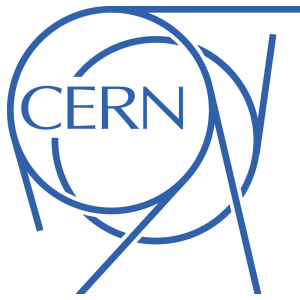




SUMMER STUDENT PROJECT

ANALYSIS OF TEST BEAM DATA OF ALPIDE, THE FINAL MONOLITHIC ACTIVE PIXEL SENSOR (MAPS) PROTOTYPE FOR THE ALICE ITS UPGRADE *

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Abstract

The ALICE collaboration is currently preparing a major upgrade of its apparatus, planned for installation during the second long shutdown of the Large Hadron Collider in 2019-20. The main pillar of the upgrade is the replacement of the current Inner Tracking System (ITS) with a new, low-material, high resolution silicon pixel detector, made of Monolithic Active Pixel Sensors (MAPS). This technology, combining front-end circuitry and sensitive layer in a single device, will lead to a higher granularity of the detector and therefore a better pointing resolution. The silicon pixel chips, called ALPIDEs, developed specifically for the new ITS, are currently characterized using test beams. A part of this characterization is presented in this work. The project involves the very first analysis of test beam data with inclined tracks. The tested ALPIDE is rotated with respect to the beam, hence the particles cross the chip with an inclined incidence angle. The influence of these rotations on the efficiency profile, the clustering and the spatial resolution were investigated. Finally, a simulation of the tracking resolution evaluating the material budget is performed and compared to the data.

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1. ALICE ITS and the upgrade

1.1. The current detector

A Large Ion Collider Experiment (ALICE) [1] is one of the four main experiments at the CERN Large Hadron Collider (LHC) [2]. The apparatus is designed to address the physics of strongly interacting matter, and in particular the properties of the Quark-Gluon Plasma (QGP) [3], studying proton-proton, proton-nucleus and nucleus-nucleus collisions. In the design of ALICE, a large emphasis was put on its capabilities to cope with high particle densities as obtained in central Pb–Pb collisions. This leads to a highly granular detector. The ALICE detector is located in a cavern 56 m underground. The detector’s overall dimensions are $26\text{ m} \times 16\text{ m} \times 16\text{ m}$ with a total weight of approximately 10 000 t and it is composed of three main parts: the central barrel, the forward muon arm and a set of small detectors for triggering and event characterization.

1.2. ITS Upgrade

The current experimental set-up is not yet fully optimized, hence ALICE is preparing a major upgrade of its apparatus, planned for installation during the Second Long Shutdown (LS2) of the LHC, in the years 2019/20. In particular, the Inner Tracking System will be fully replaced by a new silicon tracker with greatly improved features in terms of determination of the impact parameter to the primary vertex, tracking efficiency at low p_T and increased readout rate capabilities [4].

The new Inner Tracking System (ITS) will be composed of seven concentric layers of pixel detectors, grouped in two separate barrels: Inner Barrel (IB) and Outer Barrel (OB). The IB consists of the three innermost layers, while the OB contains the four outermost layers. All layers will be equipped with pixel detectors.

1.3. ALPIDE chip

The pixel chips developed for the upgraded ITS, are called ALICE Pixel Detectors (ALPIDEs) [5]. They are based on Monolithic Active Pixel Sensors [6] integrating both pixel sensors and read-out electronics to a single detection device, and are implemented in a 180 nm CMOS technology for imaging sensors by TowerJazz [7]. The process provides up to six metal layers which allow together with the small feature size a high-density and low-power circuitry.

The ALPIDE chip [5] measures $30\text{ mm} \times 15\text{ mm}$ and contains a matrix of 1024×512 sensitive pixels. The pixel size is $29.24\text{ }\mu\text{m} \times 26.88\text{ }\mu\text{m}$, which results in a spatial resolution of about $5\text{ }\mu\text{m}$. The thickness of the ALPIDE chip in the IB will be $50\text{ }\mu\text{m}$, while in the OB, where the material budget is not that crucial, it will be $100\text{ }\mu\text{m}$ thick.

2. Test beam framework

In order to characterize the ALPIDEs test beam measurements are organized, during which the chip whose performance is being evaluated, called Device Under Test (DUT), is placed between tracking planes, and the whole setup is placed in the beam. Then tracks are fitted to the hits in the reference planes. These tracks are extrapolated to the DUT, where clusters are searched in a region around the impinging point.

2.1. Test beam setup

A new test beam campaign of the ALPIDE chips, with inclined tracks, was started in May 2017, providing also the data analyzed in this work. The data were recorded using a $6\text{ GeV}/c$ pion beam from CERN Proton Synchrotron (PS) T10 beam line. A telescope setup composed of 7 planes was used. Each plane is made of a $50\text{ }\mu\text{m}$ thick ALPIDE chip wire-bonded to a carrier card, which has mostly passive components and which is connected to the readout board.

The telescope consists of two arms, each containing 3 reference tracking planes and the DUT is placed between them. The two arms and the DUT have enclosures with beam entrance and exit windows made from aluminum foil, shielding the chips from light. The aluminum foils, the chips themselves and the air between them have to be taken into account for the tracking. A schematic drawing of the telescope providing distances between different layers is shown in Fig. 2.1.

The inclined tracks are achieved by rotating the DUT around the y -axis (i.e. the vertical axis) while keeping the tracking planes orthogonal to the beam axis. For this reason the DUT is mounted on a rotary stage, which can be operated remotely. The rotation angle is defined with respect to the plane transverse to the beam axis. In order to study angles up to 60° , the distances between the DUT and the reference arms need to be sufficiently large in order to allow rotating the DUT (cf. red in Fig. 2.1). An increase of the plane distance leads to a larger extrapolation uncertainty.

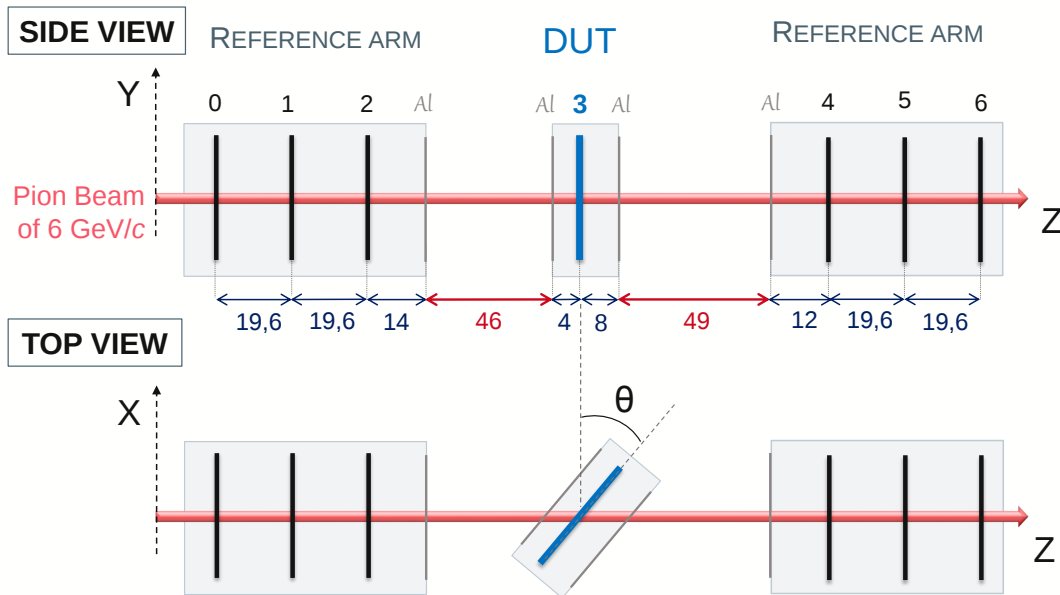


Figure 2.1.: Test beam telescope layout, (top) side view, (bottom) top view.

2.2. EUDAQ & EUTelescope

Two software packages for the use with test beam telescopes were developed within the EUDET project [8]:

- **EUDAQ**: multiplatform data acquisition system allowing easy integration of the DUT, recording raw data [9].
- **EUTelescope**: group of processors running in ILCSoftware Marlin framework [10], which allows the spatial reconstruction of tracks and the data analysis [11].

After a successful operation in test beams for many years, it has become the common test beam tool for many groups, largely due to its precise reconstruction, reliable operation and DAQ integration capabilities. This software is also used in test beams for the ITS upgrade. The ALICE ITS team contributed to the software by implementing the ALPIDE telescope in the frameworks.

2.3. Adaptation of the software

To analyze the data with EUTelescope, the framework needs to be adapted to rotations. First of all, in the analysis with parallel planes, a parameter called *AlignMode* is set to 1 in the steering file, which means that the alignment of the DUT adjust only shifts along x and y , and rotations around z -axis. As in this study the DUT is rotated the alignment has to take into account other rotations as well. By changing the *AlignMode* = 3, six degrees of freedom are available for alignment of the DUT: 3 translations and 3 rotations.

These degrees of freedom are further controlled by the *FixParameter*, also defined in the steering file. In fact, the user has the possibility to constrain the degrees of freedom in the alignment for each shift (s_x, s_y, s_z) and each rotation (r_x, r_y, r_z) in 3D space and this for each tracking plane. To do so a binary number $r_z r_y r_x s_z s_y s_x$ represents the logical inverse of the Boolean for each rotation r_i and each shift s_i . Then the conversion from binary to decimal gives an integer that has to be put as a *FixParameter*. For example to allow all rotations and all shifts: $(r_z r_y r_x s_z s_y s_x)_2 = (000000)_2 = (0)_{10} \rightarrow \text{FixParameter} = 0$ [12]. After testing several combinations, the parameters that give the best resolution for this study are: 28 28 28 0 28 28 28, i.e. all possible degrees of freedom for the rotated DUT and standard alignment for the reference planes.

The difficulty in this part of the project was to achieve the best resolution possible for each angle. This was done by studying the influence of the fixing and releasing the degrees of freedom during the alignment. Furthermore, the calculation for the extrapolated impinging point at a rotated DUT was fixed. Moreover with thinner chips and larger distances the aluminum foils play a more significant role. Properly taking them into account in the analysis helped to reduce the residual by up to 1 μm . The corresponding influence increases with the rotation of the DUT. Adding the air between the detector layers, however, was not possible with the current reconstruction software. The effect expected from simulation is, however, smaller than 0.13 μm . Possible variations of the chip thickness, the material composition of the chips were estimated to influence the residuals by less than 0.001 μm .

3. Analysis with inclined tracks

So far the ALPIDE chips were intensively studied in test beams with tracks orthogonal to the tracking planes and the DUT [13, 14]. In the detector, the sensors are arranged in a turbine geometry around the beam axis. The barrel shape of the detector, as well as the solenoidal B-field cause the tracks to impinge on the sensor surface with a wide range of angles. Consequently, the ALPIDE has to be characterized with inclined tracks as well. In this chapter, the first study of the ALPIDE performance with inclined tracks is presented. In this preliminary data analysis with inclined tracks, the studied angles range from -60° to 60° and for each angle about 500 000 events were analyzed.

3.1. Efficiency profile

First of all, the detection efficiency has to be verified. The efficiency profile with asymmetric error bars is obtained from track maps. The efficiency with associated statistical uncertainties are calculated using the Bayes' Theorem [15]. If the number of tracks with a hit in the DUT is noted k and the total number of tracks extrapolated to the DUT is noted n , the efficiency is then given by the most probable value, i.e the mode: $\varepsilon_{m.p.} = \frac{k}{n}$. The uncertainty associated to the efficiency can be calculated from the variance:

$$\sigma^2 = V(\varepsilon) = \frac{(k+1)(k+2)}{(n+2)(n+3)} - \frac{(k+1)^2}{(n+2)^2} \quad (3.1)$$

Since the efficiency is defined as the mode of the distribution, which is different from the mean $\langle \varepsilon \rangle = \frac{k+1}{n+2}$, the uncertainties are asymmetric (cf. Fig. 3.1).

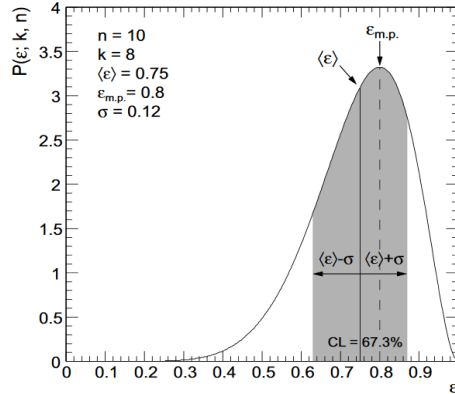


Figure 3.1.: Example of the efficiency probability density function $P(\varepsilon; 8, 10)$, with its mean, mode and errors, taken from [15].

The resulting efficiency profile with error bars is shown in the Fig. 3.2 for the rotation angles 40° and 60° . The efficiency along the x -axis stays above the limit of 99% for all angles, even for the bigger ones. Hence, the detection efficiency for inclined tracks is not degraded at nominal settings. Moreover in this figure one can notice that when the DUT is rotated by 40° the error bars at the edges of the chip become huge because of low statistics, and the beam profile appears in the figure. When the angle increases to 60° the beam covers the full width of the DUT, which is consistent with the fact that the rotation is done around the y -axis.

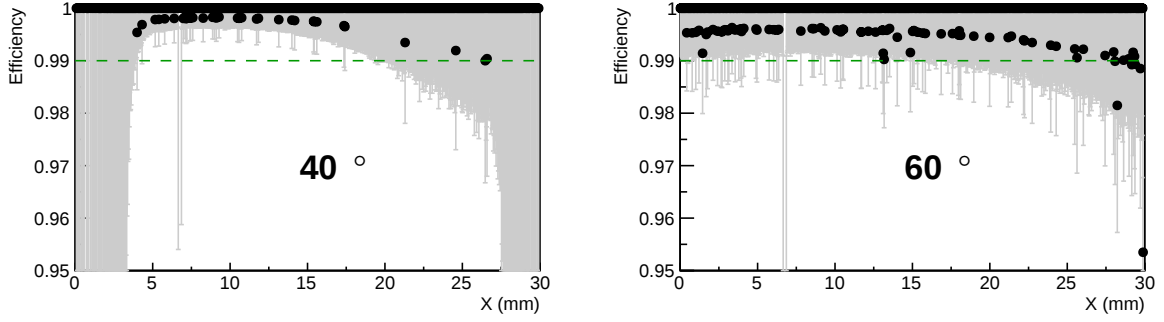


Figure 3.2.: Efficiency profile along the x -axis across the whole DUT, for 40° and 60° .

3.2. Cluster shapes and cluster sizes

The second study consists in verifying how the rotations influence the clustering. For that the likelihood of different cluster shapes occurring in the data set for different angles is plotted in Fig. 3.3. The cluster shape IDs represent different arrangements of pixels in one cluster (cf. Appendix A). The cluster shape ID ranging from 0 to 27 represent clusters made of 4 pixels maximum and the ID 28 sums up all the clusters with 5 pixels and more. As it can be inferred from the very last bin of the histogram in Fig. 3.3 the likelihood for a cluster to be made of at least 5 pixels, increases with the rotation angle from 1% up to 25%. In other words, when the incidence of the particle is 60° one quarter of all clusters are actually made up of 5 pixels or more. Also the likelihood of the ID 12 (2 by 2 pixels) increases with the angle. On the other hand, the ID 0, which is a cluster made of a single pixel, decreases from 25% to 0% when the DUT is rotated from 0° to 60° . Indeed when a particle crosses the chip with a bigger angle of incidence, it travels more inside the chip, it crosses more pixels and the charge sharing increases. This provokes that the clusters get bigger.

But not only the overall cluster size is affected but also different cluster shapes are involved depending on the angle. For big angles the new shapes become important, such as ID 5 (3 pixels in a row), ID 10 and ID 16 (see Appendix A).

And finally, the ID 1 and ID 2 are both made of 2 pixels, in the first one they are placed horizontally (along x) and in the second case vertically (along y). The likelihood of the ID 1 increases, while the other one decreases with rotation angle. This behavior is expected as the DUT is rotated around the vertical axis.

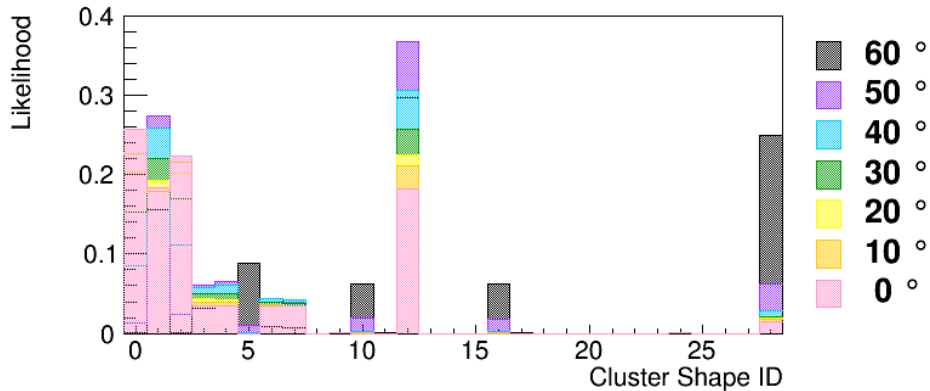


Figure 3.3.: Likelihood of different cluster shapes for different angle of incidence.

3.3. Residuals

The spatial resolution of an ALPIDE can be evaluated by means of residuals. When a hit matches with a track, the geometrical distance between the reconstructed hit position, in other words the center of gravity of the cluster, and the track extrapolation position is called the residual. The residuals follow a Gaussian distribution and the overall residual of the chip is then obtained as the sigma of the Gaussian fit, σ_{res} . The residuals along the x and y -axis are shown in Fig. 3.4.

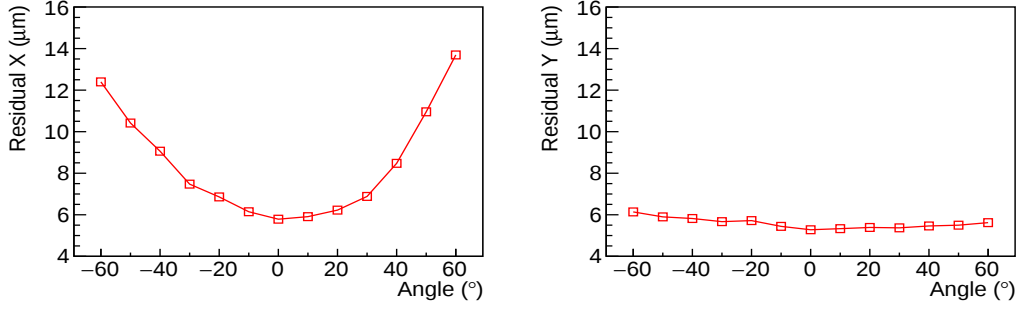


Figure 3.4.: Residuals along x and y -axis for different angles of incidence.

On y -axis the residuals are constant at approximately $6\text{ }\mu\text{m}$. This is in agreement with the fact that the rotation is performed around y -axis, so the beam stays perpendicular to the chip in y -direction. As far as the x -direction is concerned, the residuals increase with the angle, from $6\text{ }\mu\text{m}$ up to $14\text{ }\mu\text{m}$. The minimum is at 0° , since for bigger angles more material is crossed by the particles. The residuals are symmetric between positive and negative angles, only a little difference appears in big angles (50° and 60°), which is probably due to the systematics. The statistical errors are already present in the graph, but they are negligible, for the systematic uncertainties a further study of the alignment stability with subsets is needed, as well as an exploitation of the left-right fluctuations between sectors.

When rotated, one part of the DUT is closer to one reference arm and one part close to the other one. Hence the residuals could vary depending on the zone of the chip. To check this hypothesis the DUT is divided in 4 equal sectors along the x -axis and σ_{res} is evaluated separately in each sector. The result for both x and y directions is shown in Fig. 3.5. The residuals on x increase from $6\text{ }\mu\text{m}$ up to $13\text{ }\mu\text{m}$, when more and more rotated, while the residuals on y are of about $6\text{ }\mu\text{m}$, for all the angles, which is consistent with the previous results. As far as the variations among the sectors is concerned, they are all flat, so no left-right asymmetry is observed. The resolution is stable and only depending on the angle of incidence.

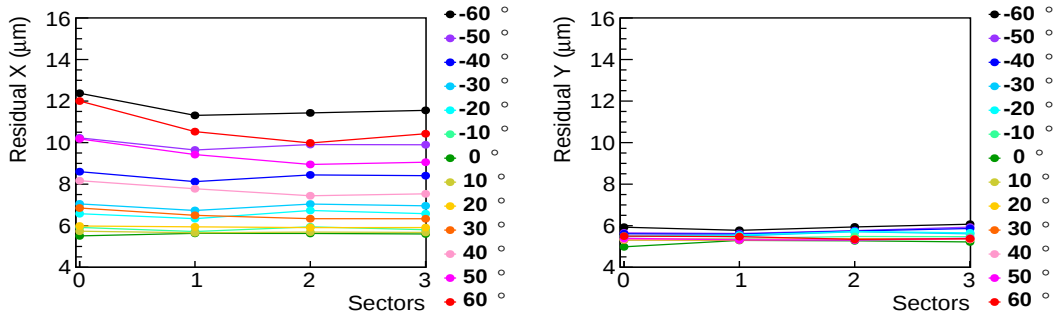


Figure 3.5.: Residuals along x and y -axis in different sectors of the DUT.

4. Simulation

In order to interpret the residuals presented in Sect. 3.3, a simulation of the test beam setup and its tracking performance was carried out.

4.1. Existing simulation tool

An existing simulation tool [16] is used to study the resolution of the track extrapolation in the DUT, i.e. the mean deviation between the impinging point of the particle into the chip and the track extrapolation to the DUT. In the current simulation, events are uniformly and randomly generated, fitting and tracking in parallel planes are performed, using the General Broken Line (GBL) algorithm, and finally the tracking resolution σ_{tr} is obtained. The simulation takes several input parameters:

- **Number of planes:** taking into account chips and aluminum foils between the first and the last tracking plane. In this study 11 planes are considered (cf. Fig. 2.1).
- **Vacuum:** (Boolean) is the telescope placed in vacuum? If no, layers of air are added between planes and taken into account for the evaluation of the multiple scattering.
- **Thickness:** material thicknesses of each plane have to be provided. Currently in the testing telescope the Al foils are 20 μm thick and the standard thickness of an ALPIDE is either 50 μm or 100 μm .
- **Radiation length:** for the Al foils the standard radiation length of aluminum is used: 88.97 mm [17]. The ALPIDEs are not made of pure silicon, they contain about 15 μm of aluminum in the metal stack-up, so the radiation length is 92.28 mm and 92.52 mm for 50 μm and 100 μm thick chips respectively.
- **Position resolution σ_{pos} :** this intrinsic characteristic of the chip represents the mean deviation between the reconstructed hit and the real impact position of the particle, for the ALPIDEs it is about 5 μm and for the insensitive planes made of aluminum foils any negative value can be used to mark them as passive layers.
- **Distances** between all consecutive planes need to be precised in mm. They are shown in Fig. 2.1.
- **DUT plane:** integer identifying which plane is the DUT, here number 6.
- **Energy:** of the beam in MeV. To simulate the PS beam it is 6000 MeV and the Super Proton Synchrotron (SPS) beam has an energy of 120 000 MeV.
- **Number of events** to generate for the tracking.

The calculation of the tracking resolution, using the GBL tracks, is based on the evaluation of the multiple scattering due to the material of the telescope. The scattering angle α follows a Gaussian distribution centered at 0 and its Root Mean Square (RMS) is given by [18]:

$$\alpha_{RMS} = \frac{13.6 \text{ MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 * \ln\left(\frac{x}{X_0}\right) \right]. \quad (4.1)$$

4.2. Adaptation to rotations

To simulate the tracking resolution with a rotated DUT a bash script is looping over an array of angles, selected by the user. For each angle it adapts the input parameters and launches the existing simulation.

First of all, the material thicknesses are modified. Indeed, when the DUT is rotated around the vertical axis, the beam incidence changes and therefore the incoming particles cross more material inside the silicon chips, as well as inside the Al foils (cf. Fig. 4.1). The actual material thickness is then obtained as the normal thickness divided by the cosine of the rotation angle.

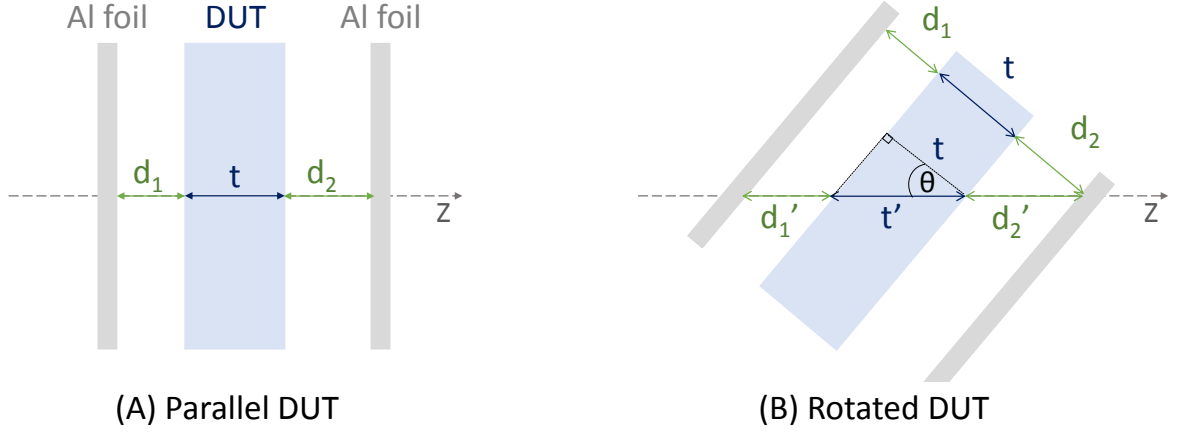


Figure 4.1.: Apparent material thicknesses of the rotated DUT.

Secondly, the two aluminum foils, that shield the DUT from light, are rotated at the same time as the DUT itself. The distances between these three planes are constant, but when rotated the apparent distance between Al and ALPIDE changes, so the beam crosses more air between them (cf. d_1 and d_2 in Fig. 4.1). And as the distance between the DUT and the two neighboring Al foils increases when rotated, the distance between the two consecutive Al foils ($Al_{ref.arm}/Al_{DUT}$) decreases in the center of the chip.

Moreover the distance between the parallel layers (i.e. two reference arms) and the rotated DUT is not constant along the x -axis of the DUT. So for each angle, the simulation is performed in several points across the chip, which corresponds to tracks passing by an odd number of points along the chip, as it is depicted in Fig. 4.2 for 5 points. This way the tracking is done in particular in the center of the chip and in its extrema. The result is the mean among all the points.

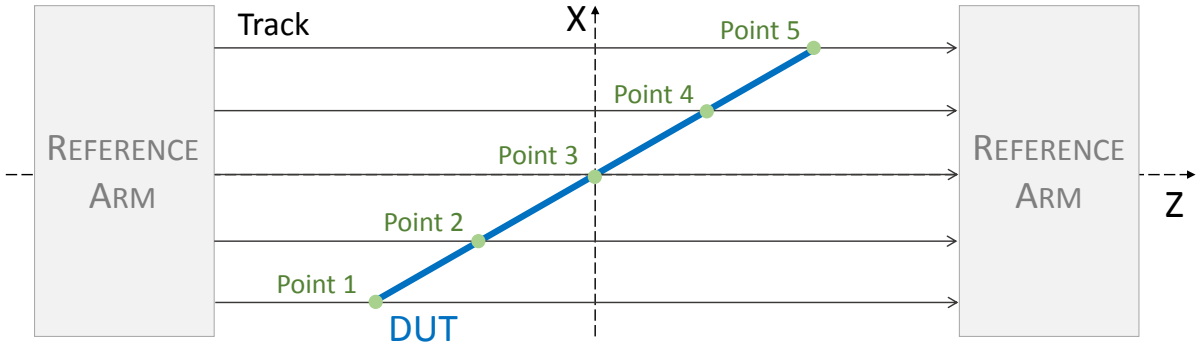


Figure 4.2.: Division of the DUT in 4 bins for the simulation.

The resolution obtained this way correspond to the resolution calculated in the parallel plane, so when the DUT is rotated it needs to be projected to the actual plane of the DUT. To simplify an approximation is adopted and the resolution in the DUT is set equal to the resolution in the parallel plane divided by the cosine of the rotation angle. This approximation is valid when the scattering angles are very small, as it can be understood from Fig. 4.3. The calculation of the maximum scattering angles, using the equation (4.1), gives:

- 50 μm chips: $\alpha_{RMS} = 83.41 \mu\text{rad} = 0.0048^\circ$
- 100 μm chips: $\alpha_{RMS} = 111.60 \mu\text{rad} = 0.0064^\circ$

The involved angles are of the order of magnitude of the milli degree, which proves that indeed the scattering angles are small, and the approximation is valid.

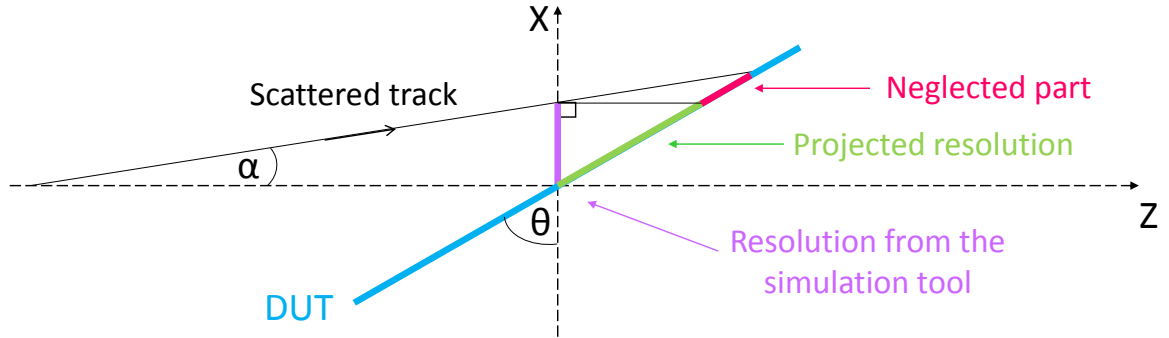


Figure 4.3.: Approximation in projection of the tracking resolution from the parallel plane to the plane of the rotated DUT.

4.3. Simulation results

Once the simulation is adapted to rotations, different parameters are tested. It turns out that the influence of the number of points across the DUT is negligible, it affects only the 5th digit after the dot. The results in this study are simulated with 5 points. On the other hand, the number of events has a bigger impact on the results, but with more than 50 000 events the simulation is stable up to the 2nd digit after the dot, therefore 50 000 events are selected, also because with the growing number of events the execution time increases. The simulated tracking resolution for different angles, two different chip thicknesses (50 μm and 100 μm) and two different beam energies (PS and SPS) are summarized in Tab. 4.1.

In this table, only positive angles are given, because the results for negative angles are exactly the same as the corresponding positive angles. The results show that the tracking resolution is improved by the higher energy of the beam, i.e. the SPS. For the PS beam the tracking resolution is better with thinner chips (i.e. 50 μm), since the material budget is reduced the multiple scattering is less important. But for the SPS beam this difference disappears. Moreover, the tracking resolution is almost an order of magnitude lower at small angles and about a factor of 5 smaller than the pixel size at large angles. Therefore, a study of the in-pixel response should be feasible.

In addition, the tracking resolution σ_{tr} from the simulation can be used to calculate the residuals for each angle of incidence in order to compare them to the residuals from the data. The residuals are calculated using the formula:

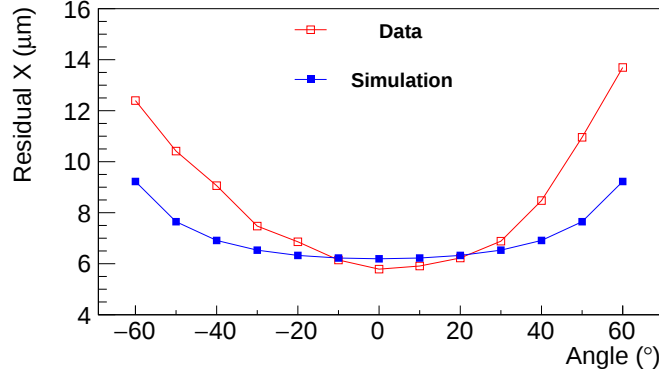
$$\sigma_{res}^2 = \sigma_{tr}^2 + \sigma_{pos}^2 \quad (4.2)$$

Table 4.1.: Tracking resolution from the simulation.

Angle	PS		SPS	
	50 μm	100 μm	50 μm	100 μm
0	3.22	3.63	2.24	2.24
10	3.28	3.71	2.28	2.28
20	3.47	3.93	2.39	2.39
30	3.83	4.36	2.59	2.60
40	4.45	5.10	2.94	2.94
50	5.52	6.38	3.50	3.51
60	7.56	8.84	4.51	4.51

The single position resolution is the same as the one found iteratively and used in the study of orthogonal tracks: $\sigma_{pos} = 5.3 \mu\text{m}$ (cf. Appendix B). Since the data were taken with 50 μm chips and the PS beam, the tracking resolutions from the second column of Tab. 4.1 are used for this calculation. The residuals from the simulation and from the data are represented in Fig. 4.4.

The first evidence from this comparative plot is that the simulation does not reproduce the data precisely enough. Moreover, the discrepancies between the simulation and the data become larger with the increasing angle of incidence, so it is not only a question of offset. Different efforts aiming to reduce these discrepancies were done. On one hand in the simulation, the chip thickness was varied by $\pm 10 \mu\text{m}$ and the thickness of the Al foils by $\pm 5 \mu\text{m}$. The amount of aluminum present in the chips was tested within the range from 1% up to 30%. The simulation was also performed with and without air between tracking planes. But none of these modifications made the residuals match the data. On the other hand, in the data, adding the missing passive layers (i.e. the aluminum foils) in the gear file reduced the residuals, but not enough.

**Figure 4.4.:** Comparison of tracking resolutions from the data with the simulation.

Up to date the discrepancies are not explained and further investigations are needed. In the current simulation, the position resolution of the DUT is assumed not to change under rotation. If there is no other source for the mismatch found, this assumption has to be reevaluated. The residuals of about 14 μm at 60° would imply a degradation of the position resolution from about 5 μm at normal incidence to about 10 μm .

Possible studies that can be carried out in the future in order to better understand inclined tracks and solve discrepancies can be: a test beam with the SPS beam in order to reduce the influence of the material budget and a study of rotations around the x -axis. An investigation whether the track extrapolation is done to the right depth in the active volume of the sensor are also foreseen, as well as the study of the distribution of incident angles of from Monte Carlo simulation (MC) of physics events. And the resolution should also be investigated by studying

the resolution as a function of the cluster shape to verify if there can be real effects caused by very long clusters.

Conclusion

The ALICE collaboration is currently preparing a major upgrade of its detector to be installed during the Long Shutdown 2, in the years 2019-20. A key item of this upgrade is the construction of a new, ultra-light, high-resolution, silicon Inner Tracking System based on monolithic silicon pixel detectors. The pixel chips developed especially for the new ITS, called ALPIDE chips, were intensively studied under various conditions and are currently tested in test beams in order to characterize precisely their behavior and response.

The current test beam campaign focuses on the study of the inclined tracks, in order to characterize the response of ALPIDEs to particles which don't hit it perpendicularly. The preliminary analysis shows that the detection efficiency of at least 99% is preserved when the silicon chip is rotated by up to 60° with respect to the plane transverse to the beam. In addition, the rotations have a direct influence on the cluster sizes, the clusters broaden with the increasing angle. Moreover the cluster shapes, i.e. arrangements of pixels in a cluster, change when the tracks are inclined. The change of the cluster shape distributions are a valuable input for the preparation of a Monte Carlo simulation (MC) of the chips.

A first comparison of the residuals with simulations show a discrepancy, which increases with the rotational angle. Studies on potential sources for the discrepancies including material budget could not explain the deviation. Here, further detail investigations like attempts to adapt EUTelescope in order to improve the spatial resolution in the data with bigger angles on incidence, a deeper analysis of the data with a rotated ALPIDE, involving larger statistics and improvement of the simulation are needed in order to optimize the position resolution of the ALPIDE with inclined tracks. After resolving these issues, next step would be to perform the analysis of the in-pixel response with inclined tracks, which would be a further valuable contribution to the detector simulation.

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A. Cluster Shape IDs

Different arrangements of pixels in a cluster for clusters made of up to 4 pixels are depicted here below. Every cluster shape has an associated cluster shape ID number.

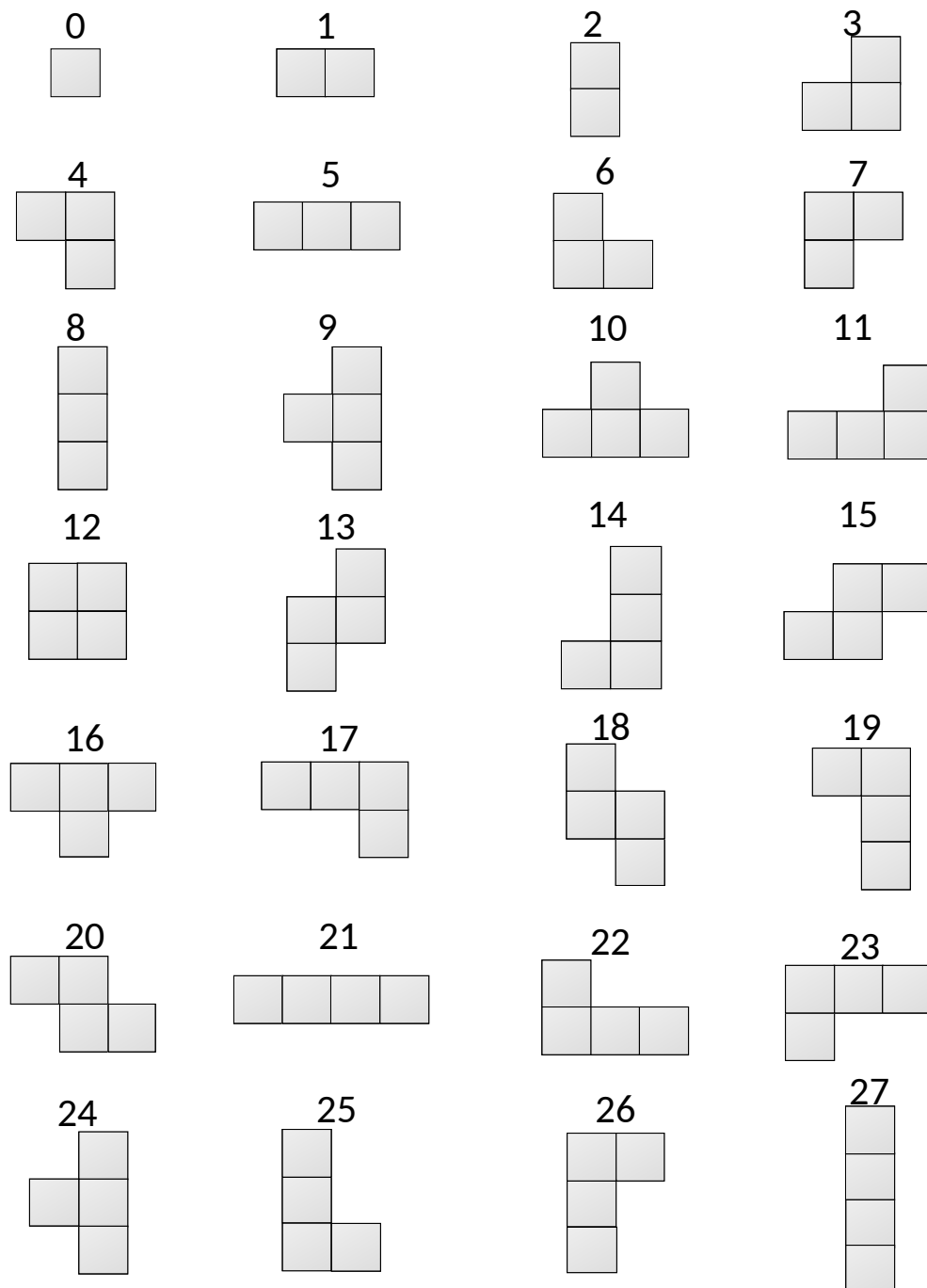


Figure A.1.: Cluster shapes and their IDs.

B. Track resolution

The tracking resolution is obtained from simulation, which is based on the same GBL tracking model as the fitter of EU Telescope. The simulation takes into account the multiple scattering in the sensors and the mechanics. As further input it needs the single point resolution of the sensors σ_{pos} . As this σ_{pos} is unknown, an iterative approach is used. The σ_{pos} is varied until the residual of the simulation matches the data. The track resolution is obtained with [19]:

$$\sigma_{tr}^2 = \sigma_{res}^2 - \sigma_{pos}^2 \quad (\text{B.1})$$

An example of a residual distribution is shown in Fig. B.1. The RMS of the residual distributions of single runs are summarized in Tab. B.1. Variations are due to the stability and precision of the alignment. The mean among all 14 runs is equal to: $\sigma_{res} = 6.0 \mu\text{m}$. The track resolution finally obtained is equal to $\sigma_{tr} = 2.8 \mu\text{m}$ with $\sigma_{pos} = 5.3 \mu\text{m}$.

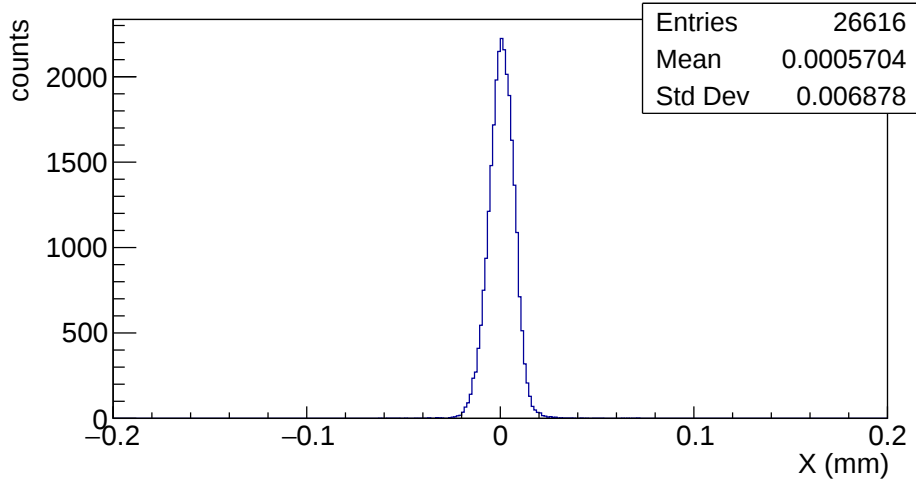


Figure B.1.: The residual distribution of the run number 3181.

Table B.1.: Standard deviations of residual distributions for each run.

Run number	3180	3181	3182	3183	3184	3185	3186
Residual distribution RMS (μm)	6.459	6.878	5.900	6.013	5.900	5.840	5.954
Run number	3187	3189	3190	3191	3192	3193	3195
Residual distribution RMS (μm)	6.005	5.813	5.848	5.864	5.853	5.879	5.900

Glossary

ALICE	A Large Ion Collider Experiment
ALPIDE	ALICE Pixel Detector
CERN	Conseil Européen pour la Recherche Nucléaire
CMOS	Complementary Metal Oxide Semiconductor
DUT	Device Under Test
GBL	General Broken Line
IB	Inner Barrel
ITS	Inner Tracking System
LHC	Large Hadron Collider
LS2	Second Long Shutdown
MAPS	Monolithic Active Pixel Sensors
MC	Monte Carlo simulation
OB	Outer Barrel
PS	Proton Synchrotron
QGP	Quark-Gluon Plasma
RMS	Root Mean Square
SPS	Super Proton Synchrotron

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