TROPix

A fast parametric Tool Reproducing the Output of Pixel detectors

Andrea Di Luca, F.M. Follega, E.Ricci, R. Iuppa

andrea.diluca@unitn.it

PIXEL2022 - Tenth International Workshop on Pixel Detectors for Particles and Imaging conference

15th December 2022

The context
The HEPD-02 detector

- The High Energy Particle Detector (HEPD-02) as part of a suite of instruments for the second mission of the China Seismo-Electromagnetic Satellite (CSES-02) to be launched in 2023.

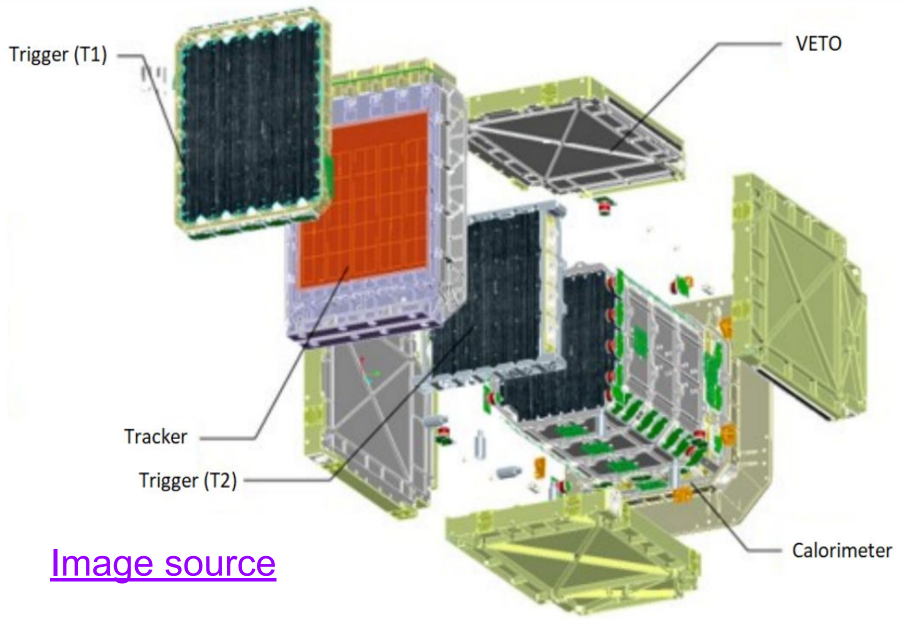
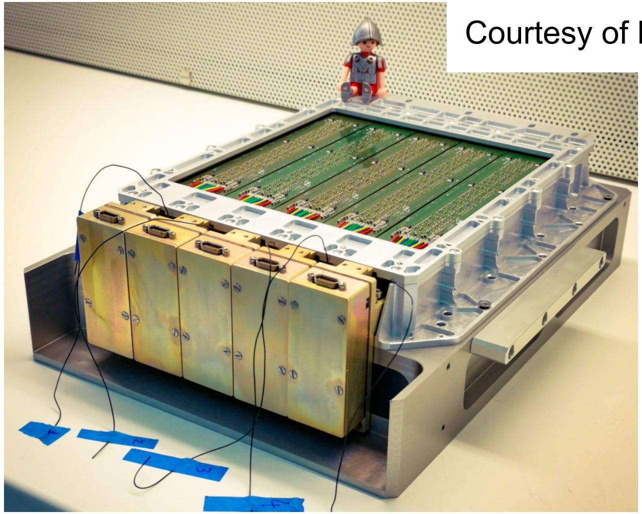


Image source

Tracker

- 3-planes detector tracker based on the ALTAI pixel sensor, derived from the ALPIDE sensor technology (developed for the ALICE experiment at the LHC).

- First MAPS detector for tracking space application.

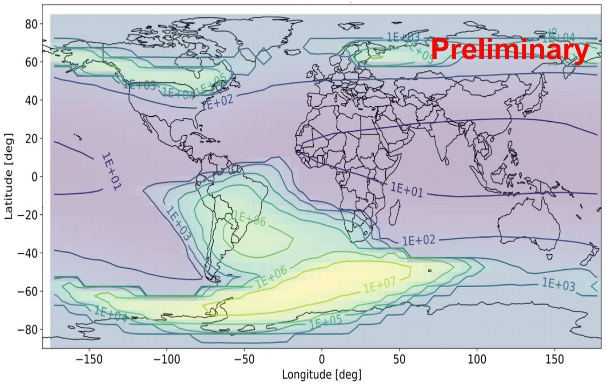


Courtesy of R.Iuppa

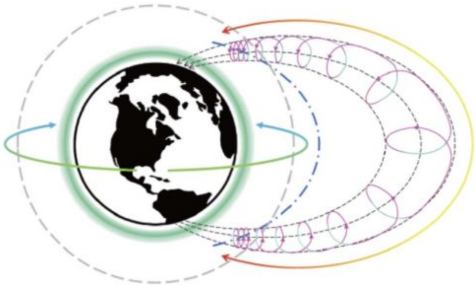
Physics of HEPD-02

Monitoring the ionosphere:

- **Investigate the ionosphere** and gather world-wide data;
- Measure the particles **perturbations of the atmo/iono/magnetosphere**;



Estimated rate for HEPD-02

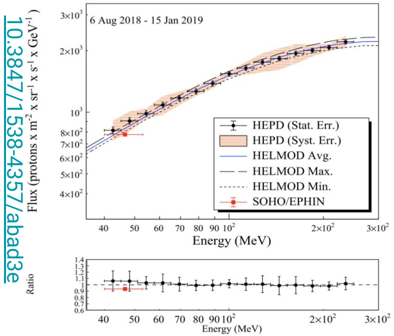


Reconstruct the particle direction is crucial to trace back the perturbation origin

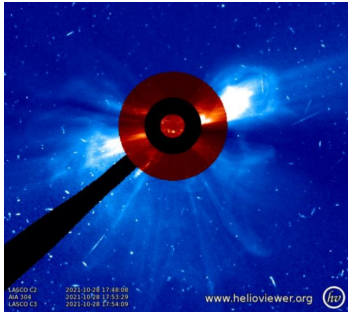
10.3847/1538-4365/ab276c

CR flux modulation

10.3847/1538-4357/abad3e



Coronal Mass Ejection



10.1029/2022SW003191

Low energy cosmic rays and solar physics:

- Study **low energy cosmic rays:**
  - electrons and protons
  - <u>light nuclei: from helium up to oxygen</u>
- Study solar modulation and solar physics phenomena (CMEs, SEPs, etc…)

TROPix

A fast parametric tool reproducing the output of pixel detectors

INPUT

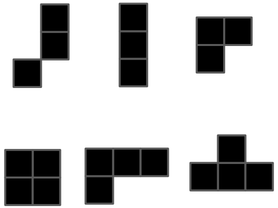
Energy depositions in pixel material

→

TROPix simulator

→

OUTPUT



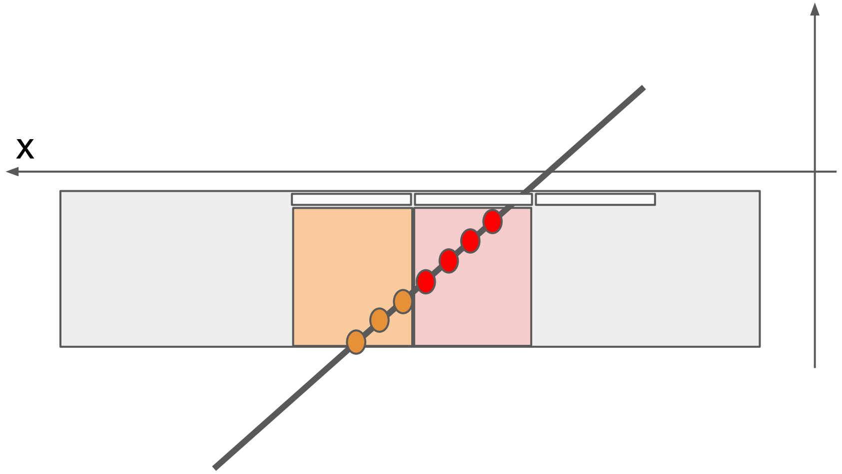
TROPix simulation steps

1. Primary charges sampling
2. Diffuse and collect primary charges
3. Add noise
4. Compare thresholds to get clusters of active pixels

Primary charges sampling

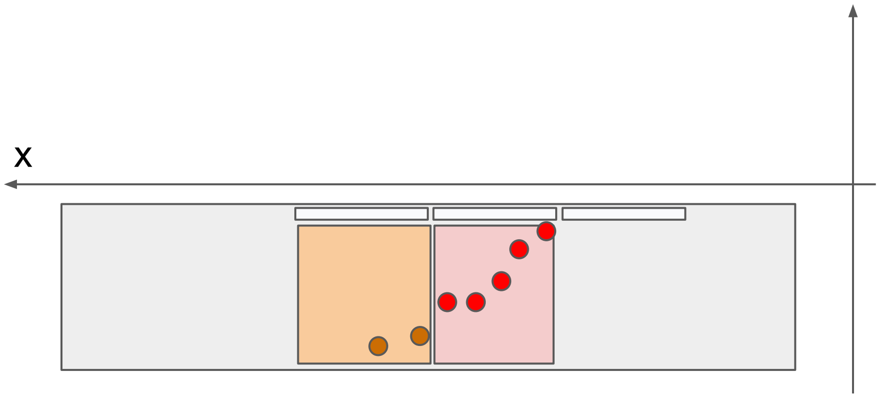
Stand-alone primary charge sampling

1. Propagation of a straight track through the sensor material
2. Energy deposited in silicon is converted to charge.
3. Charge amount proportional to the track length inside the epitaxial layer



Sampling from GEANT4 hits

1. For each hit, the energy deposited in silicon is converted to charge.



Finite size of primary charge distribution

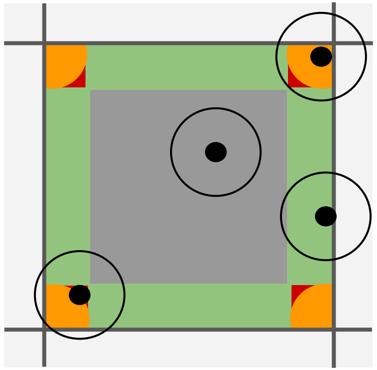
- For standalone primary charge sampling, a charge column is built around the track.
- For G4-driven charge sampling, a finite size is assigned to the hit points (spheres). For the rest of this presentation we used the radius $r = 0.7$ um.

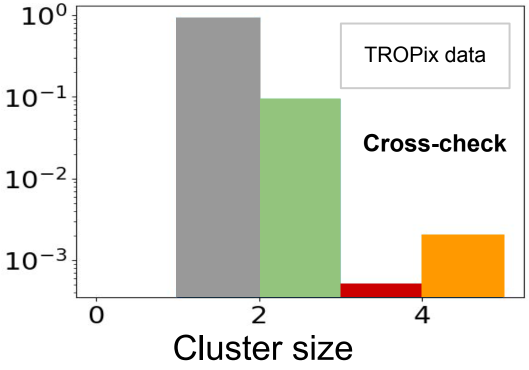
Depending on the position of the primary charge production, the column/sphere can intersect near pixels in different ways. This is relevant when no diffusion is considered.

The charge is deposited in:

Primary charge column/sphere

1 pixel
2 pixels
3 pixels
4 pixels





For tracks perpendicular to the pixel surface, the cluster size probability should match the surface fraction of the colored region over pixel area.

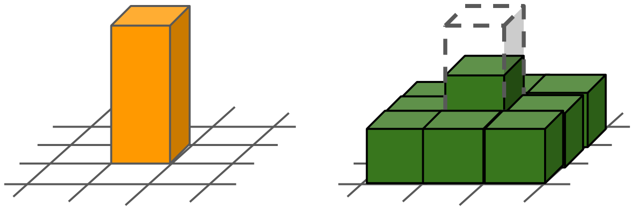
Parametric charge diffusion

Charge transport is regulated through a **parametric gaussian smearing of the primary charge**. The smearing is applied **after each step of the primary charge production**.

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

The Gaussian smearing is depending on:

- Primary charge position: for each pixel, we can use the centroid position (X_Q ,Y_Q) of the charge volume.
- *D*: the maximum distance to compute the diffusion.
- ($\sigma_{x,}$, σ_y): the standard deviation of the gaussians.



Adding noise and comparing threshold

Thermal noise added to collected charges. For each pixel, the noise map value is sampled from a normal distribution with given a mean **`NOISE_AV`** and sigma **`NOISE_SIGMA`**.

Collected charges

100	200	100
200	500	200
100	200	100

+

Noise map

1	2	0
0	1	0
2	0	3

→

101	202	100
200	501	200
102	200	103

Comparing deposited charge in pixel to sampled threshold map to actually fire the pixels. For each pixel, the noise map value is sampled from a normal distribution with given a mean **`THR_AV`** and sigma **`THR_SIGMA`**;

101	202	100
200	501	200
102	200	103

>

Threshold map

150	143	167
149	163	157
167	153	143

→

0	1	0
1	1	1
0	1	0

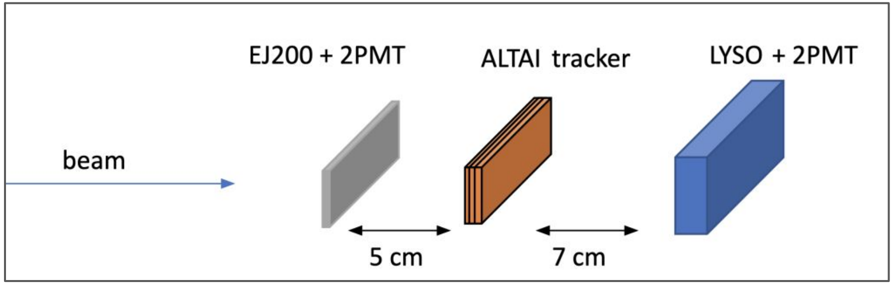
User-defined noise and threshold maps can be loaded in the simulator.

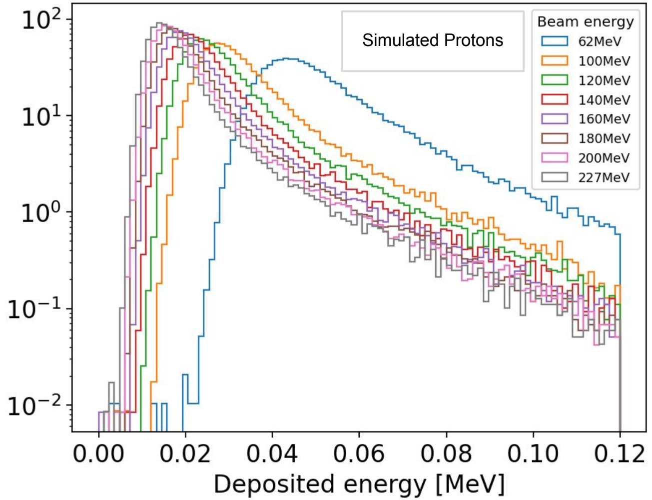
TROPix parameter tuning

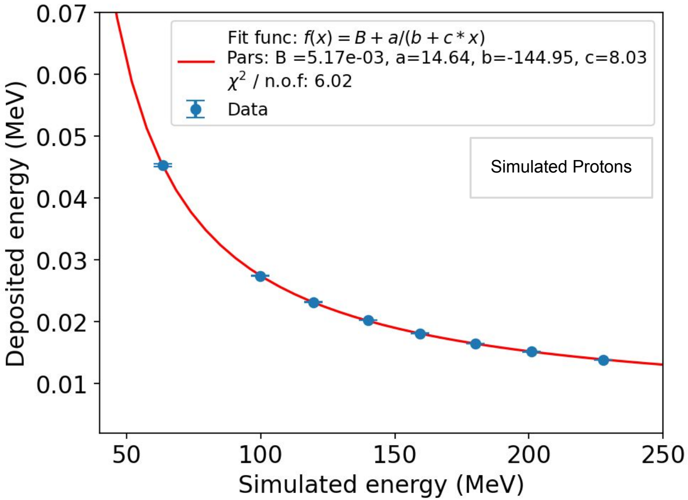
Real and simulated test beam data can be used to tune TROPIX parameters.

A **mapping** is created between **beam energy and deposited energy** in active silicon material.

Deposited energy MPV is extracted from Landau fit.

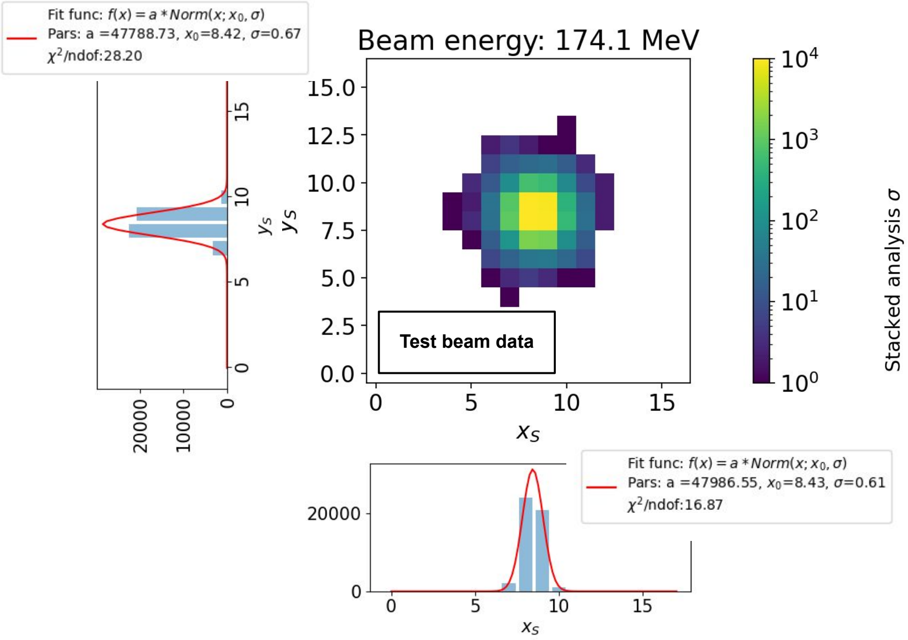




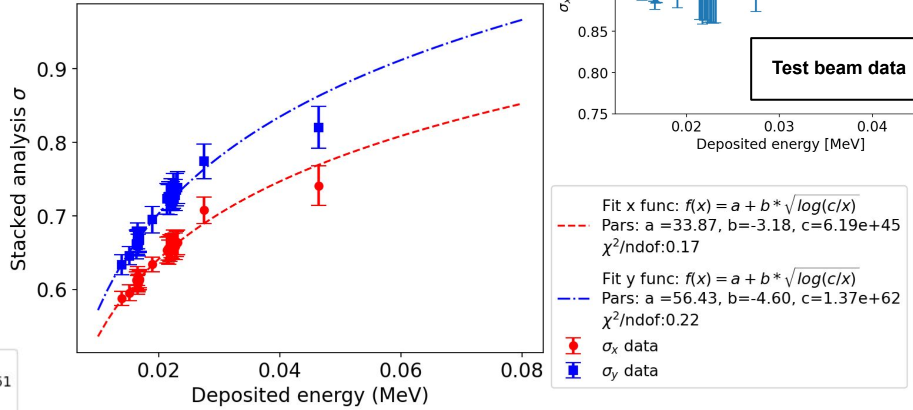


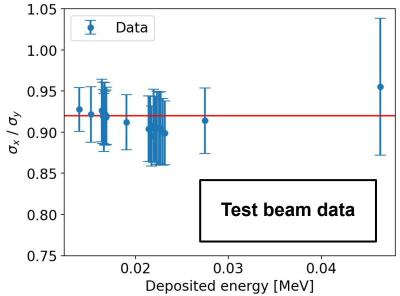
Tuning of diffusion parameters to data

Stacked analysis on **reconstructed cluster on data collected at test beam**. Cluster are stacked using centroid matching.



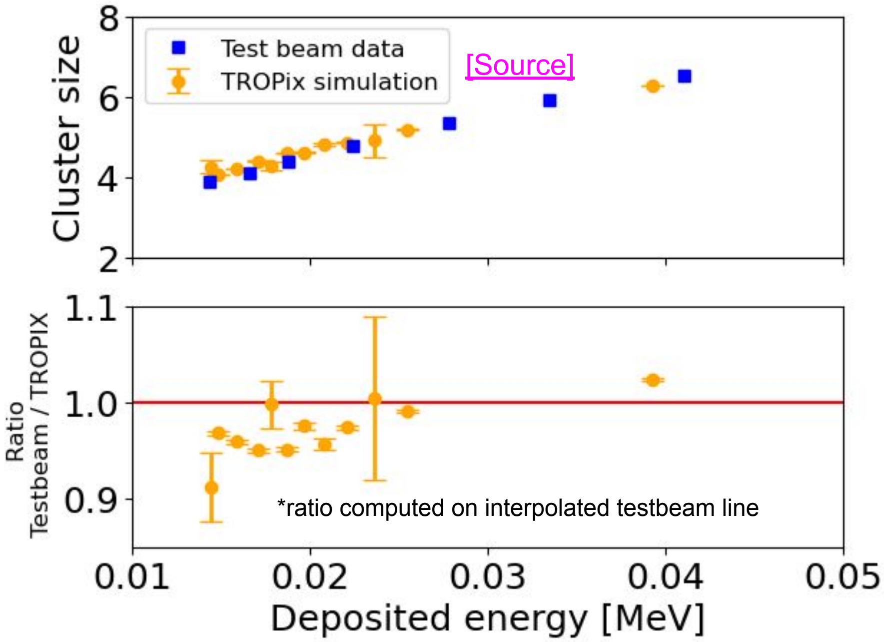
ALTAI sensor
Pixel side X: *Px* = 29.24 um
Pixel side Y: *Py* = 26.88 um
Py/Px ~0.92

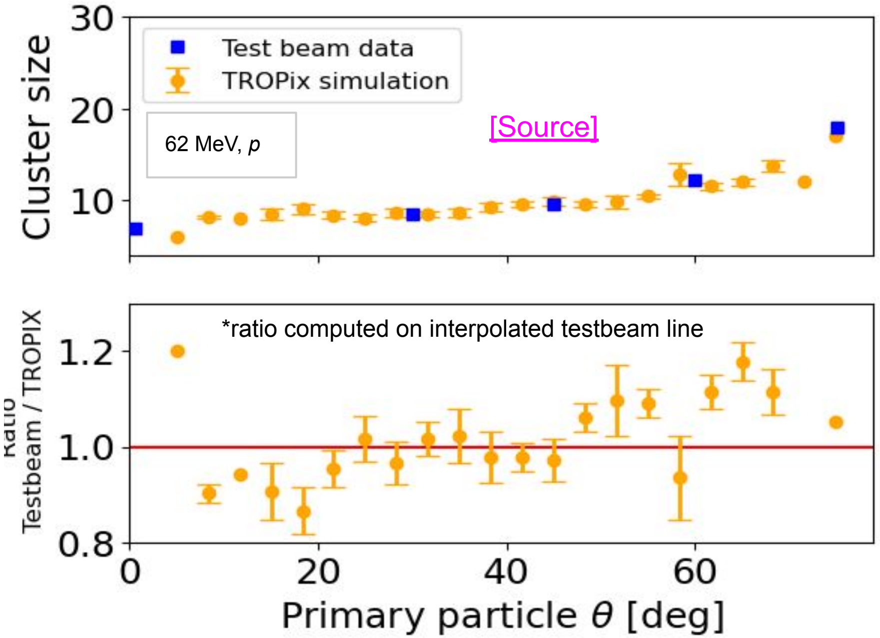




Fit function is derived analytically from pure diffusion model (gaussian distribution of the signal).

Cluster size analysis





Cluster size dependence on beam energy and angle is reproduced.
For MIPs, this result is already sufficient since no relevant information is expected from cluster shapes.

Cluster shape study

Reproducing the cluster shape distribution is by far the **ultimate test** of any tool emulating real sensors.

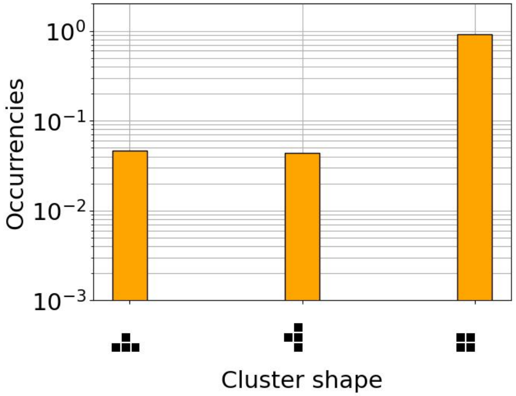
We developed a Python package to check the occurrence of given patterns.

Reconstructed clusters of given size *N*

Reference patterns of size N

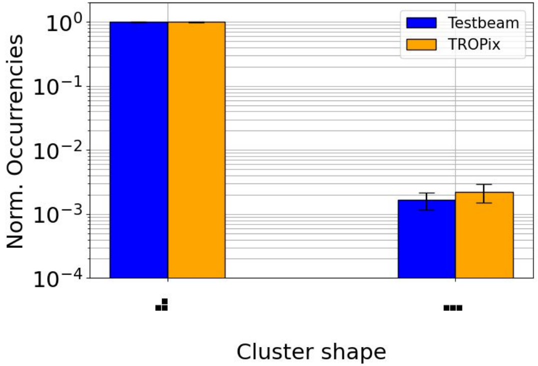
Occurrence calculation

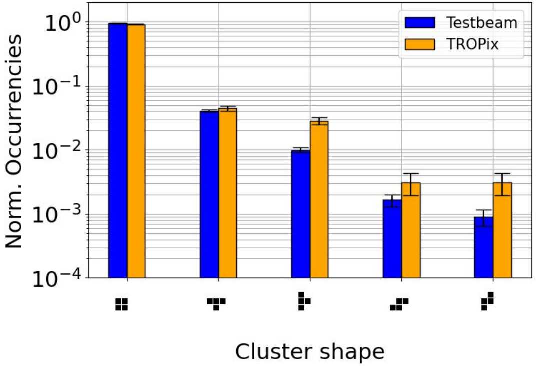
Symmetric patterns for given transformation can be merged.

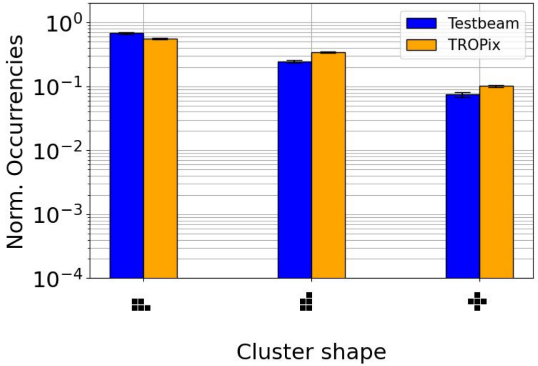


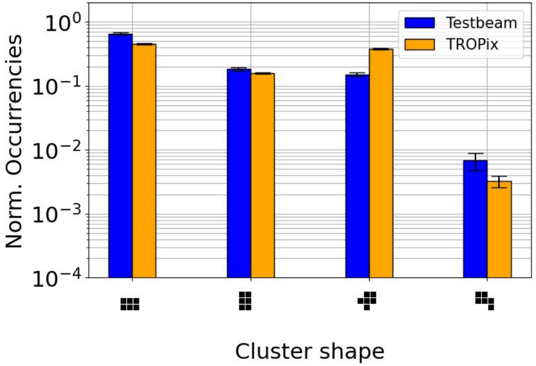
Cluster shape comparison

Result for protons depositing ~14 KeV in active silicon material.









The cluster shape study can be used to tune the threshold map sampling parameters.

Timing comparison

- Tested on my laptop: Processor Intel(R) Core(TM) i7-10510U
- Run on Windows Subsystem for Linux (WSL2)
- Tested using same test beam simulation

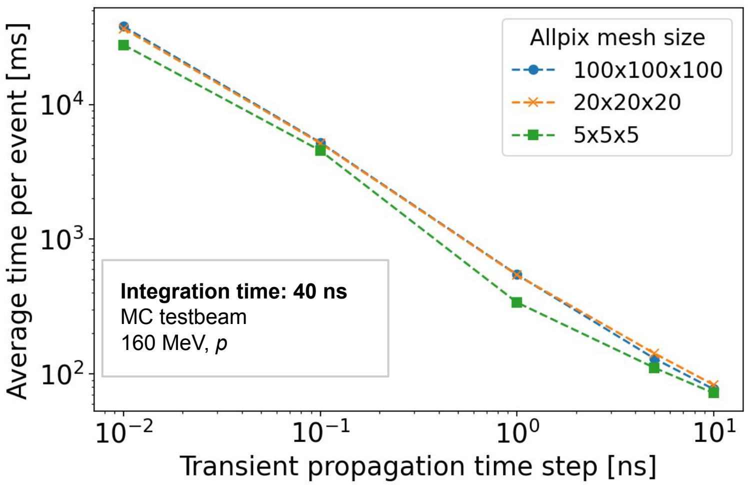
Allpix2 executed using:

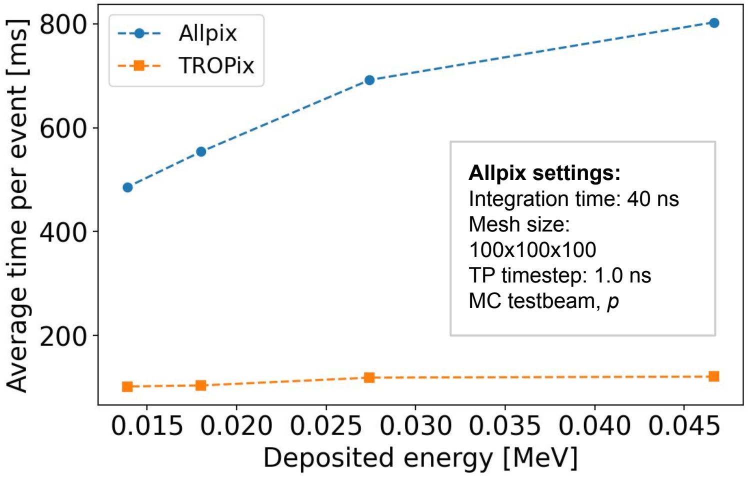
- Official docker image
- Multithreading enabled

TROPix executed using:

- GEANT4 hits primary charge production
- Gaussian smearing at each step
- Single thread (**multithreading is possible, but has to be implemented**)

*time averaged over 100 events





Conclusion

We presented TROPix, a fast parametric system for simulating the response of pixel detectors.

- Easily interfaced with particle physics simulator (as GEANT4, FLUKA (ongoing.), etc.)
- Standardized recipe to tune simulation parameters using testbeam data.
- Cluster shape analysis Python package is in place to validate simulator output on data.

We are currently investigating a Generative Adversarial Network (GAN) approach to simulate pixel detector outputs.

TROPix is currently used for the simulation framework of the HEPD-02 detector.

We are now looking at people interested in using and developing the tool.
We are writing the reference paper. TROPix repository public shortly after.

For any info: andrea.diluca@unitn.it

Participate to the
TROPix logo poll !