Test beam results with Depleted Monolithic Active Pixel Sensors (TowerJazz Investigator chip) at the SPS at CERN

Florian Dachs, Maria Moreno Llacer, Enrico Jr. Schioppa, CERN EP
on behalf of T. Kugathasan, C. Marin Tobon, S. Monzani, H. Pernegger, P. Riedler, C. Riegel, W. Snoeys, J. Van Hoorne

Outlook

- Setup at CERN North Area
- Telescope and DUT
- Data Analysis
- Results
- Conclusions

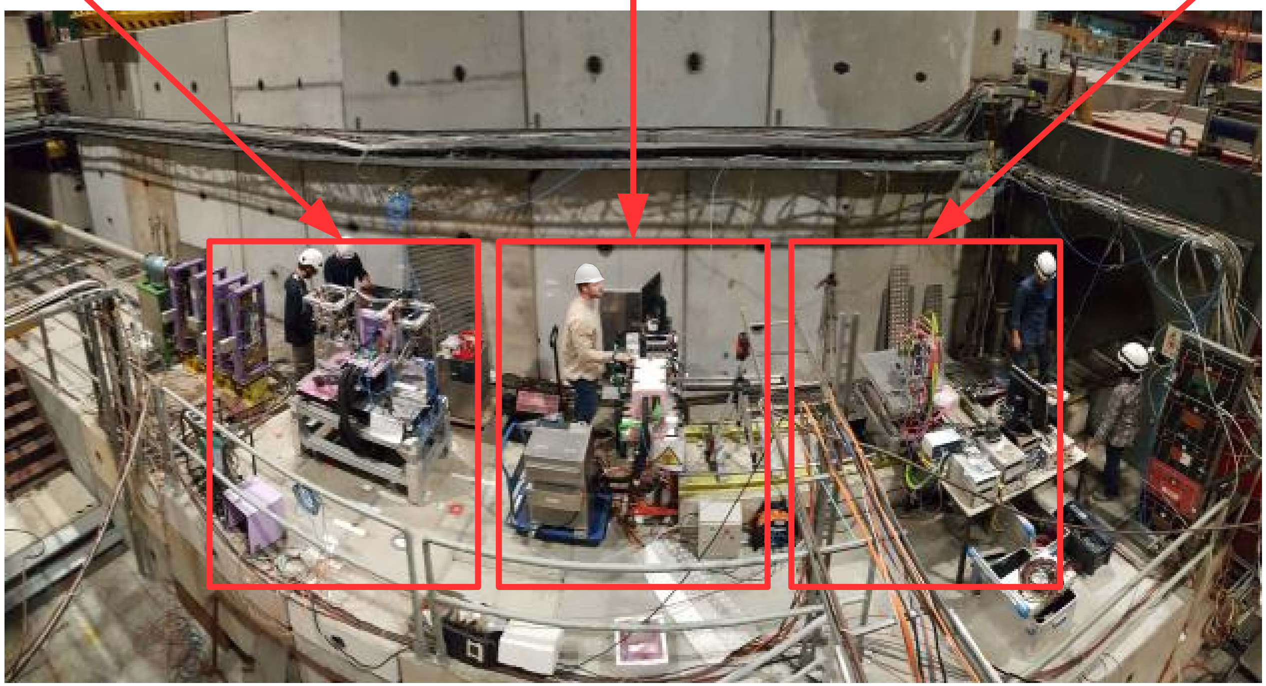
CERN SPS test beam campaign 2017

- 3 setups installed in **SPS H8b**
- 3 weeks as main users (1 in May, 2 in September)
- Most of the remaining time parasitic (from May to October)
- Mostly **180 GeV pions**
- Overall good data taking

AMS-Geneva

TJ-CERN

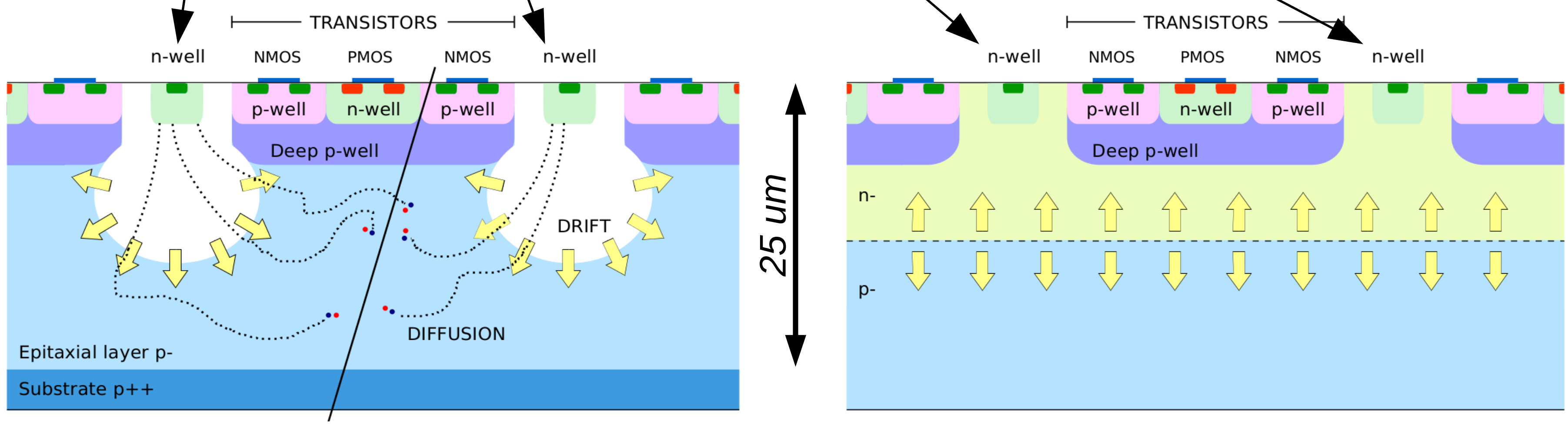
LF-Bonn (1 week)



The TowerJazz 180nm CMOS technology

- **Low input capacitance** (~fF) at the collection electrode
- **Large S/N ratio** can be achieved
- **Fast signals**

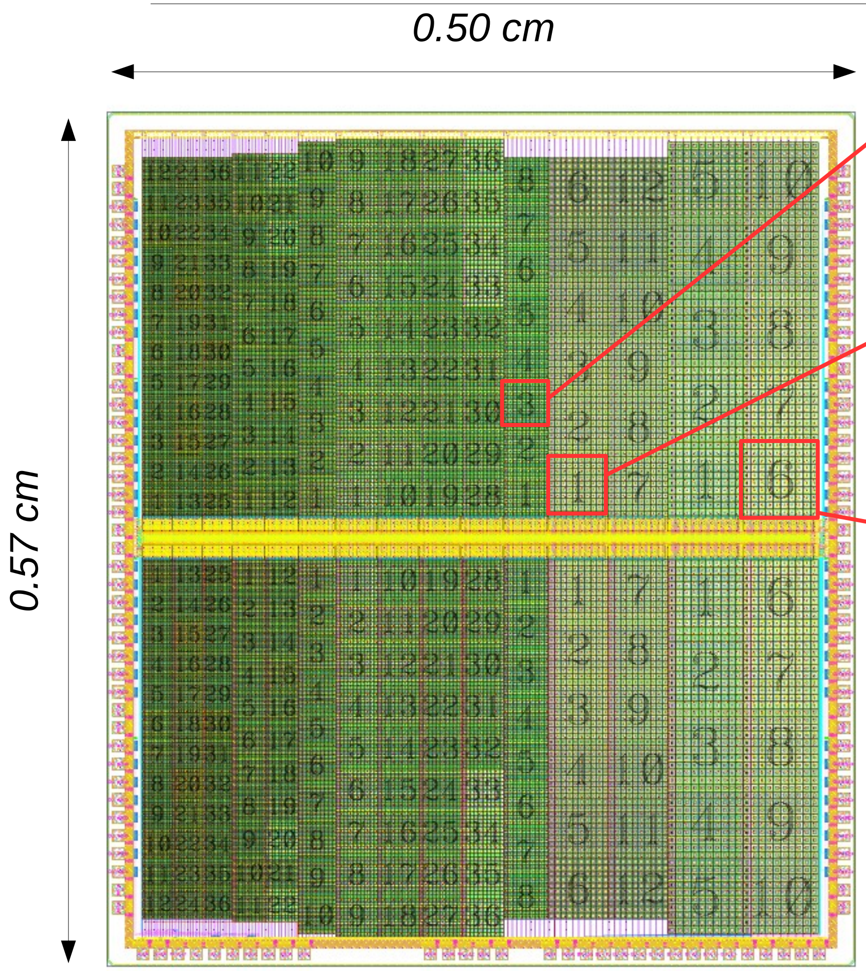
Standard process | **Modified process**



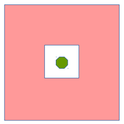
- Difficult to obtain full lateral depletion
- Not radiation hard

- A planar junction extends across the full pixel surface
- Radiation hard

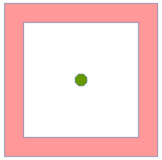
The DUT – TowerJazz Investigator



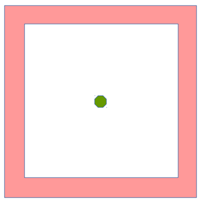
Minimatrix 106
- Pixel size 30x30μm²
- Electrode size 3x3μm²
- Opening 3μm



Minimatrix 112
- Pixel size 40x40
- Electrode size 3x3μm²
- Opening 30μm



Minimatrix 129
- Pixel size 50x50μm²
- Electrode size 3x3μm²
- Opening 40μm

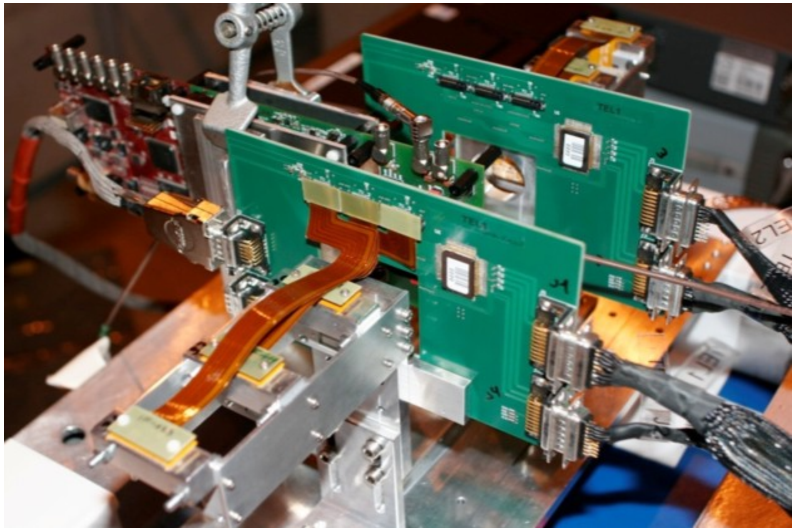


First test beam results published in 2017:
http://iopscience.iop.org/1748-0221/12/06/P06008

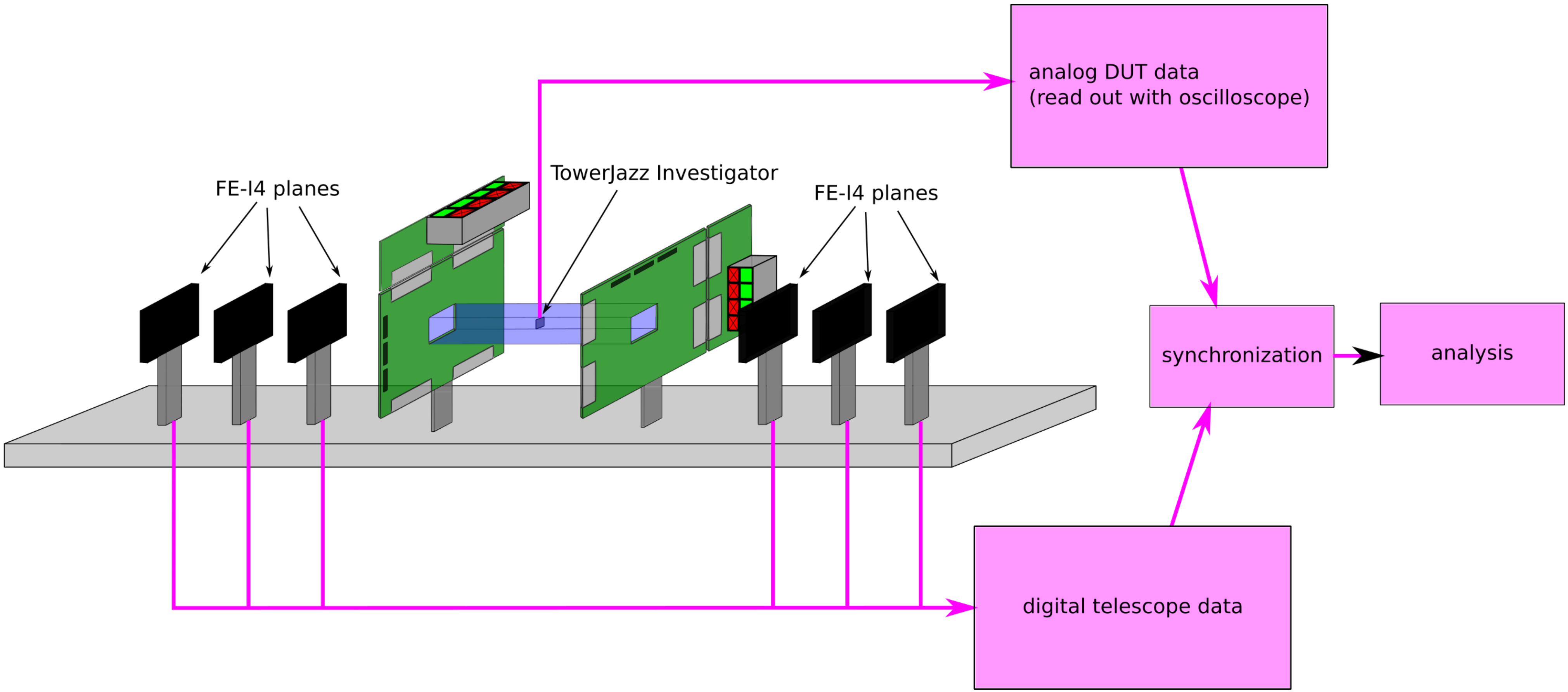
- Unirradiated
- 1×10^{15} MeV n_{eq}/cm^2
- 2×10^{15} MeV n_{eq}/cm^2 for Minimatrix 106

The telescope

- **6 planes** of FE-I4 chips solder bump bonded to silicon sensors with 336x80 pixels
- Pixel dimensions: **$50x250\mu m^2$**
- Planes are **in turn rotated by 90°** to ensure a more symmetric resolution
- Data processing and control via HSIO board / RCE server
- Very compact



Combined setup of telescope and DUT



Special considerations for this setup

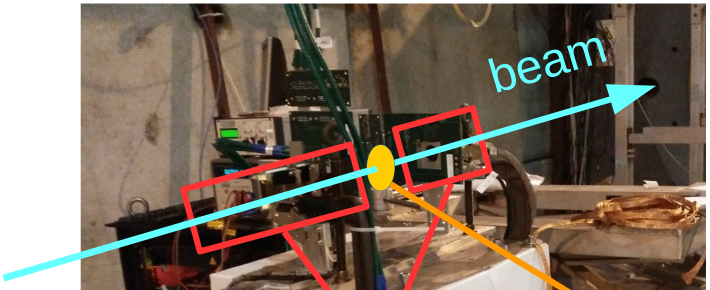
- DUT signal is **analogue**
  - Parameters acquired by fitting a signal waveform
  - **Only 2x2 pixels** read out due to hardware constraints

- DUT is **extremely small**
  - Pixel sizes range from 30µm to 50µm
  - For measurements, a **ROI is applied** to reduce amount of recorded data

- Telescope tracks must be **synchronized** to DUT signals before data analysis

- **dry ice cooling** causes DUT movement relative to telescope

SPS test beam: analysis flow



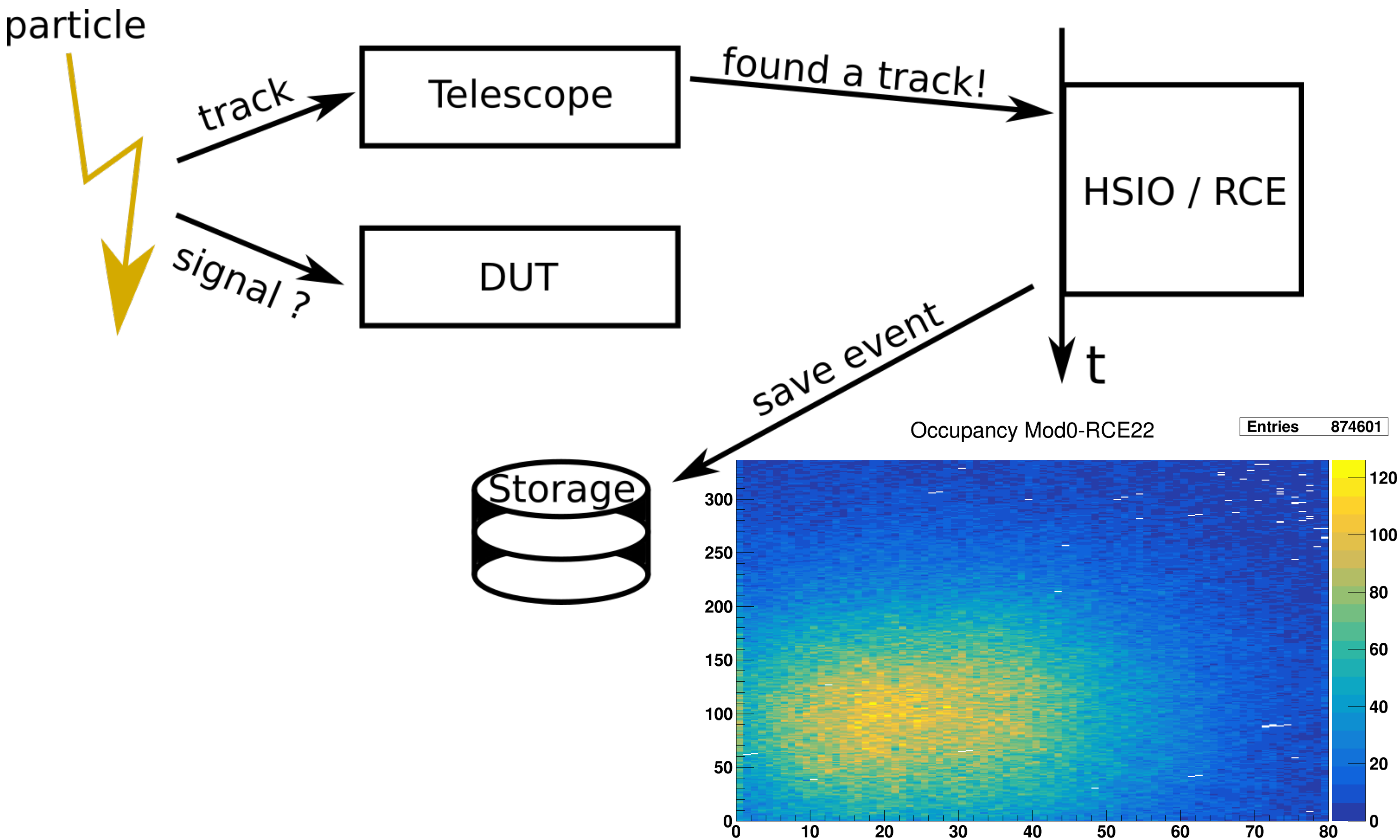
Telescope data
1) Alignment/Tracking
2) Finding DUT
3) Data taking

DUT data
1) Filtering
2) Fitting

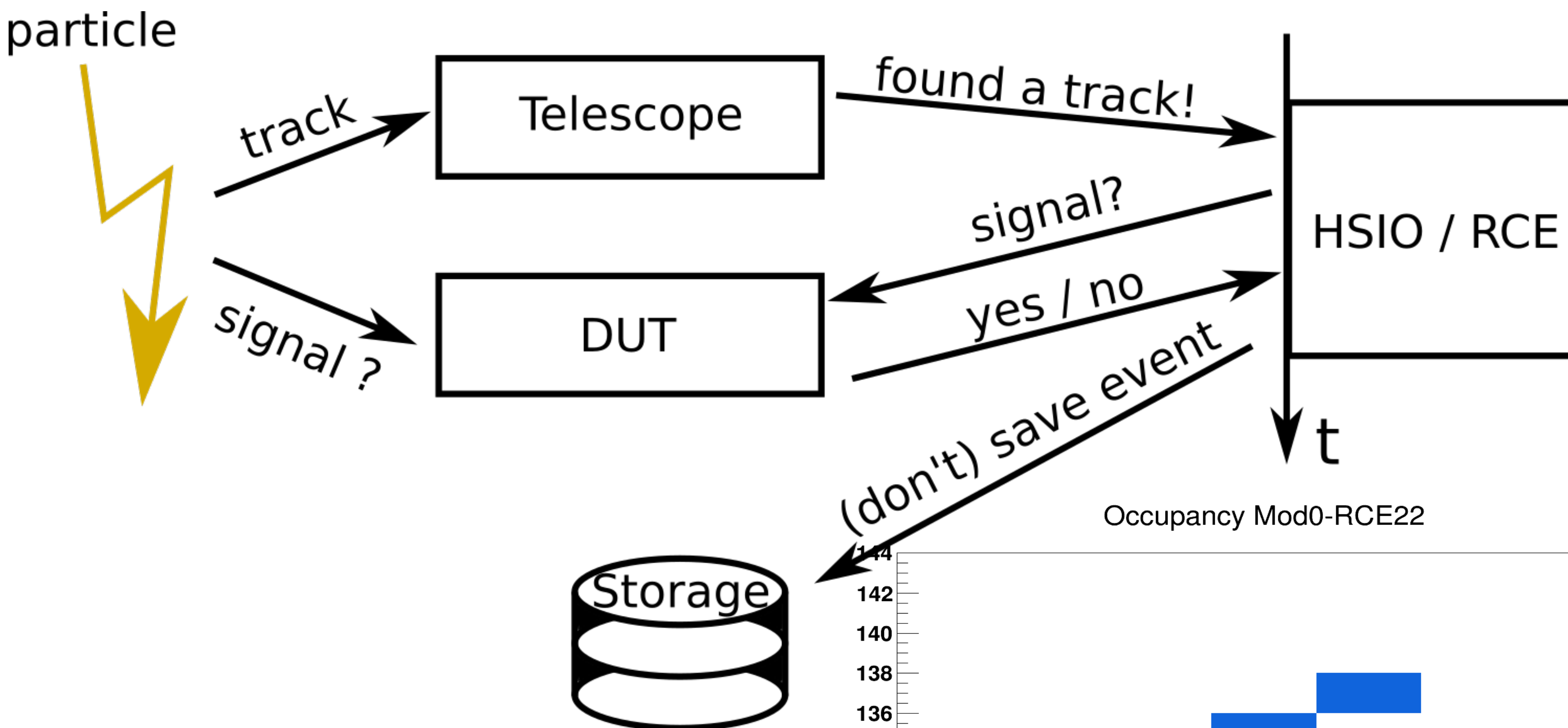
Synchronization

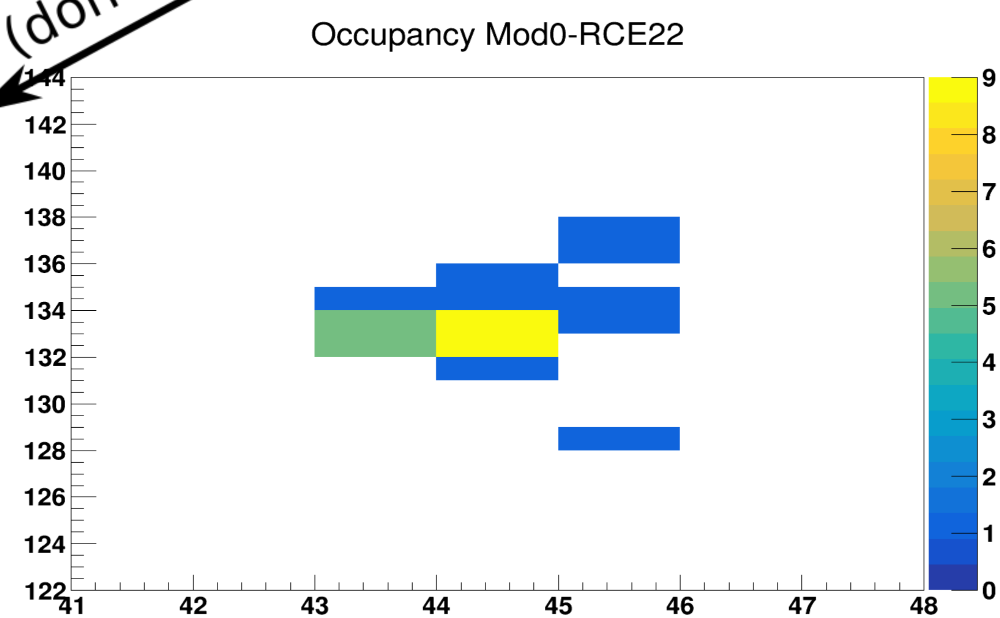
Synced data
1) Correct for possible DUT movement (dry ice)
2) Locate DUT pixels
3) Compute efficiency
4) Compute cluster size
5) Compute charge distribution
6) ...

Telescope alignment (roughly)

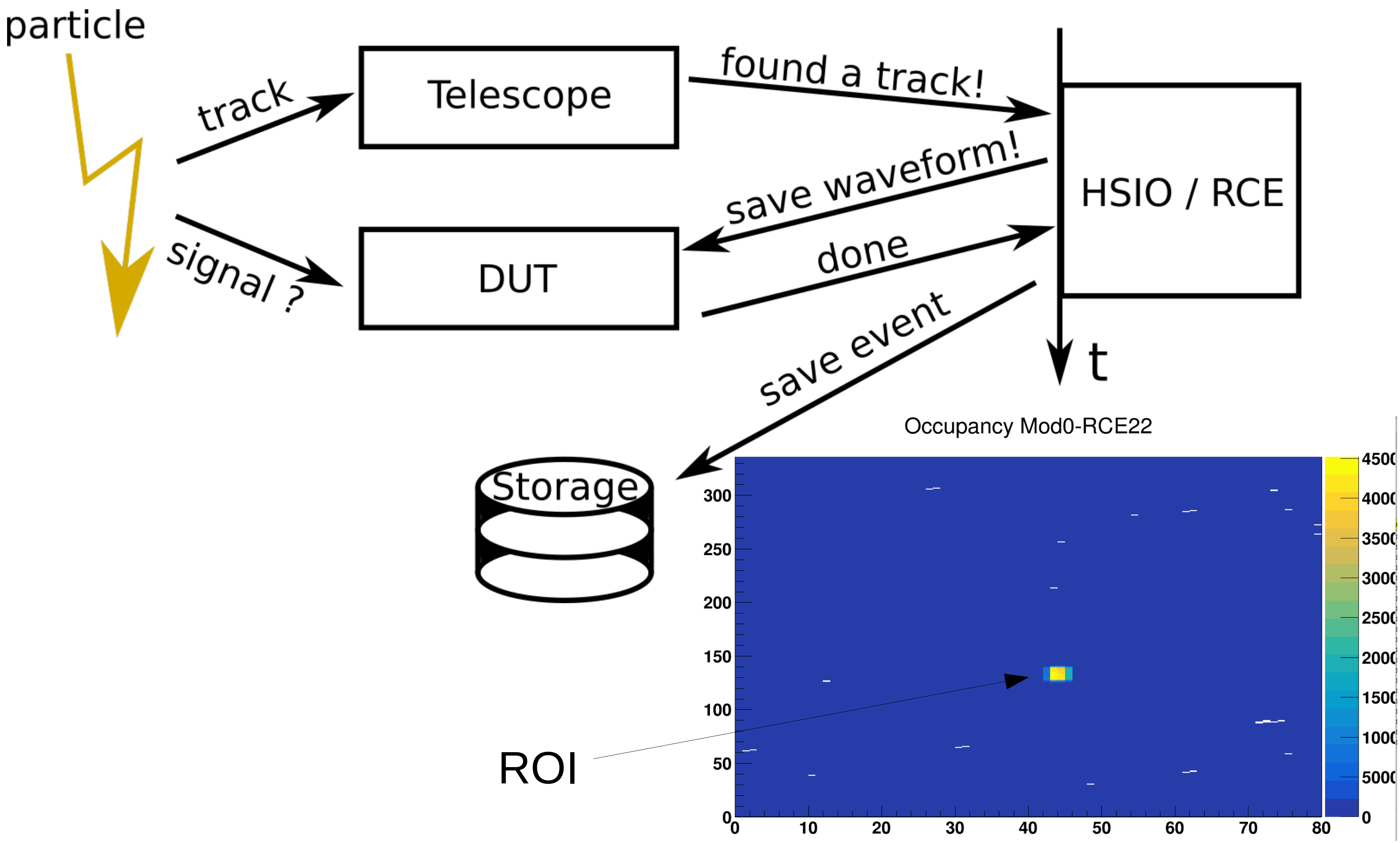


Finding the DUT (roughly)



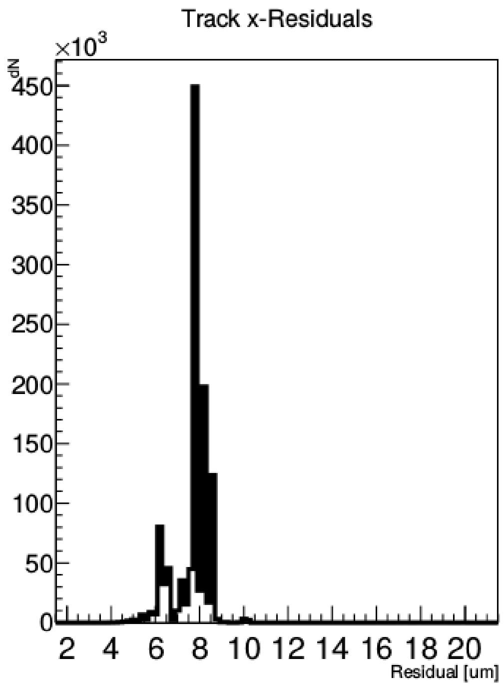


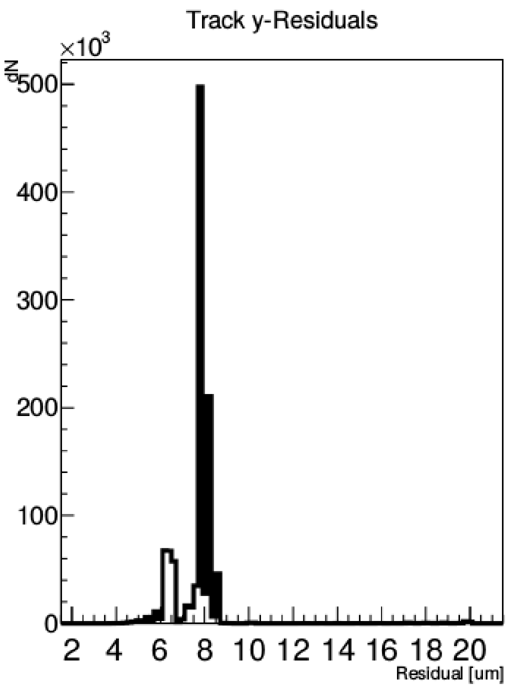
Data taking (roughly)



Alignment and tracking

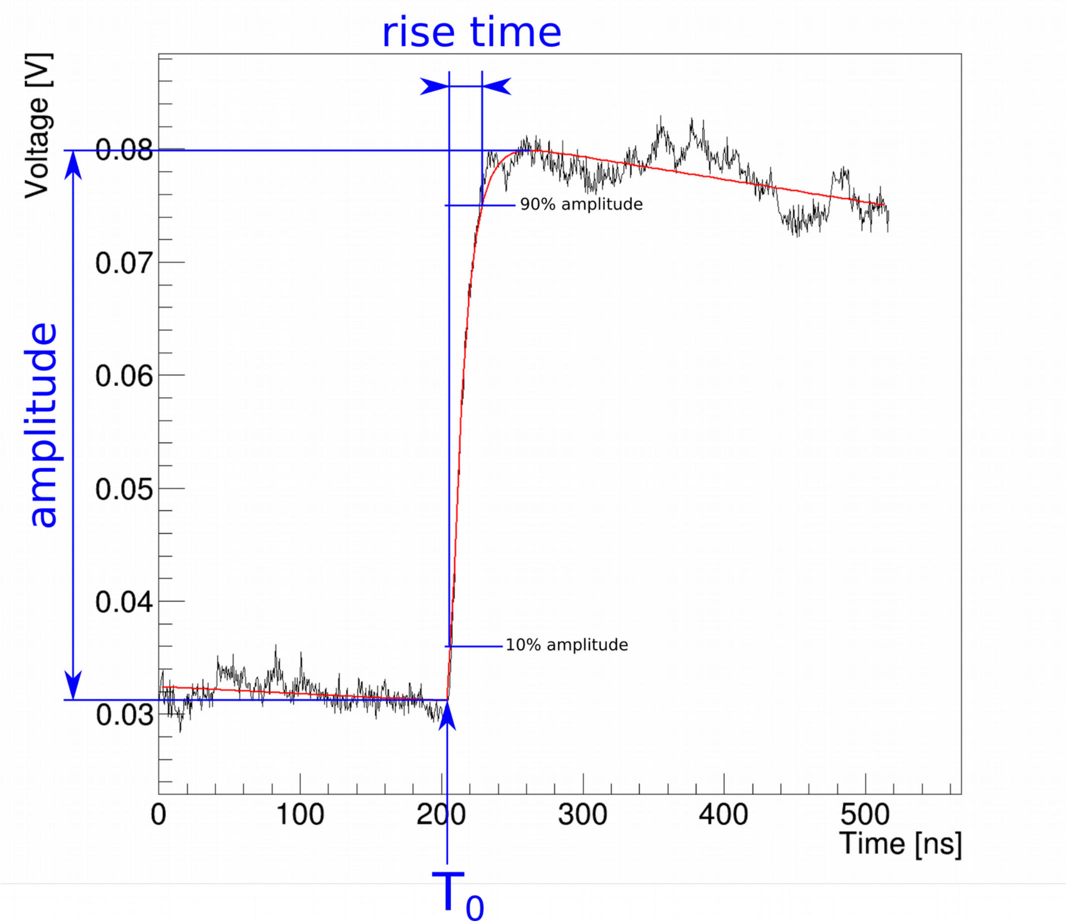
- Alignment and tracking done with **proteus**
  - **Tutorial at this workshop!**
  - Originally developed from “Judith” :
    - G. McGoldrick et al, NIM A765 140--145, Nov. 2014
  - Now developed and maintained by M. Kiehn et.al.
    - https://gitlab.cern.ch/unige-fei4tel/proteus
- Track resolution of 6-8µm reached
  - 2 peaks due to rectangular shape of pixels on telescope planes





Waveform analysis

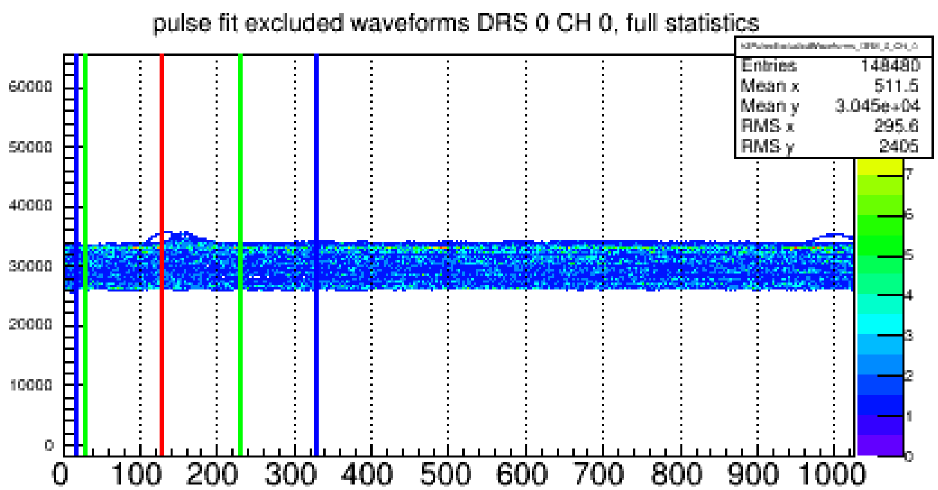
- DUT signal generated via **charge integration**
  - **Visible as step** in signal
  - Rise time, start time, amplitude and other parameters **extracted by fitting the waveform**



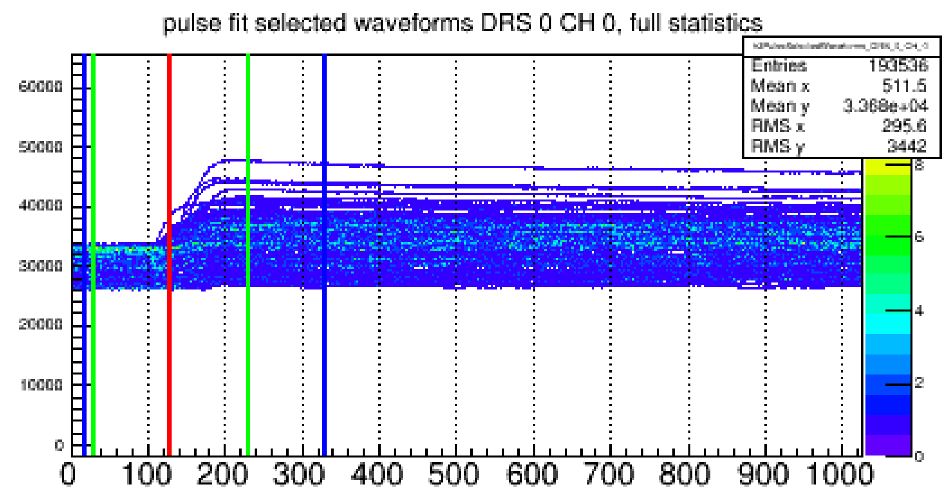
Cuts and Selection Inefficiency

- Cumulative cut applied to **T_0, rise time, amplitude and chi^2**
- Cuts were checked by looking at **selected and rejected waveforms**
- The **selection inefficiency** (i.e. the ratio of found waveforms) is not yet precisely known
  - **preliminary**, MC simulation is planned

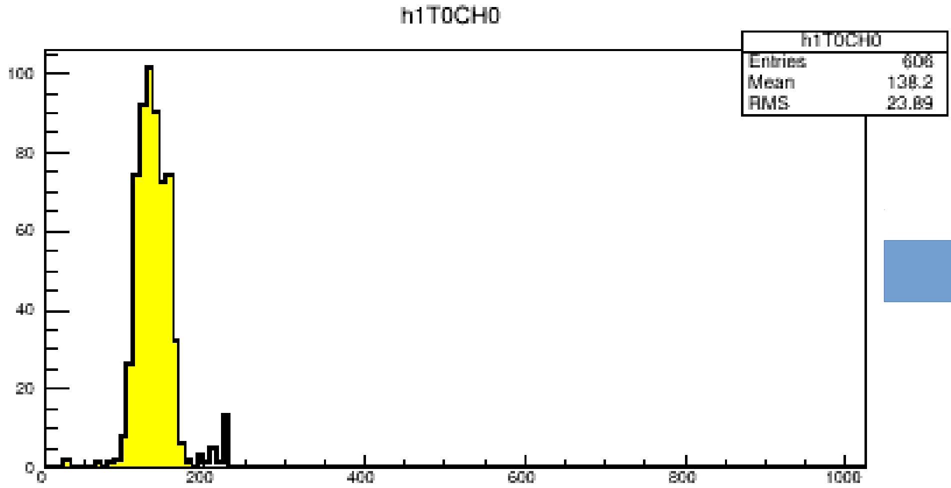
Excluded:

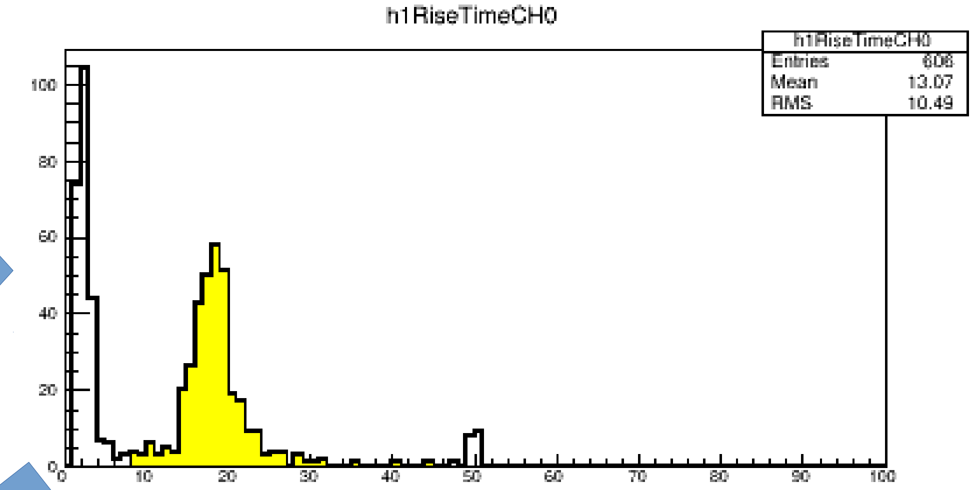


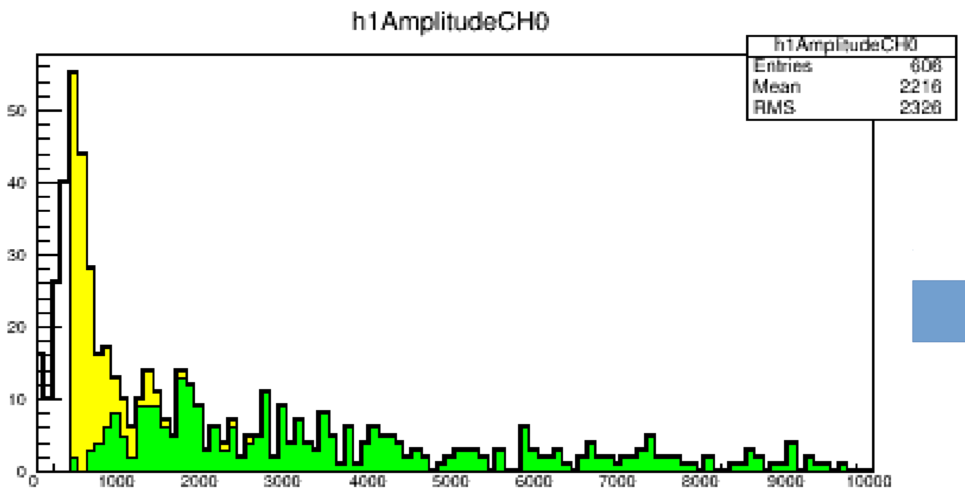
Included:

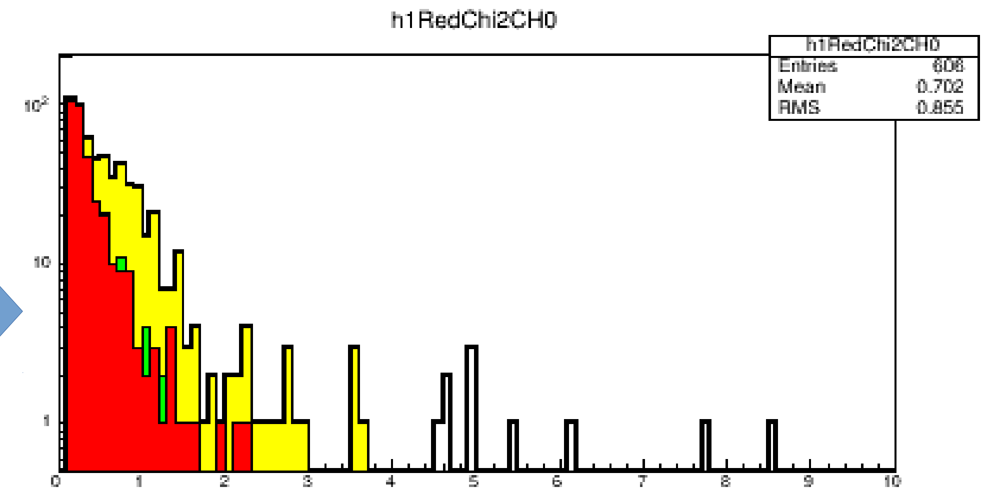


Cuts and Selection Inefficiency



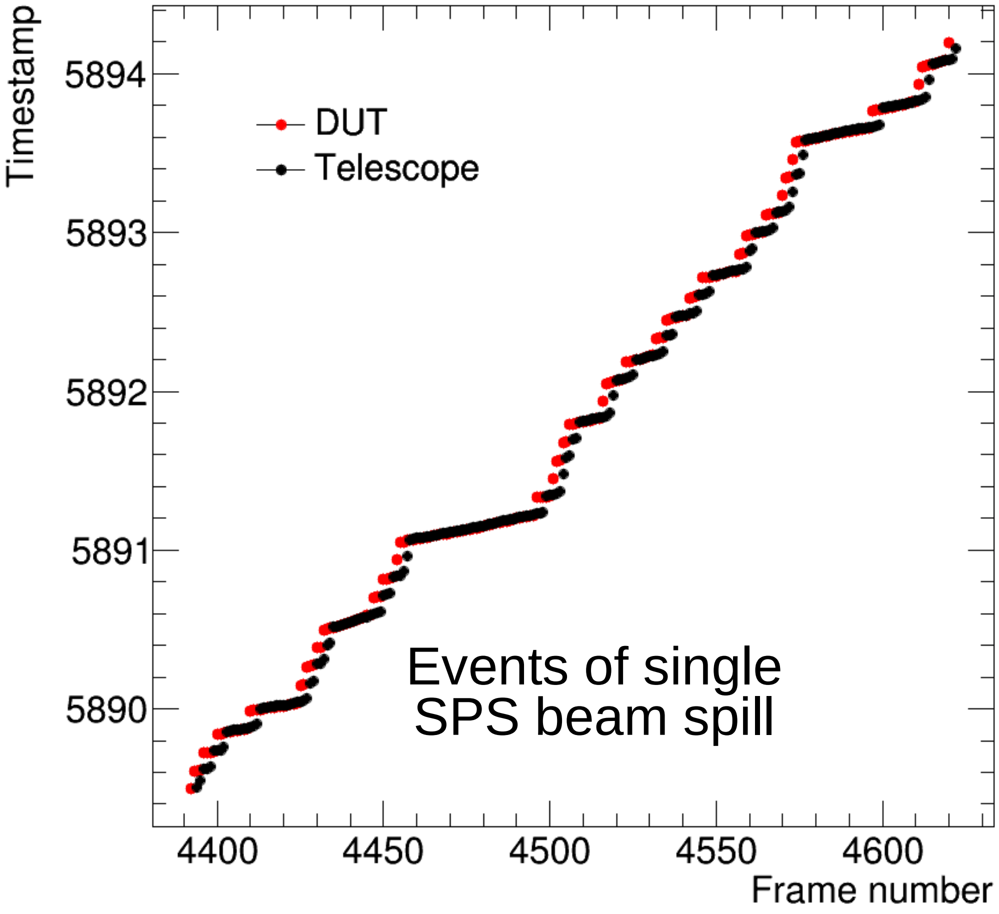






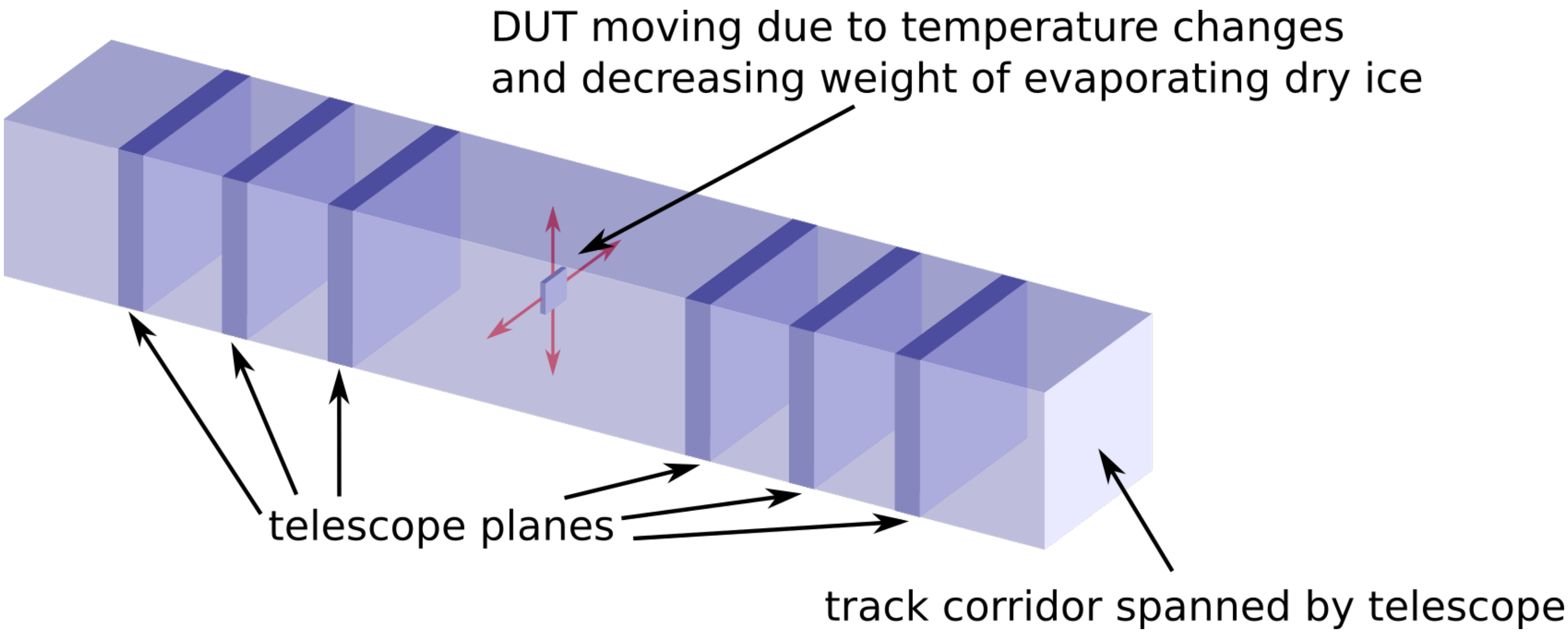
Synchronization

- Data synchronized by **comparing comparing number of events** in a single SPS beam spill in both data sets
- If the spill contains the **same number of events** in both data sets, they are correlated 1 on 1, i.e. 1st DUT event to 1st telescope event etc…
- Spills with **different numbers** of events in both data sets are **discarded**

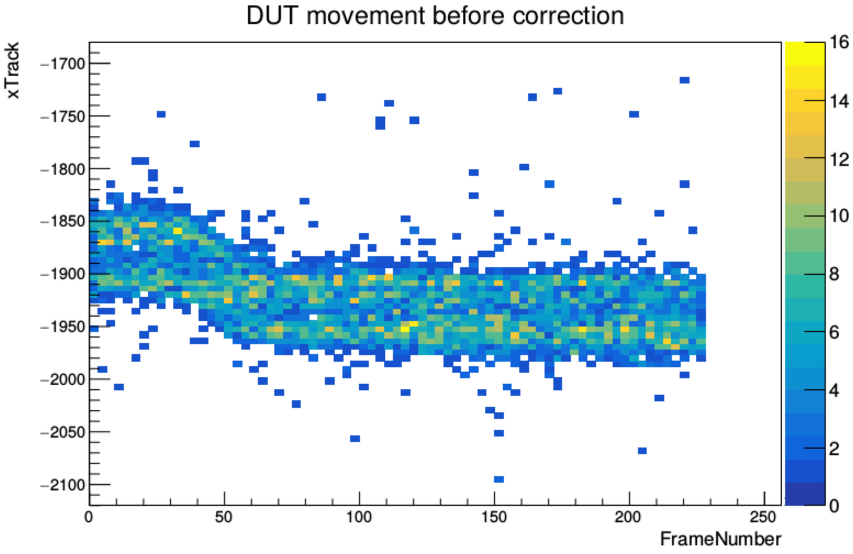


Correction for DUT movement

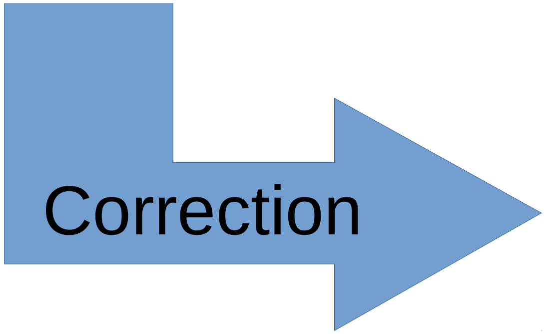
- DUT was **cooled with dry ice** during first 3 months
  - Constant refills necessary (horrible!)
  - DUT moves with respect to telescope due to evaporation of dry ice (change of mech. stress on setup) and probably also due to temperature changes
- For later runs a **silicon oil chiller** was available and solved all dry-ice-related issues

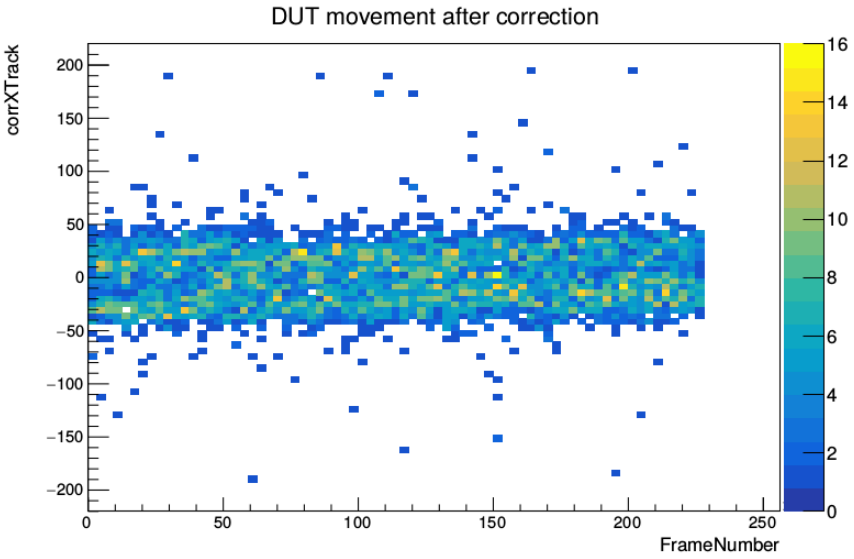


Correction for DUT movement

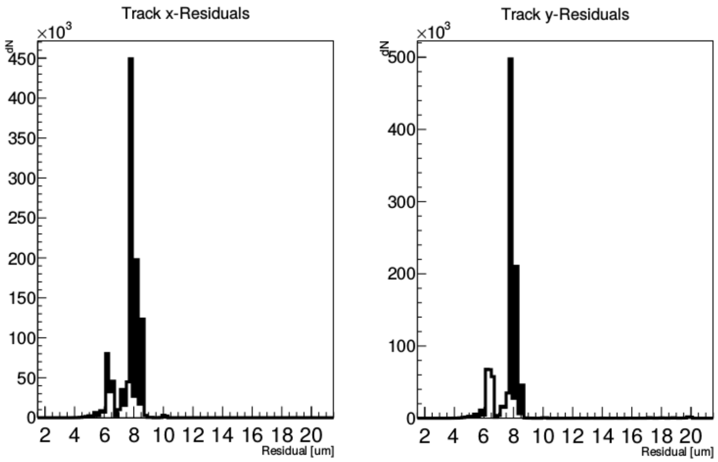


Shown are the **x coordinates of tracks** for which the DUT recorded a signal **over the frame number**

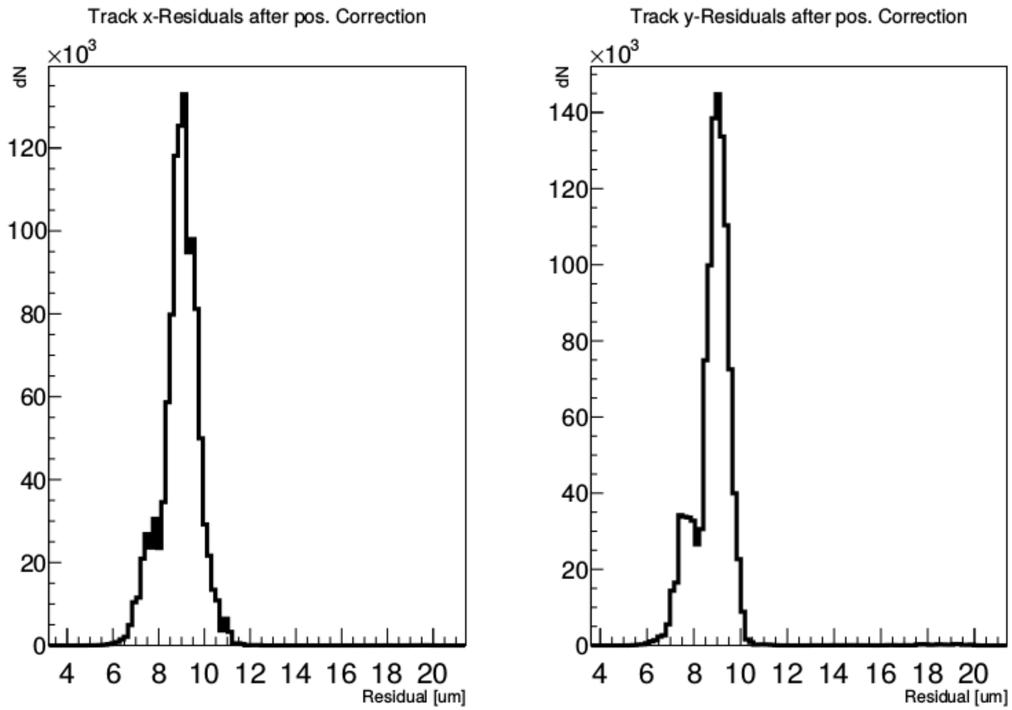




Correction for DUT movement

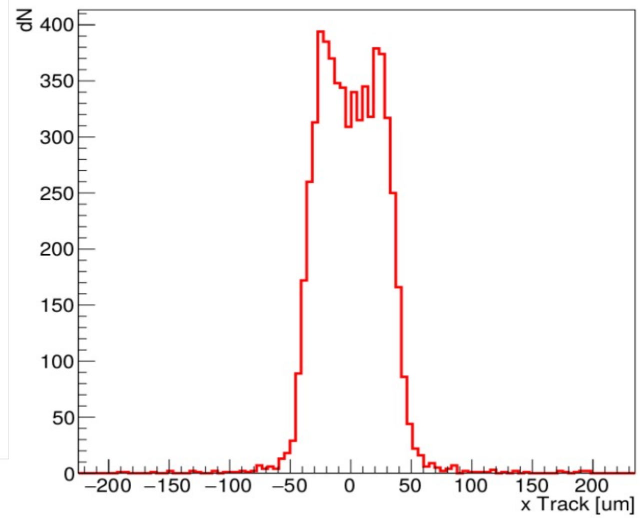


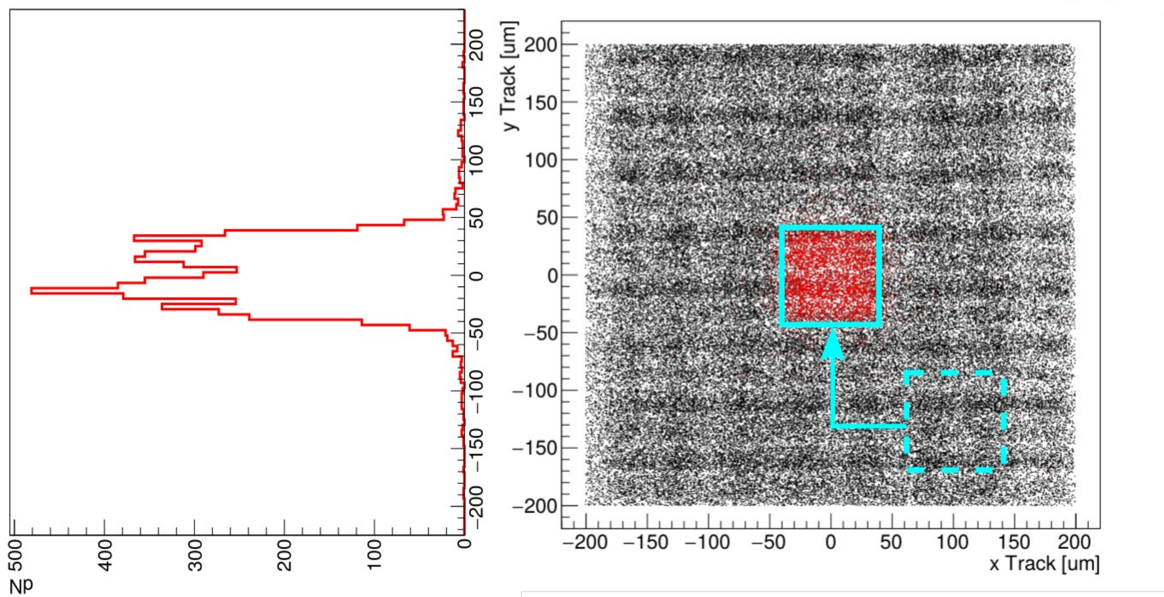
Correcting for the DUT movement **increases the errors** of the track positions and **reduces the effective resolution** of the telescope



Finding the DUT in offline data

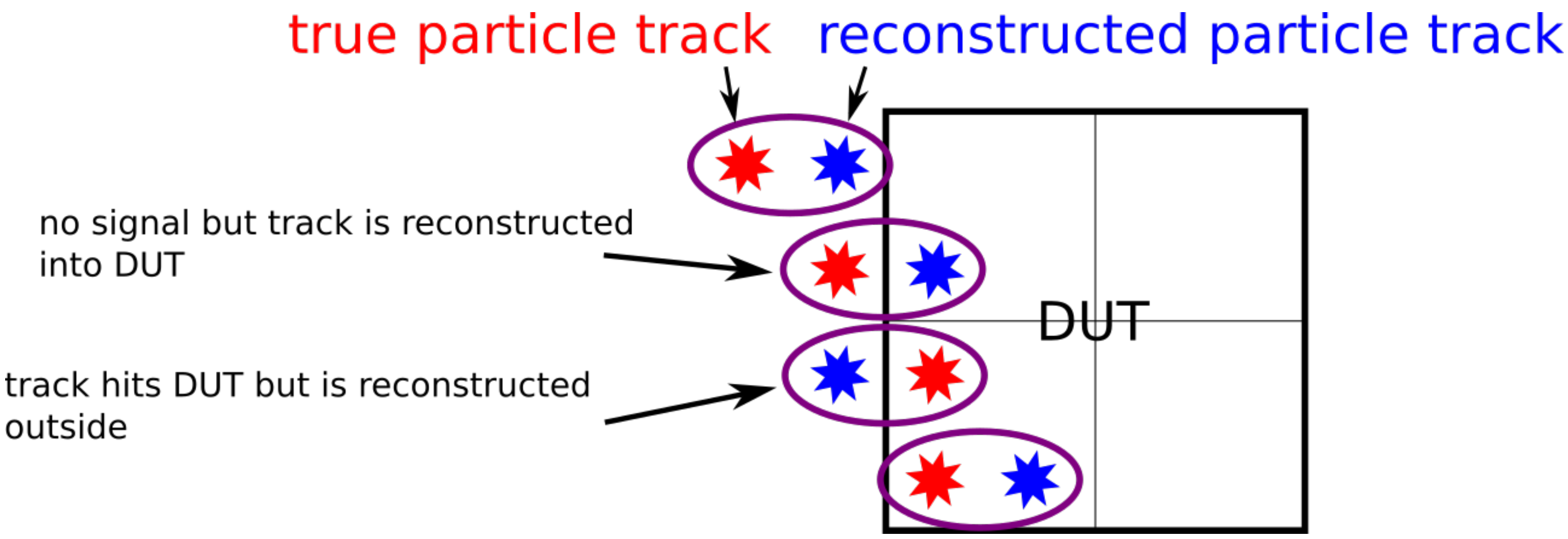
- In order to calculate the efficiency of the DUT, it **must first be located in the region of interest (ROI)**
- Size and shape of the DUT are known, so the DUT is positioned inside ROI in such a way that it **encompasses the maximum number of tracks** with a DUT signal





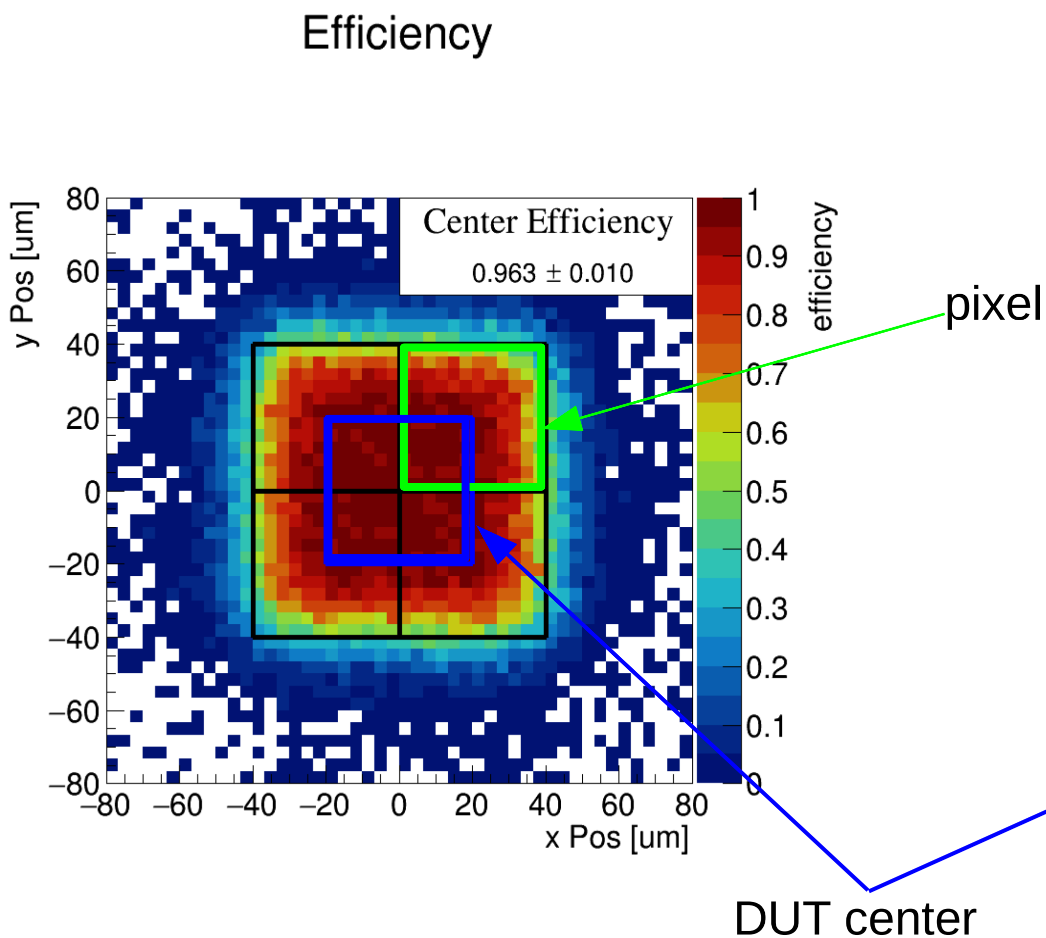
Edge effects

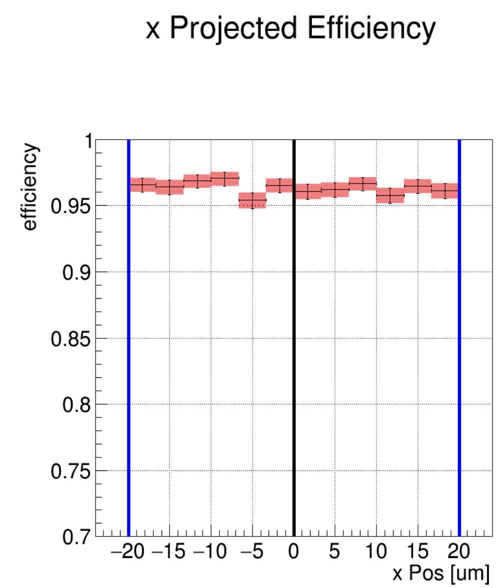
- Edge effects are considerable
  - Telescope resolution has same OOM as DUT dimensions
  - Efficiency only unaffected in the center of the DUT

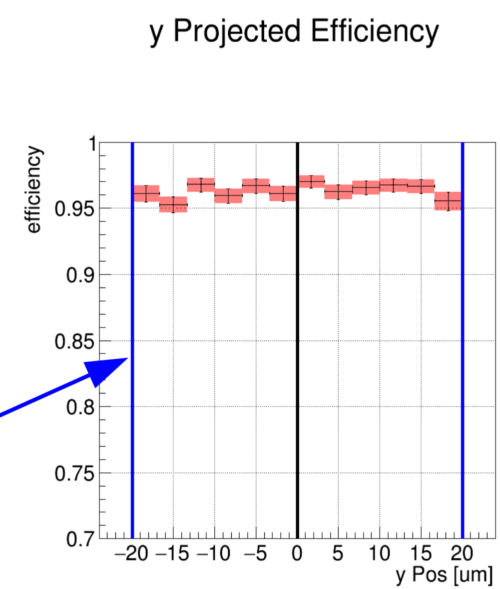


First Results - M112

- Pixel size of 40x40µm^2
- Unirradiated
- **Preliminary** selection inefficiency: **0.4%**

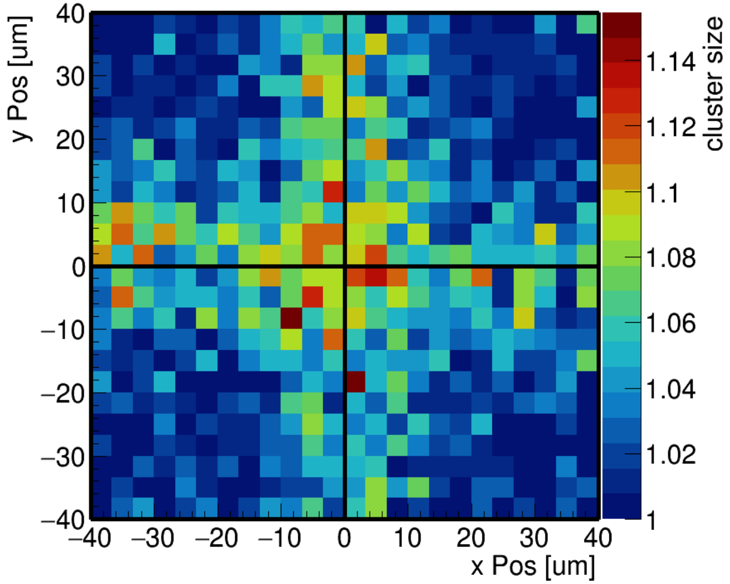




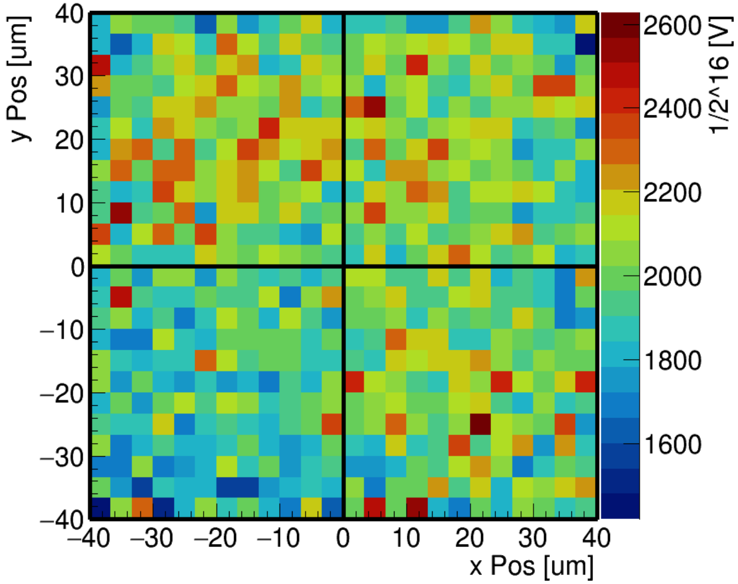


First Results - M112

DUT position resolved cluster size

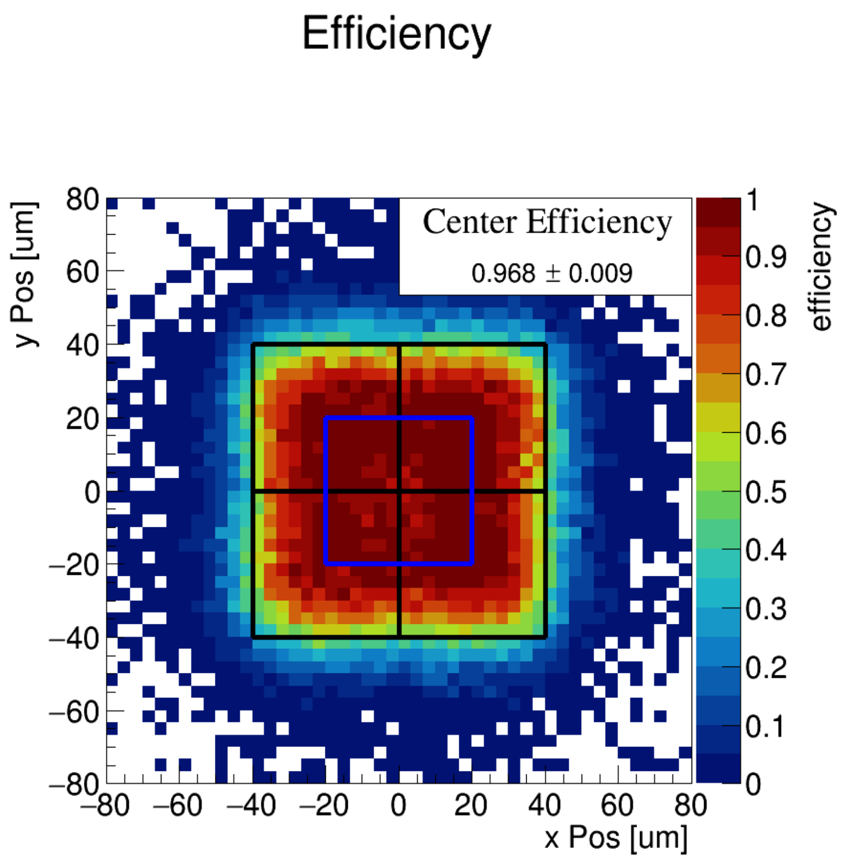


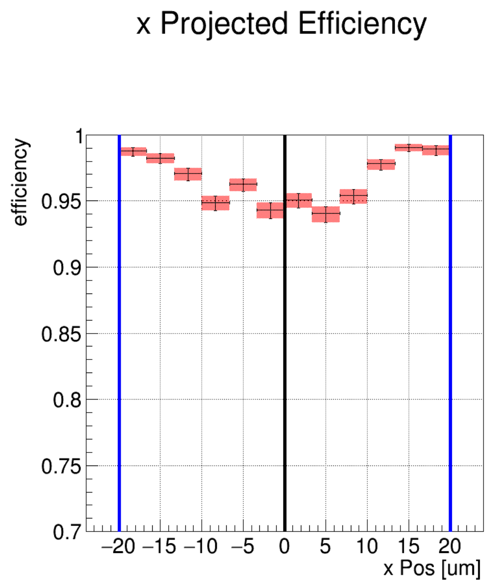
DUT position resolved amplitude size

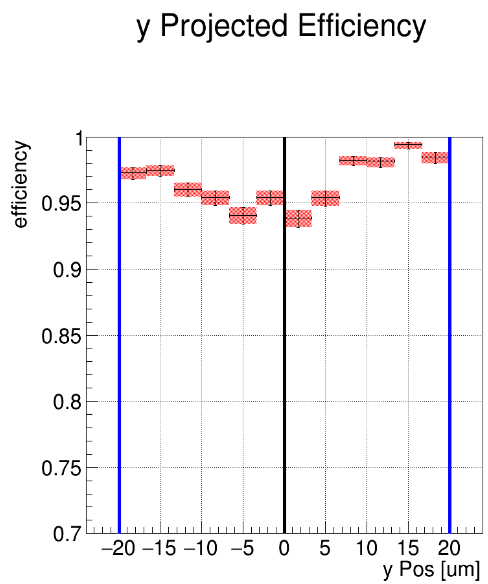


First Results - M112

- Pixel size of 40x40µm^2
- Irradiatied to **1x10^{15} n$_{eq}$/cm^2**
- **Preliminary** selection inefficiency: **0.4%**

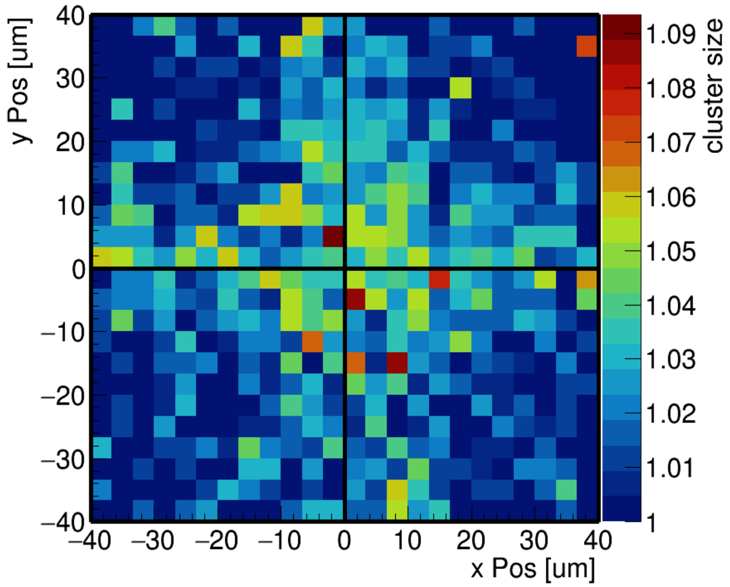




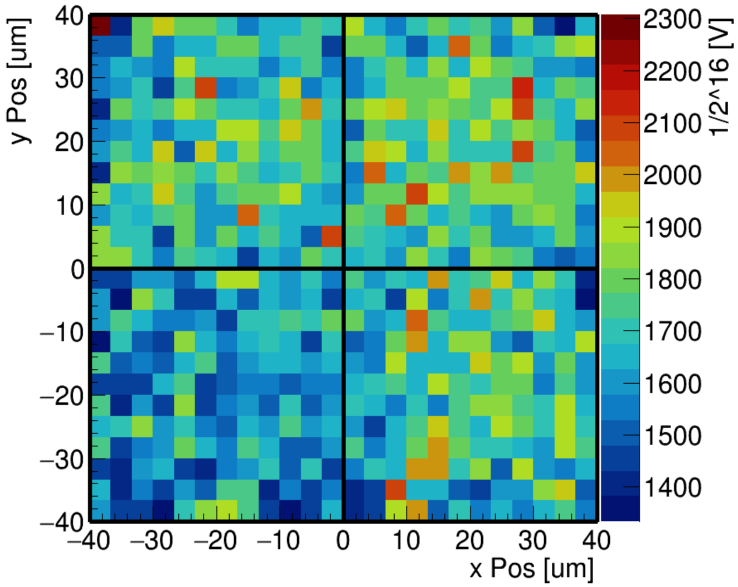


First Results - M112

DUT position resolved cluster size

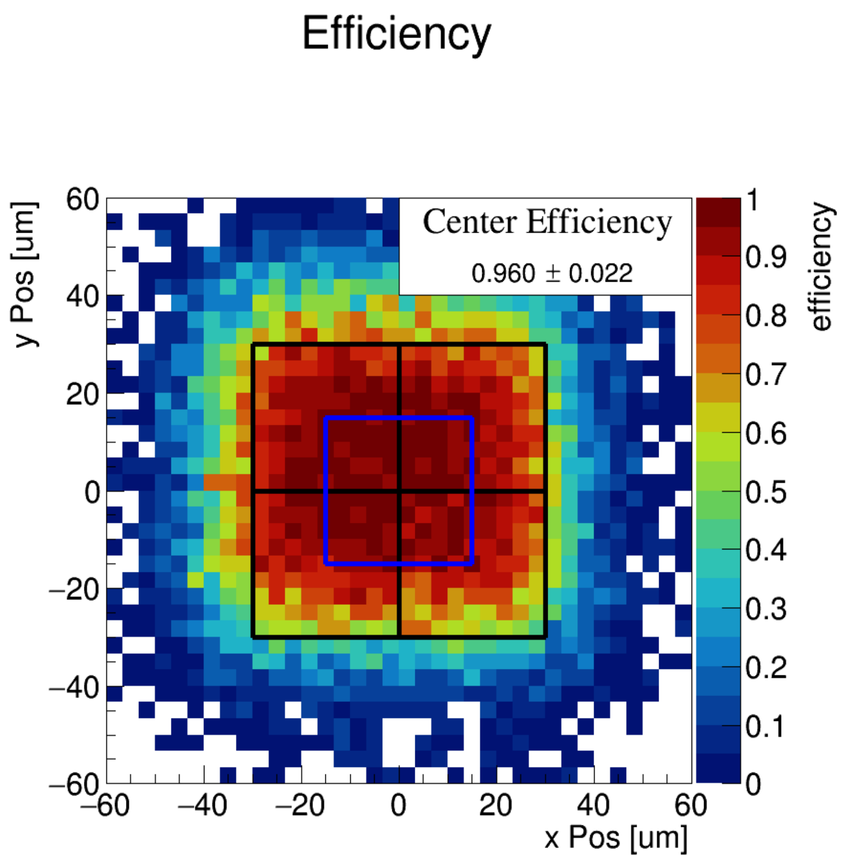


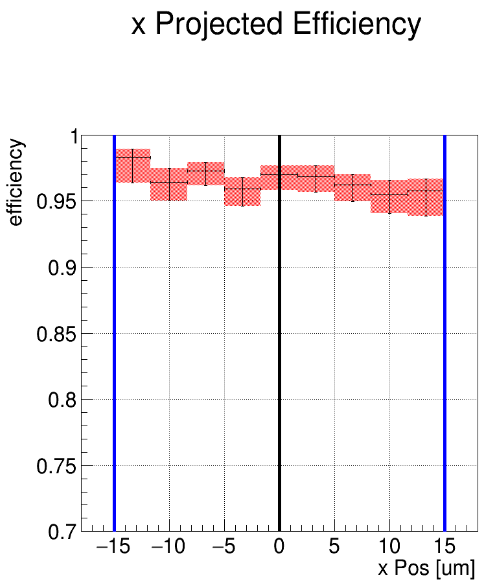
DUT position resolved amplitude size

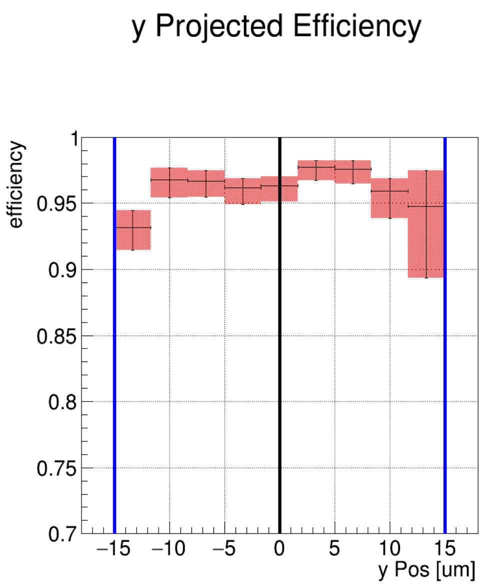


First Results - M106

- Pixel size of 30x30µm²
- Unirradiated
- **Preliminary** selection inefficiency: **0.4%**

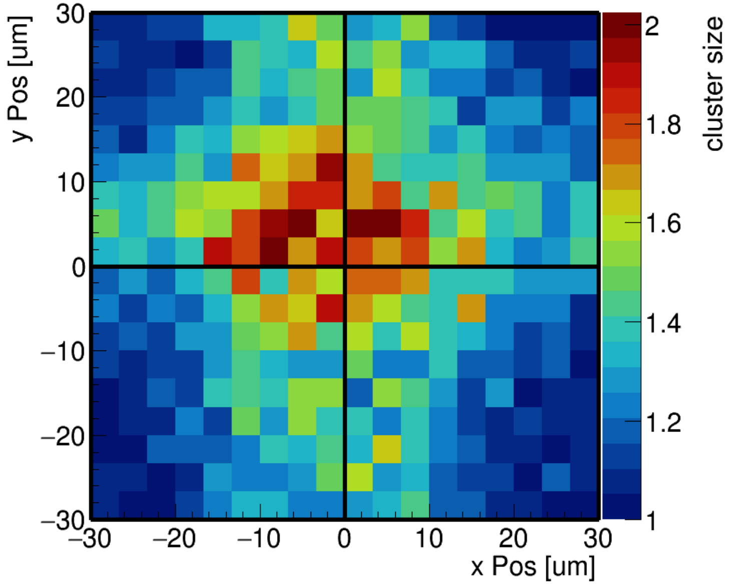




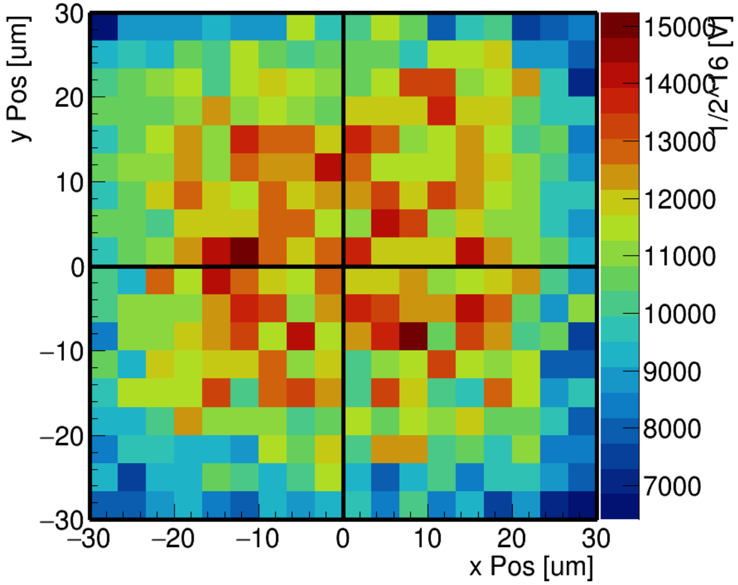


First Results - M106

DUT position resolved cluster size

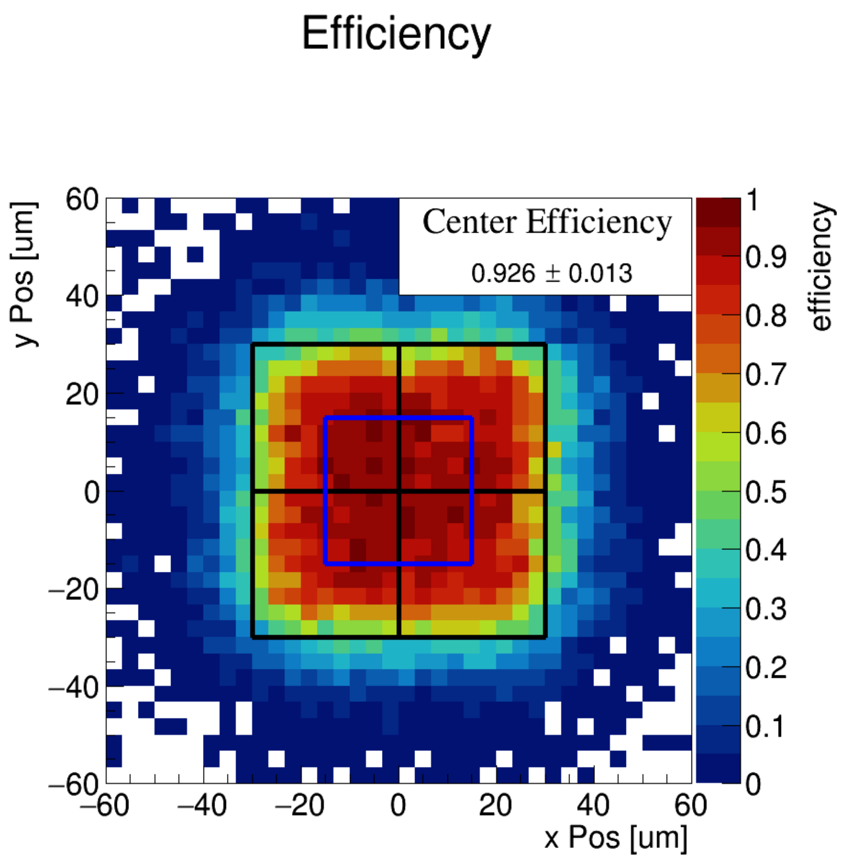


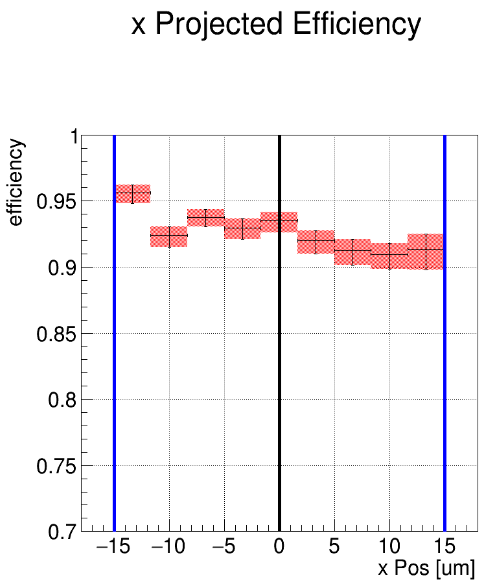
DUT position resolved amplitude size

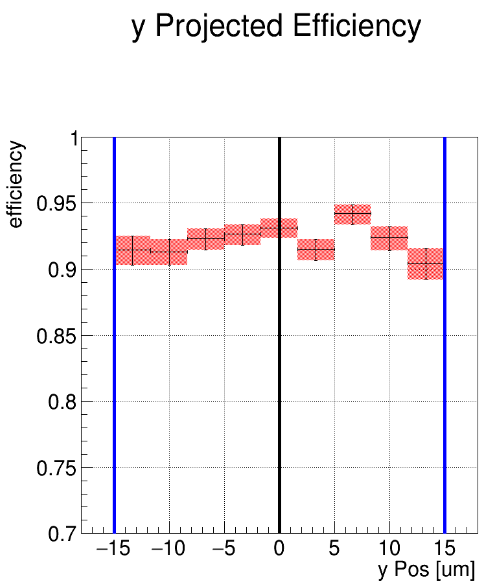


First Results - M106

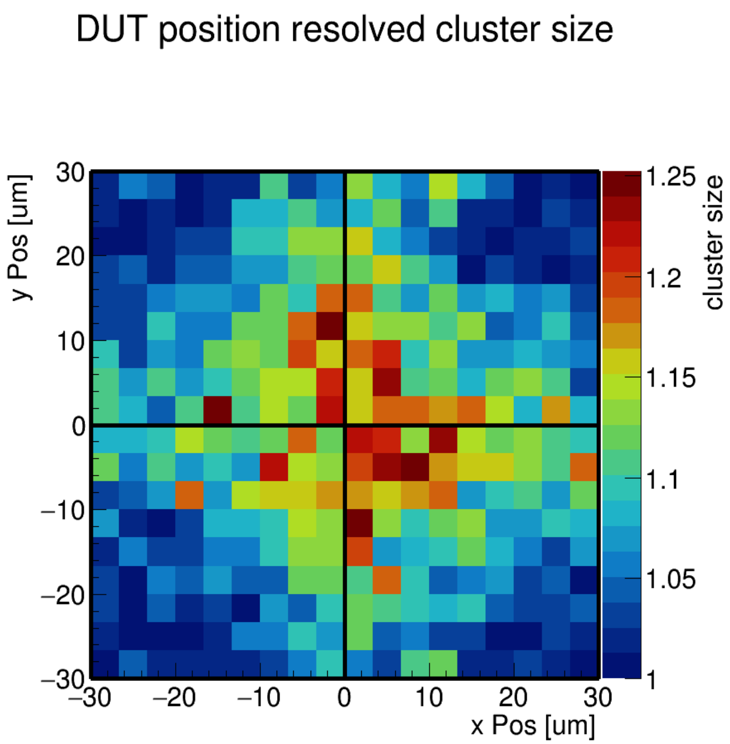
- Pixel size of 30x30μm^2
- Irradiatied to **$1x10^{15}$ n_{eq}/cm^2**
- **Preliminary** selection inefficiency: **5.04%**

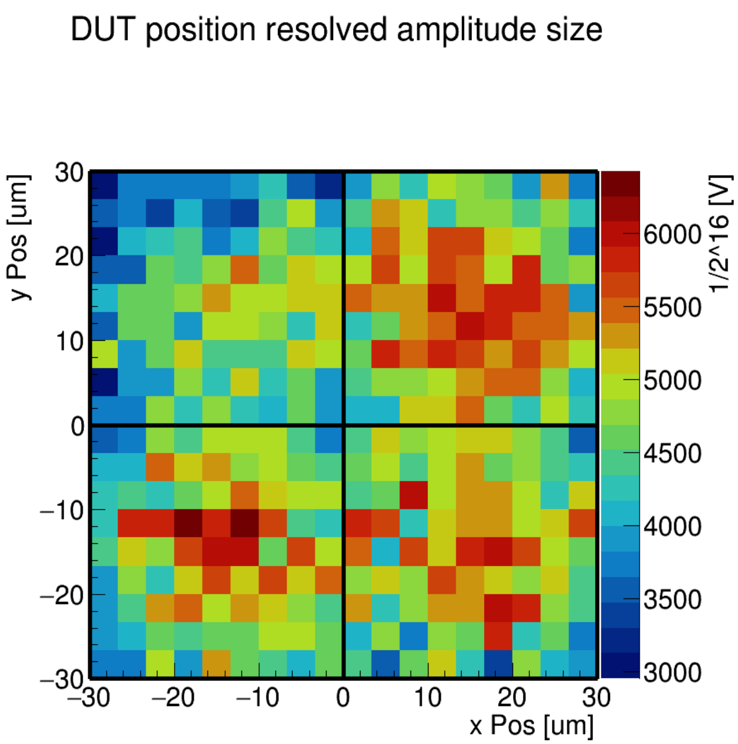






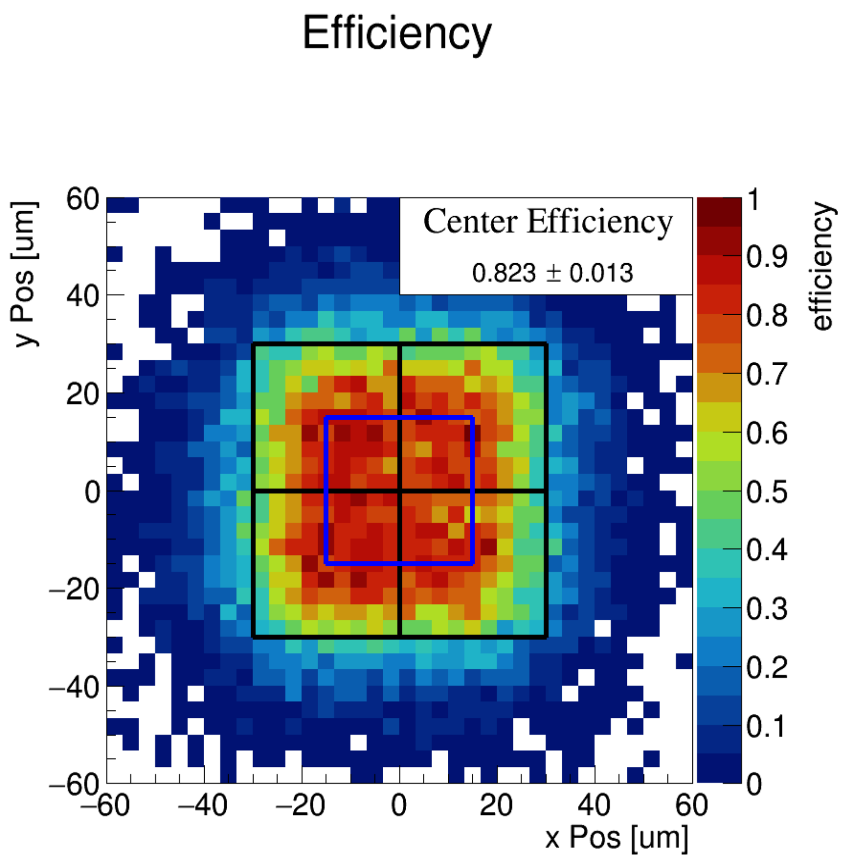
First Results - M106

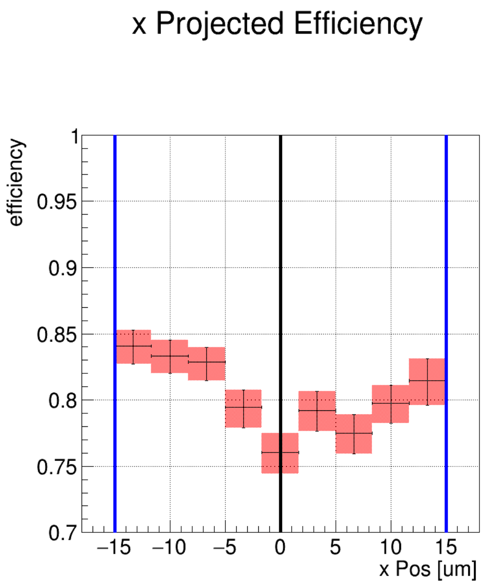


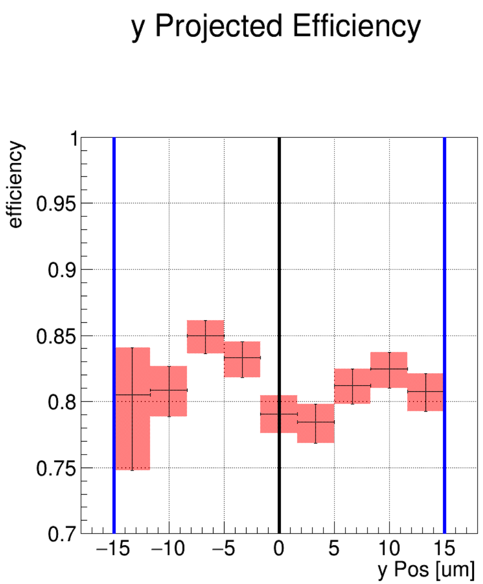


First Results - M106

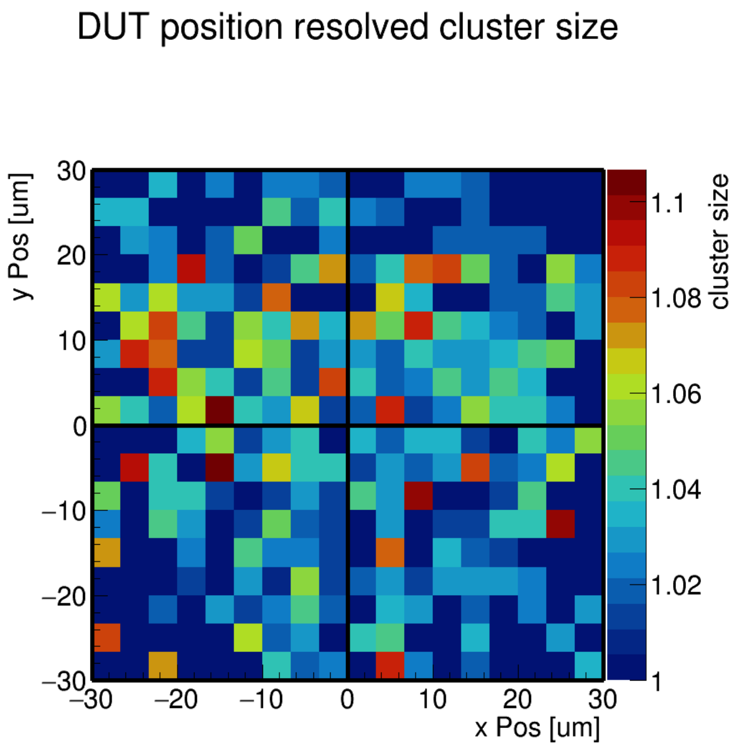
- Pixel size of 30x30µm^2
- Irradiatied to **$2x10^{15}$ n_{eq}/cm^2**
- Preliminary selection inefficiency: **13.34%**

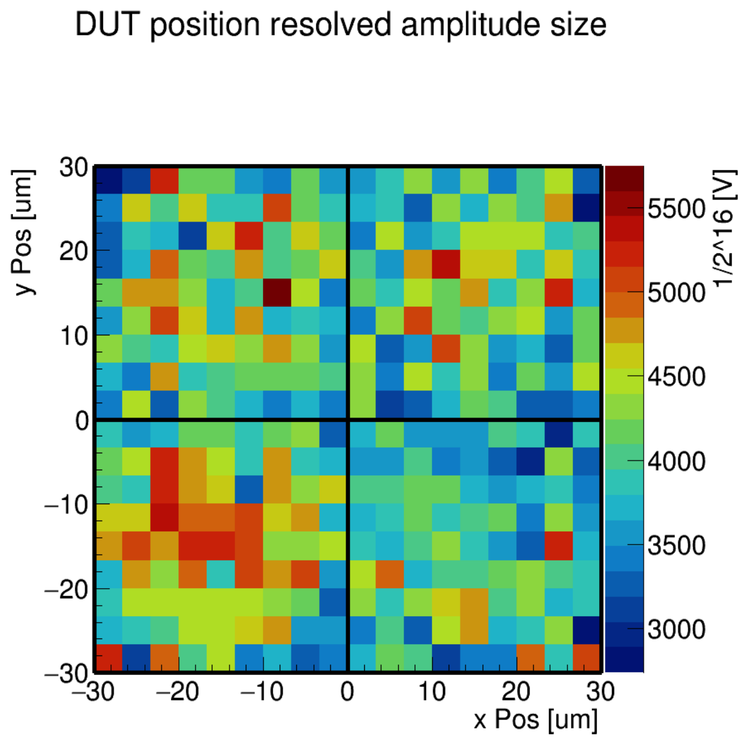






First Results - M106





Conclusion and next steps...

So far:

- Analysis chain is **set up and working**
- First results look **promising**

Next steps:

- Experimental and especially **systematic errors** must be explored further
  - Detailed study of noise and its sources
  - MC simulation to calculate selection inefficiency
- Energy calibration will be done for each pixel individually to take **different gains** into account
- Finalize detector characterization (rise time, SNR, etc.)

Thank you for your attention!

BACKUP

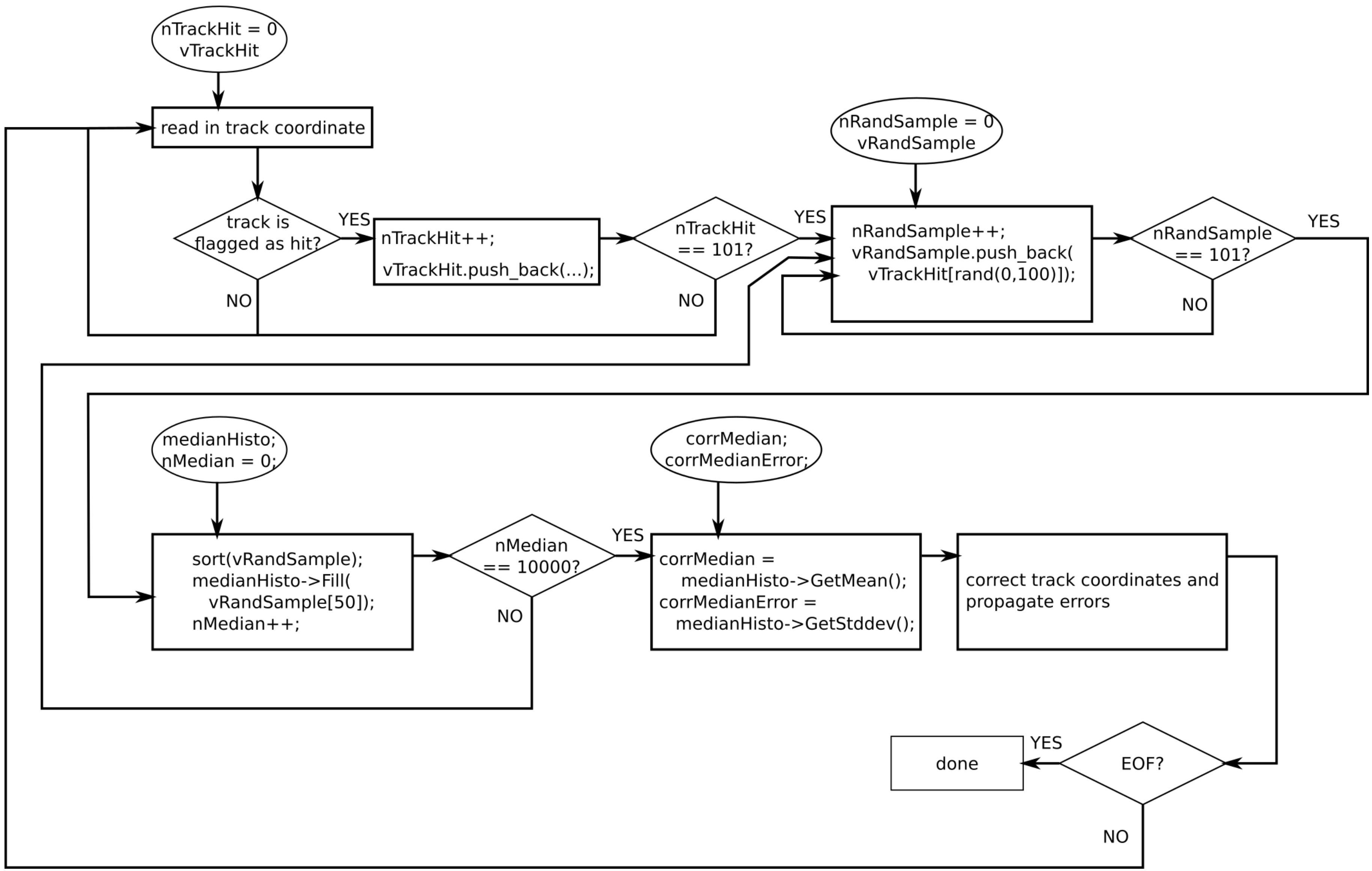
Correction for DUT movement

- It is assumed that the **DUT moves slowly** compared to the rate at which events are recorded.

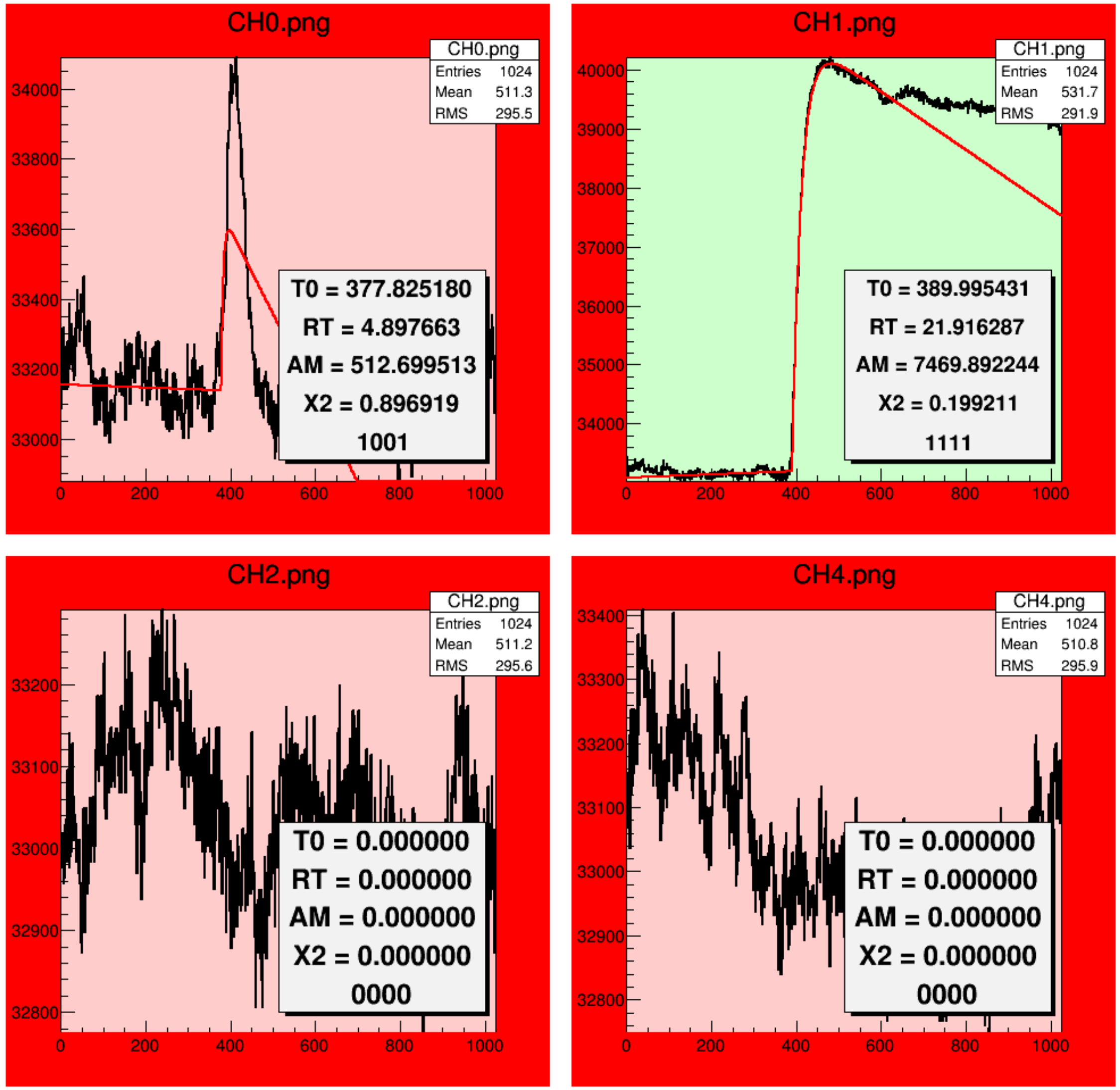
- Data from a single run is **split into time ordered “slices”**
  - A number of events is **read in until at least 100 tracks** with an associated signal from the DUT are found
  - From this set of events the **median of the track coordinates** and its error is calculated (for both x and y direction)
  - The coordinates of each track of this set of events are then **corrected by subtracting the median** value
  - The median error is added in quadrature to the track position errors

- This procedure **increases the error on track positions** and reduces the effective resolution of the telescope

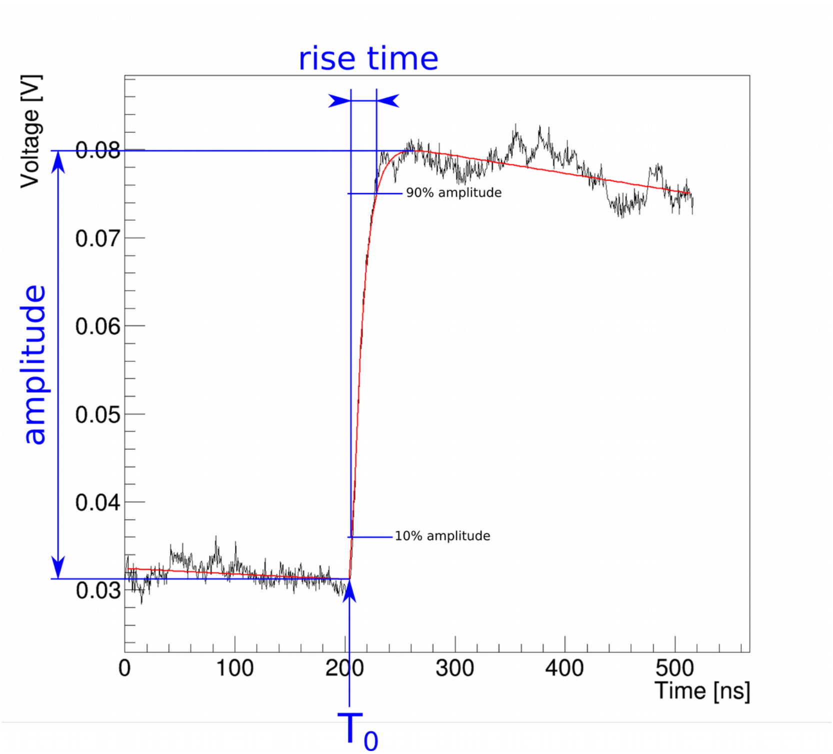
Correction for DUT movement



Channel Crosstalk



Waveform analysis

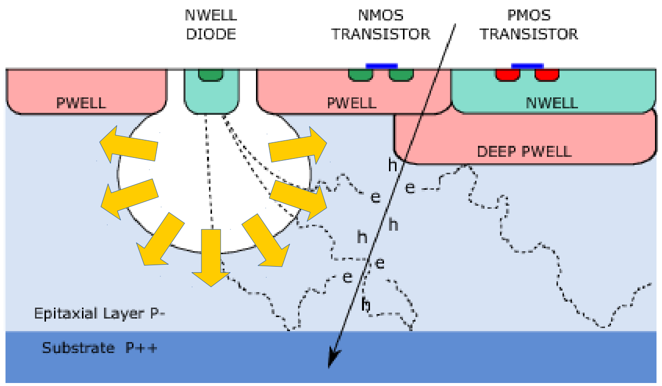


$$t < T_0: \qquad x_1 + t\,x_2$$

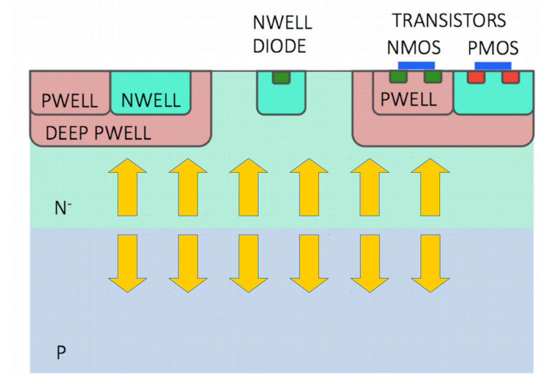
$$t \geq T_0: \quad x_3\left(1 - \exp\left(-\left(\frac{t - x_4}{x_5}\right)\right)\right)\left(1 + x_6\left(t - x_4\right)\right)$$

- x_1: offset
- x_2: slope
- x_3: amplitude (infers energy when calibrated)
- x_4: T_0
- x_5: rise time parameter (rise time = 2.2*x_5)
- x_6: pulse decay (i.e. another slope after the pulse)

Measurement goals

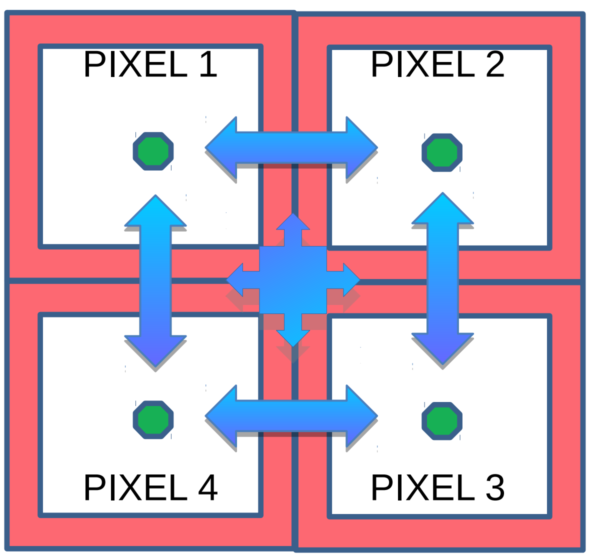


Standard TJ process



Rad-hard TJ process

- Is the **modified process** really rad-hard?
- How does it behave for different **minimatrices**?

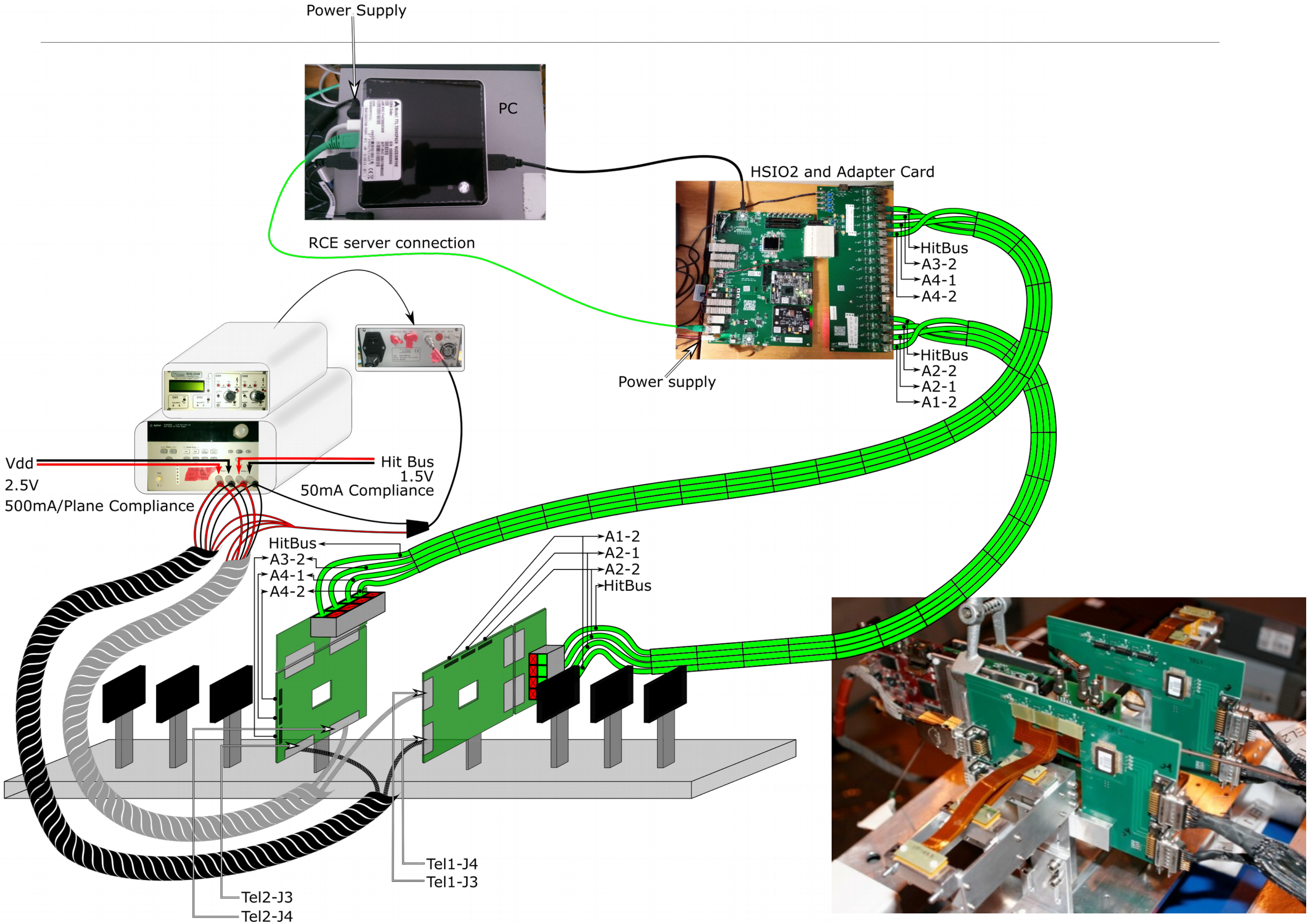


- For a given minimatrix, readout **4 pixels**
- Full **analog** information
- Measure **efficiency**

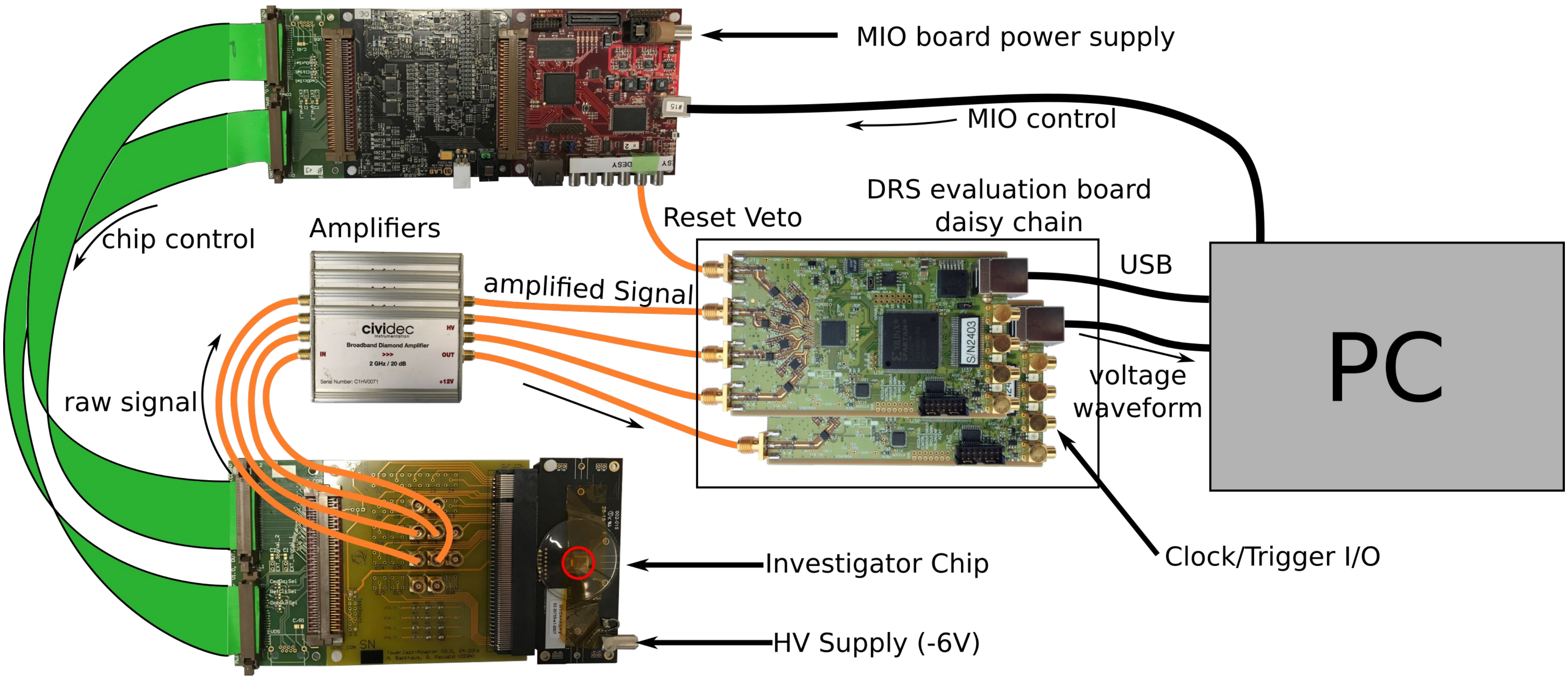
$$\eta = \frac{N^{hits}_{detected}}{N^{hits}_{total}}$$

- Are there efficiency drops at the **boundary** between adjacent pixels?
- Does efficiency drop after **irradiation**?
- How do different **minimatrices** behave?

CERN ATLAS pixel telescope



Integration of the DUT in the telescope



Correcting for edge effects

- In order to correct for edge effects, the probability p that the true track was inside the DUT is calculated for each track
- This is done by integrating a 2D gaussian over the DUT area
- The gaussian is centered around the track position and the sigmas of the gaussian are the errors of the track position
- The count of the bin where the track landed is then increased by 1/p