PROCEEDINGS OF SCIENCE

TROPIX: A fast parametric tool reproducing the output of pixel detectors

Andrea Di Luca,[a,b,*] **Francesco Maria Follega,**[a,b] **Ester Ricci**[a,b] **and Roberto Iuppa**[a,b]

[a] *Physics Department, University of Trento, Via Sommarive 14, Trento, Italy*

[b] *Trento Institute for Fundamental Physics and Applications (TIFPA), Via Sommarive 14, Trento, Italy*

E-mail: andrea.diluca@unitn.it

This contribution describes TROPix, a parametric simulation tool developed to speed up the simulation time of the response of silicon pixel detectors.

10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging (Pixel2022)
12-16 December 2022
Santa Fe, New Mexico, USA

*Speaker

PoS(Pixel2022)090

1. Introduction

The performance of segmented silicon detectors may be understood and their design can be optimized with the use of detailed simulations. Advanced simulation tools like TCAD [1] exist, however, they are resource intensive and sometimes difficult to integrate with other tools to support a Monte Carlo method. There are several specialized software programs, such as AllPix2 [2], that integrate the modeling of material effects in the experimental setup (such as multiple scattering or nuclear interactions) together with a precise description of the motion of deposited charge carriers. Despite significant advancements in such frameworks, to fully utilize multi- and many-core processing architectures for completely parallel event simulation, they still need significant computing times with dramatic consequences when treating complex detector architectures.

In this contribution, we present TROPix, a parametric simulation tool developed to speed up the simulation time of the response of silicon pixel detectors. The tool uses GEANT4 [3] energy deposition in the detection material. This makes it possible to simulate several different detector types for a variety of application scenarios. Afterward charge generation and diffusion are parameterized as a function of the impact position, the arrival direction and the density of energy deposited by the primary particle. Noise, fake rates and energy thresholds of specific pixel detectors are included in the simulation. All the simulation parameters are adjusted using experimental test-beam data. We show results for monolithic silicon pixel sensors based on the ALPIDE (ALice PIxel DEtector) technology, developed for the ALICE ITS upgrade at CERN.

2. Simulator architecture

The TROPix simulation tool is composed of several modules that work together to simulate the response of segmented silicon detectors. Figure 1 shows the simulator structure. The main simulation steps are:

1. Charge deposition: the energy deposited by particles in the active silicon material is converted to primary charges.
2. Charge propagation: the primary charges are propagated through a parametric approach
3. Digitization

Each simulation step is based on different modules designed to handle specific aspects of the simulation process. In the following sections, we will describe each module in detail, including its function, the underlying physics models, and the input and output parameters.

2.1 Charge deposition

The primary charge deposition is simulated starting from the energy deposited by particle interaction with matter. The energy deposition can be simulated in a "test beam" mode where GEANT4 libraries are used to initialize a particle beam. The geometry file of the detector is used to produce the energy deposition. Another possibility is to load pre-simulated energy deposition in TROPix. Energy is converted to charge by sampling a Landau distribution with location parameter μ and scale parameter $s = k \cdot \mu$ where $k = 3.6$ eV is the energy required to form an electron-hole

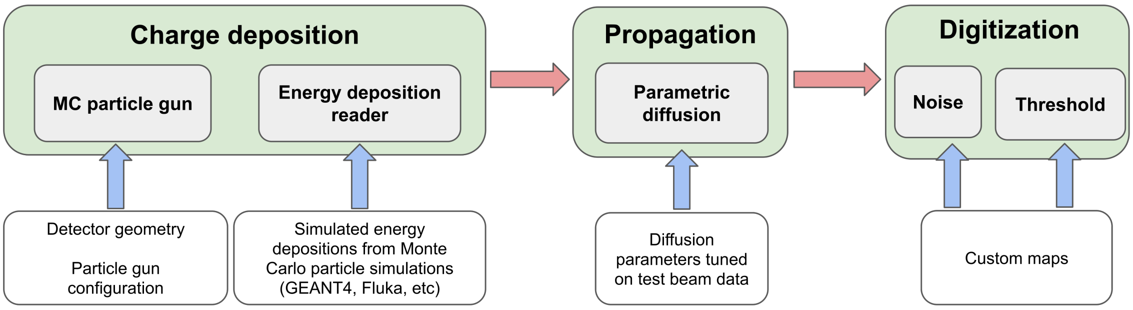

Figure 1: Structure of the TROPix simulator. The green boxes represent the main simulation steps. The gray boxes represent the modules that implement the simulation process. Also, the inputs to each module are represented by white boxes.

pair. Two modules were developed for the primary charge sampling. A stand-alone primary charge sampling that will use all the energy deposited in the silicon material is for the charge sampling. The charge assigned to each pixel is proportional to the track length inside the epitaxial layer. The other module will sample the charge starting from the GEANT4 hits. For each GEANT4 hit, the energy deposited in silicon is converted to charge.

To avoid any undesired edge effect, a finite size distribution is assigned to the deposited charge. For standalone primary charge sampling, a column of charge is considered around the track. For G4-driven charge sampling, the charge distribution is modeled by providing a finite size to the hit points (charge spheres). In the following, we will mainly use the G4-driven charge sampling and we fixed the sphere radius $r = 0.7\ \mu$m.

Depending on the position of the primary charge production, the column/sphere can intersect near pixels in different ways, as shown in Figure 2. This is relevant when no diffusion is considered. The possible intersections are shown below in the case of GEANT4 hits.

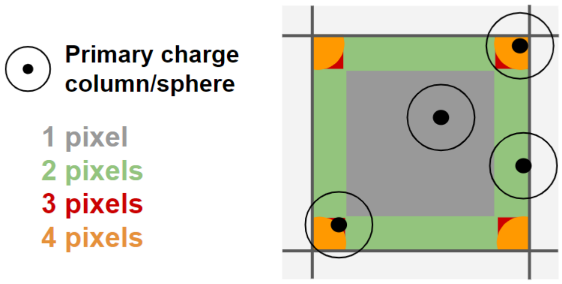

Figure 2: Charge distribution intersection with the near pixels. Different regions are highlighted depending on the number of intersected pixels.

2.2 Charge propagation

Charge transport is regulated through parametric gaussian smearing of the primary charge. The smearing is applied after each step of the primary charge production. Given the pixel at position

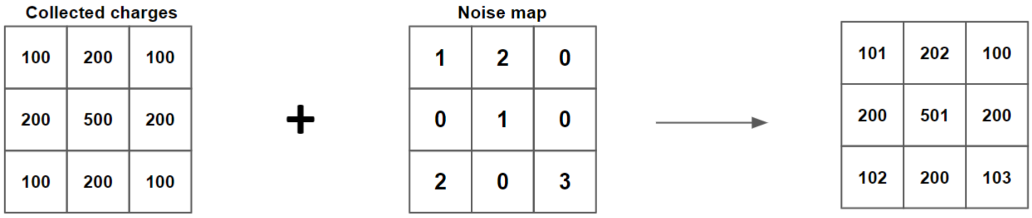

Figure 3: Schematic representation of adding noise electrons to each pixel based on pixel coordinates.

(k, l), the charge collected by the pixel after each hit is calculated as follows:

$$\Delta^{\mathrm{Hit}}[k,l] = \sum_{i,j}^{|i-k|<D,|l-j|<D} Q^{\mathrm{Hit}}[i,j] \cdot \frac{1}{2\pi\sigma_x\sigma_y} \int_k^{k+1} e^{-\frac{(X_Q^{\mathrm{Hit}}[i,j]-x)^2}{2\sigma_x^2}} dx \int_l^{l+1} e^{-\frac{(Y_Q^{\mathrm{Hit}}[i,j]-y)^2}{2\sigma_y^2}} dy \quad (1)$$

where (X_Q, Y_Q) are the coordinates of the centroid of the charge volume contained in pixel (i, j), D is the maximum pixel distance to compute the diffusion and (σ_x, σ_y) is the standard deviation of the gaussian distributions. The diffusion effects along different directions are assumed to be independent. The tuning of the (σ_x, σ_y) parameters will be described in the next section. The tuning of the D parameter will only play a role in the speed of the simulation since the contribution to far-away pixels will be negligible. In the following, we fixed $D = 4$.

2.3 Digitization

The final simulation step will produce the map of active pixels. Before that, a noise map can be added to the collected charges. The user can load the noise map or a dedicated module can compute a thermal noise map in the TROPix simulator.

After that, the charge collected by each pixel (noise included) is compared to sampled threshold map to fire the pixels. The threshold map can be loaded by the user of a threshold map and can be initialized using a dedicated module in TROPix.

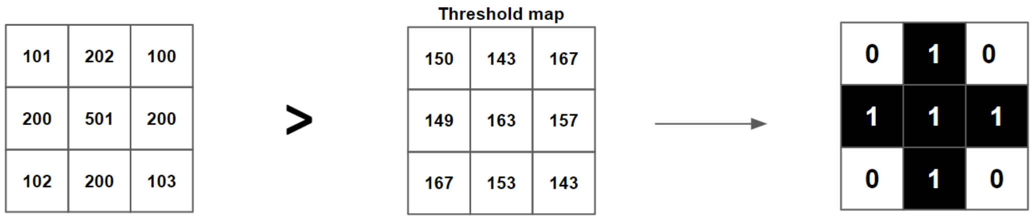

Figure 4: Schematic representation of threshold comparison based on pixel coordinates to get the active pixel map.

3. Tuning simulation parameters

The charge diffusion parameters are fixed to reproduce some relevant features of the clusters measured using actual chips during test beam data. We ran the simulator with the setup used in the actual test beam. Figure 5 shows the setup.

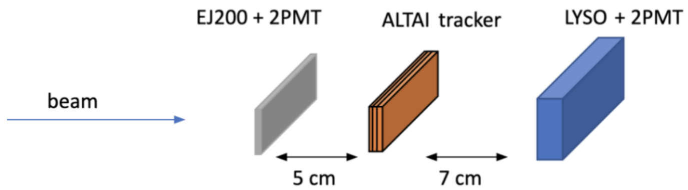

Figure 5: Schematic representation of the test beam setup implemented in the Monte Carlo simulation.

3.1 Deposited energy calibration

From simulated data, we extracted a relation to map the energy of the particle interacting with the silicon material to the deposited energy. We simulated proton beams at energies 62, 100, 120, 140, 160, 180, 200 227 MeV. For each simulated test beam, we produce the histogram of the deposited energies by protons in the active silicon material, as shown in the Left-side picture of Figure 6. The distributions of the deposited energy are fitted with a Landau function and the MPV is used as an estimate of the deposited energy. Given the MPV and the beam energy, we fit the data to obtain the final relation, as shown in the right-side plot.

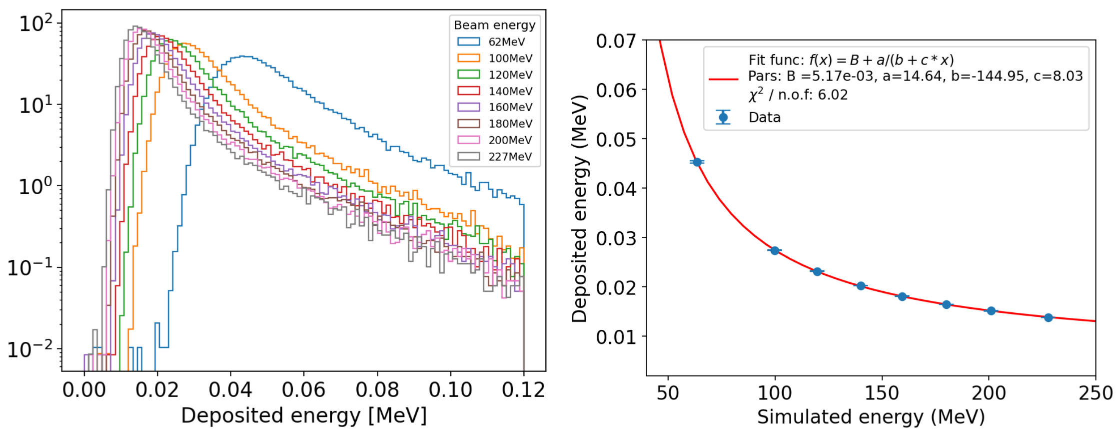

Figure 6: Derivation of the mapping between beam energy and deposited energy in active silicon material. Different test beam simulations are considered and the deposited energy distributions in active silicon material are considered (left). We fitted the distribution using a Landau fit and the deposited energy MPV is extracted from Landau fit for each beam energy. The deposited energy dependence from the beam energy (right plot) is extracted from a fit of the data points.

3.2 Diffusion parameter calibration

After the deposited energy calibration, we considered a stacked analysis of the reconstructed clusters on test beam data. The stacked map is projected on the x- and y-directions and the two distributions are fitted with a gaussian function. Figure 7 shows the results of such an approach are shown below.

For each beam energy, we end up with a σ_x and σ_y. The σ_x and σ_y, for fixed deposited energy, are different. Their ratio is compatible with the ratio of the pixel sides of the ALTAI pixel

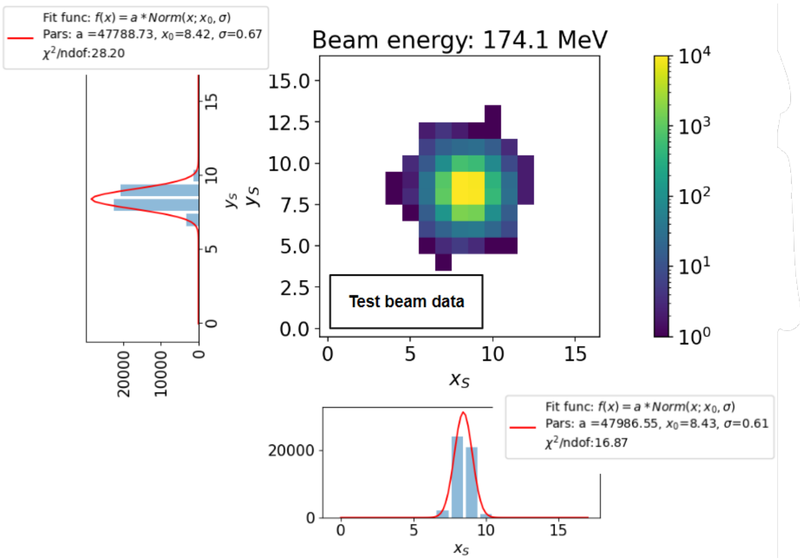

Figure 7: Example of the output produced by the stacked analysis for 174.6 MeV protons. The central 2D histogram shows the sum of all reconstructed clusters. The other plots show a projection of the histogram on the x- and y-directions. The red lines are the results of a gaussian fit of the two projections. Fit results are shown in the legend boxes.

sensor [4]. The two sets of data are then fitted using a function that is derived analytically from a pure diffusion model (gaussian distribution of the signal).

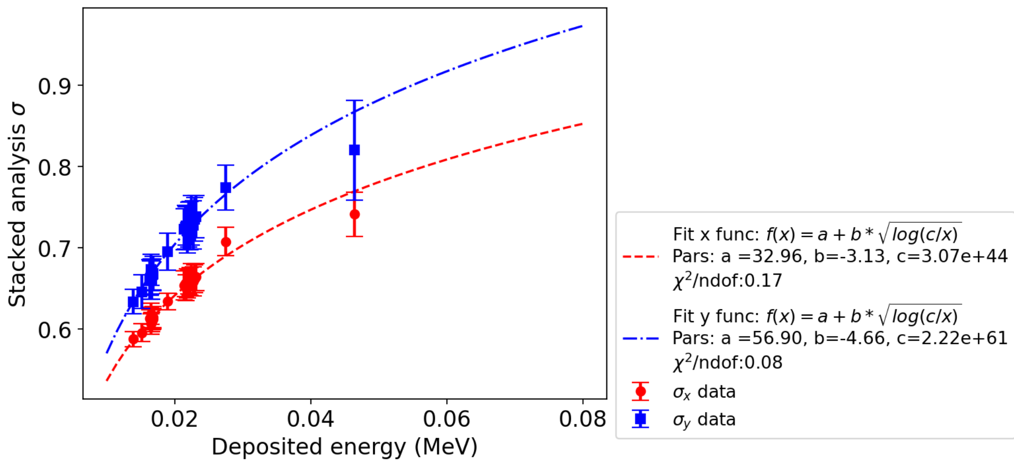

Figure 8: Stacked analysis σ (obtained in the fit) as a function of the deposited energy in the active silicon material. The blu and red lines show the result for the y- and x-projection. We fitted the data using a fit function that is derived analytically from a pure diffusion model (gaussian distribution of the signal).

4. Results

Figures 9 below show how the cluster size dependencies on beam energy and angle are reproduced by the TROPix simulator. For MIPs, this result is already sufficient since no relevant information is expected from cluster shapes. We extended the comparison also to cluster shapes.

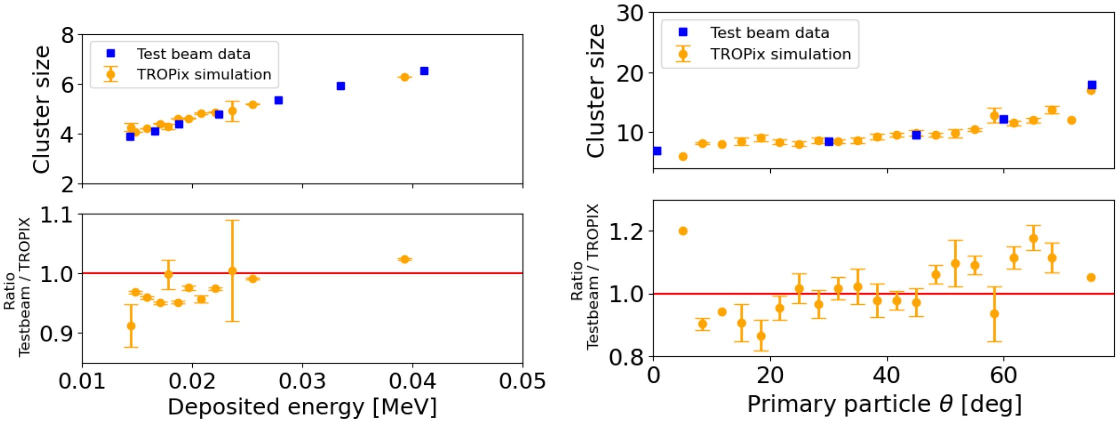

Figure 9: Cluster size dependence from deposited energy (right) in the active silicon material and the particle incoming angle θ (left). Orange points are produced using TROPix simulated events while blue points are obtained from test beam data analysis. The bottom plots are showing the ratio between the test beam and simulated data. The ratio is computed by interpolating test beam data at TROPIx data points. The θ dependence is studied for 62 MeV protons. We observed a global agreement between the real and simulated data.

Reproducing the cluster shape distribution is indeed by far the ultimate test of any tool emulating real sensors. We developed a Python package to check the occurrence of given patterns. Figures 10 show a comparison between shape occurrence for cluster size values of 3, 4, 5 and 6 between test beams data and TROpix simulated events. TROpix simulator can match the most relevant shapes and also keep a relative running between the shapes.

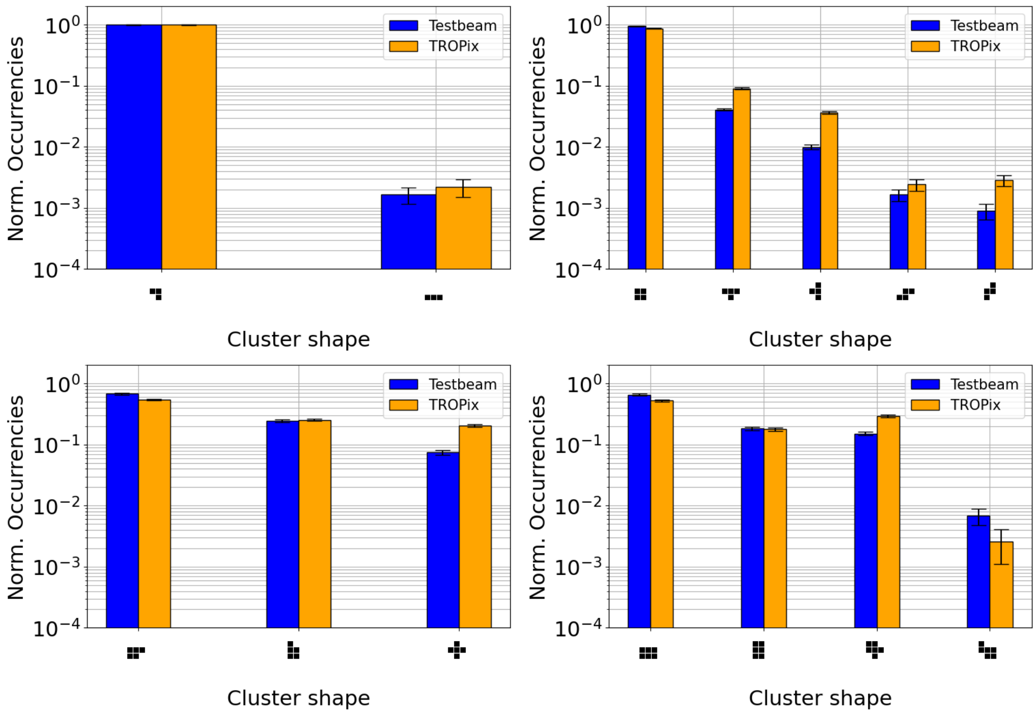

Figure 10: Comparison of the cluster shapes simulated with TROPix (orange bars) and reconstructed in test beam data analysis (blue bars). The comparison is done for fixed cluster sizes. On the x-axis, the cluster shapes are represented and the bars represent the occurrence of a shape. The result is obtained for protons depositing $\sim$ 14 KeV in active silicon material.

5. Conclusion

In this contribution, we presented TROPix, a parametric Tool Reproducing the Output of Pixel detectors. The tool is easily interfaced with a particle physics simulator (as GEANT4, FLUKA (ongoing.), etc.) and it comes with a standardized recipe to tune simulation parameters using test beam data. The tool can reproduce cluster size dependencies from deposited energy and incoming particle direction, but also reproduce the relative rankings among cluster shapes. Further developments are ongoing to speed up the simulation by allowing for the multi-threading processing of events.

References

[1] *Synopsys TCAD software*, 2023.

[2] S. Spannagel, K. Wolters, D. Hynds, N. Alipour Tehrani, M. Benoit, D. Dannheim et al., *Allpix2: A modular simulation framework for silicon detectors*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **901** (2018) 164.

[3] GEANT4 collaboration, *GEANT4–a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.

[4] M. Mager, *Alpide, the monolithic active pixel sensor for the alice its upgrade*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **824** (2016) 434.