Material-mapping with multiple scattering of the CMS Pixel Detector

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September 9, 2015

Abstract

In the following text my work during the DESY Summer Student Programme 2015 in the CMS group is presented. DESY participates in the development of a new CMS pixel detector that will be installed at the end of 2016. In particular, detectors are currently tested and produced at DESY. My contribution to the testing at the DESY synchrotron test beam is presented in this report. We analysed multiple scattering with a row of pixel detectors, in which the detectors worked as tested subject and telescope object. With the taken data we analysed the material in respect of multiple scattering.

Contents

1 The CMS Pixel Upgrade Phase 1

The Large Hadron Collider(LHC) is the world's most powerful particle accelerator, providing the ability to answer the questions of particle physics. In the first operational run between 2010 and 2013 it reached a center-of-mass energies up to 8 TeV and a peak instantaneous luminosity of $7.7 \times 10^{33} cm^{-2} s^{-1}$. [3]
The LHC has been in a long shutdown (LS1) in order to prepare the machine for higher collision energies and larger luminosities since the beginning of 2013.
One of the large-scale experiments at the LHC is the Compact Muon Solenoid(CMS). The CMS Pixel Detector is the innermost component of the CMS tracking system. It plays a key role in the precise measurement of the first space points of charged particle trajectories, close to the pp interaction point.
The present pixel detector was designed to operate under conditions of 40 MHz bunch crossing frequencies and instantaneous luminosity up to $1 \times 10^{34} cm^{-2} s^{-1}$. It can no longer operate efficiently at significantly higher values in the coming run periods. It is anticipated that until 2018 the peak luminosity will double its value. Therefore it is necessary to update the current pixel detector.

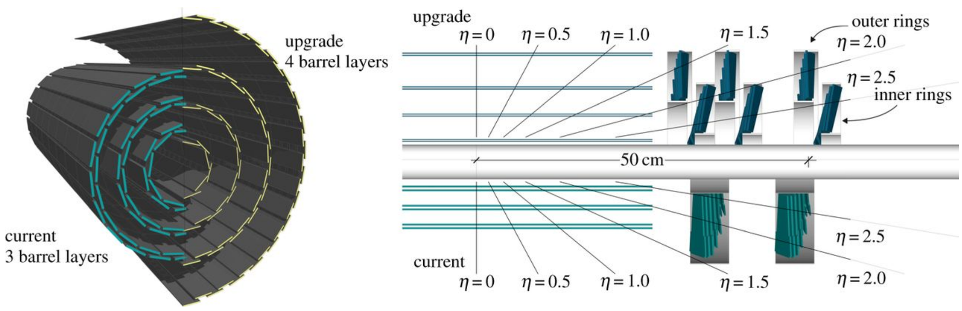

Figure 1: A comparison of the different layers and disks in the current and upgrade pixel detectors.[1]

Contemporary the pixel detector consists of three barrel layers at radii 44mm, 73mm and 102 mm, and two forward/backward disks. Due to additional bunch crossings pattern recognition becomes more difficult. Under those conditions the tracking efficiency can only be sustained at the expense of higher level of fake tracks. Furthermore for higher value of pseudorapidity the current detector consists of a sizable amount of material. This leads to problems with bremsstrahlung of electrons and multiple scattering. Therefore the current setup will be replaced by an additional barrel layer and an 3 forward/backward disks. Furthermore the innermost barrel layer will be reduced from 44mm to 29mm, which will improve the performance of the pixel detector in terms of impact parameter resolution and vertex resolution. [4]

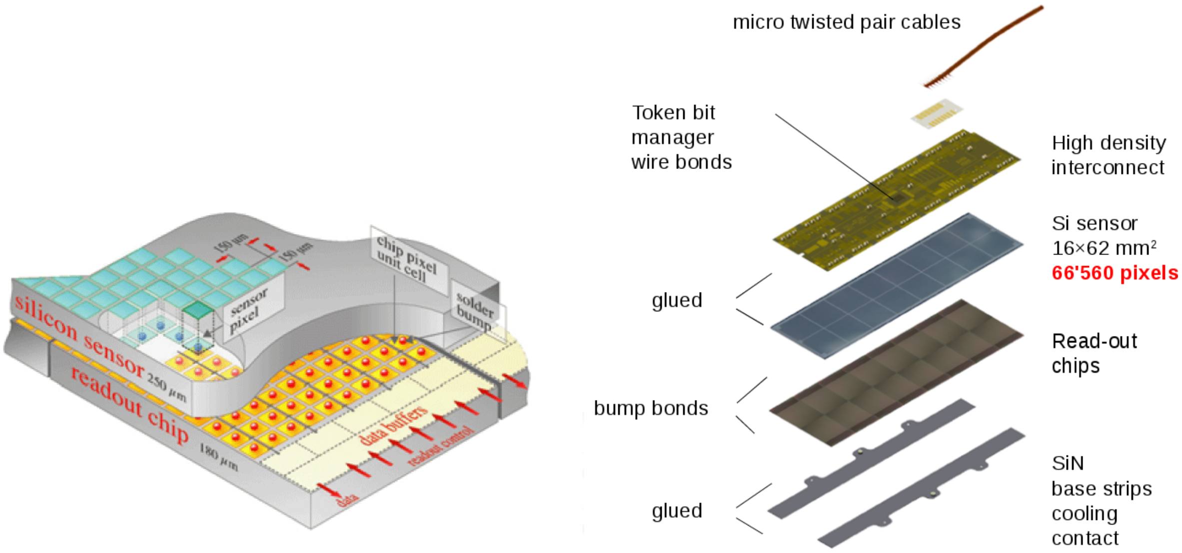

Figure 2: Left: Schematic illustration of a hybrid pixel detector where sensor and readout chip come from separate wavers and are bonded together by bump solder bonds. Right: Composition of a CMS pixel detector module. Source: CMS Pixel Group, DESY

A $n^+ - \text{in} - n$ sensor layout with pixels the size of $100 \times 150 \mu m^2$ has proven its durability and radiation hardness. So it is still the choice for the sensor. The sensor is bump-bonded to the read-out chips(ROC).

The architecture of the ROC remains the same, fabricated in the same 250 nm process . It contains 52 columns x 80 rows of pixels. The read-out of the hit events is organized double column wise, in which both operates independently. One buffer at the periphery of the ROC reads out and stores two columns independently. The ROC reads out two adjacent columns independently and the zero suppressed hit information for the pixels in both columns is stored in the same buffer at the periphery. Upon an external token passage hits verified by the CMS Level-1 trigger are read-out.

The current pixel detector would act inefficient up to the double amount of current luminosities. It would suffer at data loss from 16% up to 50%.

The inefficiencies are caused most importantly by limited data size for buffering and latencies, which leads to overflows in timestamp and data buffers. Another reason is the speed limitation in the transfer of hits from the pixels to the double column periphery. Also dead time of a double column while waiting to be read out. In the upgraded pixel detector the number of data buffers has been increased from 32 to 80 and timestamp buffer from 12 to 24 while reducing cells to prevent overflow at high hit occupancies in the peripheries. Another feature is introduced with the global read-out buffer, to which all pixel hits are transferred to from the double column buffers. In addition a new read-out buffer on the ROC will be added to buffer pixel hits, that were verified by the CMS trigger, until the external read-out token passage. Also the 40MHz multilevel encode analog read-out is replaced with a new digital read-out with a 160MHz LVDS data link. For this upgrade a additional 8 bit analog-to-digital converter (ADC) is necessary to encode the charge information for every pixel hit. Along with enhanced analog performance, namely reduced crosstalk and time walk, a lower threshold will be reached (from approximately 3500 down to 1500 electrons).

This upgrades keeps the data loss due to dead time below 4.7% in the innermost layer. Likewise the improved pixel detector will have a better and longer lasting performance in the presence of radiation damage, due to a larger window for operational parameters.[**?**]

2 Multiple Scattering

When charged particles move through matter, they get distracted by elastical scattering from their previous direction and pass the end of the material with an amended angle, which is the result of multiple previous single distractions. For sufficiently thick materials the number of interactions increases to a amount where the angular dispersion can be modelled as Gaussian. This interaction is called Multiple Scattering.[5]

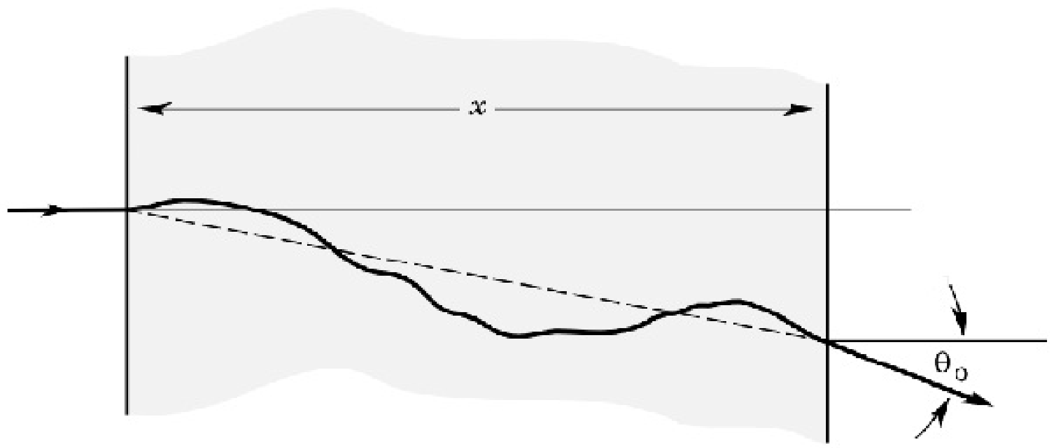

Figure 3: Effect of multiple coulomb scattering [6]

Referring to multiple scattering, that is the most common situation, naming the solid angle into which is concentrated the 98% of the beam after a thickness X of material, if we define $\theta_0 = \theta\sqrt{2}$ as the projection of on a plane, the angular dispersion can be calculated by the highland formula:

$$\theta_0 = \frac{13.6}{\beta cp} z \sqrt{x/X_0}\ [1 + 0.038 \ln x/X_0]$$

where p is the momentum and X_o is the radiation length.[6]
The Simulation of Multiple Scattering in this report is done by Geant4, which uses the Lewis Theory of Multiple Scattering which simulates the scattering of the particle after a given step, and also computes the path length correction and the lateral displacement. [8]

3 Experiment Setup at the DESY Testbeam

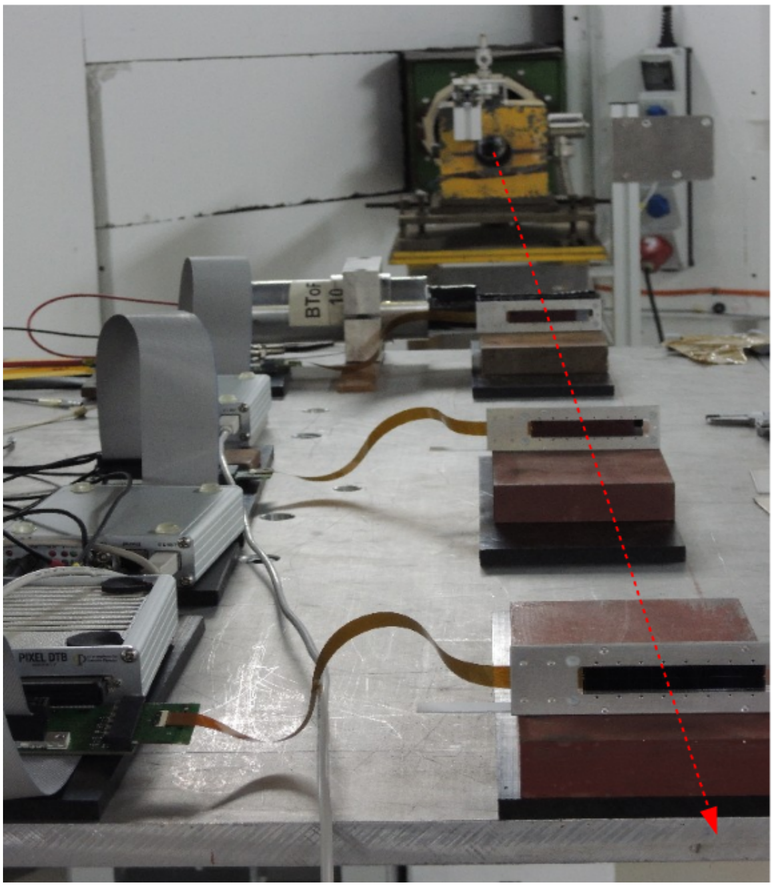

Figure 4: Setup of the Pixel Detectors inside the testbeam

The Pixel Detectors testing was carried out at the DESY test beam facility using electrons from the DESY synchrotron. The DESY synchrotron is primarily used as a pre-accelerator for the PETRAIII storage ring. Besides the test beam can be produced via conversion. First a bremsstahlungsbeam is created by accelerator beam crossing a carbon fiber. The photons are guided onto a copper plates, which converts the photons due to pair production into electrons and positrons. This test beam is spread out in a dipole magnet which separates either electron or positron in an range of $1 - 6$GeV. The final beam is cut out with a collimator.

Triggering was provided by a scintillator in front of the pixel detectors. Due to the freedom of this setup, we was able to change the distance between the detectors and the angles of the detectors in respect of the beam.

Instead of the DESY testbeam telescope we used 3 detectors in a row as shown in Figure4. The turn and the tilt angle was 0. The spacing between the detectors was 530mm. The middle detector operated as device under test(DUT). This enables studies of the detector behaviour with inclined particle tracks.

3.1 Detector Setup

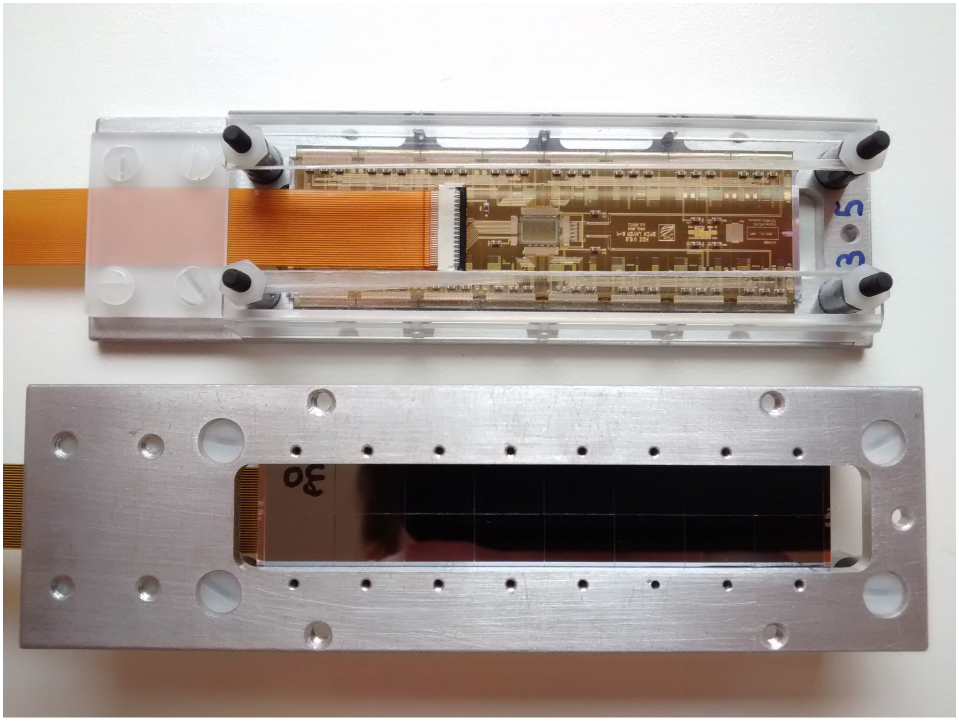

Figure 5: The Pixel Detector in its case and aluminum holder

The pixel detector was mounted on an aluminum holder in a Makrolon case to prevent scattering and second order electron tracks. The material was reduced by cutting holes in the Makrolon case and the aluminum holder as shown in Figure 5.

3.2 Data taking and analysis

The data for the multiple scattering analysis was taken by a beam energy of 1.2 GeV. For each detector a digital test board reads out the hit information and the data was saved with EUDAQ Software on a Linux box in EUDAQ data format. Later a EUDAQ decoder processed the data and filled ROOT histograms with it. The alignment for the pixel detectors was made with histogram profile plots comparing dx, dy, X and Y.

The Analysis of the next section was done with data of 13 million events at 1.2 GeV.

4 Multiple Scattering Analysis

For using the pixel detector inside the CMS Detector, it is necessary to know the angular distribution for each point of the detector. The Figure 6 shows a 2 dimensional profile plot where kink angle for each pixel is filled in squared.

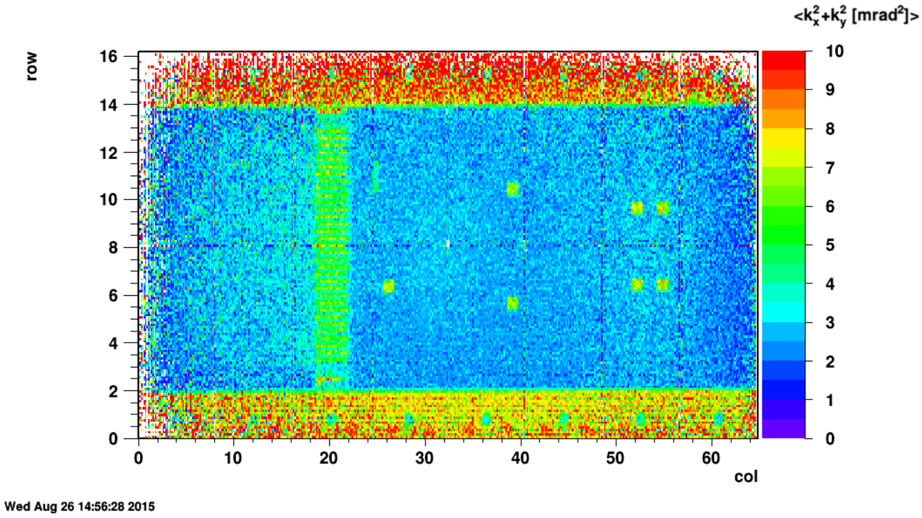

Figure 6: 2D Profile plot of the squared kink angle distribution

This map of the angle distribution was retransformed via the Newton-Raphson-Method using the Highland Formula in a map shown in Figure 7.

$$\theta_0 = \frac{13.6}{\beta c p} z \sqrt{x/X_0}\ [1 + 0.038 \ln x/X_0]$$

The result is a map showing the thickness in value of percent of the radiation length of silicon.

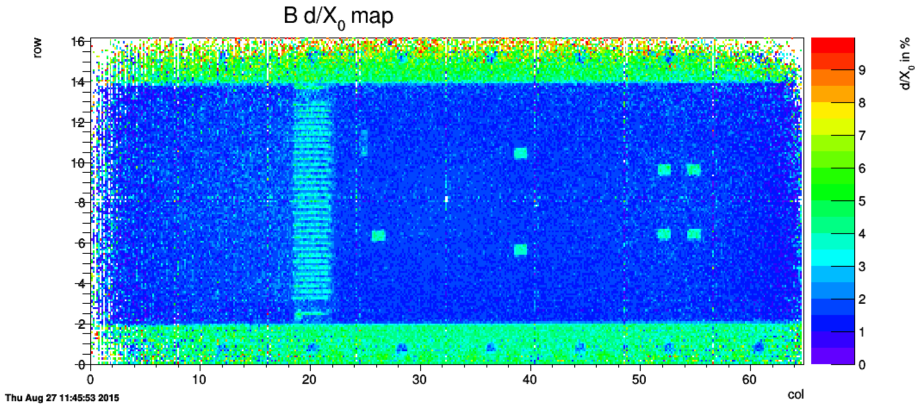

Figure 7: A map of the thickness in values of $X_{0_{\text{Silicon}}}$ for each pixel

You can cleary see the impact of some periphery of the detectors. To more visualize the effects in Figure 8 the chip structure is overlayed with the material map.

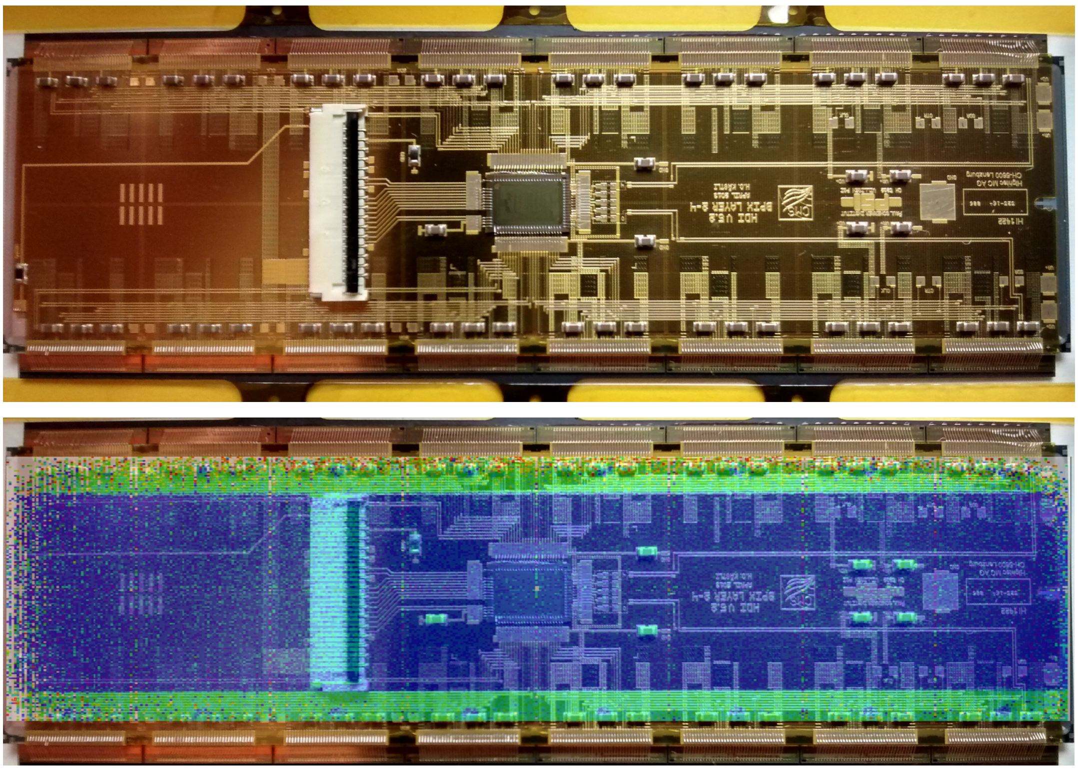

Figure 8: Top: Chipstructure of the Pixel Detector. Bottom : Overlaid with the X_0-Map

You can see that connector and the SMD capacitor components have a huge impact. Therefore in Figure 9 the connector is shown in an profile over y. and in Figure 10 the SMD capacitors are shown. On both side the impact of the aluminum holder rises the d/X_0 value. Also the 33 pins of the connector are clearly visible.

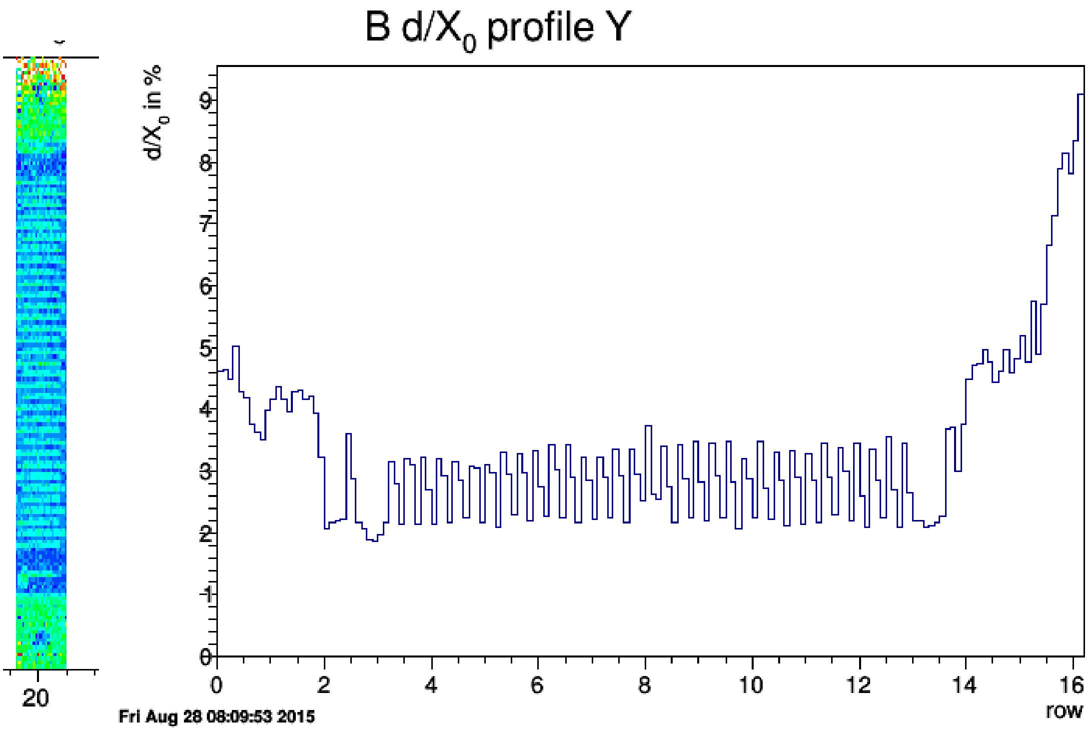

Figure 9: Profile plot of the connector

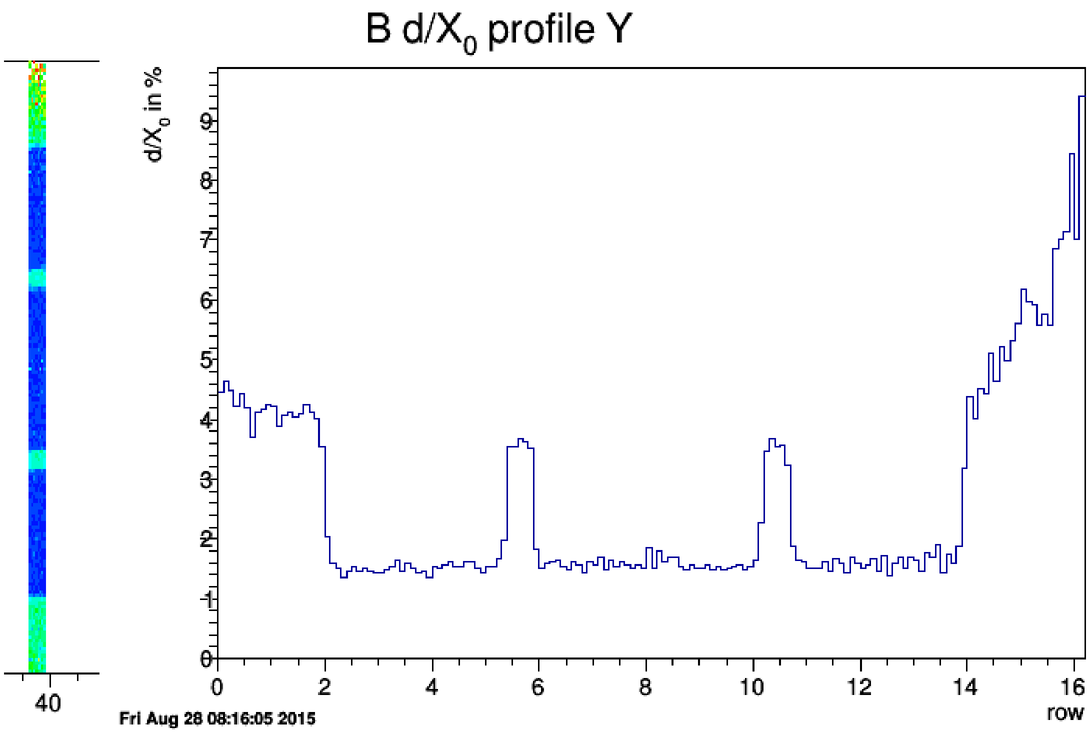

Figure 10: Profile plot of the SMD capacitors

The capacitors increases the thickness in respect of X_0 by a factor 2.7. So for a charged particle passing the capacitors the angular distribution would differ from the rest of the detector. The rise of the right side on the aluminum is explainable with not perfectly cut out Makrolon shown in Figure 5.

4.1 Simulation with Geant4

For understanding the results the detector with part of his components needed to be simulated. Therefore the track of 40 million electrons through the detector sketched in Figure detector design was simulated in Geant4, spread with the real resolution of the detector.

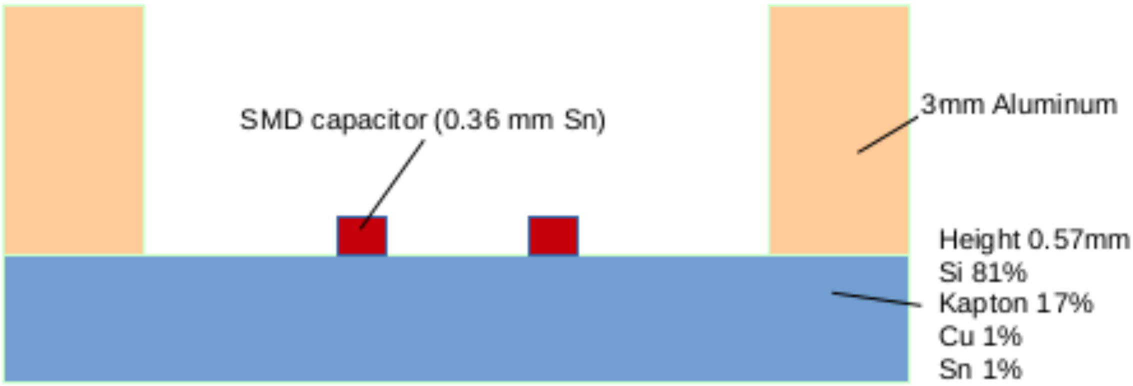

Figure 11: The frugal detector design for the Geant4 simulation

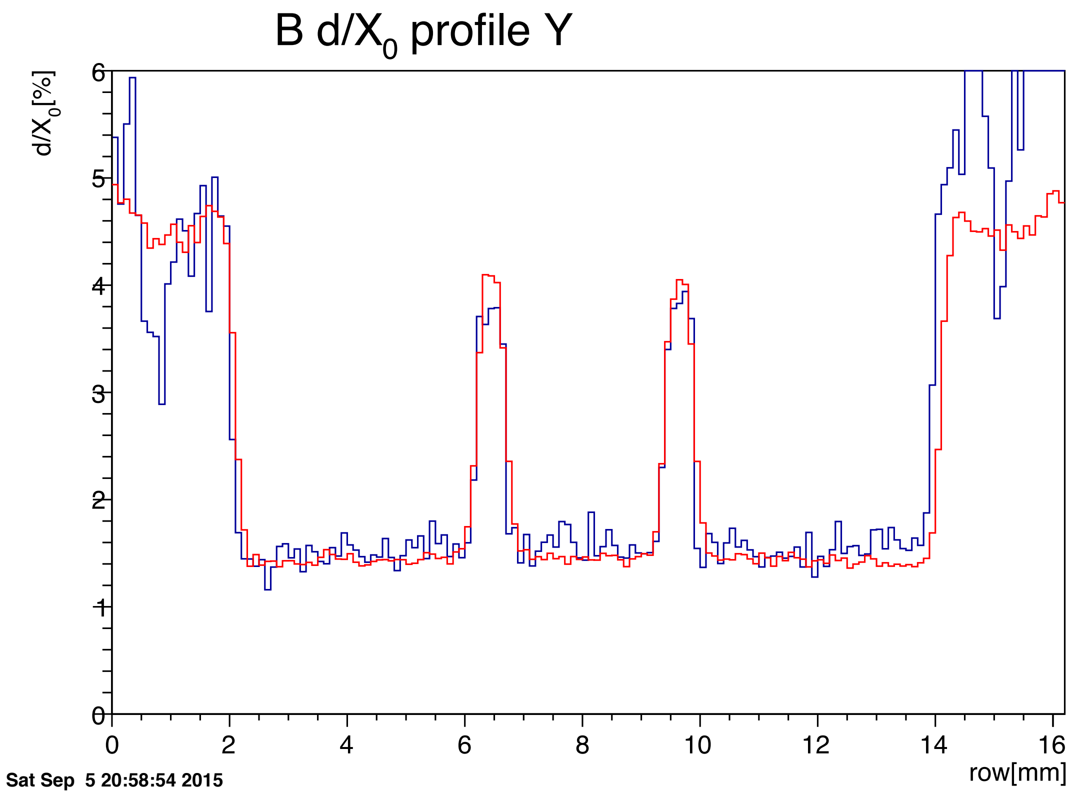

Figure 12: Real data is shown in blue, overlaid with the simulated profile plot in red

This simulation compared to the real measurements are shown in Figure 12.

5 Conclusion

Multiple Scattering in the detector material has an impact on the beam direction and the material has to be considered carefully in detector development. Like it is shown in this report, avoid materials with high atomic numbers.
On the other side you can be used as a tool for material analysis. We were able to see components of our pixel detectors and their thicknesses. Our results validate Geant4. In general one can say that the experiment and the simulation are in a good agreement. Like it is shown in this report, the pixel detectors can be used as a beam telescope. A rail rack would be ideal to improve future setups. Then it would be a faster supplement to the more accurate Mimosa beam telescope.

References

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[4] Plans and Status of the Phase I Upgrade of the CMS Pixel Tracker *Hanno Perrey*

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[6] Multiple scattering for particles in the matter *Stefano Meroli*

[7] Phys. Rev. 78 (1950) 526. *H. W. Lewis*

[8] Multiple Scattering in Geant4 *L. Urbán*