Analysis of test beam data of ALPIDE, the Monolithic Active Pixel Sensor (MAPS) for the ALICE ITS upgrade

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Abstract
The ALICE experiment has scheduled a major upgrade of its experimental apparatus for the Long Shutdown 2 of LHC in 2019-2020. Within this enterprise, CERN is strongly involved in the development of a novel Inner Tracking System (ITS). The ITS will be based on Monolithic Active Pixel Sensors (MAPS), a cutting-edge technology that will allow to improve the detector performance significantly. The final sensor, called ALPIDE, is in production since December 2016.

This project is focused on the characterization of irradiated ALPIDE sensors.

1 Introduction
With the planned increase of the luminosity in Pb-Pb collisions at the Large Hadron Collider (LHC) in 2019-2020, an upgrade of the ALICE experiment is required. The expected interaction rate and corresponding particle flux through the Inner Tracking System (ITS) imposes moderate radiation hardness requirements (cf. Tab. 1) on the detector and the ALPIDE MAPS. In this work, two ALPIDE sensors which were irradiated to two different levels of combined Total Ionising Dose (TID) and Non-Ionising Energy Loss (NIEL): 500 krad and 1 Mrad, as well as $5.5 \times 10^{-12}$ $1\text{MeV}$ $\frac{n_{eq}}{cm^2}$ and $1.1 \times 10^{-13}$ $1\text{MeV}$ $\frac{n_{eq}}{cm^2}$, respectively, were characterized.
Table 1: Requirements for the pixel chip of the ALPIDE ITS upgrade [1, 2].

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>$\sim 5 , \mu m$</td>
</tr>
<tr>
<td>Time resolution</td>
<td>$\sim 2 , \mu s$</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$&gt; 99%$</td>
</tr>
<tr>
<td>Fake Hit Rate</td>
<td>$&lt; 10^{-6} , \text{hits/pixel-event}$</td>
</tr>
<tr>
<td>TID radiation tolerance</td>
<td>2700 krad</td>
</tr>
<tr>
<td>NIEL radiation tolerance</td>
<td>$1.7 \times 10^{-12} , 1 \text{MeV} \frac{n_{eq}}{\text{cm}^2}$</td>
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</tbody>
</table>

2 MAPS technology

The upgrade of the Inner Tracking System (ITS) is based on the installation of new Monolithic Active Pixel Sensors (MAPS). MAPS unify readout electronics and active volume in the same piece of silicon. The ALPIDE MAPS consists of a 25 $\mu m$ thick high-resistivity epitaxial layer grown onto low-resistivity substrate, a matrix of charge-collecting diodes (i.e. pixels), and front-end electronic circuits for signal amplification and digitization. The epitaxial layer is used as the sensitive volume where particles generate charge which is collected. Figure 1 shows a schematic cross-section through an ALPIDE pixel cell [2].

![Figure 1: Schematic cross-section through an ALPIDE pixel cell [2].](image-url)
ALPIDE sensors

The ALPIDE sensor is the final version of the family of sensors, developed by the ALICE collaboration for the upgrade of the ITS. The ALPIDE chip has a pixel matrix of $1024 \times 512$ pixels and is thinned down to a total thickness of $50 \mu m$.

3 Test-beam measurements

The test-beam measurements were carried out at the CERN Proton Synchrotron (PS) T10 beam line with a 6 GeV/c pion beam. The scheme of the so-called telescope setup is shown on the figure 2. The telescope consists of two arms, each contains three ALPIDE sensors (one for each plane). The sensor, which is studied - the Device Under Test (DUT) - is placed in the center, between two arms of the telescope. The beam entrance and exit windows of the arms and the DUT enclosure are covered with an aluminium foil.

![Figure 2: Scheme of the telescope setup. Distances between planes and position of scattering material in mm.](image)

Data acquisition is based on the EUDAQ software package [3, 4] and the data analysis on the EUTelecope framework [3, 5]. The data processing procedure is presented in the figure 3 [6].

![Figure 3: EUTelecope analysis flow [6].](image)
The analysis includes converting raw data into the LCIO format, detecting and excluding dead double columns, excluding noisy pixels, combining pixels to clusters, calculating the cluster center as the center of gravity, pre-alignment and alignment of the telescope planes. As noisy pixels are considered pixels with hit frequency above $10^{-3} \frac{\text{hits}}{\text{pixel-event}}$. The alignment procedure uses straight tracks. Then the procedure of noisy pixels excluding, clustering and hitmaking is repeated after using a less stringent cut of $10^{-2} \frac{\text{hits}}{\text{pixel-event}}$ on noisy pixels to prevent a loss of efficiency in the tracking planes. At the final step tracks are fitted using a General Broken Line algorithm [7]. More information about the measurements procedure and data acquisition can be found in [6].

The aim of these measurements was to estimate detection efficiency and position resolution of irradiated chips as function of the pixel threshold current $I_{THR}$.

For each test-beam run, the corresponding laboratory measurements were carried out using the same settings in order to obtain the charge threshold in units of electrons and the fake-hit rate. The charge threshold is determined using charge injections to the pixel front-end. The injected charge is varied and for each value the probability of the pixel to fire is calculated. The curve of firing probability versus injected charge looks like a so-called S-Curve, which can be described by (1) for each pixel

$$p_{\text{Hit}}(q_{\text{inj}}) = \frac{1}{2} (1 + \text{Erf}\left[\frac{q_{\text{inj}} - \mu}{\sqrt{2} \cdot \sigma}\right]) $$

where $q_{\text{inj}}$ is the injected charge, allowed us to determine $\mu$ - the charge threshold value and $\sigma$ - the temporal noise value.

The fake-hit rate of the pixel chip is obtained by reading events without external stimulus like a radioactive source, pulsing or a test beam. The fake-rate is defined as the probability of a pixel to be fired per event without an external stimulus. The ALPIDE chip contains internal logic which allows the masking of noisy or stuck pixels. In this work, the masking of noisy pixels is performed offline. For the chips with 1Mrad TID dose the 50 most noisy pixels were masked. For the chips with 500 krad TID dose pixels were not masked because of the low number of noisy pixels (<50).

The fake-hit rate was also estimated using a model [8] (green line in the figures 5, 6). The input parameters of the model are the average temporal noise and its pixel-to-pixel RMS as well as the average charge threshold and its pixel-to-pixel RMS.

The measurement of the detection efficiency itself, i.e. the probability of registering a particle crossing the sensor, is based on tracking: after finding tracks in the telescope one can search for corresponding hits in the DUT and determine the likelihood to find a hit in the DUT at the impinging point which is obtained in the extrapolation from the six reference planes.
The square of the position resolution $\sigma_{pos}$ is defined by:

$$\sigma_{pos}^2 = \sigma_{res}^2 - \sigma_{track}^2,$$

(2)

Where $\sigma_{res}$ is the RMS of the residual distribution and $\sigma_{track}$ is the track extrapolation error, defined by the telescope geometry and material. Residual distribution is the distribution of geometrical distances from the cluster center-of-gravities to the impinging point of the track in the DUT.

4 Threshold measurements

The TID irradiation alters the behaviour of the front-end and hence at the same settings in terms of $I_{THR}$ and $V_{CASN}$ do not lead to the same threshold anymore. As the data after 1 Mrad of irradiation, however, was taken at the very same settings as the data at 500 krad, the charge threshold is very low and in a regime where the front-end circuit starts to malfunction. In order to assess the reliability of the measured charge threshold, the number of working fits in the threshold measurement was analysed. Figure 4 shows the dependencies of the number of processed hits for the threshold determination on the threshold current. In the ideal case, all tested pixels (10495) should be processed; with increasing $I_{thr}$, the number of hits also should increase until the maximal level, what could be seen for the 500 krad irradiated sensors. For proper front-end settings, each pixel should show an S-curve which can be fitted. Misbehaved pixels which are stuck or show a too low threshold because of erroneous front-end settings combined with TID irradiation the corresponding S-curves cannot be fitted well. In figure 4 one can see that for a low values of $I_{thr}$ at 500 krad and for almost every value of $I_{thr}$ at 1 Mrad the majority of S-curve fits fail, what means that these measurements should not be taken into account.
4.1 Test-beam results

Figure 5 are presents detection efficiency and FHR as functions of the threshold (in units of electrons). Figure 7 presents detection efficiency and FHR as functions of the threshold current. One can see that detection efficiency for 1 Mrad irradiated chips is higher than 99% at the threshold range between 10 and 130 e, as well as for the most part of the measurements with 500 kRad irradiated samples, but with increasing threshold the detection efficiency decreases. For the W7R41 chip (500 krad) detection efficiency became worse than 99% at the threshold 300 e. Unfortunately threshold measurements carried out do not allow us to define if the points where the decrease of detection efficiency starts are differ for 1 Mrad and 500 krad irradiated samples.

Fake-hit rate measurements show, that irradiation does not strongly affect the FHR. The number of noisy-pixels as well as the magnitude without masking are higher for the 1 Mrad irradiated chip, but after masking the FHR has almost the same order for both cases. Moreover, theoretical calculations overestimate the magnitude of the FHR. Fake hit rate analysis for the 500 kRad irradiated samples was made without masking due to the low number of noisy pixels (<50 for the most part of measurements).

The charge threshold ranges of performed measurements before and after irradiation are not the same, so that the results were difficult to compare.

The result of calculations for the position resolution (figures 7,8) shows, that for both 1 Mrad irradiated and 500 krad irradiated chips the position resolution remains worse than 5 $\mu$m. Taking into account the fact that the resolution does
not increase significantly in high irradiated case and that there are deviations of the resolution values ($\sim 5 \div 7\mu m$) to the previous measurements [9], the value of resolution causes doubts and has to be further investigated. These problems could be caused by problems in the alignment or software settings.

The cluster size analysis (figures 7,8) does not show a big influence of the high irradiation. Increasing of the cluster sizes is likely to be a consequence of the decreasing threshold value, since less charge needs to be collected to fire the pixel. Normally, the cluster sizes and the resolution values are strongly correlated. Here such a correlation is not observed, what support doubts about the values of resolution.

All figures below are plotted for the dependencies on the $I_{th}$ value and on the charge threshold values (in units of electrons). Settings for all measurements are presented in the table 2.

**Table 2:** Settings for the measurements.

<table>
<thead>
<tr>
<th>Backbias voltage (V_{bb})</th>
<th>3.0 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{casn2}</td>
<td>117</td>
</tr>
<tr>
<td>V_{casn}</td>
<td>105</td>
</tr>
</tbody>
</table>

Mask stages (number of pixels for which an s-curve measurement is performed): 82

**Figure 5:** black: detection efficiency as a function of the charge threshold; red: Fake Hit Rate as a function of the charge threshold; green: theoretical prediction of FHR. For the 1Mrad chips the charge threshold measurements are questionable (ref. sec. 4).
Figure 6: black: detection efficiency as a function of threshold current; red: Fake Hit Rate as a function of threshold current; green: theoretical prediction of FHR.

Figure 7: black: position resolution as a function of the charge threshold; red: mean cluster size as a function of the charge threshold. For the 1Mrad chips the charge threshold measurements are questionable (ref. sec. 4).
5 Conclusion

TID irradiation leads to a reduced charge threshold at constant settings. In the data analysed during this summer student project, the DAC parameters of the ALPIDE sensors have not been adjusted for this effect. As a consequence, the chip was operated in a regime of very low charge threshold. At such low threshold, a substantial fake-hit rate is measured. As no data for higher thresholds and consequently lower fake-hit rates is present, it is difficult to conclude about the operational margin and the severity of the radiation damage. The in-detail study of the threshold measurement data furthermore suggests that the measurement fails for the majority of the pixels and hence is unreliable for the chips irradiated up to the 1Mrad.

References
