CHAPTER 4

CHARACTERIZATION AND TEST ON PIXEL SILICON SENSORS

“L’infinito non si può esprimere se non quando lo si sente bensì dopo sentito: e quando i sommi poeti scrivevano quelle cose che ci destano le ammirabili sensazioni dell’infinito, l’anima loro non era occupata da veruna sensazione infinita; e dipingendo l’infinito non lo sentiva. I sommi dolori corporali non si sentono, perché o fanno svenire o uccidono”.

G. Leopardi, “Zibaldone di pensieri” - 12 febbraio 1821
4.1 - Overview

The purpose of this chapter is to provide a detailed description of the electrical test performed on FBK-irst Double side Double Type Column (DDTC1) with 2,3 and 4 electrodes per pixel\(^1\) and a comparison with the ATLAS planar n-in-n and Full Stanford 3D sensor modules behavior. The modules are usually called *Single Chip Assembly (SCA)* and consist of the PCB boards with one single sensor mounted onto matched to one ATLAS FE-I3 read-out chip and a LVDS chip for digital communication [ATLAS Project Document No: ATL-IP-QP-0144.]. The considered fabrication technology is simpler than that required for full 3D detectors with active edge, but the detector efficiency and radiation hardness critically depend on the columnar electrode overlap and should be carefully evaluated.

Selected results from the electrical and functional characterization with radioactive sources are also here discussed.

4.2 - Sensor and performances properties tests

The following tests are aimed to analyze the specific sensor properties:

- Leakage current distribution
- Noise in function of bias voltage

while the following tests are aimed to analyze the performance of the detectors:

- Threshold and noise tuning (at 3200 e\(^{-}\))
- Time over Threshold (ToT) tuning (for one M.I.P. at 60)
- Source test with \(^{109}\text{Cd}\), \(^{241}\text{Am}\), \(^{90}\text{Sr}\)

Tests have been performed at room temperature (23-24 °C), and also involving a climate chamber\(^2\) in order to make measurements with temperature and humidity control.

4.3 – Set up

The experimental setup used for the characterization of the detectors is the so-called *TurboDAQ setup*, developed at the LBNL [17]. It is also used to perform automated electrical test of ATLAS Pixel Detector Modules during the production phase. It runs under Windows and is based on National Instruments LabWindows development suite [Ref.http://www.ni.com/lwcvi/].

For completeness a layout of the system is given in order to easily refer to specific equipment in the test description:

**Hardware components:**

- PC equipped with Pentium 4 processor or higher with at least 512 MB RAM

\(^{1}\) oriented to the ATLAS upgrade  
\(^{2}\) Vötsch Industrietechnik VC 2020
• VME (Versa Modular Eurocard) crate [ref. http://www.wiener-d.com/M/11/8.html]
• ATLAS Turbo Pixel Low Level card (TPLL) [beccherle]
• ATLAS Turbo Pixel Control Card (TPCC) [beccherle]
• Up to 4 Flex Read Out Card per TPCC for flex module characterization and/or custom made probe card for bare module testing
• Two LV power supplies with two channel each for TPCC and flex module front-end bias with at least ±5V and 2A rating³ (GPIB controlled)

Software components:
• Windows 2000 or Windows XP operating system
• Visual Studio 6.0 or above
• National Instruments Measurement Studio 6.0 or above
• ATLAS Pixel TurboDAQ software [ref. http://physik2.uni-goettingen.de/~jgrosse/TurboDAQ/]
• Cern Root software vrs. 5.20.00 [ref. http://root.cern.ch/drupal/ ] to be used together with Pixel Module Analysis framework in order to analyze data from the TurboDAQ more easily [http://physik2.uni-goettingen.de/~jgrosse/TurboDAQ/ModuleAnalysisFrame.html]

The measurements are performed by TurboDAQ software parametric scans. The scans are standardized and their parameters are stored in configuration files (.cfg). For each kind of measurement a specific scan is selectable from the software [appendix TDAQ]. Data for each modules are stored in a directory tree with the top level identified by the module S.N.⁴, automatically generated the first time a new module is connected to the TurboDAQ by writing the S.N. in the CONFIGURATION CONSOLE of the software [appendix TDAQ]. For data integrity it is essential that entering the S.N. is the first operation which is done after connecting a module to the system. If a module has already been tested (even in a different laboratory), a configuration files containing module information should be available and must be loaded into the software. If not, a new configuration must be created. It should contain the measured values of the capacitances used for charge injection (C_{hi} and C_{lo}) and the measured slope of the V_{cal} DAC used for internal injection.

Within the above mentioned directory tree all measurement data files will have standard names, and a test name for each test. The names are set from the TurboDAQ DATA CONTROL panel [appendix TDAQ], and for our purposes have been of the kind YEAR_MONTH_DAY_MEASUREMENT, and then TurboDAQ adds proper suffixes and extensions according to the measurement chosen (e.g. 2009-03-10-iv.iv for an I-V scan measurement).

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³ Agilent E3631A
⁴ Serial Number for the specific detector module
4.4 - TurboDAQ

The 3D TurboDAQ standard measurement system is built as shown in figure 1:

4.5 - Hardware description

The hardware setup has the scope to allow the communication between the board under test and the test system custom. This is routed by the VME controller board, while the TPLL board is used for clock generation and synchronization, data FIFO, trigger FIFO, 16 Mbytes board SRAM support module level histogramming, and FPGA.

A flat cable is used to connect the module board to the TPLL, and this latest to the TPCC board: this bridge transfers data coming from the detector under test to the TPCC, which converts them in order to render transmittable on the VME bus to the PC.
The TPCC card receive from two LV power supplies four different values of tension, to respectively supply itself (with +5 V for the analogical part and -5 V for the digital part) and the FE electronics on the module board (with +1.6 V for the analogical part and +2 V for the digital part).

The leds on the left of the board serves as control of a correct communication start between the TPCC and the TurboDAQ software: if green, the communication has been set correctly, while if red problems of initialization has occurred. Moreover, an orange leds starts in correspondence of the initialized channel, right to the connector for the module board in use.

Picture 6 shows in detail a module board (or Detector Under Test, DUT): it is, as an example, the module FBK-2EM2, that is a 3D-FBK pixel silicon detector with two electrodes per pixel in the sensor configuration and the FE-I3 read-out electronics bump bonded under it (in the centre of the card). The high voltage cable supplies the voltage to deplete the sensor (negative voltage values).
4.6 - Fixed setup at CERN Lab 161

Figure 5 shows a snapshot of CERN ATLAS Pixel fixed setup of Pixel Lab 161. The main feature from the mobile setup is the equipment with the climate chamber, operatives in a range between -25°C and 100°C.

![Climate chamber](image)

Figure 6 - Fixed set up [CERN Lab 161]

Inside the climate chamber was housed the experimental set up used to make measurements, characterizations and source tests:

![Set up for beta source test](image)

Figure 7 - Set up for beta source test
The fixed set up is composed by:

- The climate chamber, in which it has been mounted a self custom made Plexiglas base [figure 7] to fix the boards during the measurements and to assure the reproducibility of tests. With this structure it has been possible to put the sources straight onto the sensor, and in correspondence with a scintillator, placed on the bottom of the base, with the scope to give trigger signals out when recognizing a particle passing through, and so passing also through the detector. A brass collimator has been used to create a straight fluency for the β particles coming out from the $^{90}$Sr source, trying to avoid lateral particles scattering;

- A three logic units crate aimed to manage β source test, made of a discriminator that receives the triggers in from the scintillator (in NIM$^5$ logic) over an adequately set threshold, a level adapter to convert NIM logic signals into TTL$^6$ (TTL is the standard used by the VME, that only after this conversion can receive triggers too), and a counter, which shows the rate of particles hitting the scintillator and so useful to set the discriminator threshold;

- The TurboDAQ software installed on a PC;
- An oscilloscope used as a checker for the signals coming out from the scintillator;
- A voltmeter connected with the amplifier used for the amplification of the signals coming out from the scintillator (as a check for the amplifier set).

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$^5$ Nuclear Instrumentation Module, with true logic signal of -2V
$^6$ Transistor-Transistor Logic, with true logic signal of +5V
4.7 - Software description

Thought and built at Berkeley University & LBNL, it runs under Windows, and it's based on National Instruments's LabWindows development suite. TurboDAQ speaks to the Pixel Modules via a combination of custom electronics ("TPCC", "TPLL") and a generic PC-to-VME interface.

This software permits to pilot the data acquisition and to display the readout from the pixel detector. It is written in CVI language, this is why the software LabWindows CVI from National Instrument is needed.

An exhaustive introduction on how it works and on how it performs scans and measurements is given in the Appendix 1 of this thesis.
4.8 - Test results and characterization

Table 1 collects the sensor stored (or passed-by) Lab 161 at CERN, with the corrispective ID, the institute of manufactory, the type of sensor and the Clo, Chi and Vcal values given from the manufacturer:

<table>
<thead>
<tr>
<th>SENSOR ID</th>
<th>Institute</th>
<th>Type</th>
<th>Clo</th>
<th>Chi</th>
<th>Vcal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2EM2</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>8.03</td>
<td>47.564</td>
<td>0.905</td>
</tr>
<tr>
<td>2EM4</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>7.802</td>
<td>47.973</td>
<td>0.94</td>
</tr>
<tr>
<td>2EM6</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>8.043</td>
<td>48.926</td>
<td>0.93</td>
</tr>
<tr>
<td>3EM1</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>8.19</td>
<td>49.561</td>
<td>0.808</td>
</tr>
<tr>
<td>3EM5</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>7.691</td>
<td>47.541</td>
<td>0.896</td>
</tr>
<tr>
<td>3EM7</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>8.001</td>
<td>47.952</td>
<td>0.867</td>
</tr>
<tr>
<td>4EM3</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>7.696</td>
<td>48.967</td>
<td>0.868</td>
</tr>
<tr>
<td>4EM8</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>7.964</td>
<td>49.149</td>
<td>0.901</td>
</tr>
<tr>
<td>4EM9</td>
<td>FBK</td>
<td>DDTC-1</td>
<td>8.16</td>
<td>50.417</td>
<td>0.931</td>
</tr>
<tr>
<td>2EA</td>
<td>Stanford</td>
<td>Full 3D</td>
<td>7.047</td>
<td>42.201</td>
<td>0.795</td>
</tr>
<tr>
<td>3EG</td>
<td>Stanford</td>
<td>Full 3D</td>
<td>7.1</td>
<td>41.3</td>
<td>0.907</td>
</tr>
<tr>
<td>4EB</td>
<td>Stanford</td>
<td>Full 3D</td>
<td>7.043</td>
<td>38.587</td>
<td>0.851</td>
</tr>
<tr>
<td>Planar</td>
<td>Bonn</td>
<td>N-on-N</td>
<td>7</td>
<td>42</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 1 - Detectors at CERN Lab 161

The FBK-DDTC 2EM2, 3EM5, 3EM7, 4EM9 have been fully tested.

4.9 – Lab test and results

For each test a description of its purpose and how it is implemented by the software is given. In most cases the operator should simply select from the TurboDAQ menu the scan to be performed and start it. Here follows a list of the main tests executed and a table with reference of on which SCA they have been done. Each single test is going to be discussed in a separate paragraph among this chapter.

1. Leakage currents
2. Threshold and noise measurements
3. Noise vs bias voltage
4. ToT self-calibration measurements
5. 109Cd source test
6. 241Am source test
7. 90Sr source test

Table 2 - SCA test performed
4.9.1 - IV measurements

4.9.1.A - Measurement description

When a reverse bias is applied to a silicon sensor, a leakage (or dark) current of free recombining intrinsic charges is created by the contribution of:

1. Volume generation current, generated by the charge flow due to the bias (current increases proportional to the square root of the bias)
2. Surface generation, additional small contribution
3. Avalanche breakdown, at very high voltages

After full depletion the IV-curve displays a plateau region in which the current increase is very small before electrical breakdown occurs at very high voltages. The sensor has always to be operated at voltages well below hard breakdown values in order not to damage or even break it.

Considered as a very powerful tool for sensor testing, IV-curves are a check for sensor damages after dicing and chip flipping, and give also the information about the correct bias voltage to be applied in order to work in fully depletion condition. This measurement is somehow uncorrelated to the other scans, and its only requirement is thermal stability during the measurement, so it can be performed at the most comfortable stage during testing sequence. Since the biggest component of leakage current of a module before irradiation is actually a surface current, temperature for this test is also not critical.

Measurements of IV have been performed from 0 to -70 (-80, value of beginning breakdown) V at 1.33 (-1.5) V steps for 3D sensor, whereas from 0 to 600 V at 10 V steps for the planar sensor, obtaining sensor characteristic IV curves. After each voltage step a 10s settling time is waited before starting the measurement of the current, repeating the measurement until two consecutive readings of current differ by less than 1%. The source meter (Keithley 2410) is set with a current limitation of 100 (200) μA and the measurement gets in compliance when this value is reached. The measurement can be done over the

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7 61 points taken
entire sensor also for the 3D pixel configuration because all the p+ columns are connected with a back metallization on which it is possible to apply the voltage values.

A leakage current in the 0.1-0.2 μA range at -35 V depletion voltage and an avalanche breakdown above 70 V for FBK and Stanford sensors and in the 1 μA range at -150 V depletion voltage and an avalanche breakdown above 400 V for planar sensors is an acceptable result. Problems may be expected if leakage current is one order of magnitude higher. Earlier breakdown or not monotonous pattern of the leakage current should trigger a rejection of the module.

As for the leakage current of a single pixel, it has been found to be quite large as compared to predictions based on the measurements performed on test diodes, but it still remains at an acceptable level (~100 pA/pixel) [G.F. Dalla Betta et al. "Development of 3D-DDTC pixel detectors for the ATLAS upgrade". Conference Record of 7th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors, Hiroshima, Japan].

4.9.1.B - Measurement results on FBK and planar sensors

Figure 2 provides an overview of the I-V curves of all 3D-DDTC sensors available in the lab. It is noticeable that these values of the technology dependent parameters (such as leakage current and breakdown voltage are), show very similar behavior, evidence of the good reproducibility of FBK process. As for the breakdown voltage, it is normally larger than 70 V, a value that is determined by the n+/p-spray junction at the top surface. Possible problems in the sensor production process lead to a deviation of the curve from the expected shape.

Two samples show breakdown at lower expected voltages, probably due to some damage during the assembly, and so they have not been considered for further tests.

The plateau zone starts from -10 V to -40/-50 V, and a good compromise for having all the DUTs tested under the same condition is to bias the sensors at -35 V, with a leakage current correspondent to 0.1-0.4 μA range.

Figure 3 - I-V measurements of 3D-FBK DDTC1 sensors at CERN, Lab 161

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8 Demonstrating the difficulties in factury producing 3D DDTC sensors
Figure 3 focuses on a comparison between the 2E, 3E and 4E sensors. Leakage current is characteristic of how the entire sensor has been constructed during the building process, and globally does not “really” depend on the detector concept.

To see temperature and humidity effects in figure 4 a comparison plots of IV measurements is shown, with a scan performed inside the climate chamber (21 C and 20% of humidity check) and outside it at environment temperature (24 C, no humidity check).

It is important to underline that the humidity changes the value of the leakage current, while temperature does not have noticeable impact at this low differences.

Figure 4 - FBK 2E, 3E, 4E comparison

Figure 5 - Temperature and humidity check during IV measurements
Figure 5 shows a different behavior for a yet built FBK-dtc2b sample sensor (column overlap of 110 µm) from the IV scan, where a sharp increase of the current occurs already at low voltage. Four sensors have been produced from this kind of batch so far tested have all shown the same behaviour (only 3E sensors have been initially considered in view of their use in a beam test at CERN). Such an early breakdown should be related to the presence of local defects. From maps of the pixel leakage current at different voltages it has been noticed that a few pixels start exhibiting high leakage current as the voltage is increased [G.F. Dalla Betta et al. "Development of 3D-DDTC pixel detectors for the ATLAS upgrade". Conference Record of 7th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors, Hiroshima, Japan].

Nonetheless, the behavior of this sensor has been tested during May Testbeam at CERN [chpt. 6] while kept at -8 V of bias voltage, showing correct working responses.

As a comparison reference for the new 3D-FBK DDTC1 sensors, it follows the IV plot behavior obtained from an ATLAS n-in-n single-chip module, shown in figure 6.

The main difference is that the same little values of leakage current are obtained with consistently higher values of bias voltages.

Usually a good compromise for a satisfying low level of leakage current is to apply a $V_{\text{bias}}$ of -150 V to these kind of sensor.
4.9.1.C - Leakage current from Monleak Scan

The FE-I3 chip provides an useful extra feature: the Monleak Scan. It is a measurement of the combined feedback and leakage current from the feedback circuit as described by the following relation:

\[ I_{\text{monleak}} = I_{\text{leak}} + 2I_{\text{feedback}} \]

where \( I_{\text{feedback}} \) is defined by the IF and TDAC parameters (each of both divided by some correction factors and then summed together) of the feedback current of the FE preamplifier and \( I_{\text{leak}} \) is the sensor leakage current per pixel [http://physik2.uni-goettingen.de/~jgrosse/TurboDAQ/ModuleAnalysisFrame.html].

This measure is made possible by a “monleak” ADC: the pixel to be measured is selected with the hitbus mask bit of the FE-I3 and its \( I_{\text{monleak}} \) is digitalized to a precision of 0.125 nA in a range up to 128 nA [J. G. Knetter – “Vertex Measurements at a Hadron Collider – The ATLAS Pixel Detector” – Universitaat Bonn]. This procedure is designed to read the leakage current pixel by pixel, which relates to radiation damage providing a useful monitoring and diagnostic tool. The few defect pixels can be clearly identified as they draw a leakage current wide outside of the dynamic range of the inbuilt measurement circuit.

![Picture 4 - Map of the raw MonLeak readings and map of the leakage current values](image)

The pictures just show the result of one monleak scan from a random sensor (FBK-4EM9) taken as example. The sum over all pixels is also specified in the text pad at the top of the canvas. The first plot on the top shows the behavior over the entire chip map, the plot in the middle points out the mean value and the sigma of the measurement over all channels, and the plot on the bottom shows the values channel per channel. The TurboDAQ log file for the monleak scan is used to determine \( I_{\text{feedback}} \) (if no logfile is found, a
default of $I_{\text{feedback}} = 2 \text{nA}$ is assumed). The absolute accuracy of the measurement is very limited due to the implementation of the measurement circuitry in the chip. Comparison between various measurements shows a mean leakage current of 1 nA for 3D detectors.

4.10 - Threshold scan

4.10.A – Measurements description

The purpose of this test is to measure the threshold and noise of each pixel, either globally or respectively, where only pixels with a charge deposit above a set threshold are taken into account for readout by the front-end electronics. Signals are induced in each pixel by means of on-chip charge injectors (an on-chip chopper generates a $V_{\text{pulse}}$ to be injected into $C_{\text{low}}$ or $C_{\text{high}}$ capacitors of each pixel, and the input of the preamplifier sees a signal equivalent to $V_{\text{pulse}} \times C_{\text{low}}$ (or $C_{\text{high}}$) charge), and the number of collected hits versus the injected charge is recorded. Ideally a step function with an immediate transition of the detection efficiency from 0 to 100 % at the threshold would be expected, but in a real world, because of the pixel noise, some injected charges below the threshold are detected while some others are not. The error function, which is a convolution of the ideal step function with the Gaussian pixel noise distribution, is the best candidate to describe the discriminator output:

$$f_{\text{error}}(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{u^2}{2}} du$$

The plot of this function, the so-called S-curve, is fitted to the threshold scan result of each pixel.

The 50% hit efficiency on the S-curve defines the threshold value of a pixel. Here follows the exact procedure that allows to have such a result:
1. 100 digital injections per pixel are made

2. The injected charge is of between 0 and 9000 e⁻ value in 45 e⁻ steps

3. Then the collected hit number for each pixel and each injected charge is recorded

The probability of detecting a charge is given by the following formula, that collects all the considerations done until now:

\[ P_{hit}(Q) = \frac{1}{2} \text{Erfc} \left( \frac{Q_{\text{thresh}} - Q}{\sqrt{2} \cdot \sigma_{\text{noise}}} \right) := \frac{1}{\sqrt{\pi}} \int_{Q}^{\infty} \exp \left( \frac{Q - Q_{\text{thresh}}}{\sqrt{2} \cdot \sigma_{\text{noise}}} \right) dQ, \]

The noise of a pixel is inversely proportional to the steepness of the transition from no detected hits to full efficiency:

\[ \sigma = \frac{Q_{70\%} - Q_{30\%}}{f_{\text{error}}(70\%) - f_{\text{error}}(30\%)} \]

The threshold calibration is obtained by first setting the GDAC (global setting) most correct value [see chapter 3, paragrafo col plot GDAC], then by correcting its performance with the TDAC tuning (pixel setting) file, obtained from a TDAC Tuning scan. Scans are repeated to reduce the threshold dispersion by adjusting a DAC-parameter individually for each channel, the TDAC [I. Peric, et al., Nucl. Instr. Meth. Phys. Res. A 565 (2006) 178., ATLAS Project Document No: ATL-IP-QP-0144]. For FE-I3 this test can be performed in the so-called “auto-tune” mode, where a fixed charge, corresponding to the desired threshold, is continuously injected into each pixel and a counter internal to the pixels checks for which TDAC values its count rate is 50%. This tuning procedure is extremely fast, even if it may show some systematic patterns.

An expression of the threshold dependence of each pixel on the TDACS is fitted to these data using the parameterization:

\[ \text{Threshold}(TDAC) = A + B \log_{128} \frac{TDAC}{TDAC} \]

This relationship is used to determine the TDAC value which is for that pixel the nearest possible to the target threshold [T. Stockmanns, “Messungen an der PIRATE Front-End-Elektronik fur den ATLASPixeldetektor”, Diploma thesis, Universitat Bonn, 2000 - ATLAS Project Document No: ATL-IP-QP-0144].
4.10.B – Measurements results on FBK and planar sensor

The set of the correct value of threshold is the first step to calibrate the front-end with the suitable configuration to recognize particles, and it has been performed on all those sensors not affected by early breakdown problems.

The results of the Threshold-Scan, performed at a bias voltage of 35 V on sensors tested at CERN Lab 161 are summarized in Table 3:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>$&lt;$TH$&gt;$ (e')</th>
<th>$\sigma$(TH) (e')</th>
<th>NOISE (e')</th>
<th>$\sigma$(N) (e')</th>
<th>HV (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBK 2EM2</td>
<td>3299,00</td>
<td>50,29</td>
<td>202,30</td>
<td>8,95</td>
<td>-35</td>
</tr>
<tr>
<td>FBK 3EM7</td>
<td>3300,00</td>
<td>43,79</td>
<td>215,40</td>
<td>8,45</td>
<td>-35</td>
</tr>
<tr>
<td>FBK 4EM9</td>
<td>3306,00</td>
<td>45,76</td>
<td>225,40</td>
<td>9,64</td>
<td>-35</td>
</tr>
<tr>
<td>Planar</td>
<td>3275,00</td>
<td>34,46</td>
<td>169,30</td>
<td>8,94</td>
<td>-150</td>
</tr>
</tbody>
</table>

Table 3 - Threshold scan results

As an example, Figs. 10 and 11 show a threshold measurement and a noise distribution for a FBK-DTC2-2E sensor, with the entire chip map and the mean value with correspondent sigma over all channels for both measurements, and the threshold value channel per channel (plot on the bottom of Figure 7):
Concerning the noise values obtained, as shown in Table 3, from the number of electrodes per pixel comparison it is noticeable that the 4E is noisier than the 2E and the 3E, with the same operating conditions.

4.11 - Noise versus bias voltage of the sensor

4.11.A – Measurement description

The noise is correlated with the bias voltage given to the sensor; to prove this fact a threshold scan over various bias voltages, from 0 V to -80 V at -5 V steps, has been performed and the threshold and noise have been determined, using the same configuration file for each bias voltage value (same TDAC/FDAC settings).

4.11.B – Measurements results on FBK and planar sensors

Figure 9 shows the noise vs voltage curves of FBK-DTC2 samples for 2E, 3E, 4E configuration:

![Noise vs. Vbias](image)

Figure 10 - Noise vs Bias voltage for FBK-DTC2

It is clear from it that having more electrodes per pixel increases the noise (under the same operating conditions). The reason why is that it is equal to having more capacitors connected in parallel, so it grows the total capacitance and consequently the total noise because there is more charge enrolled (\(C_{2E} < C_{3E} < C_{4E}\)). It also shows that for little voltage values the noise is higher than for high values.

Since the noise is determined from threshold scans with the same TDAC settings, it is useful to check the dependence of the threshold to the bias voltage. Threshold should be almost independent from the bias voltage because of the fact that the threshold scan is fitting an S-curve which is a convolution of a Gauss
and a step function set to a fixed value, as already explained. The value of the step function is the threshold and should thus not be affected by changing the width of the Gaussian that is overlaid.

This is verified with the following measurements:

- Threshold as a function of the bias voltage:

![Threshold vs. Vbias](image)

Also the width of the threshold and noise are plotted as a function of bias voltage, in order to see if there is any dependence from it:

- Noise and threshold width as a function of the bias voltage:

![Sigma Noise vs. Vbias](image)

![Sigma Threshold vs. Vbias](image)

From the information given by the IV plots and the noise versus bias voltage plots, and knowing the theoretical depletion value for this kind of sensors (-10 V) it has been chosen as reasonable to have always
a depletion voltage of -35 V for these sensors during all the test, in order to be sure to have full depletion and meanwhile being affected from as little as possible noise.

The same behavior has been discovered performing the measurement on a planar SCA, with one order of higher bias values:
4.12 – Time over Threshold (ToT) measurements and internal calibration of the detector

4.12.A – Measurements description

In silicon, the mean energy loss is of 1.66 MeV g\(^{-1}\)cm\(^2\), while the density is of 2.33 g cm\(^{-3}\); so the loss of energy is 390 eV/\(\mu\)m. From the theory it is known that in order to generate a hole-electron couple an energy of 3.6 eV is needed, and so a MIP creates \(~110\) couples per \(\mu\)m in the silicon. For example, with a thickness sensor of 250 \(\mu\)m, a MIP is almost equal to 20000 hole-electrons couples (talking in terms of charges) [G. Aad et al., JINST 3 (2008) P07007]. The ToT (Time over Threshold) is used to measure the deposited charge of a hit: it is the length of the discriminator signal in units of the 40 MHz LHC bunch crossing clock\(^9\), and depends on the deposited charge itself, on the discriminator threshold and on the preamplifier feedback current.

The on-chip injection circuit of FE-I3 is again used to calibrate the ToT (Time over Threshold) response of a signal into charge. The standard tuning aims to a ToT of 60 units for a charge of 20000e, so given a standard threshold of 3200e this corresponds to a charge of about 250 – 350e per ToT unit. The ToT calibration does test injections varying charges above threshold and measures the average ToT coming out from it. Feedback current (and thereby the ToT) is determined by a global current DAC per FE chip (IF) and a DAC in each pixel (FDAC). Tuning chooses the feedback current in order to have the ToT response as the desired 60 @ for a MIP of 20ke\(^{-1}\).

The purpose of a ToT scan is to tune the ToT response to a MIP of each pixel in order to have a uniform signal of the collected charge in a time acceptable for operation of detectors (such as ATLAS or CMS), and to calibrate the relationship between the measured ToT and the collected charge.

Figure 11 - ToT dependances [Dobos]

The pixel detector has an indirect pulse height information using the Time over Threshold (ToT) technique: the pulse shape is approximately triangular and the time by which the preamplifier output stays over the threshold is approximately proportional to the pulse height, as already explained [descry. Chip]. Then the

\(^9\) 25 ns
slope of the return to baseline of the triangular pulse is determined by the feedback current of the amplifier, which can be tuned at the chip level changing the IF DAC register and at the pixel level using the 3-bit FDAC pixel register.

The ToT tuning consists of two parts. At first, the ToT response of all pixels to the charge deposited by a MIP is made uniform by proper setting of the IF and FDACs: this is done by injecting a fixed charge of 20000 e\(^{-}\), corresponding to the most probable energy loss in the 250 μm thick silicon sensor, and choosing the above mentioned DACs in order to have an average ToT response of 60 clock cycles. The 60 clock cycles target allows to keep full efficiency up to deposited charges of 4 MIPs. The subsequent step is to inject different charges, compute the average ToT observed for each pixel and each charge, and fit a calibration function to these data.

\[
ToT = P_1 + \frac{P_2}{F_3 + Q_{inj}}.
\]

This is performed using both the \(C_{lo}\) inject capacitance, which allows a fine granularity measurement of the ToT-charge relationships in the region of charge up to 1 MIP, and the \(C_{hi}\) inject capacitance to cover the region of very high charge. These calibrations will be used to translate ToT to charges when collecting data with real particles. Since changing the feedback current also slightly affects the threshold, after IF and FDAC tuning the threshold tuning needs to be re-done.

The procedure of the tuning begins with the setting to 20000 e\(^{-}\) the ToT reference charge in the TurboDAQ, and then going through an FDAC Scan. From it can be observed the average ToT value of each chip and the change of IF DACs can move it toward the desired average ToT response of 60. This scan is repeated until all chips have a matching average ToT response. After this tuning is finished it has to be performed a full FDAC tuning scan (FDAC Tune Internal-Cal): the results of FDAC determination are put in files \#_fdacs_.out, files that are moved from the data folder in the module directory tree to the FDACs one. Then these files are loaded in the module configuration file and saved.

Finally it has to be performed the ToT calibration, which consists of two scans (TOT Calibration Internal-Cal. CLow Concurrent, TOT Calibration Internal-Cal. CHigh Concurrent). The \(C_{lo}\) capacitance is best to fit low values of charge, while \(C_{hi}\) capacitance is used for high values, as shown in simulations [1]:

![Figure 12 - Simulation of ToT using the two injection capacitances](ppt vuoto)
4.12.B – Measurements results for FBK and planar sensors

The aim is to obtain calibrated SCA ready to be used as detectors for MIPs. Here follows the results found with FBK sensors:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>ToT</th>
<th>σ(ToT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBK 2EM2</td>
<td>60.04</td>
<td>1.767</td>
</tr>
<tr>
<td>FBK 3EM7</td>
<td>60.19</td>
<td>1.985</td>
</tr>
<tr>
<td>FBK 4EM9</td>
<td>57.25</td>
<td>1.835</td>
</tr>
</tbody>
</table>
4.13 – Gamma source measurements

4.13.A – Measurements description

$^{241}$Am and $^{109}$Cd gamma sources have been chosen to calibrate the detectors. The source test has been also used to identify eventual dead or noisy pixels showing undesired signal because disconnected, merged, defective or badly tuned. The main point of this test is to obtain the characteristic photoelectric peaks of $^{241}$Am and $^{109}$Cd, so having a proof of the correct working condition and calibration of the detectors. $^{241}$Am ($^{109}$Cd) gamma source emits 60 keV (22 keV) photons which can convert anywhere in the bulk to a 60 keV (22 keV) primary electron. If ionization takes place in the substrate region where columns overlap, a signal of 16.5 ke (6.1 ke) is expected\(^{10}\). On the other hand, if a photon converts in a high doping region or close to the surfaces, a fraction of the charge could be lost. Thus, in the charge distribution, a high-end pick at 16.5ke (6.1ke) and a tail towards smaller values are expected.

4.13.B – Measurements results on FBK and planar sensors

Figures 14 and 15 show spectra for $^{241}$Am and $^{109}$Cd respectively, as reconstructed from the ToT reading with the 60 ToT calibration discussed in the precedent paragraph, and with a sensor bias voltage of 35 V. In both cases, the position of the main peaks agrees with expectations within the uncertainty due to the calibration process, which has been estimated of being in the order of 10-15% [J. Weingarten. Multi-Chip-Modul-Entwicklung für den ATLAS-Pixeldetector. PhD thesis, Universität Bonn, Bonn, Germany, 2004]. To perform the measurement there has been used the standard TurboDAQ scan of Source Test Self Trigger, that collects data with the self capability of the FE-I3 to send out signal only when a gamma particle has hit a pixel (one hit-one trigger mode) and with the possibility to create mask files to cover noisy pixels that melt the signal coming from the source. The plots refer to a 2E board:

\[\text{Figure 14 - } ^{241}\text{Am spectrum for FBK-2EM2 taking 50000 events}\]

\[^{10}\text{given a 3.6 eV value of ionization energy in the silicon}\]
The same behaviour has been obtained on the other sensor configurations [see Appendix1]. This is not surprising, since no appreciable difference in the charge collection process is expected between the different layouts after irradiation.

A more interesting point is to see that the measurement remains almost the same also varying the bias voltage of the sensor. Figures show the source spectrum of $^{241}$Am with different set of bias voltage (-15 V, -55 V) for the FBK 2EM2 module:

4.13.A - Measurements description

β source test is considerable as a simulation of real working conditions for the detector, which consists in MIP passages through the sensor ionizing it.

Ionization is subject to statistical fluctuations and the value returned by the Bethe Block formula [chp.2] of energy loss is only an average value of a Landau distribution. If a particle is not stopped in the sensor its response varies around the peak of the distribution with a significant probability of high signals, and due to this tail the average value is higher than the most probable value of the distribution. The fluctuation around the maximum of this distribution becomes higher for thinner sensors. The main reason for the Landau fluctuation is the rare but measurable occurrence of the so-called δ-electrons (or knock-on electrons) which obtain enough energy by the interaction to become ionizing particles themselves. They have a typical direction perpendicularly to the direction of the incoming particle that leads to irregular charge clouds and degrades the spatial resolution.

4.13.A - Measurements results on FBK and planar sensors

The single chip module on PCB frame is mounted with a hole under the sensor especially designed for this kind of tests, which provide the passing through of β particles, and TurboDAQ, with the scintillator set up described in paragraph 4.inizio, uses the β sources oriented Source Test External Trigger capability of FE-I3, which allows to collect data from the detector only when the MIP is also recognized by the scintillator, giving out the acquisition trigger.

Before going through the description of gamma source test, there has to be considered the trigger delay of the setup, which is given by the latency of the FE to read out the event (stored locally and discarded after this time) and the external delay, that is set to catch 16 consecutives “bunch crossing” around the one that contains the actual trigger (since the particle hit the scintillator and the sensor at the same time and we are only interested in the "bunch crossings" associates with the trigger).

Figures 4 shows the pulse height spectrum in response to a Sr90 β-source in a FBK-dtc2 3EMS biased at \(-35 \, \text{V}\)\(^{11}\), obtained using a brass collimator\(^{12}\). The distributions have been fitted with the expected Landau curve. The front-end electronics have been tuned with 60 ToT at 20000e, suitable for a silicon pixel sensor of 250 μm like the ATLAS planar is, for that the most probable charge value is about 16900e with a sigma of 1570e (cluster size one) and about 18300e with a sigma of 1.470e (cluster size two). The observed difference should be attributed to the error due to the calibration process (about 10-15%, propagated from the known value of the FEI capacitor Clow and Chigh). For the fbk-dtc2 3EMS assembly the most probable charge value is about 13600e with a sigma of 1150e (cluster size one) and about 14900e with a sigma of 1350e (cluster size two). In this case the nominal sensor thickness is of 220 μm, so that the expected value of the most probable charge should be approximately of 17500e. At FBK Institutes some C-V measurements on planar diodes coming from the same wafer of dtc2 sensors have been done in order to understand better the charge collection from the Sr90 source tests [Appendix for ATLAS-3D beam tests report Alessandro La Rosa CERN]. From these measurements a thickness about of 200 μm has been estimated.

\(^{11}\) For the plots a 4E (M9) board as comparison, see the Appendix 2
\(^{12}\) Distance source-detector: 20 mm
instead of nominal one, so the expected value of the most probable charge should be of 14300e instead of 17500e, keeping the observed difference between expected and measured value attributed to the error due to the calibration process.

Figure 17 shows the pulse height spectrum in response to a $^{90}$Sr beta source in a 2E sensor biased at 35 V. The distribution is related to a cluster size 1, and charge values in excess of 12 ke have been fitted with a Landau function, which is also shown in the figure. The most probable charge value is ~14100e with a sigma of ~1160e. It should be noted that the front-end electronics has been tuned with 60 ToT at 20000e for a pixel sensor of ~250 µm, and in this case the nominal sensor thickness is of 220 µm, so that the expected value of the most probable charge should be in proportion approximately of 17500e. The observed difference should be ascribed to the already mentioned error due to the calibration process, but also to the fact that the wafer thickness is probably smaller than the nominal one, in the order or 210 µm.

For all sensors available, it has been measured the pulse height spectrum in response to a $^{90}$Sr source [see appendix1]. As a result the wafer thickness has been estimated in relation to planar thickness and its Sr90 source response. The obtained value is about 203 µm which is in agreement with the estimated thickness by C-V measurements.
Measurements results

The β source test gives a ToT value of less than the calibrated 60, because of the less depth of 3D sensors (in fact the value of 60 was fitted for the planar kind of pixel detectors). Moreover, the plot is expected to be of Landau shape: this result was found only applying a clusterization to the data taken from the test, while without clusterization it is obtained Gaussian shaped curves, mainly because of multiple scattering of β particles. In fact, without clusterization, a single events, which generates also δ rays, that touches more than one pixel is read as a different number of events as many pixels are touched: on those hit pixels the TurboDAQ does the mean charge value obtaining out a Gaussian distribution. The clusterization contains an algorithm that recognizes and collects the charge given from a single events touching more than one pixel together, making a better interpretation of the source test and so producing Landau curves representing also the high energetical δ rays. This kind of clusterization applied is called “Digital Clusterization”.

Results on planar

The planar SCA has been built with a golden layer on the bottom of the board, from which beta particles can pass through re-creating the layer shape in the measurement results, as shown in Figure:

Results of the measurements are shown in Figure:
Rate of 5-10 particles per second for 90Sr test with collimator;

Rate of 70-100 particles per second for 90Sr test without collimator.

For both set the threshold to the NIM discriminator

**Tabella con tutti i risultati+commento**

Digital clusterization (spiega) : 1 single events producing a delta is read as 3 different events if touches 3 different pixels giving birth to further ionization → Gaussian shape (see Appendix for the plots)

The clusterization recognizes ToTs belonging to a same events with a specific algorithm, and attributes the correct ToT to the event taking the highest ToT value between the 3 pixels (clu size1), or the highest plus the second between the higher (clu size 2):