IOP Conf. Series: Journal of Physics: Conf. Series **1337** (2019) 012008 doi:10.1088/1742-6596/1337/1/012008

# AllPix$^2$ simulations of silicon strip detectors for ATLAS Upgrade ITk

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**Abstract.** Together with the ongoing works on preparations of High-Luminosity LHC, there is a need to enhance the performance of various experiments on the collider as well. This is also the case of the experiment ATLAS and its subdetectors such as Inner Detector which will be completely replaced by new all-silicon Inner Tracker (ITk). This article deals with computer simulations of silicon strip detectors for ATLAS Upgrade ITk. For this purpose, we are using framework AllPix$^2$ [1]. It enables to simulate everything from the interaction of the particle with silicon, charge propagation in electric and magnetic fields, charge collection, up to signal digitization.

We focused on two aspects in the simulations. The first is a precise characterization of used detectors and the second is a simulation of the test beam measurements. These simulations are important not only because they help us to better understand processes happening inside the detector, but they are also used as a validation of testing measurements. As a result of this, we are able to point out the effects of the experimental setup (or detector itself) which have an impact on measured results or better estimate physical characteristics of our detector.

## 1. Introduction

With increasing computing power, simulations became an important part of physical research and speaking of particle physics, in particular, simulations became an almost indivisible part of today's experiments. They are used not only to validate experimental results but also in the development and testing of future detectors and experiments, which is also the main motivation in this article.

In this article, we are going to describe simulations which were done in order to be compared to the results obtained during one of the test beam campaigns in DESY. These simulations help us not only to validate the measurements but also to better estimate properties of tested silicon strip detectors for ATLAS ITk. Thanks to the fact that we have real measurements available, we are able to determine actual parameters of the detector that would be known only approximately. This is, for example, the case of active thickness which should be, according to ATLAS ITk technical design report, more than 90% of physical thickness, nevertheless actual value is unknown. Also, these simulations allow us to determine some properties of the particular detector piece which we test.

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### *1.1. Strip detectors for ATLAS ITk*

This article deals with the problematics of simulations of the strip detectors for ATLAS ITk which will be placed in the barrel section of the ATLAS experiment inner tracking detector after the high luminosity LHC upgrade.

They are silicon detectors with 1280 readout channels, the physical thickness of $300-320$ $\mu$m, and the pitch of 75.5 $\mu$m. The active area of these barrel sensors foresees to be $96.640 \times 96.699\,\mathrm{mm}^2$ [2].

## 2. Testing of strip detectors for ATLAS ITk

### *2.1. Collected charge and threshold scan*

Amount of collected charge can be estimated easily by detectors with analog readout in a single event measurement, nevertheless, if we have binary readout (which is the case of strip detectors for ATLAS ITk) the task is not this straightforward. To find out the information about a charge collected by the detector with a binary readout we can perform threshold scan. Threshold scan is a series of measurement in which we estimate detection efficiency for a set of discrete values of thresholds within a given threshold range. If we do this we get a relation which is, in fact, a complementary cumulative function of energy loss distribution (see Fig. 1). In other words if we designate probability energy loss distribution (distribution is normalized to 1) as $\omega(E)$ complementary cumulative function is then

$$g(x) = 1 - \int_0^x \omega(E). \tag{1}$$

For the typical probability energy loss distribution which applies in our detectors, threshold scan gives us a sigmoid function which we fit by a complementary skewed error function which is defined as

$$f(x) = \epsilon_{max}\mathrm{erfc}\left[x\left(1 + 0.6\frac{e^{-\xi x} - e^{\xi x}}{e^{-\xi x} + e^{\xi x}}\right)\right] \tag{2}$$

where erfc is the error function, $\xi$ is a skew factor and $\epsilon_{max}$ is half of S-curve maximum.

As a mean value of collected charge we then take fifty percent point of the curve ($x$ value where $f(x) = 0.5$). This corresponds to the mean value of probability energy loss distribution $\omega(E)$.

### *2.2. Cluster charge and cluster size*

Cluster size is an important quantity which is usually studied in testing measurements of silicon strip detectors. By cluster, we mean a group of neighboring strips which have a signal above the threshold and bearing this in mind we can define cluster size as an average size of the cluster over several events. Alternatively, to cluster size we can define a cluster charge as an average amount of charge contained in one cluster. These two quantities are influenced by the geometry of experimental setup as well as by detector's properties.

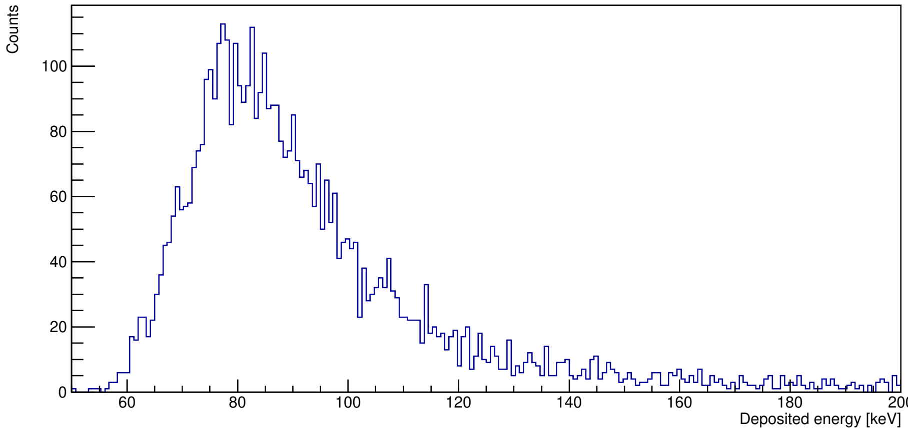


**Figure 1.** Simulated distribution (not normalized) of energy deposited by 4 GeV electron in 280 $\mu$m thick silicon detector. For this simulation photoabsorption model (PAI) was used. This model is suitable for simulations of thin silicon layers which is also the case of our tested detector. The simulation was done for 5000 events.

## 3. Simulations of detector parameters

As it was already mentioned, simulations can help us also better estimate detector properties. Even though the manufacturer of the detector declares some values, there is usually some spread or uncertainty. In order to know the properties of a particular piece of the tested detector, we can do simulations and try to tweak detector parameters in the simulation so that the simulation best fits the measured data. But we have to be careful because some parameters might have the same influence on measured quantities. This fact can cause that we find a value of some parameter so that simulated data match a real measurement but in fact, the value we found doesn't correspond to the reality. This might happen because we could have tweaked some different detector properties in our simulation instead. To avoid mistakes like this we should know at least approximate values of parameters we are inspecting.

### *3.1. Active thickness estimation*

The active thickness of the detector is a thickness of a volume of the detector from which we are able to collect the charge by the applied electric field. This is the parameter which is crucial to know well if we want to simulate the detector properly. The exact value of the active thickness for ITk strip detectors is not given exactly even in ATLAS ITk technical design report. It is only said there that the active thickness should be more than 90% of physical thickness which varies between $300 - 320$ $\mu$m [2].

In order to find this parameter out, we compared simulations of detectors of different thicknesses with the test beam data and tried to find the value of active thickness parameter which best describes measured data. Comparison of simulations with respect to the test beam data are shown in Fig. 2. It can be seen that active thickness of 280 $\mu$m has the best agreement with the data. If we compare this number

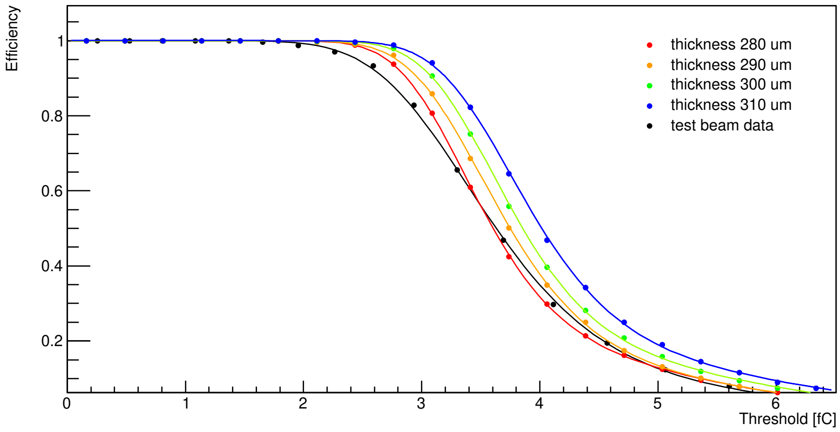


**Figure 2.** Threshold scan simulations for different active thickness compared to the data measured at DESY test beam with 4 GeV electrons.

with physical thickness we find out that it is about $90 - 93\%$ of physical thickness which is in agreement with ITk technical design report [2].

### *3.2. Crosstalk estimation*

In this article, we call crosstalk the effect of charge induction on neighboring strips due to the capacitive coupling between these strips. Crosstalk can be roughly estimated as

$$k \approx 2\frac{C_{int}}{C_{coupl}} \tag{3}$$

where $C_{int}$ is the interstrip capacitance and $C_{coupl}$ is a coupling capacitance. These values for ITk strips are declared to be $C_{int} = 0.7 - 0.8\,\mathrm{pF}\cdot\mathrm{cm}^{-1}$ and $C_{coupl} = 24.26\,\mathrm{pF}\cdot\mathrm{cm}^{-1}$ which gives us $k = 0.06 - 0.07$ .

We simulated this effect by the following approach. We checked the strip charge which was generated on the strip after the propagation and we moved fraction $k$ of that charge away but at the same time, we added fraction $\frac{k}{2}$ of the charge from each of the directly neighboring strips to the charge of the original strip. In other words, if we designate charge collected by middle strip as $Q^*$ and charge collected by strips on left and right $Q_l$ and $Q_r$, respectively, after application of crosstalk we have on the middle strip charge $Q$ which can be expressed as

$$Q = Q^*\left(1 - k\right) + \frac{k}{2}\left(Q_l + Q_r\right). \tag{4}$$

We assume that there is the same crosstalk coefficient of $k$ for all the stips which, in fact, doesn't have to be exactly true.

Based on the assumptions presented above we attempted to include this effect into our simulations and see whether this simplified model is able to describe real data. For this purpose we simulated beam of 4 GeV electrons hitting the ITk strip detector of active thickness 280 $\mu$m. Results of the simulations can be seen in Fig. 3.

We can see that the best matching value of crosstalk coefficient (i.e. the value which allows us to match mean collected charge value) is $k = 0.06$ which is in accordance with the calculation presented above.

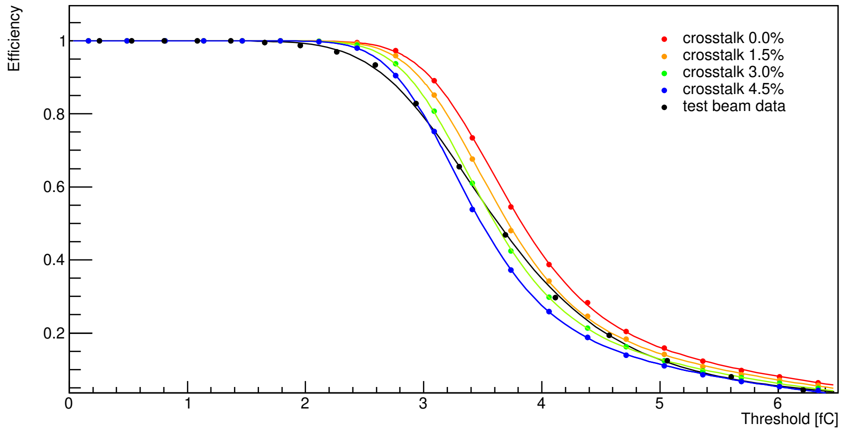


**Figure 3.** Threshold scan simulations for different crosstalk coefficients $k$ compared to the data measured at DESY test beam with 4 GeV electrons.

### *3.3. Noise estimation*

We also studied the effect of different noise levels on the simulated S–curve. We simulated the noise as a random signal with Gaussian distribution added on top of the actual signal generated by charge carriers in silicon. The random signal was generated so that its distribution follows Gaussian distribution with a mean value $\mu = 0$. If we suppose that the major noise sources generate Gaussian noise, we can simulate all these sources by one random Gaussian–distributed signal with standard deviation $\sigma_{tot}^2 = \sum_i \sigma_i^2$ where $\sigma_i$ is the standard deviation of particular source of noise. The proof of this claim is based on the fact that the convolution of two Gaussian distributions with standard deviations $\sigma_{1,2}$ and mean values $\mu_{1,2}$ is again Gaussian distribution with $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$ and mean value $\mu = \mu_1 + \mu_2$. Given value of the noise level is then $\sigma_{tot}$ of this Gaussian distribution.

Fig. 4 depicts simulated S–curves for different noise levels. By looking at this plot we see that the noise changes a slope of the S–curve but preserves the mean collected charge value. It can be noticed that there is an almost perfect agreement between orange line – noise 3000 e – and test beam data. It is important to say that a measured value of noise from the test beam is around 750 e. Because of this huge disagreement between data and simulation, we may deduce that the simulation of noise is not correct or there is another effect which has the similar influence on S-curve as noise (e.g. readout electronics).

At this point, we would like to point out the importance of having at least a rough idea of parameters we are trying to simulate because different parameters can have the same influence on the measured/simulated result. If one is not aware of this it can easily happen that some parameters might be over or underestimated.

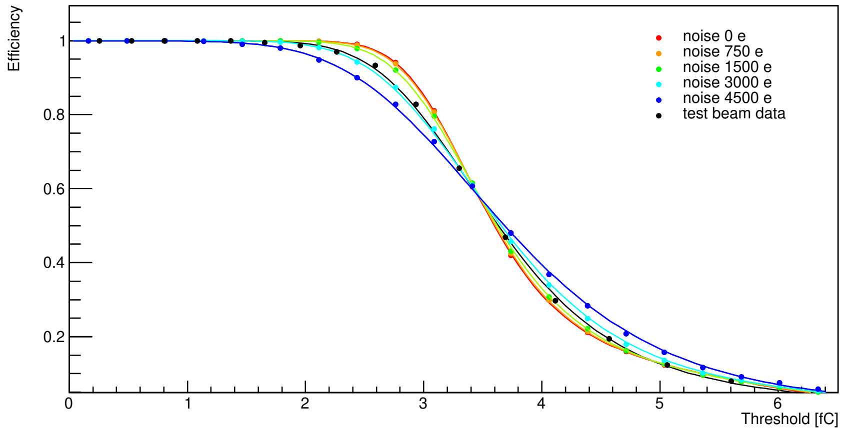


**Figure 4.** Threshold scan simulations for different noise levels compared to the data measured at DESY test beam with 4 GeV electrons.

## 4. Test beam simulations

With the use of the results presented above, we tried to simulate results obtained during the test beam campaign in DESY in 2018.

In our simulations, we did not simulate all the test beam setup which is used, but instead, we simulated only the device under test and the beam of electrons of energy 4 GeV, omitting other test beam structures like for example Mimosa planes. In all simulations of the test beam, we used Geant4 physics list FTFP_BERT_LIV. We also used a precise electric field computed for the particular detector in TCAD.

### *4.1. Collected charge*

First, we compared the simulation with test beam data for the collected charge. To find out the information about mean collected charge we did a threshold scan and compared the S–curve we got with data from test beam. Result of the simulation can be found in Fig. 5.

The mean collected charge was estimated by resampling method in which we did 300 threshold scans for random 30%–subsets of events from simulated data set. The mean collected charge and its uncertainty was then estimated as a mean and its standard deviation of the distribution of the mean collected charge of all threshold scans performed on these random subsets. By this method, we obtained the mean collected charge in the simulation of test beam to be $(3.61 \pm 0.01)$ fC which is compatible with value 3.6 fC from test beam. However, it is necessary to mention that the measured value can vary in order of $\mathcal{O}(10^{-1})$ fC based on the settings of front-end electronics.

There is a little discrepancy in shape of simulated S–curve in comparison to the measured one. This can be seen especially for points where S–curve starts to decrease (between $2.0 - 3.4$ fC). This bump with respect to test beam data can be caused by several effects. Possible explanations are that this is because Shockley–Ramo theorem is not included in simulations, charge trapping is not included as well, or it may be

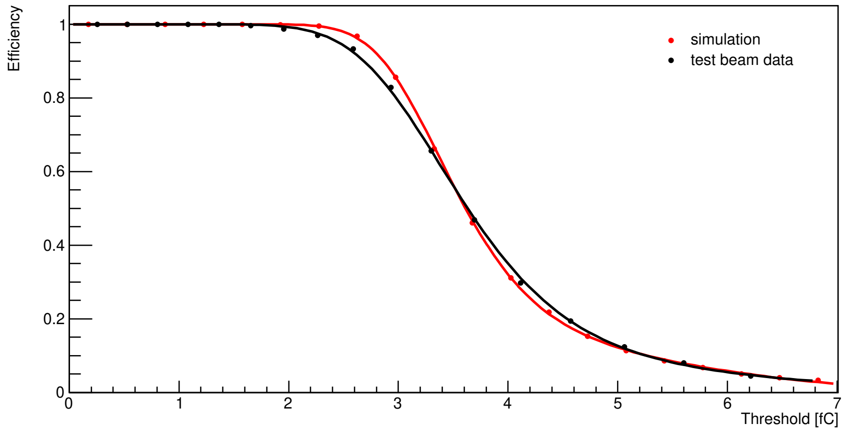


**Figure 5.** Comparison of measured and simulated S–curve from test beam in DESY. Uncertainty of simulated data points was estimated by resampling and was found to be in order of $\mathcal{O}(10^{-5})$ for and simulated data point. Uncertainty of measured data points from test beam is in order of $\mathcal{O}(10^{-2})$ or less.

some kind of hysteresis effect which is hard to simulate, or we are not simulating interstrip region properly – which shows up to be the most probable explanation.

### *4.2. Cluster size*

We also tried to reconstruct the dependence of cluster size with respect to the applied threshold. Fig. 6 compares data obtained by the simulation with the data measured during the DESY test beam.

The reason why the simulation doesn't match the real data well is not entirely clear, nevertheless, will be very likely caused by the same reasons presented at the end of subsection 4.1.

## 5. Conclusion

In this article, we reviewed results of simulations of silicon strip detectors for ATLAS ITk that were presented at Trans-Siberian School of HEP 2019 in the conference section. For all simulations, we used AllPix$^2$ framework. The first part of the article was dedicated to detector parameters estimation. By comparison of the test beam data we found an active thickness of the detector to be 280 $\mu$m and a crosstalk coefficient $k$ equal to 0.06. These values were used in further simulations of test beam measurements. We also simulated the detector noise, nevertheless we did not get a good agreement between the simulation and the data. For this reason, we used noise value 750 e in the rest of the simulations, which is the experimentally measured value.

The second part of the article was dedicated to the simulations of the test beam measurements obtained during the test beam campaign in DESY in 2018. We were able to reproduce S–curve from the test beam up to the region where the S–curve starts to decrease. This disagreement was discussed and was attributed to the possible wrong

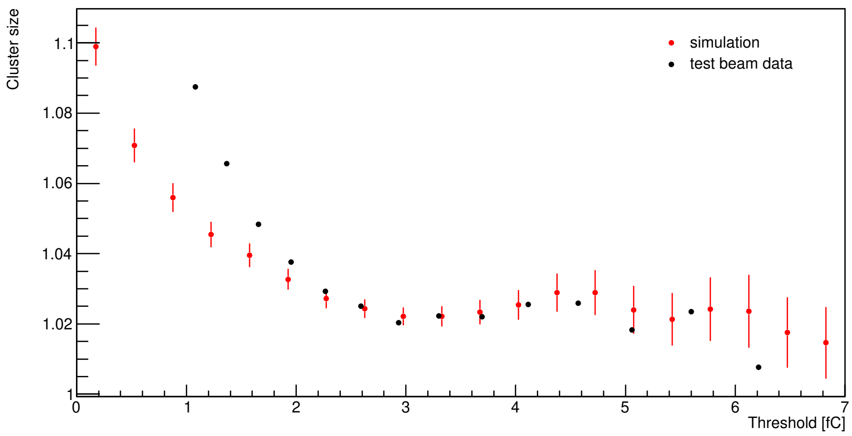


**Figure 6.** Simulation of cluster size compared to the data obtained at DESY test beam with 4 GeV lectrons.

simulation of the interstrip region and/or missing implementation of Shockley-Ramo theorem in AllPix$^2$. We also simulated cluster size as a function of the detection threshold and compared our results to the test beam measurements.

## References

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[2] The ATLAS Collaboration. ATLAS Inner Tracker Strip Detector - Technical Design Report. Technical report, CERN, 2017., online `https://cds.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf`