ATLAS 3D Sensors - Lab characterization (N01)

Abstract
For future tracking detectors at LHC different type of solid-state sensors are currently being studied. The activity of CERN ATLAS Pixel Group is focused on studies of different sensors types, connected to LHC-relevant FE electronics, in comparative measurements. The tests include measurements on base sensors as well as tests of sensor plus FE electronics. This note presents the preliminary measurement of 3D Double-side Double-Type Column (DDTC) detectors on p-type substrates bump-bonded on the ATLAS Pixel chip (FE-I3) in comparative measurement with Stanford 3D and with current ATLAS Silicon Pixel detectors.

Introduction
An upgrade of the LHC towards a 10 times higher luminosity will require tracking detectors with unprecedented radiation tolerance. Furthermore, the high track density will call for fast and high granularity detectors, which also fulfill the boundary conditions of low radiation length and low costs. Over the last years several promising material developments and design concepts for the next generation of silicon mini-strip and pixel detectors have been brought forward. The activity of CERN ATLAS Pixel Group is focused on studies of different sensors types, connected to LHC-relevant FE electronics, in comparative measurements. The tests include measurements on base sensors as well as tests of sensor plus FE electronics.

In this note the preliminary measurement of 3D Double-side Double-Type Column (DDTC) detectors on p-type substrates bump-bonded on the ATLAS Pixel chip (FE-I3) in comparative measurement with an N-in-N Silicon planar sensor and with a Stanford 3D Silicon detectors are presented.

FBK 3D Silicon sensors
Fondazione Bruno Kessler (FBK), in collaboration with INFN, has developed a new detector concept called 3D-DDTC (Double-side Double-Type Column). As figure FB01 shows, columns of different doping types are etched from both wafer side. The etching is stopped at few tens of micrometers from the opposite surface. As regards the pixel layout, three different inter-electrode distances have been implemented, with 2, 3 or 4 columnar electrodes per pixel (50um x 400um). The advantage of a high number of columns per pixel consists of the short collection distance at the expense of an increased pad capacitance, thus, an increased noise. In the 2-electrodes configuration (called 2E) the inter-electrode distance is 103um, in the 3-electrodes configuration (3E) is 71um and in the 4-electrodes configuration (4E) is 56um [ZOB01]. The sensor thickness is 220um and the columns overlap is about 100um.

Reference sensors
Two kinds of Silicon sensors bump bonded on ATLAS Pixel readout chips have been used as a reference to compare the 3D-DDTC performances.
- N-in-N Silicon Planar sensor (the currently ATLAS pixel sensor) [JIN01].
- Stanford 3D Silicon sensors (full column passing-through, active edge) [KEN01].
Single-chip assembly
All sensors under test are bump bonded on ATLAS Pixel chip called FEI3 and the detector (sensor + FE) is housed in PCB module as showed in Figure SC01. The front-end chip (FE-I3) is implemented in 0.25um CMOS technology and special layout rules have been used in order to obtain the required radiation tolerance up to a total dose of 50 Mrad. The chip consists of 2880 readout cells of 50um x 400um size arranged in a matrix of 18 x 160. Each cell contains an analogue block where the sensor charge signal is amplified and compared to a programmable threshold by a discriminator. The digital readout part transfers the hit pixel address, a hit time stamp and digitized amplitude information, the Time over Threshold (ToT – length of discriminator signal) to buffer at the chip periphery. These hit buffers monitor the age of each stored hit by inspecting the associated time stamp [PER01].

The FE-I3 uses two power supplies, the digital supply VDD, referenced to DGND, with a range from about 1.4 V to 2.5V and a nominal value of 2.0 V, and the analogue supply VDDA, referenced to AGND, with a nominal value of 1.6 V. VDDREF is used to provide power only to the preamplifiers and is the reference for the preamplifier inputs. It is connected to VDDA outside the FE. Current consumption is roughly 75 mA on VDDA and 35 mA on VDD. AGND and DGND are connected together outside the module.

The analogue injection circuit, used to test, threshold tune and ToT calibration is showed in Figure SC02. Two separate injection capacitors, with nominal values of 8 fF for $C_{lo}$ and 40 fF for $C_{lo}+C_{hi}$ are used. Either direct pulse on the Ext-Injection line can enter into the capacitors or using the signal to switch the capacitors from VDDREF down to VCAL generates a voltage step, which is a voltage provided by a DAC in the bottom of column region.

The ToT of a hit is determined by the width of the injected pulse and depends on: the deposited charge, the discriminator threshold and the feedback current. To measure the charge of a hit the discriminator output pulse is recorded in units of the 40 MHz crossing clock.

Experimental setup
The experimental setup, which has been used to characterize the detector, is based on TurboDAQ. TurboDAQ is the software used to perform automated electrical test of ATLAS Pixel Detector Modules during the production phase. TurboDAQ runs under Windows. It is based on National Instruments LabWindows development suite. TurboDAQ speaks to the Pixel Modules via a combination of custom electronics (TPCC, TPLL) and a generic PC-to-VME interface [GOE01].

Figure ES01 shows a snapshot of CERN ATLAS Pixel setup, which is allocated in a semi-clean room with safety precaution for cleanliness and radiation zone. It is equipped with a climate chamber (where the source and the module under test are housed), which can operate in a range between -25 C and 100 C. All measurements with CERN ATLAS Pixel setup have been done at 20 C with a relative humidity of 12%.
Test results
The performance of 3D-DDTC have been studied by measuring:
- Leakage currents;
- Threshold and noise measurements;
- Noise versus bias voltage;

Leakage currents. The main test (IV-Scan) has consisted of the measurements of the IV curve from 0 to 80 (90) V at step of 1.33 (1.5) V. A 10s settling time takes place after each voltage step before starting the measurement of the current. Then the current is measured until two consecutive readings differ by less than 1%. The source matter (Keithley 2410) has been set with a current limitation of 100 uA. This kind of test has been also useful to check for sensor damages after different stages of the assembly.
Figure LC01 provides an overview of IV curves of all 3D-DDTC sensors available while figure LC02 shows the curve for Stanford 3D with three electrodes per pixel.
A second test that has been done is called Monleak-Scan, which has been used to measure the leakage current for each pixel. In the Monleak-Scan the leakage current, which is collected by each pixel, is measured by comparison with the feedback current of the pre-amplifier. Figure LC03 shows the leakage current distribution in DAC units (1 DAC = 125 pA) of FBK 3D sensors (2EM2) detector with a bias voltage at -35 V.

Threshold and noise measurements. The Threshold-Scan has been performed to measure the threshold and noise of each pixel and test the operation of the FE analogue injection circuitry.
An on-chip chopper, connected to the VCAL DAC, generates a voltage pulse \( V_{\text{pulse}} \) which is injected into the injection capacitor \( C_{\text{lo}} \) or \( C_{\text{hi}} \) of each pixel. Hence the input of the preamplifier sees a signal equivalent to a signal generated by a charge \( V_{\text{pulse}} \) times \( C_{\text{lo/hi}} \).
100 digital injections are performed for each pixel and each injected charge value between 0 e- and 9000 e- in ~ 45 e- steps. The number of collected hits for each pixel and each injected charge is recorded.
The schematic result of a threshold scan is showed in figure TN01. All injected charges above the adjustable discriminator threshold should create a preamplifier output signal, which can pass the discriminator and results in a hit detection. But all injected charges below this threshold should not be detected. In this ideal case a step function with an immediate detection efficiency change from 0 % to 100 % at the threshold is expected. Because of the pixel noise, e.g. preamplifier noise, in the real case, some injected charges below the threshold are detected and some injected charges above the threshold are not detected. The error function, a convolution of the ideal step function with the Gaussian pixel noise distribution, describes the discriminator output and is the integral of the Gaussian function.
It is fitted, so-called S-curve fit, to the threshold scan result of each pixel. The 50 % efficiency on the S-curve defines the threshold value of a pixel. The noise of a pixel is inversely proportional to the steepness of the transition from no detected hits to full efficiency [ST001].
The results of the Threshold-Scan are summarized in Table TN01. Figures TN02 and TN03 show an example of threshold and noise measurement for a FBK detector.
**Noise versus bias voltage measurements.** The noise study presents three different noise trends as a consequence of different capacitive loads of each pixel type: $C^{2E} < C^{3E} < C^{4E}$.

Figures NV01 and NV02 show respectively the noise of FBK and Stanford detectors.

**Source tests.** The Am-241 and Cd-109 gamma-source have been chosen to calibrate the detectors. The source test has been also used to identify pixels which don’t answer to ionization because disconnected, merged, defective or badly tuned.

Am241 (Cd-109) gives the 60keV (22keV) photon which converts anywhere in the bulk to a 60keV (22keV) electron. If full contained in the column overlap region a signal of 16.5ke (6.1ke) is expected. If the electron path is not fully contained, e.g. photon converts too early or too late in the overlap range, there should be a tail of smaller values, a distribution with a high-end pick at 16.5ke- (6.1ke-) and a long tail towards smaller values is expected.

Figures ST01 and ST02 show the source spectrum respectively of Am-241 and Cd-109 measured using an FBK-3EM5 module. Previous figures show the source spectrum as a sum over all pixels without any clustering.

Figure ST03 shows the source spectrum of Am-241 with different set of bias voltage. In table ST01 the peak values of the source spectrums with respectively spread are reported for each detector illuminated with Am-241 including also measures obtained with N-in-N Planar and Stanford 3D detectors.

Figure ST04 shows an Am-241 source spectrum that has been obtained using FBK, Stanford 3D and N-in-N Planar detectors.

The Am-241 gamma-source gives also photons of 26 keV which gives rise to secondary peak at 7.3 ke-. The Stanford 3D is a full 3D sensor and the difference between its and other spectrums could find origin in 3D-full-sensor presenting a lower charge sharing than the Planar and FBK (Double-side Double-Type Column) sensors.

Figure ST05 shows a Cd-109 gamma-source spectrum that has been obtained using FBK, Stanford 3D and N-in-N Planar detectors, while in table ST02 the peak values and their spread are reported.

**Summary**

In this note the preliminary measurement of nine FBK 3D Double-side Double-Type Column (DDTC) detectors on p-type substrates with ATLAS Pixel readout chips have been presented in comparative measurement with ATLAS Silicon Planar and Stanford 3D Silicon detectors.

The performance of the detectors have been studied by measuring:

- Leakage currents;
- Threshold and noise measurements;
- Noise versus bias voltage;
- Am-241 and Cd-109 gamma-source tests;

Nine FBK detectors have been tested. One of them (3EM1) has showed problems in IV scan (breakdown about -10V), while one (2EM4) has presented problems in the FE calibration.
References


[GOE01] J. Goettingen http://physik2.uni-goettingen.de/~jgrosse/TurboDAQ.

[JIN01] ATLAS pixel detector electronics and sensors. 2008 JINST 3 P07007.


**Figures**

**Figure FB01.** Sketch of a FBK 3D-DDTC sensors on p-type substrate.

**Figure SC01.** Snapshot of a Single-Chip Module.

**Figure SC02.** Overview of the analogue block in the readout channel.
Figure ES01. Snapshot of CERN ATLAS Pixel experimental setup.

Figure LC01. Overview of IV curves of all FBK 3D-DDTC detectors available.

Figure LC02. IV curve for a Stanford 3D sensor.
Figure LC03. Leakage current distribution in DAC units (1 DAC = 125 pA) for an FBK-2EM2 module detector with a bias voltage of -35 V.

Figure TN01. Schematic results of a threshold scan for a single pixel, the ideal step function and the real error function.
Figure TN02. Threshold measurement of FBK-2EM2 module with bias voltage of -35V (FE tuned at 3200e- with 60ToT at 20ke-).

Figure TN03. Noise measurement of FBK-2EM2 module with bias voltage of -35V (FE tuned at 3200e- with 60ToT at 20ke-).

Figure NV01. Noise versus bias voltage of FBK detectors with 2, 3 and 4 electrodes per pixel.
**Figure NV02.** Noise versus bias voltage of Stanford 3D detectors (3 electrodes per pixel).

**Figure ST01.** Am-241 spectrum measured with FBK-3EM5 module using the self-trigger capabilities and the ToT charge information.
Figure ST02. Cd-109 spectrum measured with FBK-3EM5 module using the self-trigger capabilities and the ToT charge information.

Figure ST03. Am-241 spectrum measured with FBK-3EM5 module with a bias voltage of: 25V(a), 35V(b) and 55V(c).
Figure ST04. Am-241 spectrum measured with FBK-3EM5, N-in-N Planar and Stanford 3D detectors.

Figure ST05. Cd-109 spectrum measured with FBK-3EM5, N-in-N Planar and Stanford 3D detectors.
Tables

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>$&lt;\text{Th}&gt;$ [e]</th>
<th>$\sigma$(th) [e]</th>
<th>$&lt;\text{Noise}&gt;$ [e]</th>
<th>$\sigma$(noise) [e]</th>
<th>HV [V]</th>
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<tr>
<td>FBK-2E</td>
<td>3200</td>
<td>58.6</td>
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<td>FBK-3E</td>
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<td>FBK-4E</td>
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<td>41.27</td>
<td>229.8</td>
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<td>STA-3E</td>
<td>3246</td>
<td>63.2</td>
<td>273.3</td>
<td>12.78</td>
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<td>N-in-N</td>
<td>3259</td>
<td>42.96</td>
<td>181.1</td>
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Table TN01. Threshold and noise measurements of FBK and Stanford 3D detectors and Planar N-in-N detectors.

<table>
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<th>Detector</th>
<th>Peak ($10^4$ e)</th>
<th>Spread (e)</th>
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<tr>
<td>FBK-3D-2EM2</td>
<td>1.411</td>
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<td>FBK-3D-2EM6</td>
<td>1.401</td>
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<td>FBK-3D-3EM5</td>
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<td>778.4</td>
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<td>FBK-3D-4EM3</td>
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<td>775.2</td>
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<tr>
<td>FBK-3D-4EM9</td>
<td>1.415</td>
<td>760.0</td>
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<tr>
<td>Planar (N-in-N)</td>
<td>1.501</td>
<td>688.4</td>
</tr>
<tr>
<td>STA-3EG</td>
<td>1.720</td>
<td>-</td>
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Table ST01. Summary of peak values of the source spectrums for each detector illuminated with Am-241.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Peak (e)</th>
<th>Spread (e)</th>
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<tbody>
<tr>
<td>FBK-3EM5</td>
<td>5658</td>
<td>521.8</td>
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<tr>
<td>Planar (N-in-N)</td>
<td>5741</td>
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<td>STA-3EG</td>
<td>6385</td>
<td>661.9</td>
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Table ST02. Summary of peak values of the source spectrums for different detectors illuminated with Cd-109.