 5700 electrons and (b) 11 600 electrons.
- Fig. 13** Same as fig. 11, but only the middle plane 2 is shown for three different settings of the binary delay: (a) $I_{dn} = 5.625 \mu A$, (b) $I_{dn} = 6.375 \mu A$ (nominal) and (c) $I_{dn} = 6.875 \mu A$. The left-right asymmetry is becoming apparent.
- Fig. 14** Projection on the x-z plane of the truncated pyramid used to select the events in our analysis. The drawings are not to scale.

FIGURE CAPTIONS (cont'd)

- Fig. 15** Diagrams representing the number of hits detected for each pixel in the planes 1, 2 and 3 after the cut. The horizontal length of each box is proportional to the number of hits.
- Fig. 16** Distribution of the number of hit pixels per plane and per event.
- Fig. 17** (a) Schematic picture illustrating our cluster definition: in this example a cluster of width = 1 (single hit) and width = 2 (double hit) are shown.
(b) Cluster width distribution.
- Fig. 18** (a) Sketch of the apparatus in the x-z plane; the ratio n (sign inverted) between the constant and the slope of the linear fit ($-b/a$) represent the intercept along the beam (x) axis.
(b) Distribution of the “ $-b/a$ ” parameter for 12 745 events with one cluster/plane: the function $F = 995 e^{-0.5 ((x - 1.24)/1.035)^2} + 116.5$ is used to fit the distribution.
- Fig. 19** Distribution of the residual Δz for 12 745 events with one cluster/plane: a gaussian shape is used to fit the distribution.
- Fig. 20** z-coordinates correlation plots for the so-called “good events”: z_i $i = 1, 3$ is the barycentre value (cm) of the cluster on the plane i , z_{2F} is the z intercept on the middle detector with the line made using z_1 and z_3 : (a) z_2 versus z_1 , (b) z_3 versus z_1 , (c) z_3 versus z_2 and (d) z_{2F} versus z_2 .
- Fig. 21** z-coordinates correlation plots for the events with $\text{var} > 10^{-2}$ cm and $\Delta z > 3 \sigma$ z_i $i = 1, 3$ is the barycentre value (cm) of the cluster on the plane i , z_{2F} is the z intercept on the middle detector with the line made using z_1 and z_3 : (a) z_2 versus z_1 , (b) z_3 versus z_1 , (c) z_3 versus z_2 and (d) z_{2F} versus z_2 . Only a correlation between z_2 and z_3 in the detectors right-up corner is visible.
- Fig. 22** Schematic view in the x-z plane of one event with one cluster/plane generated by two tracks.
- Fig. 23** The z-coordinates correlation plots for events with $10^{-4} < \text{var} < 10^{-2}$ cm and $\Delta z > 3 \sigma$ z_i $i = 1, 3$ is the barycentre value (cm) of the cluster on the plane i , z_{2F} is the z intercept on the middle detector with the line made using z_1 and z_3 : (a) z_2 versus z_1 , (b) z_3 versus z_1 , (c) z_3 versus z_2 and (d) z_{2F} versus z_2 .
- Fig. 24** (a) Distribution of the beam axis intercept for events with one cluster/plane.
(b) Distribution of the beam axis intercept for events with one cluster in the planes 1 and 3 and no hits in the middle plane. In both cases a gaussian shape is used to fit the distribution.

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