Particle tracking with semiconductor pixel detector Timepix

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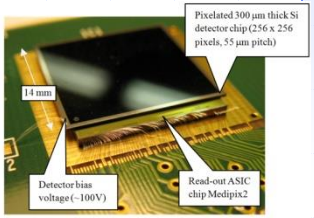
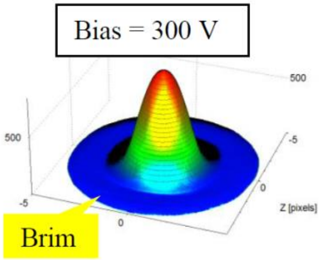
Outline

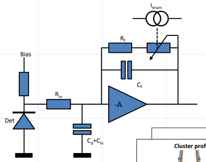
Introduction & Motivation

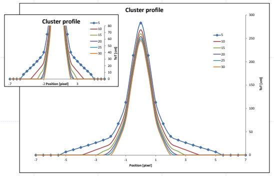
- Recorded unexplained properties of Timepix device
  - Energy calibration
  - Cluster shape
- Understanding pulse shape => calibration
- Understanding charge collection => cluster shape
- Full model

Summary and conclusions









Timepix pixel device
single particle counting pixel detector

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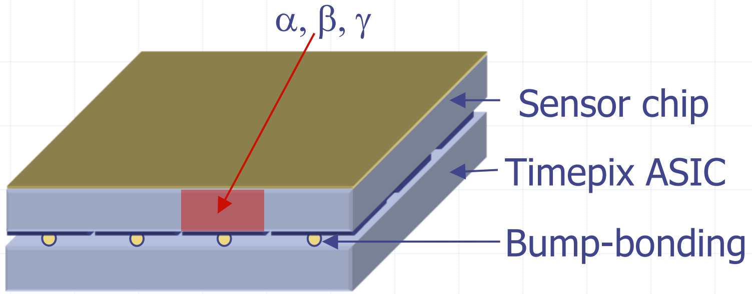
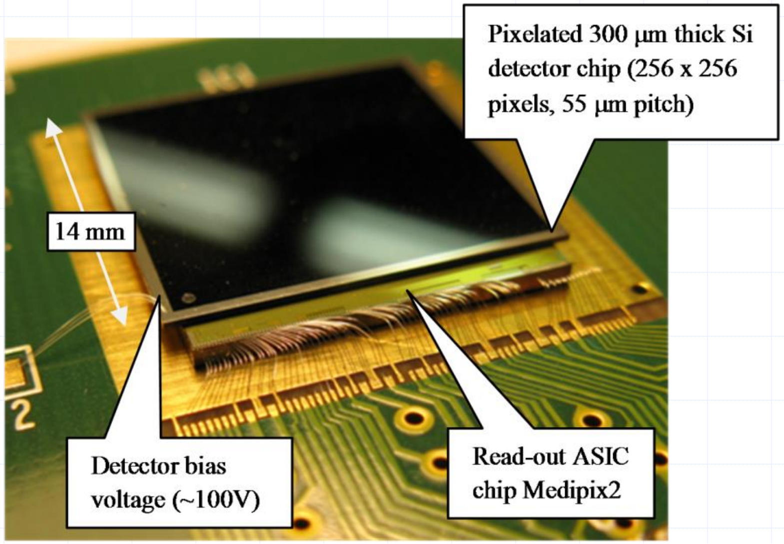
- Planar pixelated semiconductor sensor (Si, GaAs, CdTe, thickness: 150/300/700/1000 μm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or **ADC** or Timer
- Features:
  - ✓ 256 x 256 pixels
  - ✓ 55 μm pixel pitch
  - ✓ 14 bits/pixel
  - ✓ Minimal threshold: 3.5 keV





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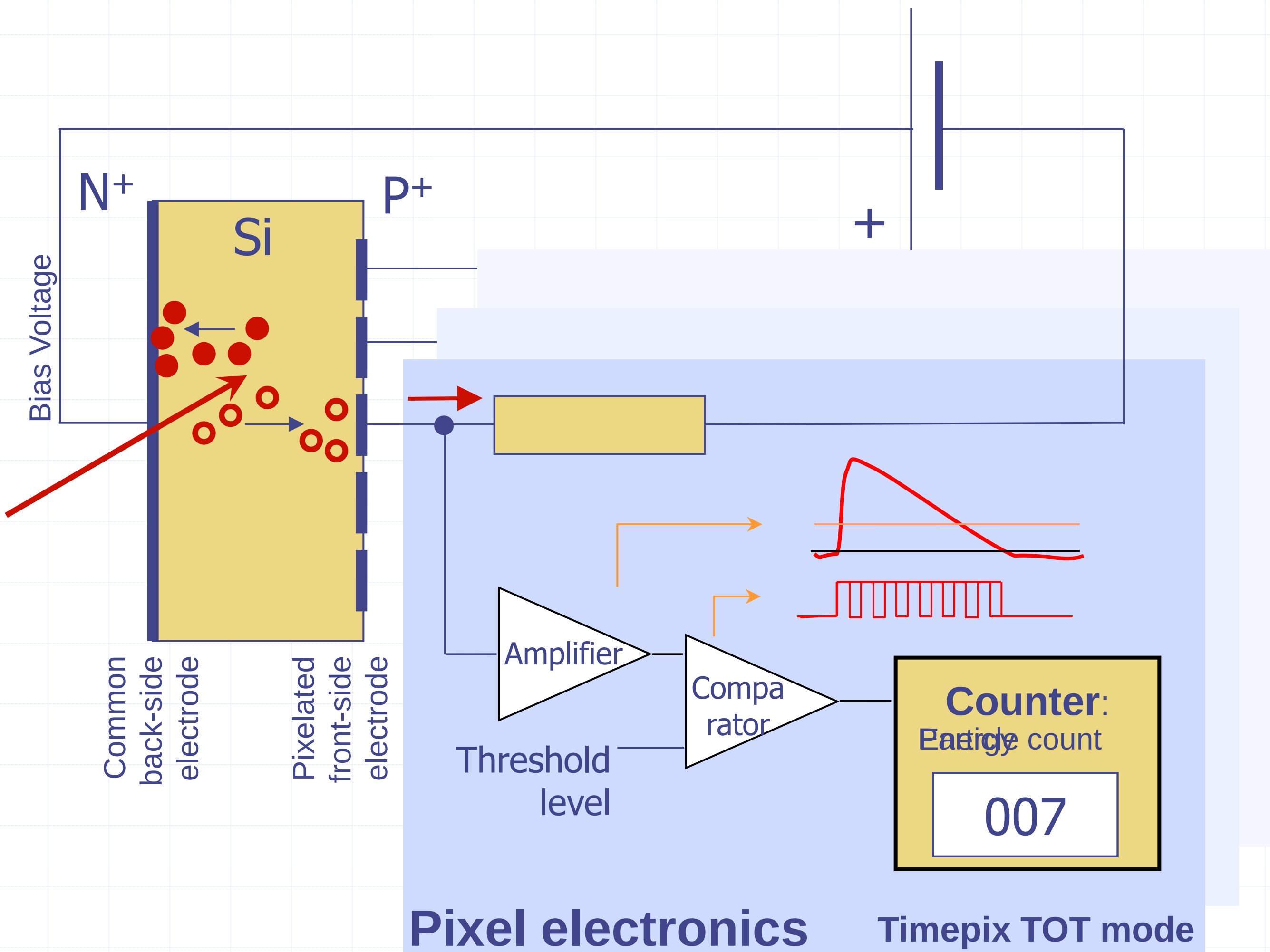
Semiconductor single quantum counting pixel detector



Threshold level above electronic noise
⇒No false counting.

Digital integration (counting)
⇒ No dark current.

Unlimited dynamic range and exposure time.

Detected count obeys poissonian distribution

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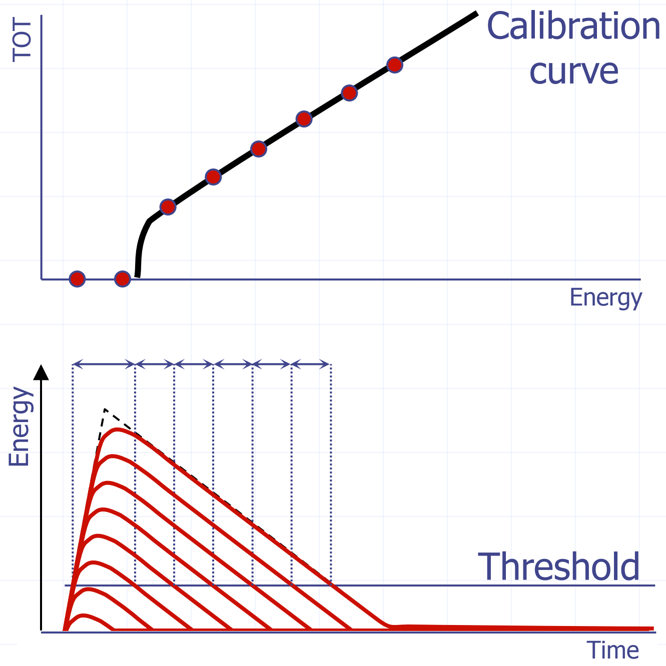
TimePix and its TOT mode

Counter in each pixel can be used as Wilkinson type **ADC** to measure energy of each particle detected.



- If the pulse shape is triangular then Time over Threshold is proportional to collected charge i.e. to energy.
- Due to limited bandwidth the pulse can be NEVER perfectly triangular.
- **Non-linear TOT to energy dependence**

Basic per pixel calibration

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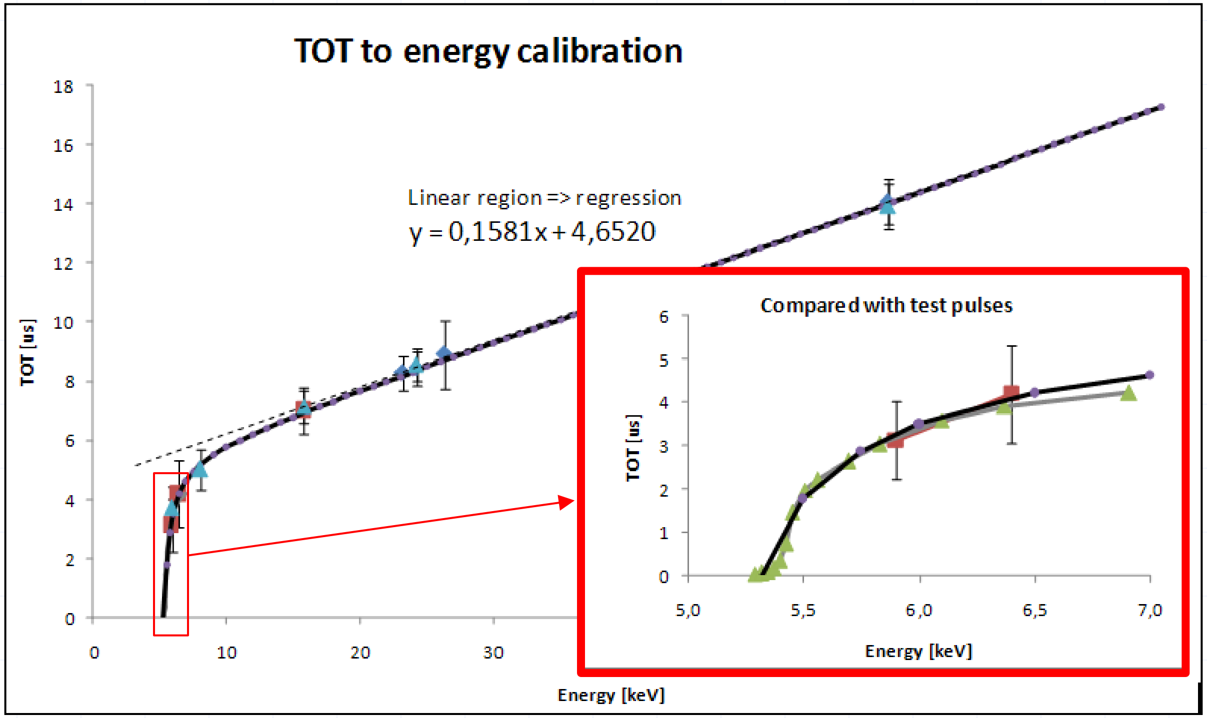
$$f(x) = ax + b - \frac{c}{x - t}$$

Meaning of parameters:

a,b – linear regression in high energy range
c – curvature (bandwidth related)
t – threshold related



Parameters computed Using global calibration data:

a=0.158
b=4.65
c=2.4
t=4.86

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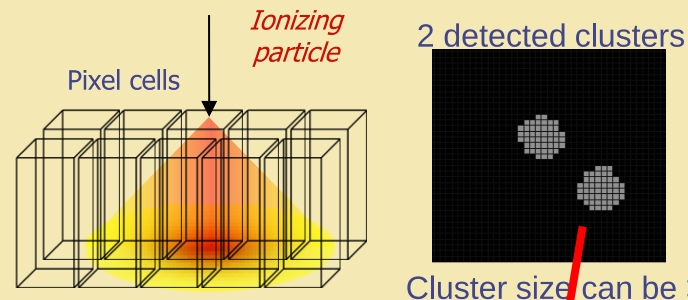
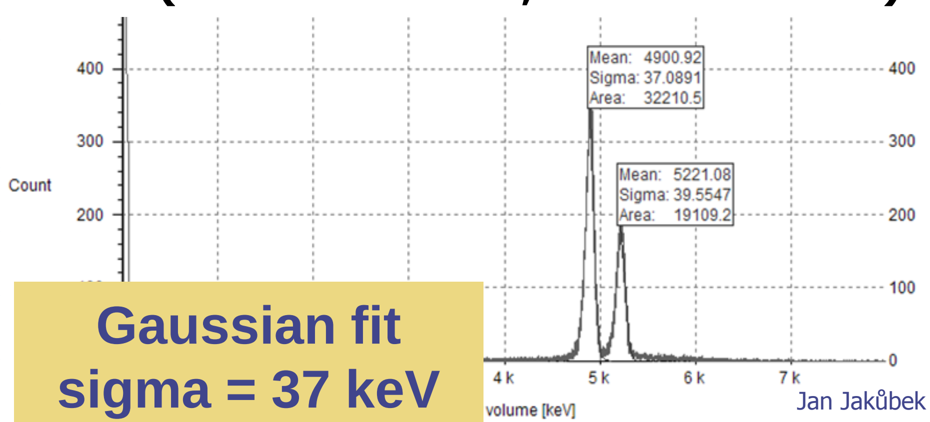
Heavy charged particles:
Charge sharing effect

- Particle creates a huge charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- The charge cloud expands (diffusion, repulsion, …)
- The charge cloud overlaps several adjacent pixels => **CLUSTER**
- Pixels overlapped by the charge cloud detect the charge if it is higher then threshold.

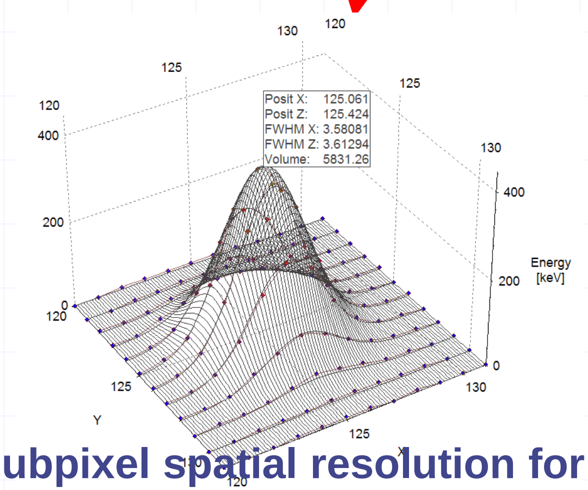
Ionizing particle can creates huge charge signal in several adjacent pixels forming **cluster**.
Cluster volume depends on particle energy.



Am241+ Pu239 combined alpha source (5.2 and 5.5 MeV, measured in air)



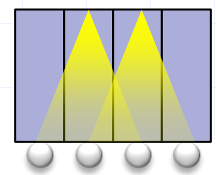
Gaussian fit sigma = 37 keV



Subpixel spatial resolution for 10 MeV alphas is 320 nm !!

Calibration for large charge?

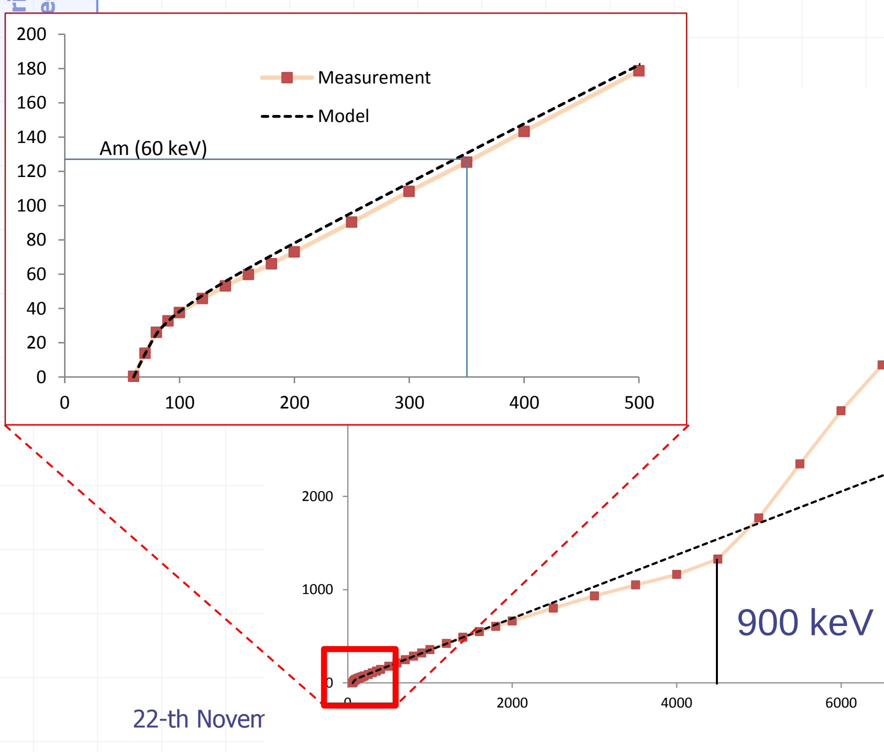
- We cannot use ions for calibration as their charge spreads over many pixels and we don't know precise charge cloud shape
- Alternative method: Visible light (short and bright LED flashes)

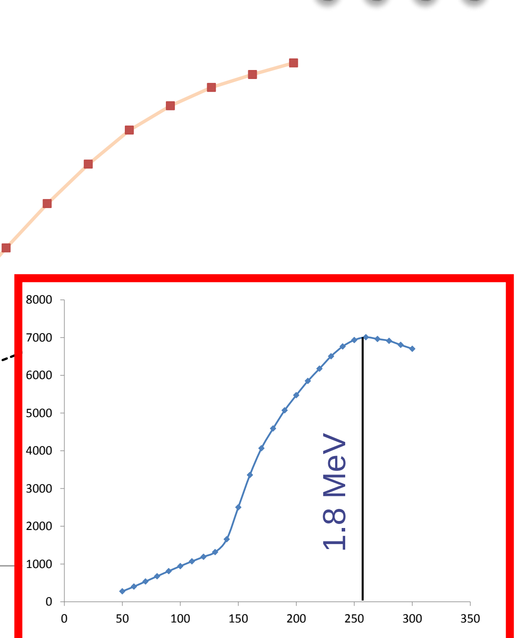


LED diode flash illuminates many pixels

Advantage:

Influence of charge sharing effect is canceled !!





Not understood behaviour of Timepix in ToT mode in some situations

1. Calibration dependence on threshold

2. Distorted cluster shapes for highly ionizing particles (ions).

Threshold dependence of Energy calibration in ToT mode

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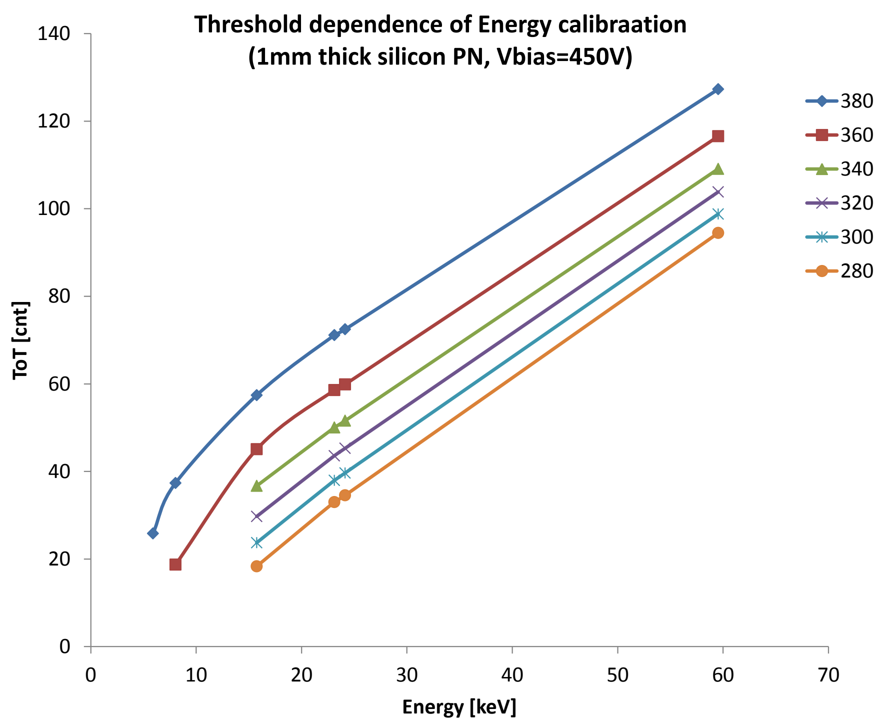

Measured with:

^{55}Fe	5.899 keV
Cu	8.04 keV
Zr	14.744 keV
Cd	23.106
In	24.136
^{241}Am	59.541

Doesn't work: Too simple

Simplified pulse shape

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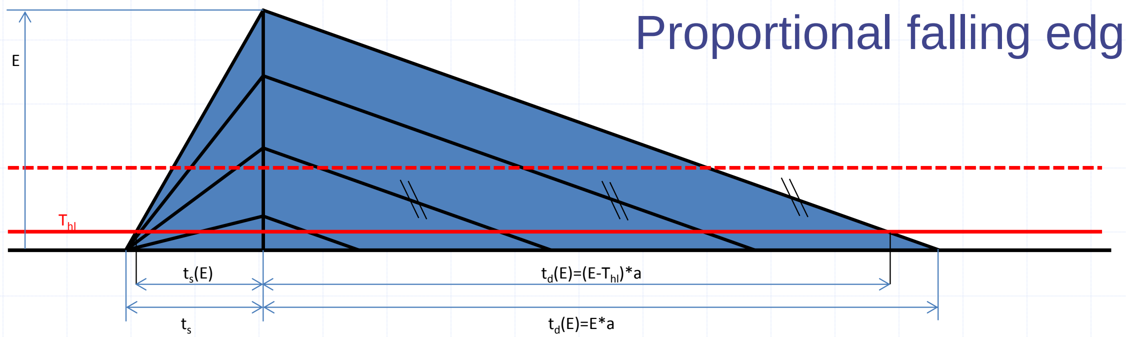
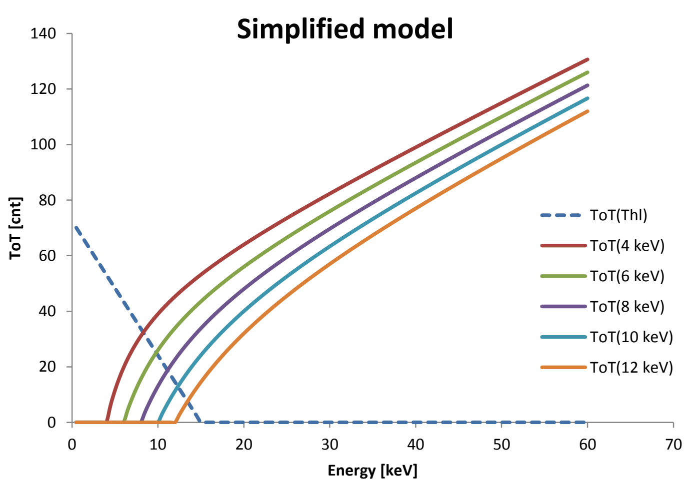
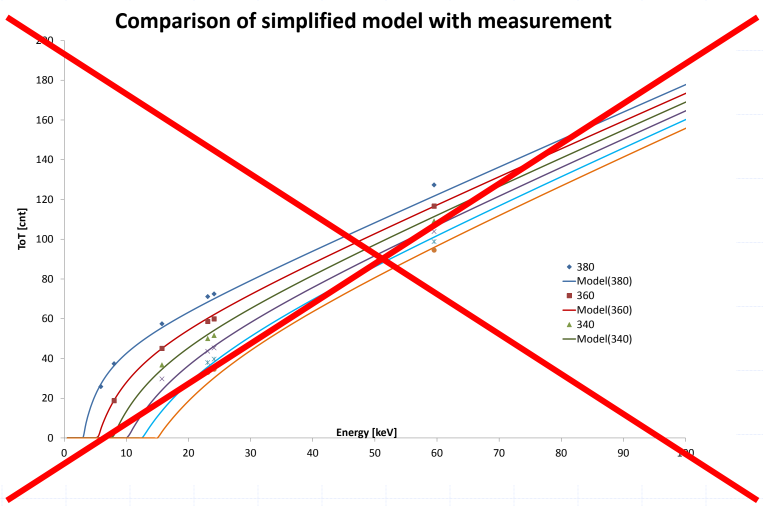
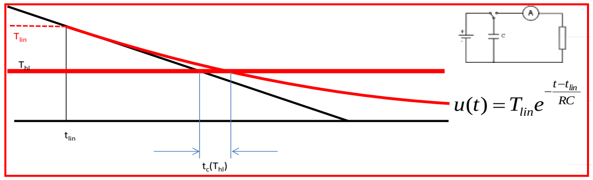
Constant duration of leading edge
Proportional falling edge

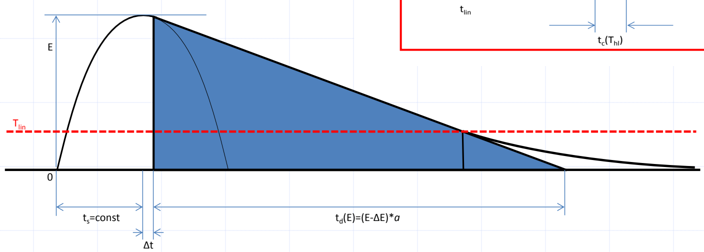


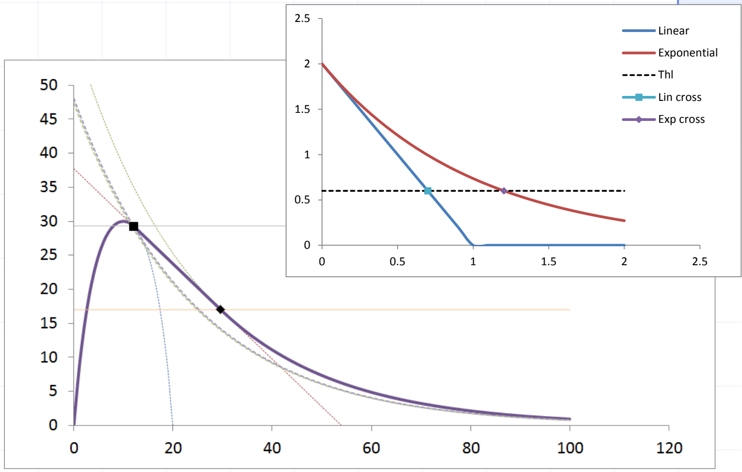


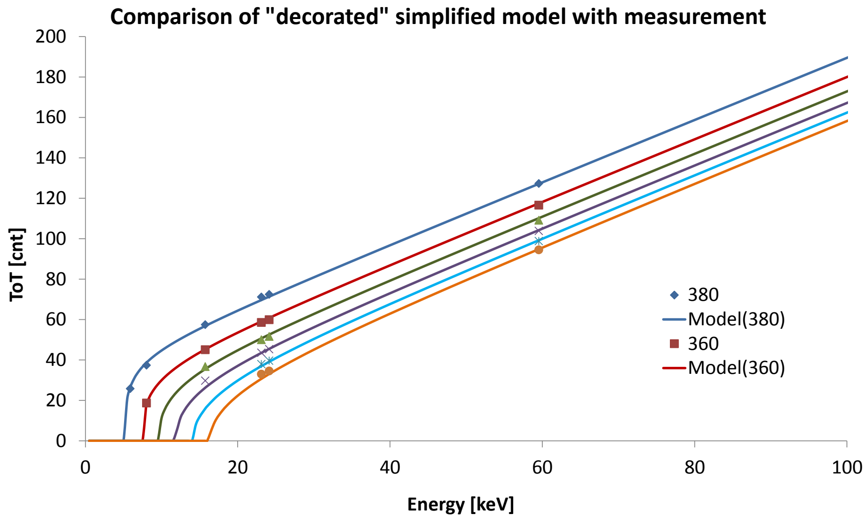


"Decorated" pulse shape: - Limited bandwidth and exponential decay









Good fit !!!

Well, it is pure heuristics.
What about more rigorous approach?

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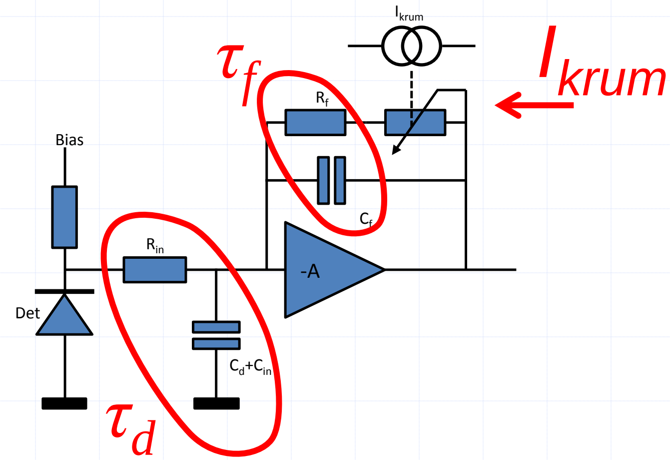
The more realistic model of preamplifier and comparator has to be based on its real functionality:

- Input RC constant
- Feedback RC constant
- Constant current source (Ikrum) discharging feedback capacitor
- The Ikrum source closes itself when signal is close to baseline (to avoid undershot).



Charge sensitive amplifier model created and tested with test pulse (step)

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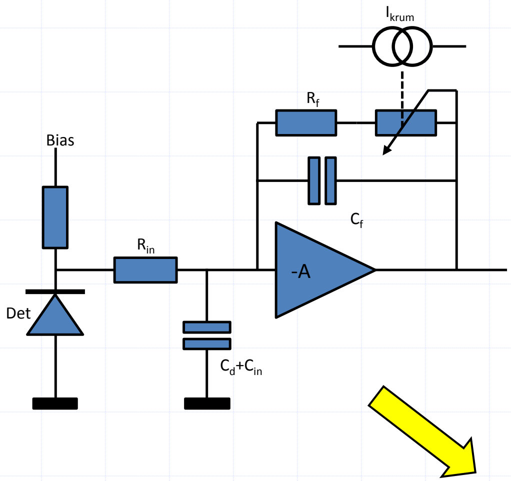

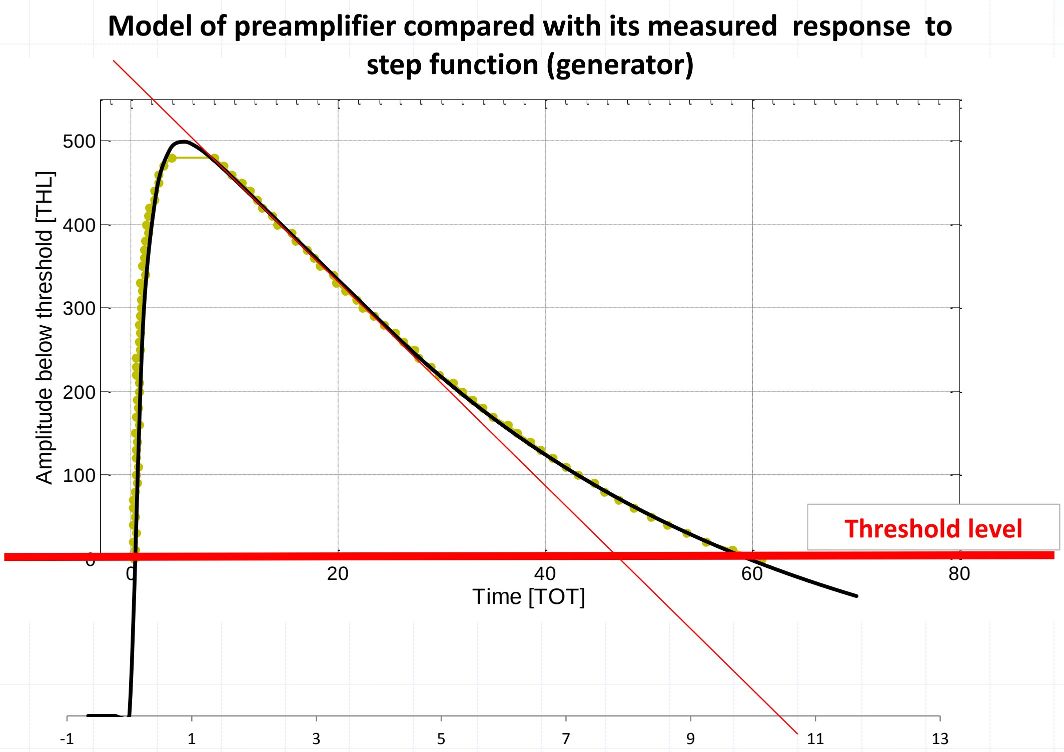

Pulse shapes and TOT calibration functions for delta function

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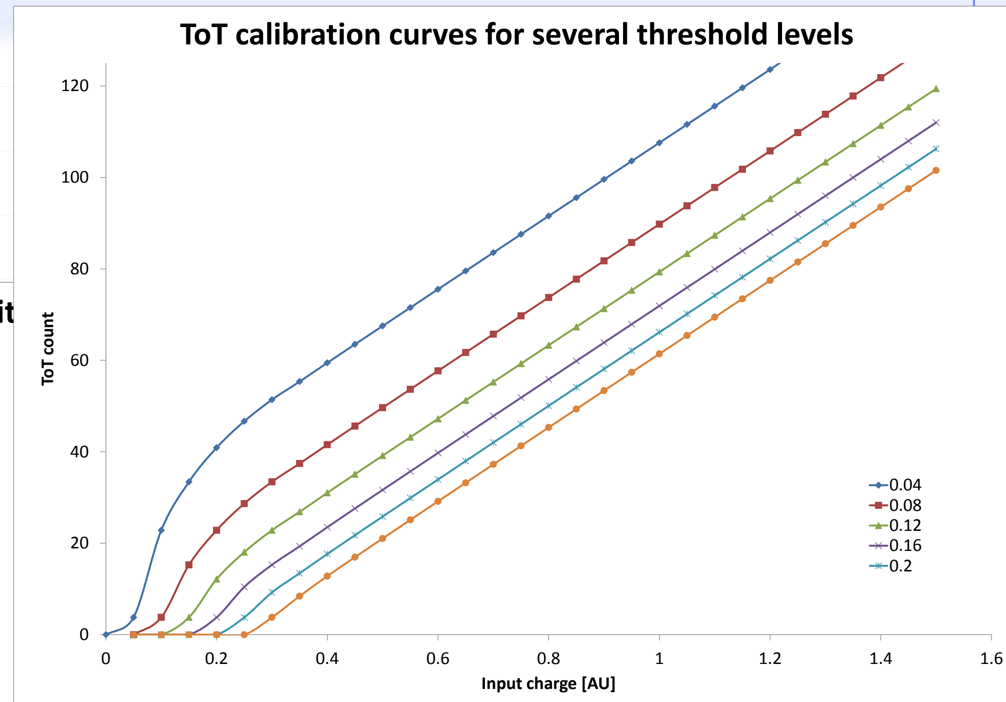

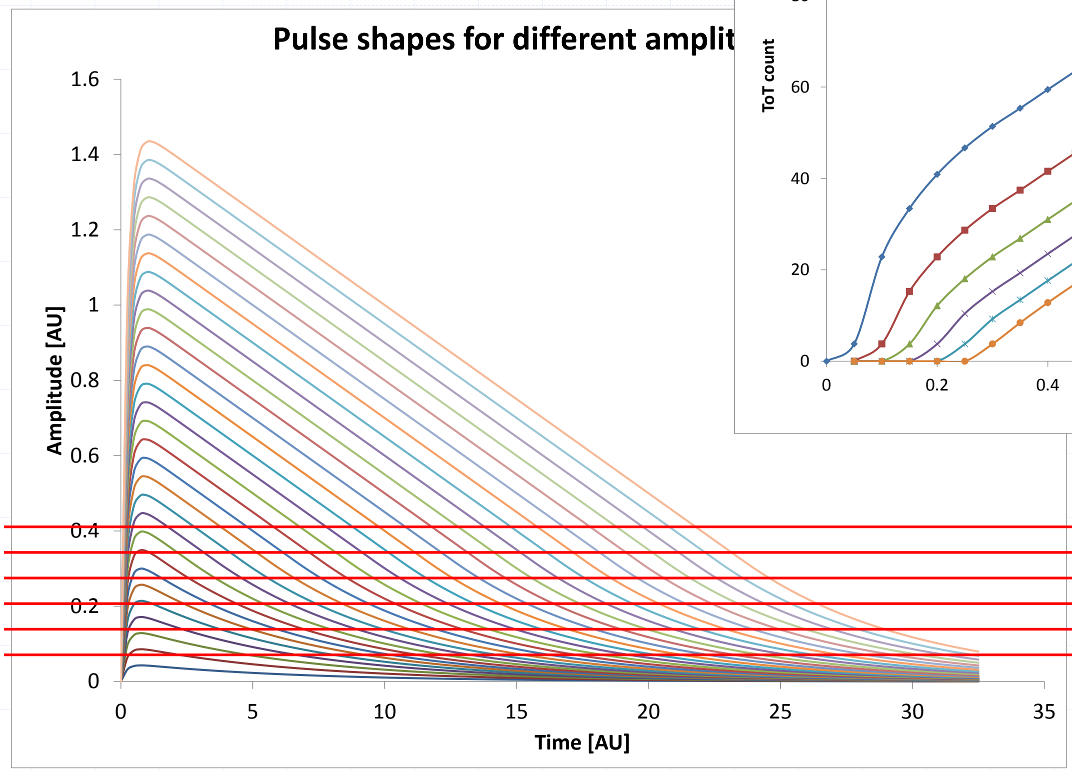

Good, but what about real input signal from sensor?

Consequence:
Energy resolution depends on threshold

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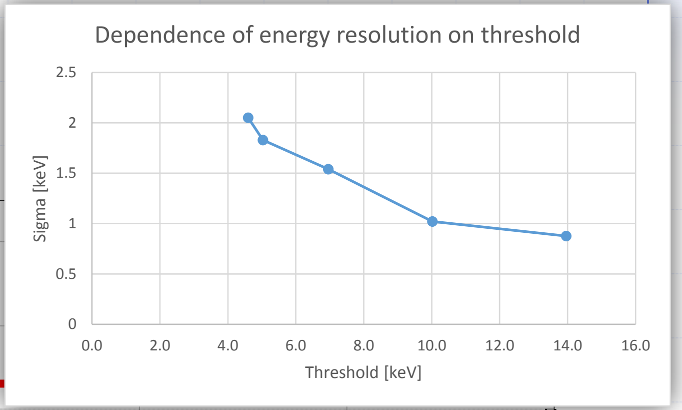
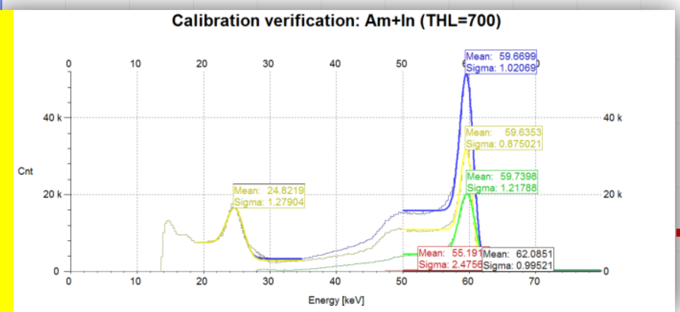
The energy determination is performed via time measurement
Since the signal shaping is irregular but noise is constant
=> The time measurement precision depends on threshold

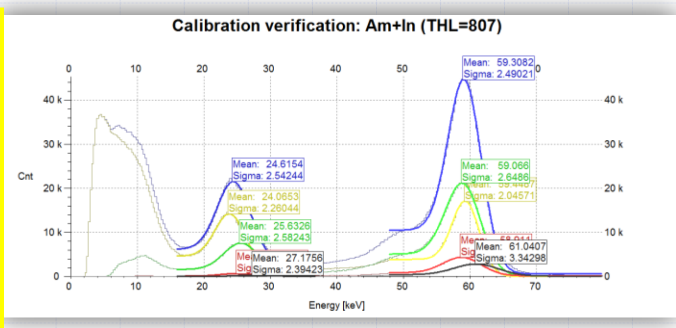


THL=14 keV

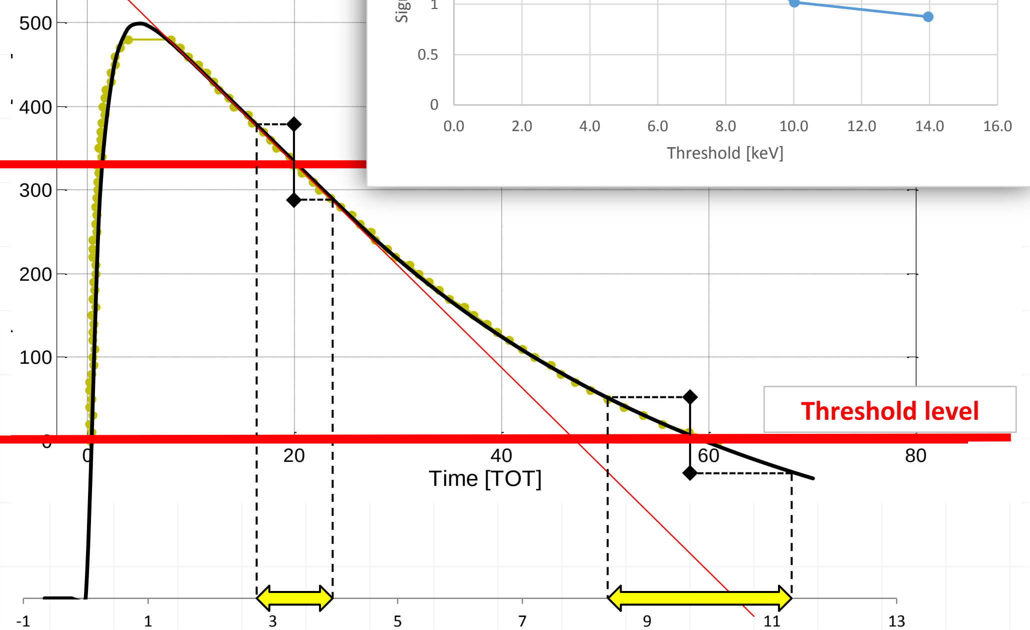


ρ=1.0 keV

THL=4.5 keV



ρ=2.5 keV



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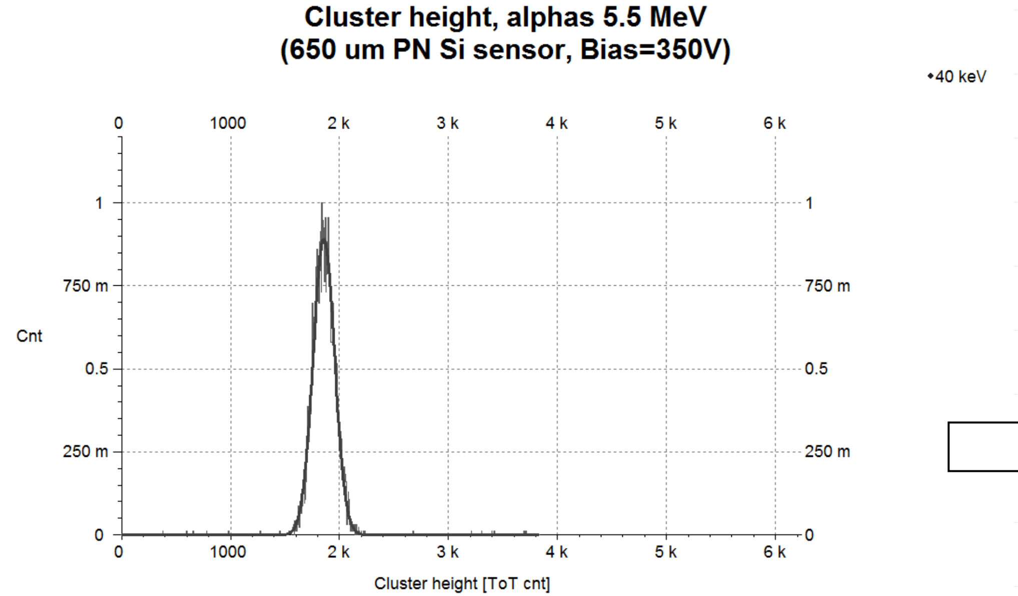
Further issues:
Saturation at high energies? – No Overshot

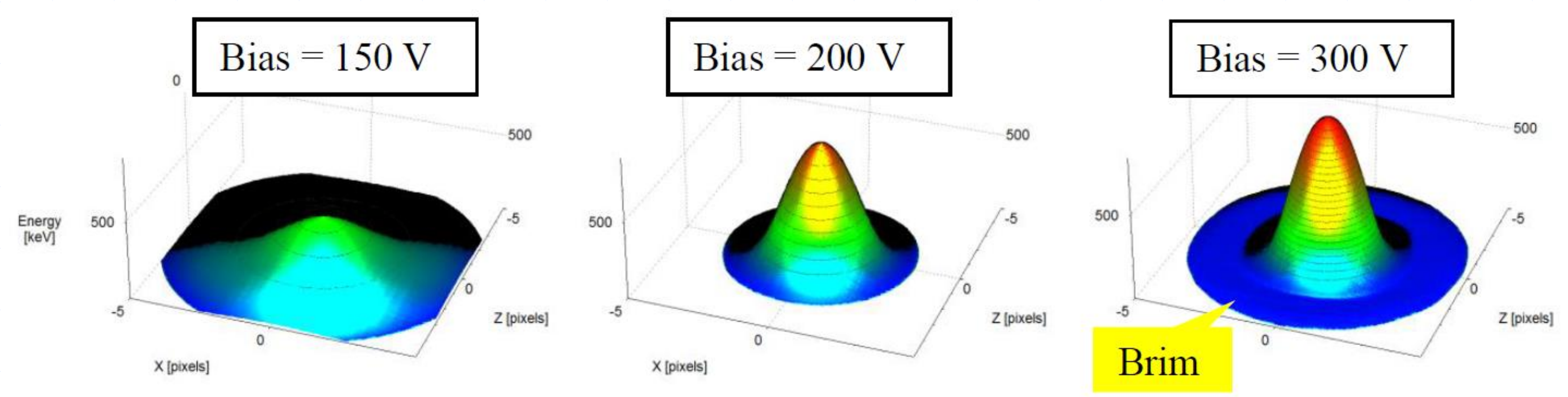
In high energy range (e.g. ions) the signal starts to grow faster
How does this effect depend on threshold?

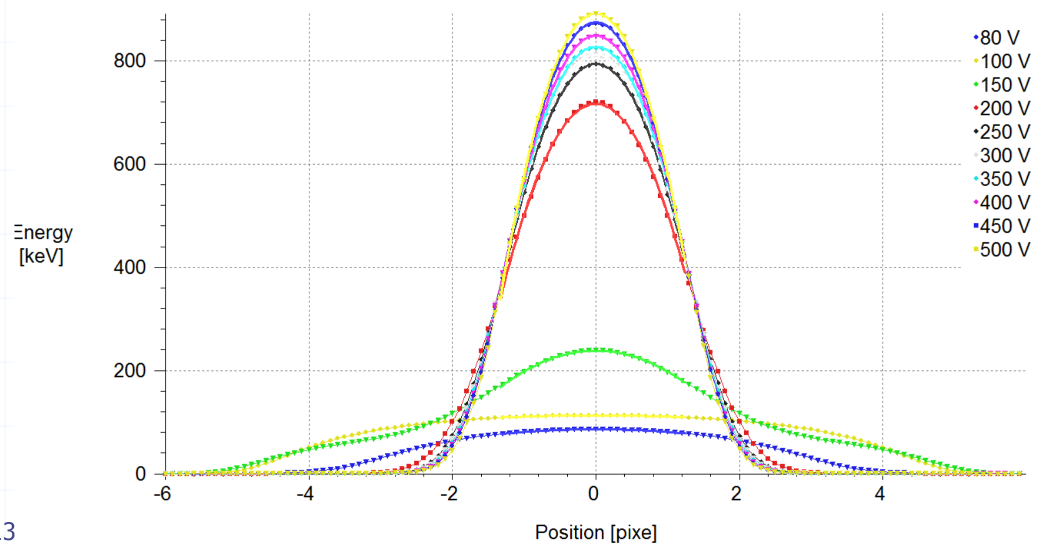


But first let us describe the second problem:

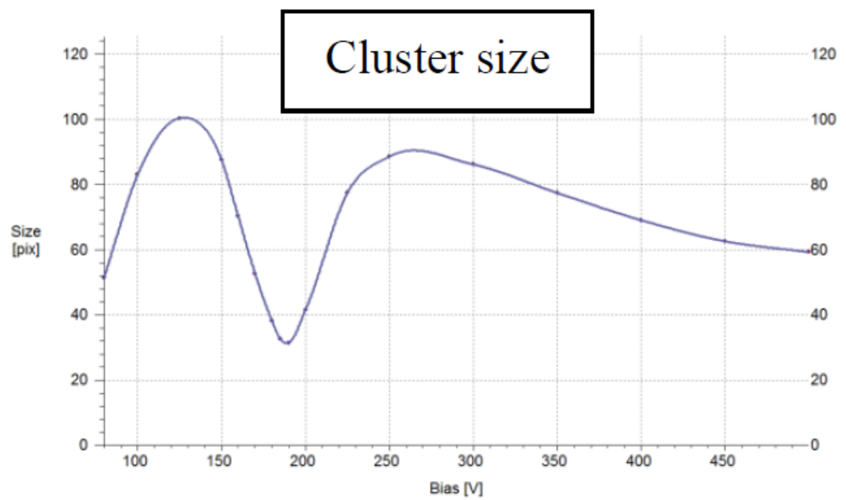
1. Calibration dependence on threshold
2. Distorted cluster shapes for highly ionizing particles (ions).

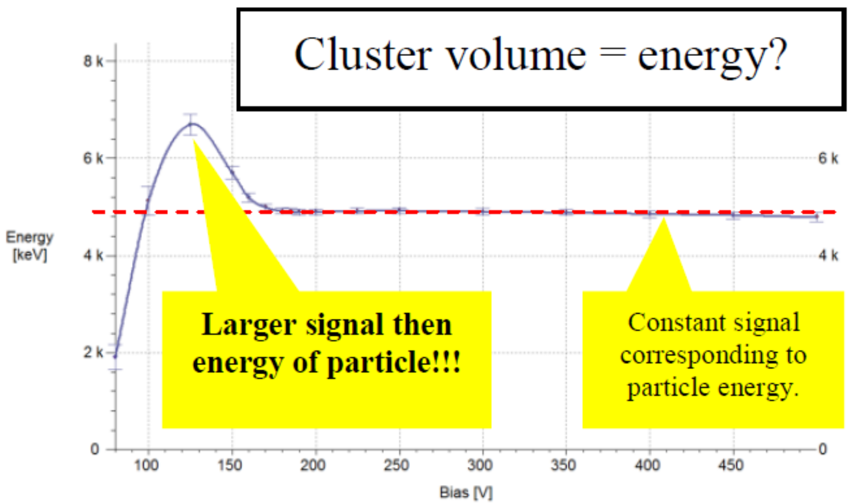
Recorded cluster shapes:
Alpha particles (5.5 MeV), 1 mm thick Si PN sensor





Dependence of cluster measures on bias voltage





Dependence of cluster size (e.g. number of pixels contained in the cluster) on bias voltage.

Dependence of cluster volume which should correspond to particle energy on bias voltage.

For undepleted sensor we would expect decrease of charge collection efficiency.
In contrast to this we see **unexpected increase of signal for low bias voltage**.

Recorded cluster shapes:
- alpha particles, 300 um thick Si PN sensor

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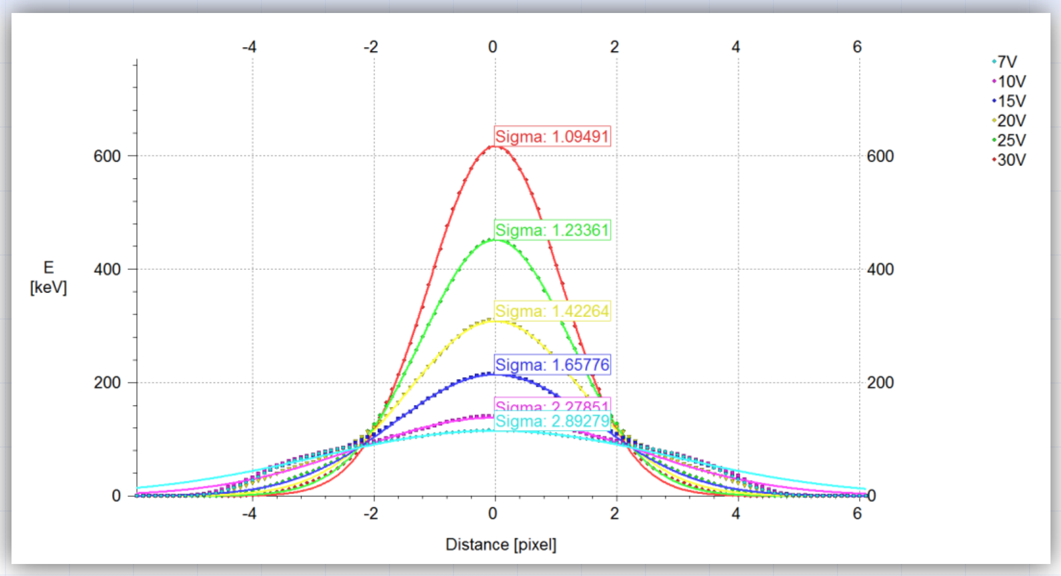
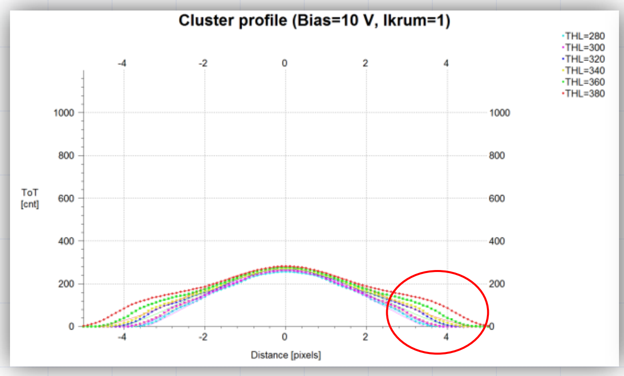
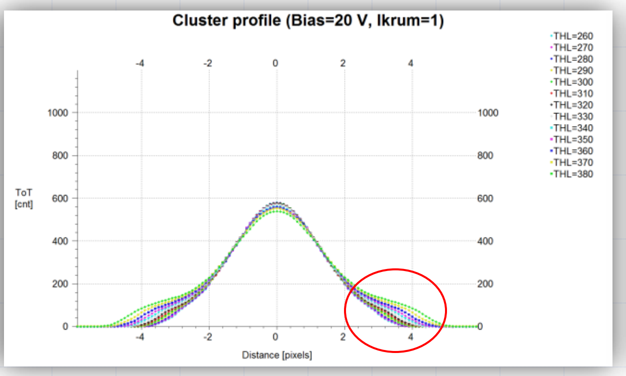
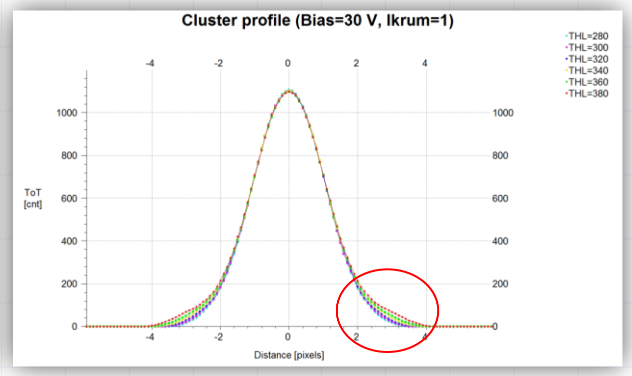


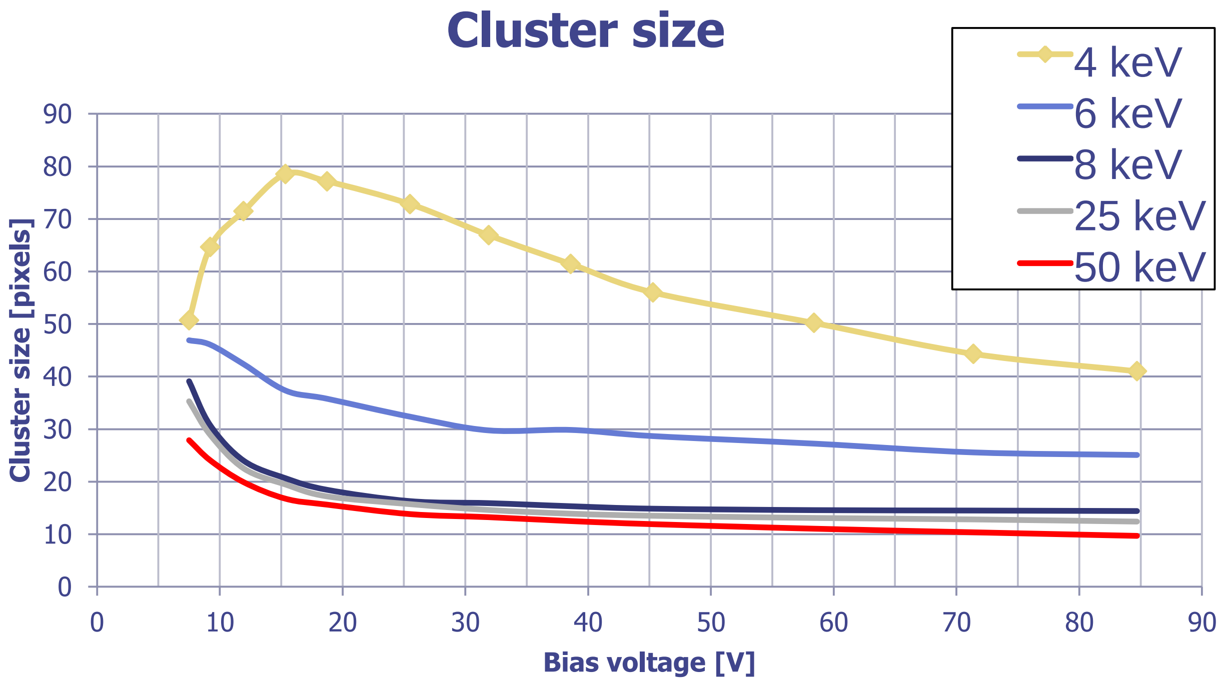
Interesting dependence of cluster shape on threshold:







Dependence of cluster size on threshold level and bias voltage



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Charge collection model

Analytical charge collection model was created

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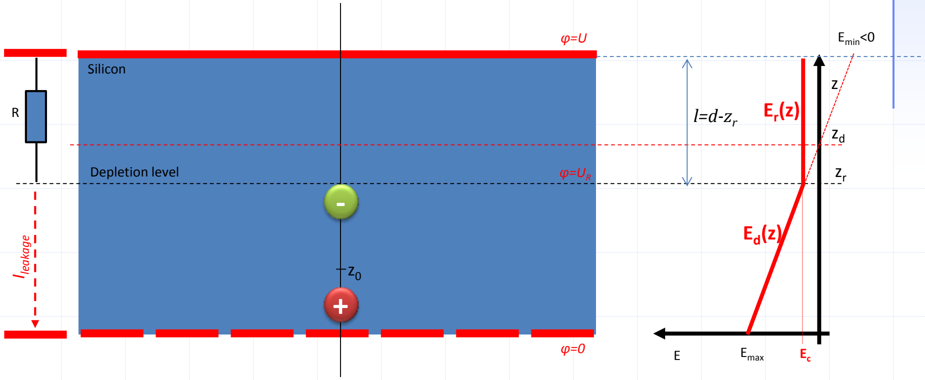
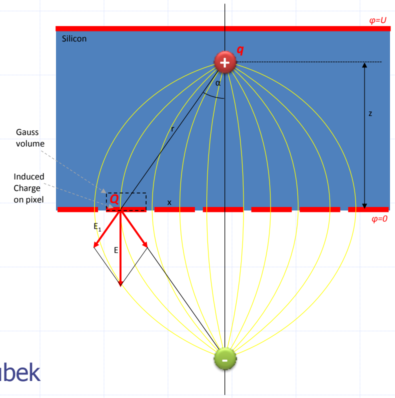
1. Electric field in semiconductor sensor: **Full depletion approximation** in depleted region

2. Constant electric field in nondepleted region (defined by resistivity and leakage current)

3. Simplified Model of charge drift in gradient field combined with:
   - Charge expansion due to columbic repulsion
   - Simple model of charge diffusion

4. Model of charge induction





Example:
Charge expansion (repulsion + diffusion)

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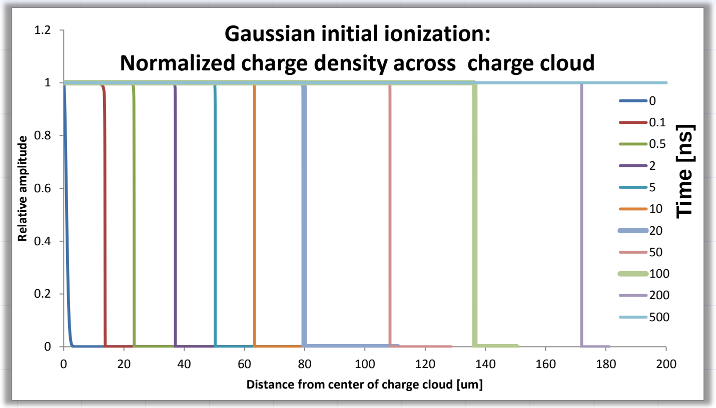
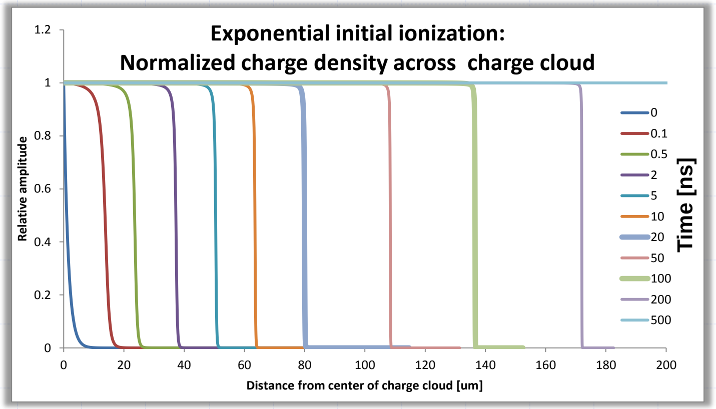
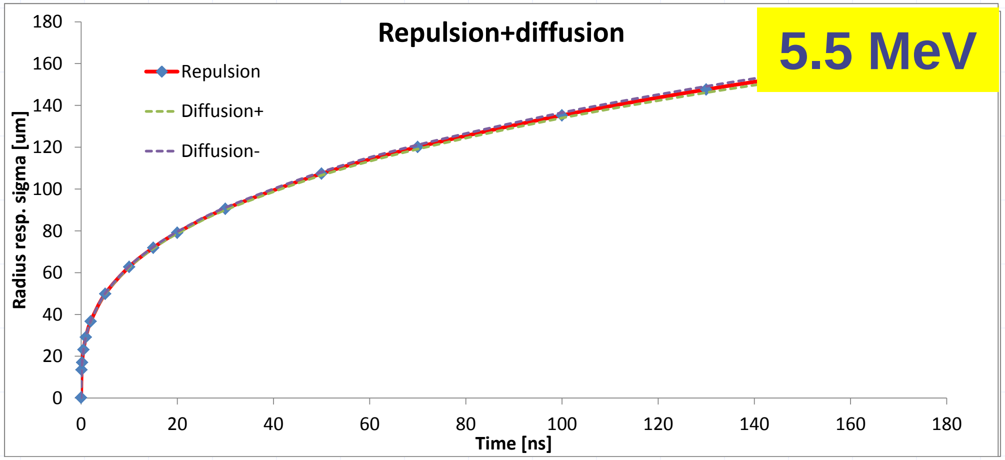
1. Columbic repulsion solved firstly for stationary charge cloud of initial density described by:
   - Homogeneous sphere
   - Gaussian distribution
   - Exponentially decreasing density

2. Gaussian diffusion added to the model analytical solution was not found => upper limit was determined for given charge cloud







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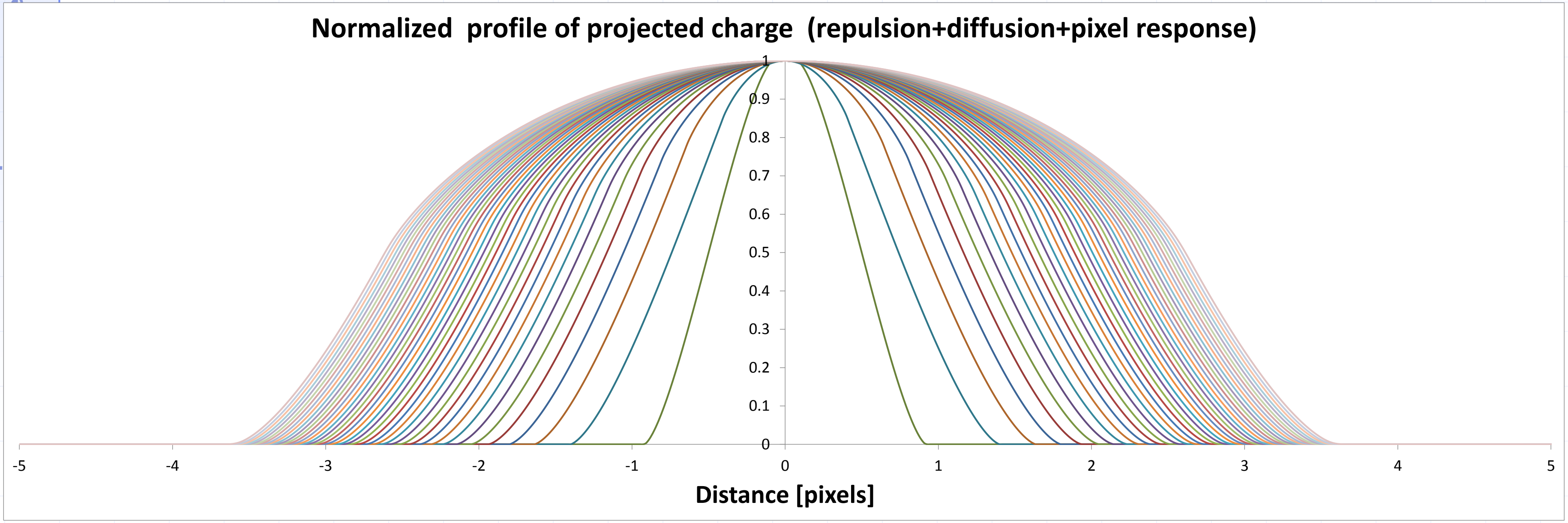
Example2:
Drifted charge cloud profile



Profiles are shown for different drift times:

0.5 ns, 1 ns, 5 ns and then with step of 5 ns

(80 ns corresponds to charge collection time in 300um Si at 30 V)

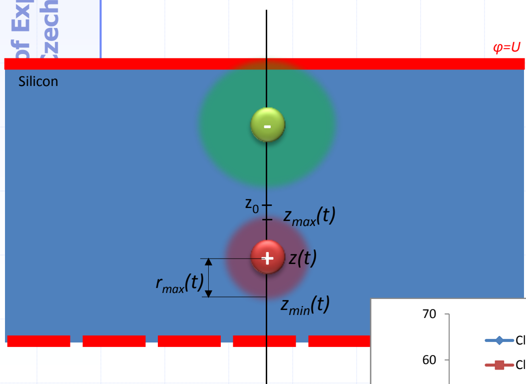
Example3:
Drifted charge cloud deformation

Charge cloud drifts in gradient electric field

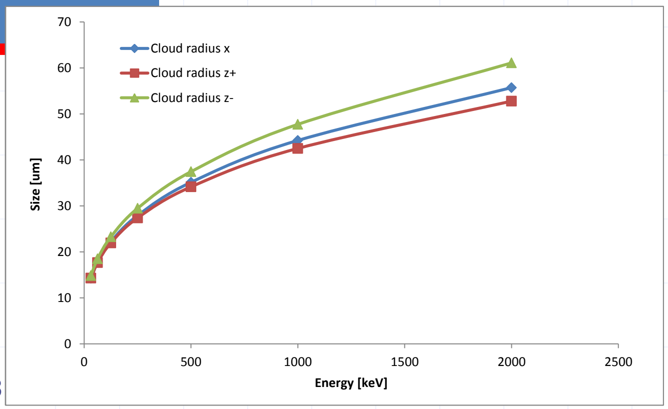
⇒ Bottom part is attracted more than upper part

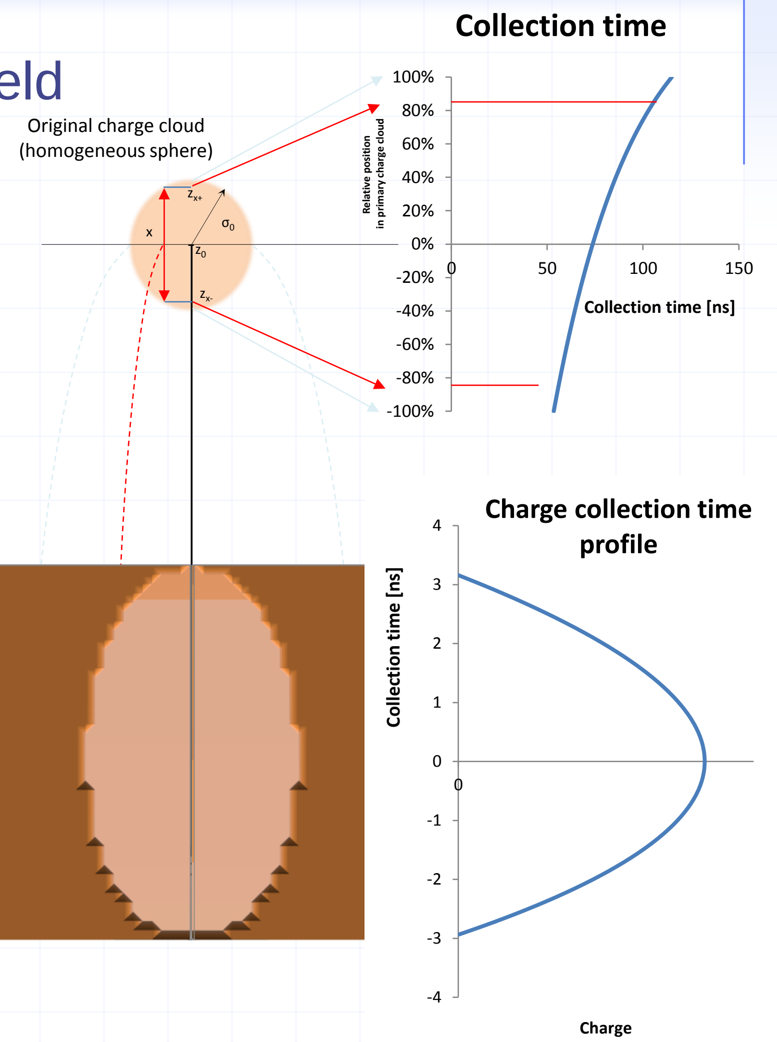
⇒ Deformed shape

⇒ Deformed pulse



Bias=100 V





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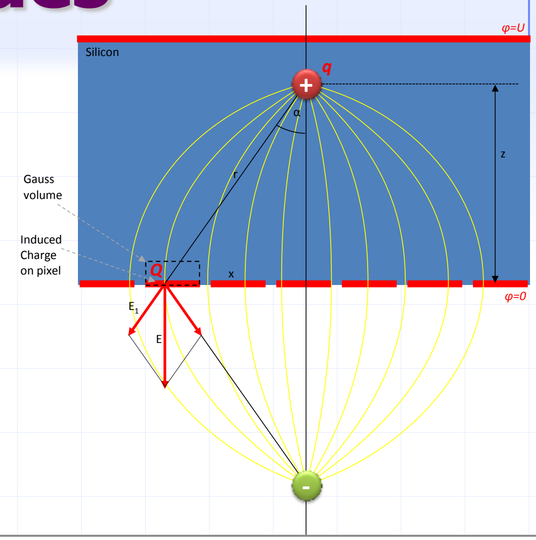
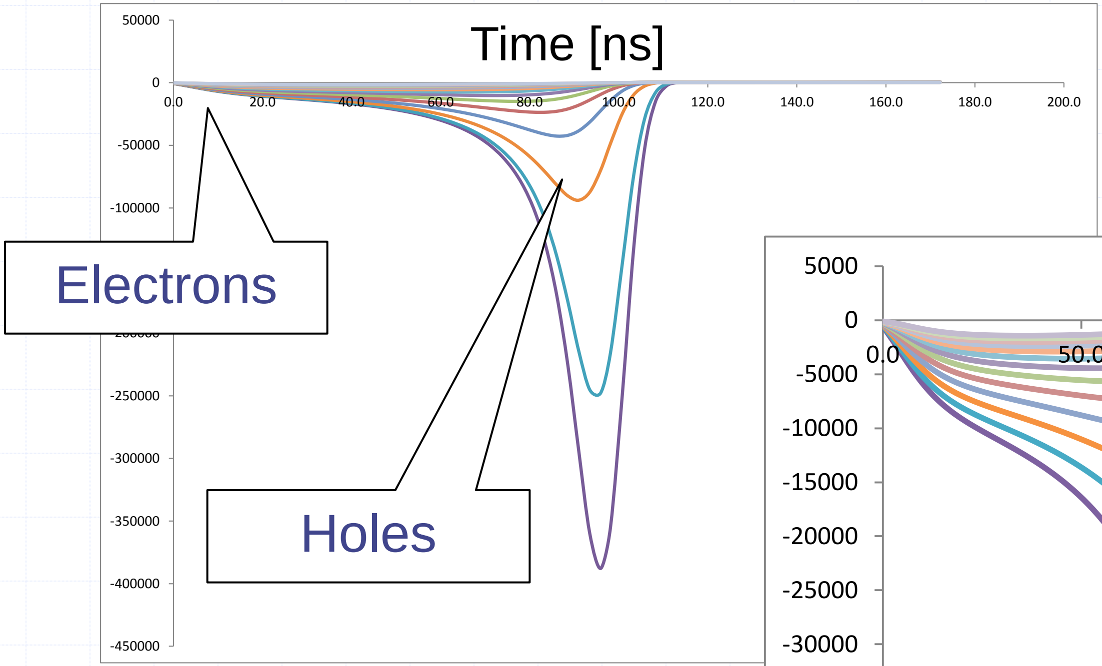
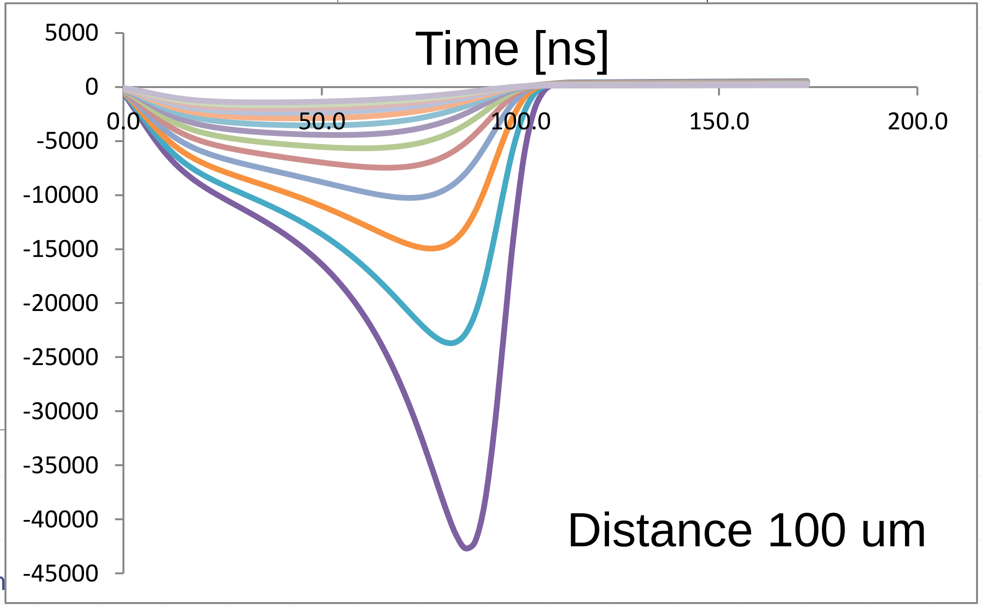
Example3:

Induced charge in pixel electrodes







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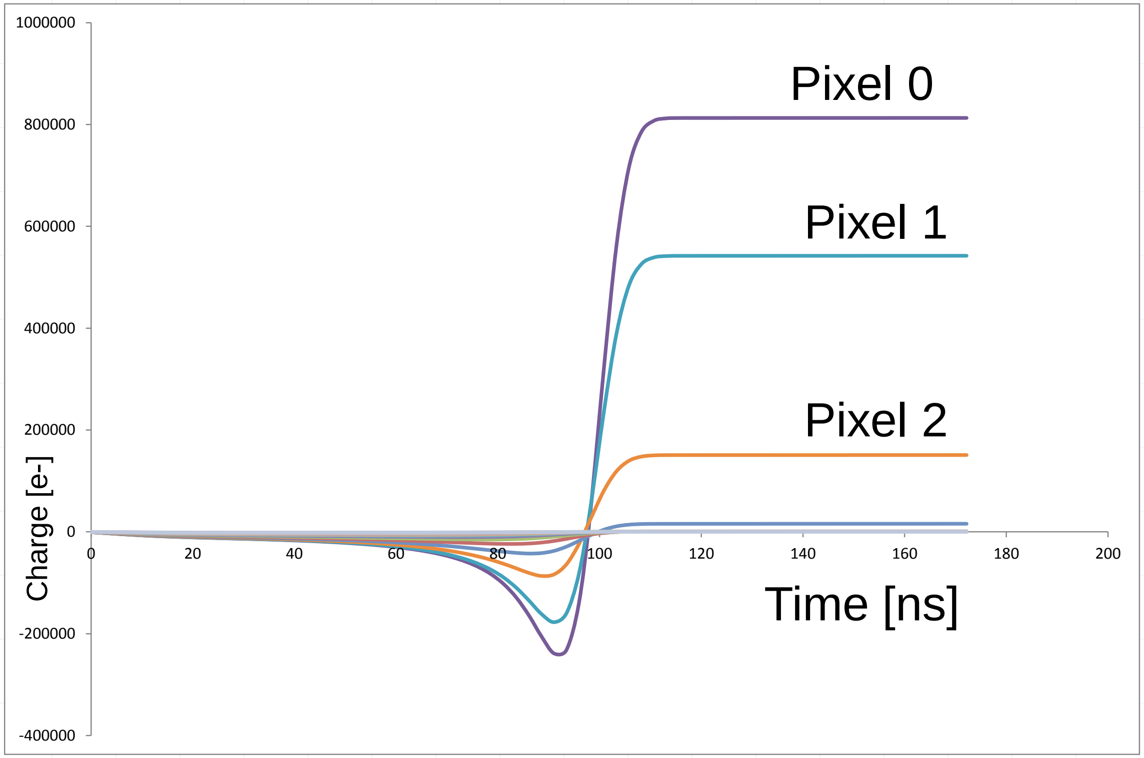
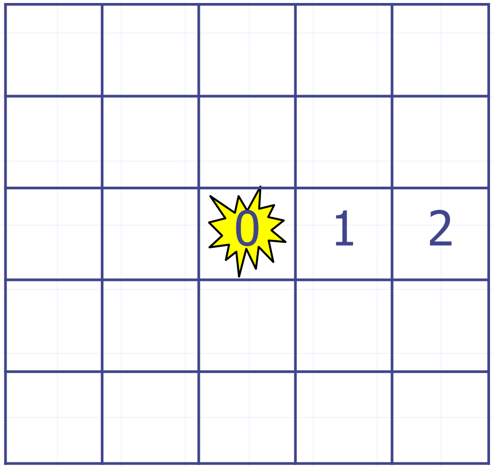
Result:
Combining drift+induction





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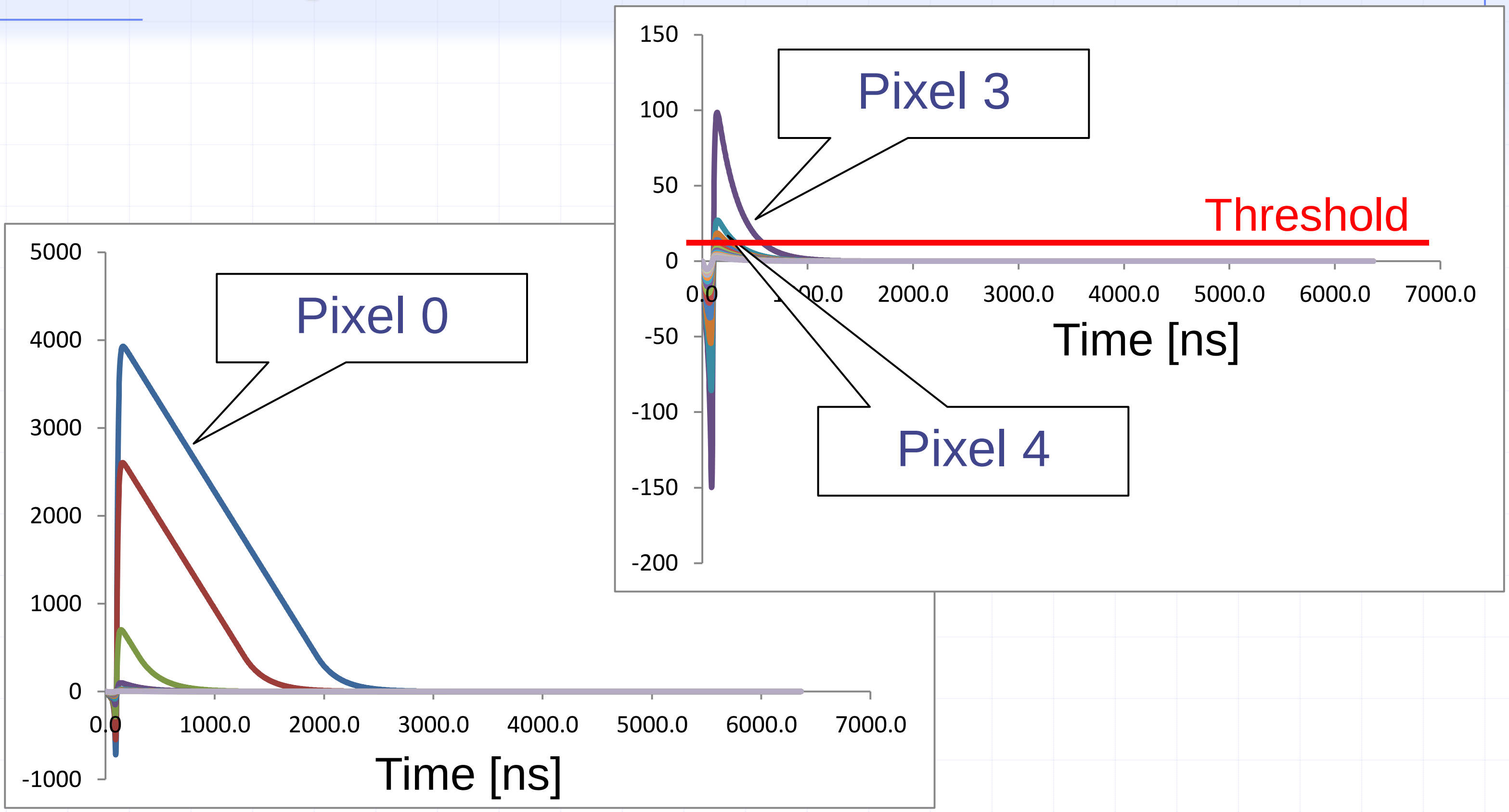
Result:
Amplifier response



=> Even pixels very distant from interaction point see positive signal

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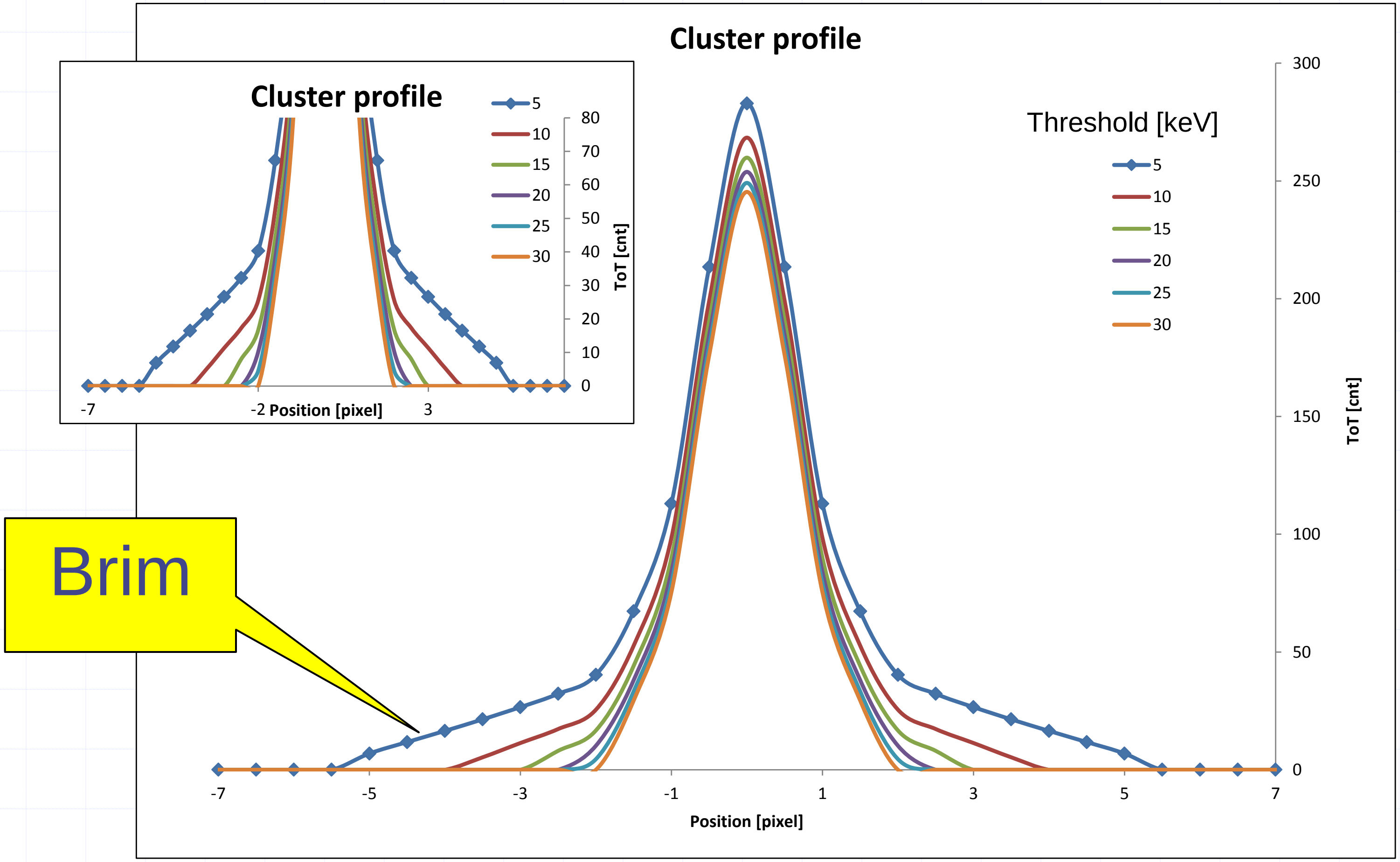
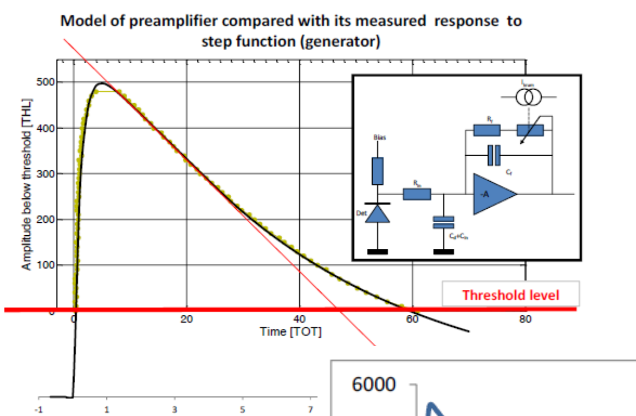
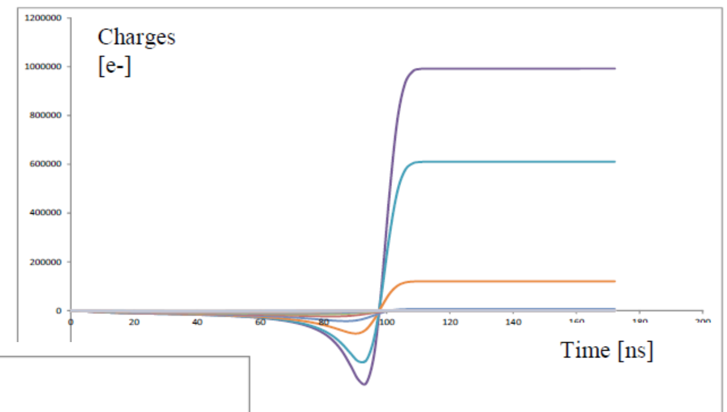
Result:
Cluster shape in dependence on Bias

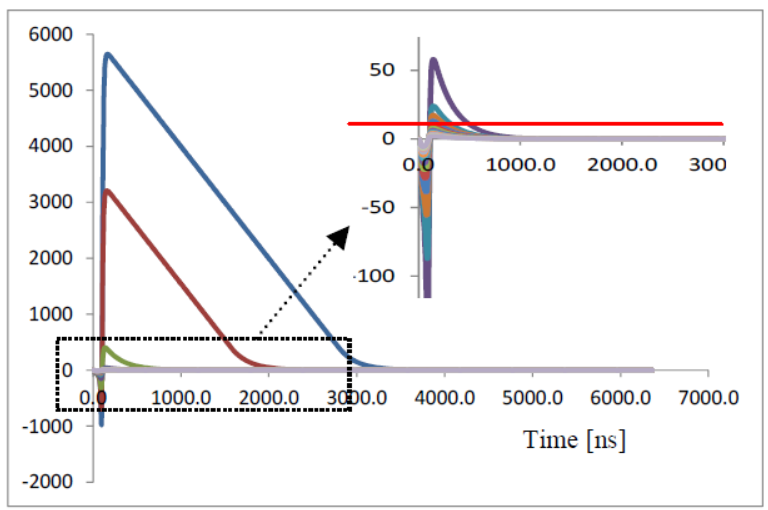


Possible reasons for such behaviour: Brims

a) Signal deformation in analogue pixel electronics
b) Consequences coming from signal formation during charge collection
c) Combination of both reasons







Fit to real data:
500 um thick Si sensor (P on P type)

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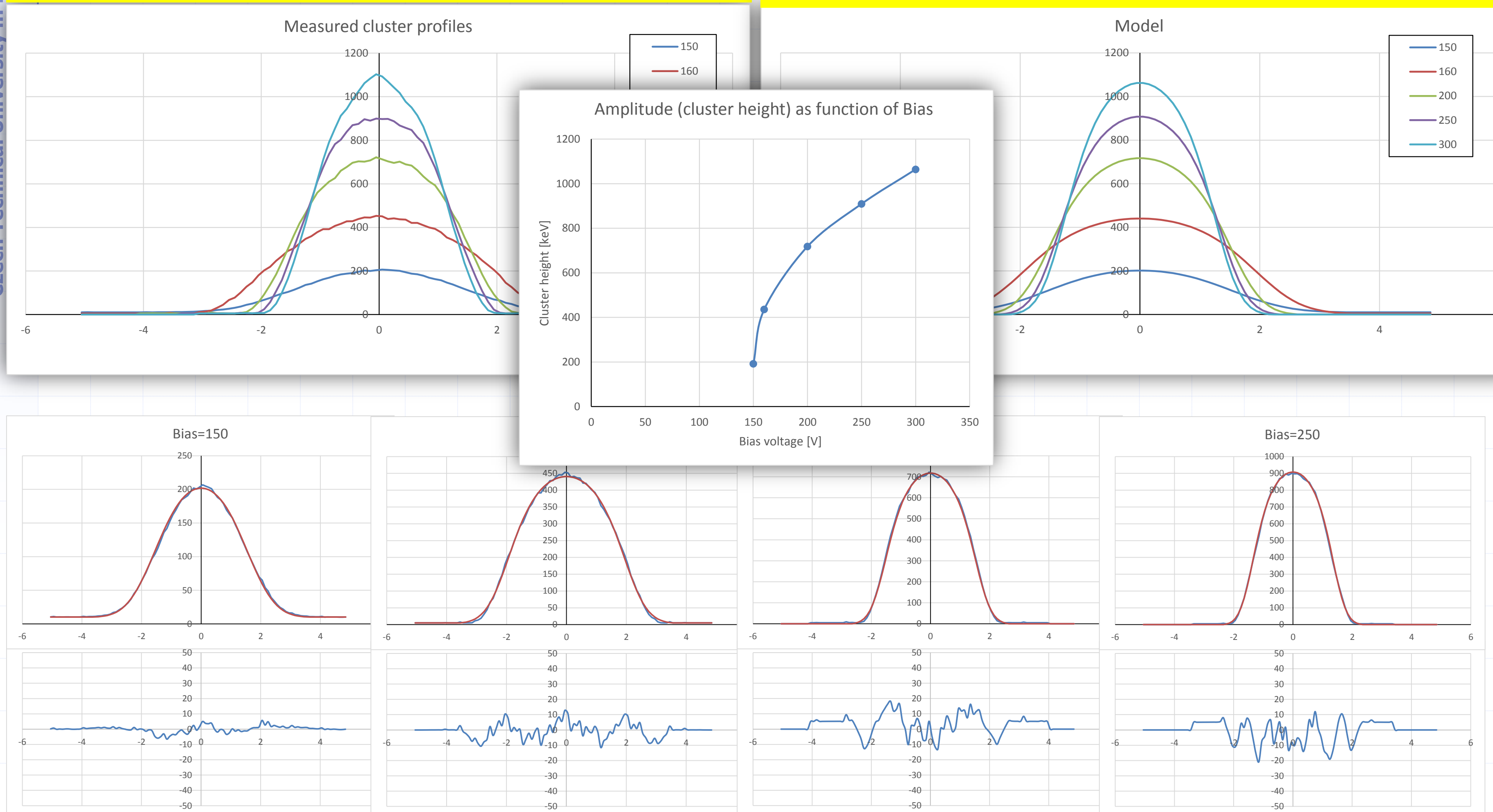
Measured cluster profiles (alphas 5.5 MeV)

Measured cluster profiles



Conclusions

- The “brim”, “skirt” or “corona” surrounding pixels is caused by induced charge in combination with dynamic behavior of preamplifier (**discharging during integration**)
- For low bias voltages the charge collection process takes longer time => “brim” is more pronounced
- For undepleted sensor the signal is mostly caused by induction only
- The induced signal has different shaping
  - Threshold has different meaning
  - Wrong (delayed) timestamp in Timepix mode due to different slope of the leading edge
- The induced signal is linearly dependent on primary charge created by particle

Bonus II: High res neutron imaging

- Properly equalized Timepix allows deeply subpixel resolution
- **Spatial resolution 2.5 µm** => 26 Megapixels

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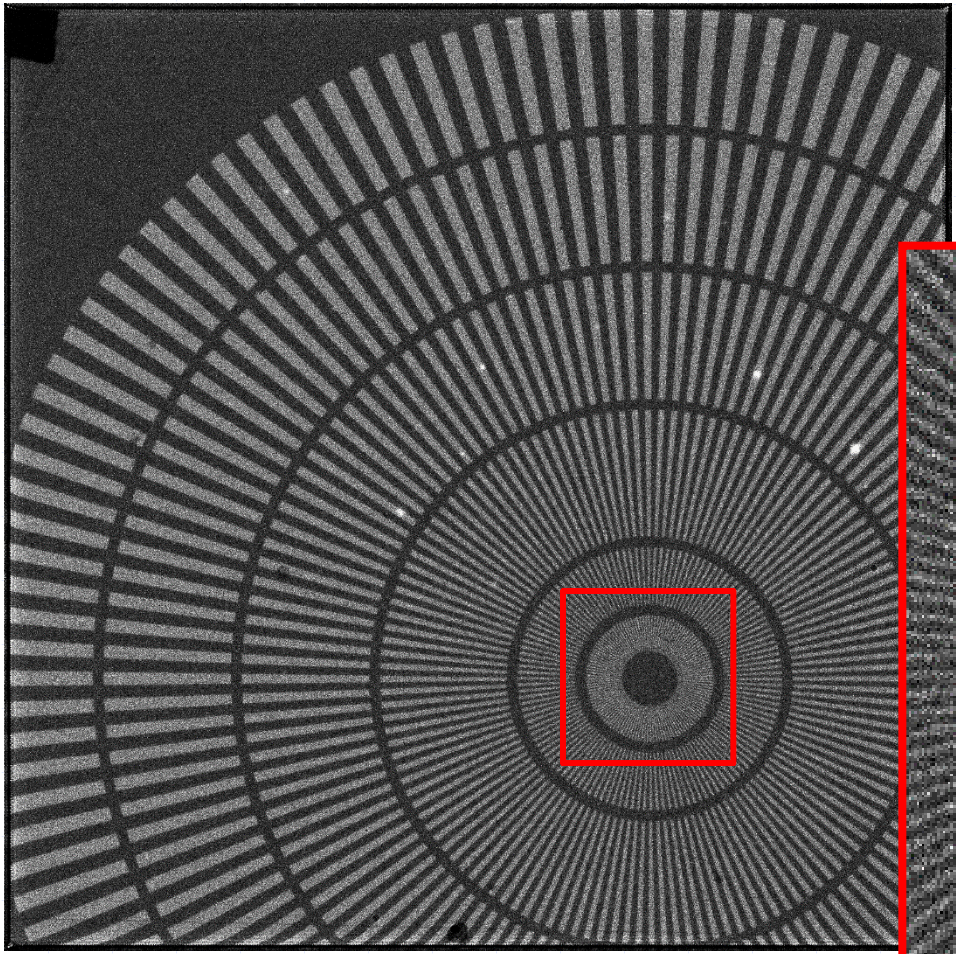
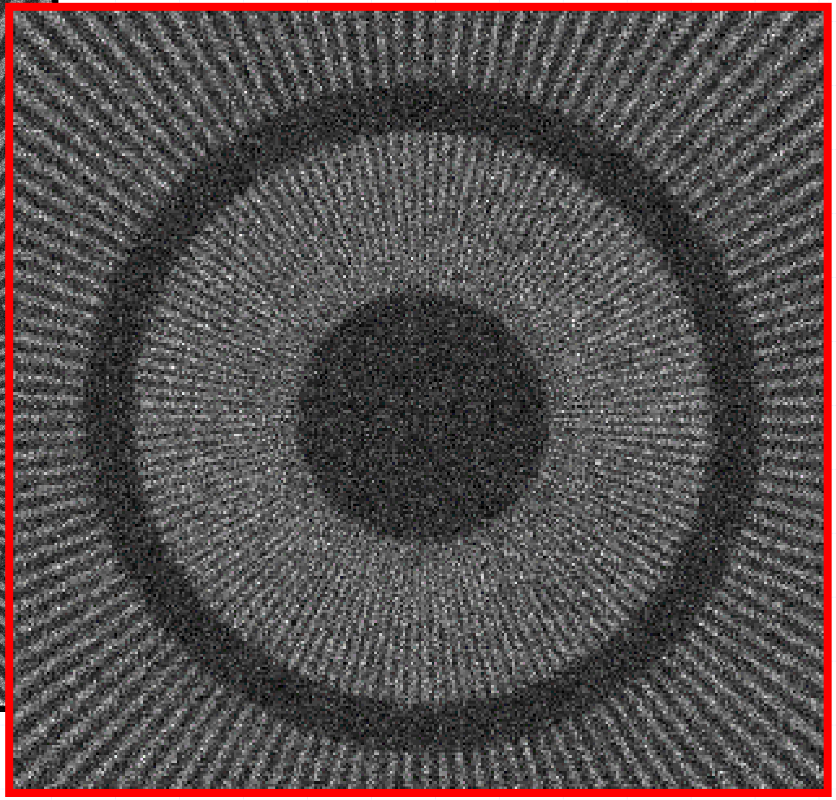


Siemens star pattern (smallest features 5 um)
Measured in ICON neutron beam in PSI.
Single Timepix device in ToT mode, each track was fitted to find exact impact point.



Summary and future work

- The model describing response of Timepix detector in ToT and TPX mode was created.
- The model is fully analytical and can be calculated effectively => it is possible to use it for fitting to real particle tracks.
- The model can be easily adapted for very penetrating particles depositing constant primary ionization along track.
- Cluster fitting using correct model will allow to improve tracking precision.

Thank you for patience!