



# Study of the charge sharing in silicon pixel detector by means of alpha particles interacting with a Medipix2 device

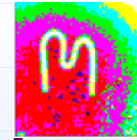
*Michael Campbell<sup>1</sup>, Erik Heijne<sup>1</sup>, Tomáš Holý<sup>2</sup>, John Idárraga<sup>3</sup>, Jan Jakubek<sup>2</sup>, Celine Lebel<sup>3</sup>, Claude Leroy<sup>3</sup>, Xavier Llopart<sup>1</sup>, Stanislav Pospíšil<sup>2</sup>, Lukas Tlustos<sup>1</sup> and Zdeněk Vykydal<sup>2</sup>*

**<sup>1</sup>CERN, <sup>2</sup>IEAP CTU in Prague, <sup>3</sup>Montreal University**

Work carried out within the CERN Medipix Collaboration

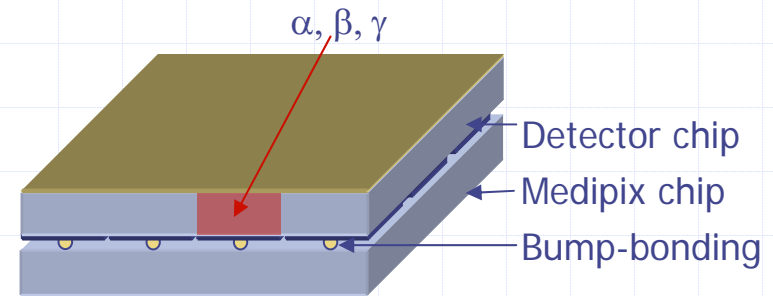
# Outline

- ◆ About Medipix2 type pixel device
- ◆ Charge sharing effect demonstration by visualization of tracks and traces in response of the Medipix device to
  - natural background
  - X-rays and electrons
  - Alpha particles
  - fast neutrons and neutron induced background
  - to fission fragments
  - muons
  - pattern recognition of tracks and traces of individual quanta of radiation
- ◆ Dependence of the charge sharing induced by alpha particles on threshold level and on bias applied to the detector
- ◆ An attempt to describe the charge sharing effect theoretically
- ◆ What we could see with Timepix?
- ◆ Conclusion



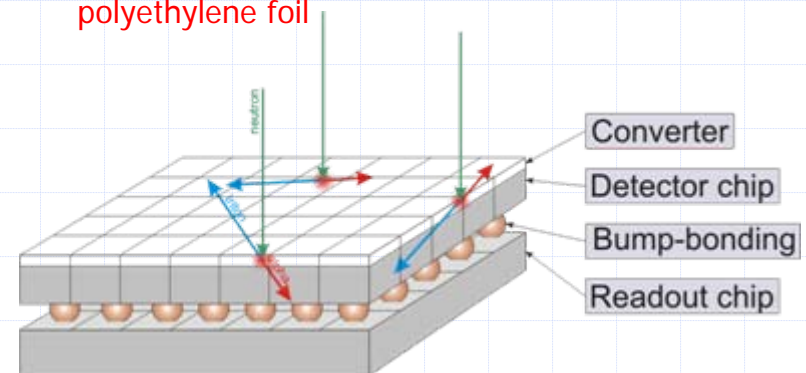
# Medipix2 device - a single X-ray photon counting pixel detector

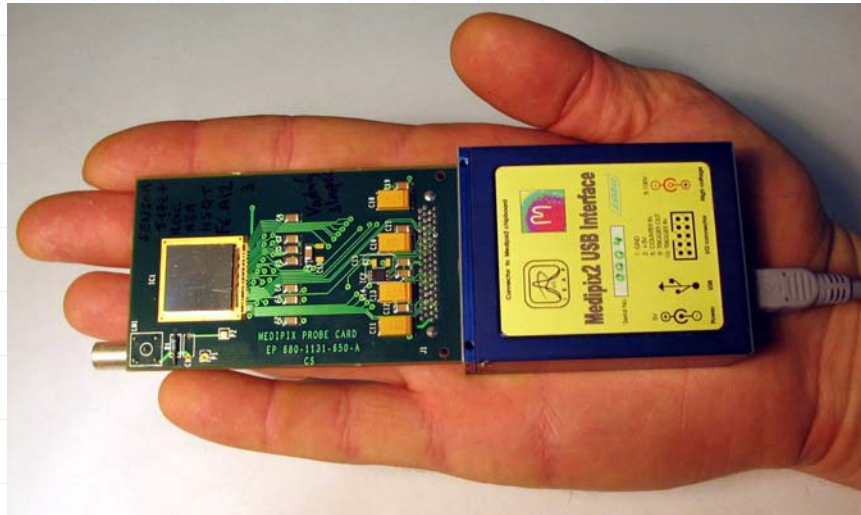
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000 $\mu\text{m}$ )
- Pixels: 256 x 256, 55 x 55  $\mu\text{m}^2$  each, detector area: 1.5 x 1.5  $\text{cm}^2$
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter



Converter materials to detect neutrons:

- thermal:  ${}^6\text{LiF}$ ,  ${}^6\text{Li} + n \rightarrow \alpha(2.05\text{MeV}) + {}^3\text{H}(2.72\text{MeV})$
- fast: polyethylene foil

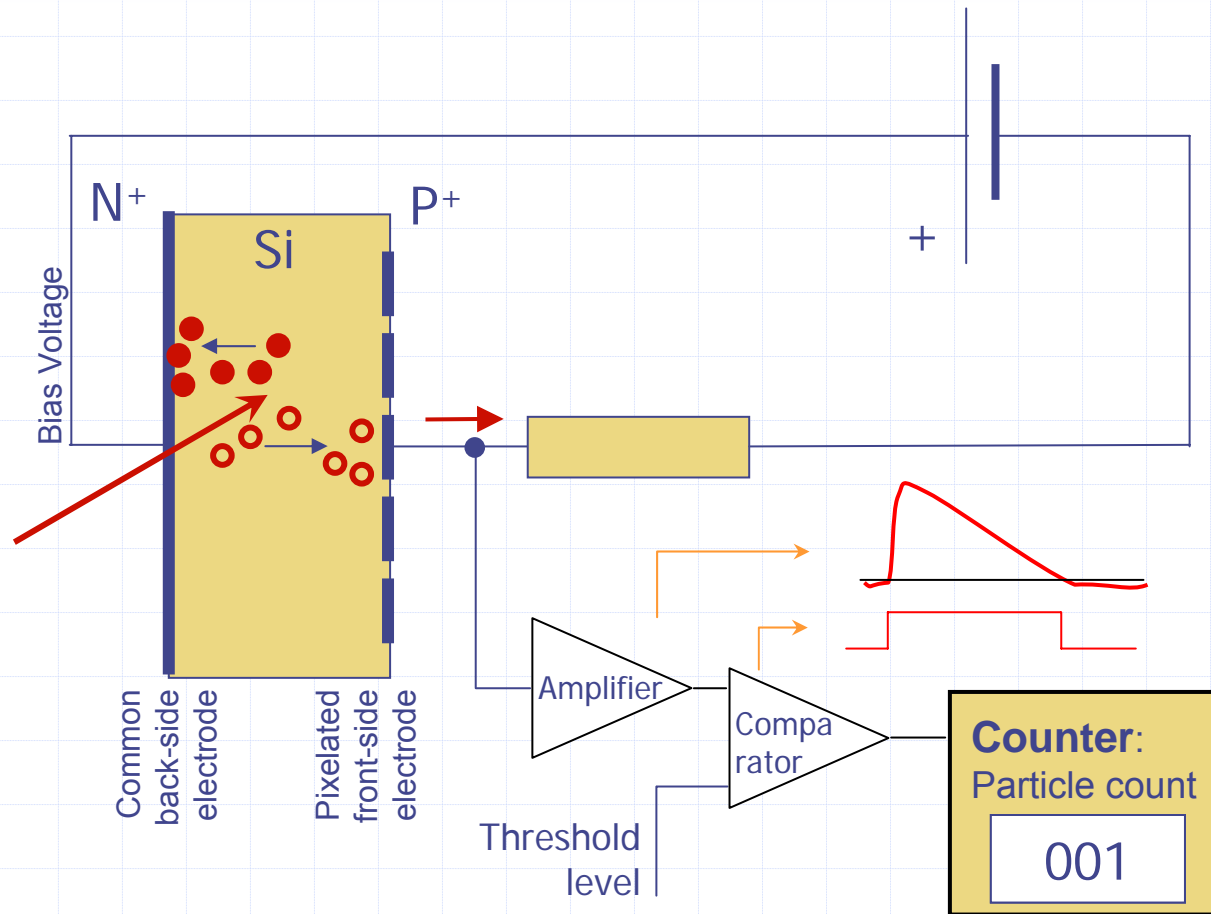




- ◆ The MEDIPIX-USB device connected to the portable PC. Up to 5 frames per second (USB 1 option). One PC can effectively run up to 50 MEDIPIX-USB devices (each in individual regime), or simultaneously.
- ◆ View of the MEDIPIX-USB device (<http://www.utef.cvut.cz/MEDIPIX>). The Medipix2 motherboard (left PCB, 80x46mm<sup>2</sup>) is assembled to the USB interface board which is placed in a duralumin box (64x50x20mm<sup>3</sup>) for shielding and mechanical purposes. The motherboard can also be placed in a duralumin box with an appropriate entrance window.

# Counting mode of pixel detector

(counting of single radiation quanta interacting in a pixel volume)



Threshold level above electronic noise  
 $\Rightarrow$  No false counting.

Digital integration (counting)  
 $\Rightarrow$  No dark current.



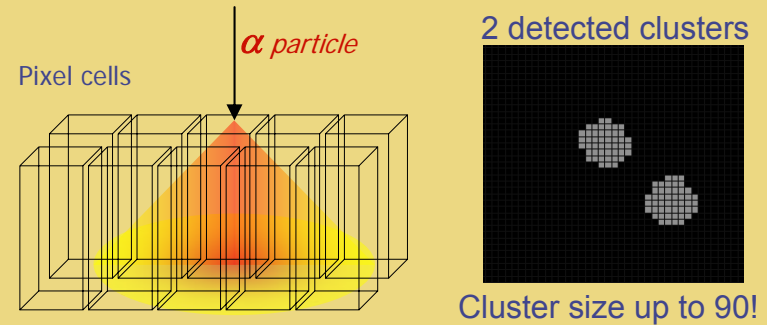
Unlimited dynamic range and exposure time.

Detected count obeys poissonian distribution

# Charge sharing for position and energy sensitive detection of heavy charged particles with pixel detectors

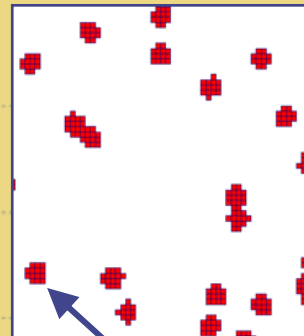
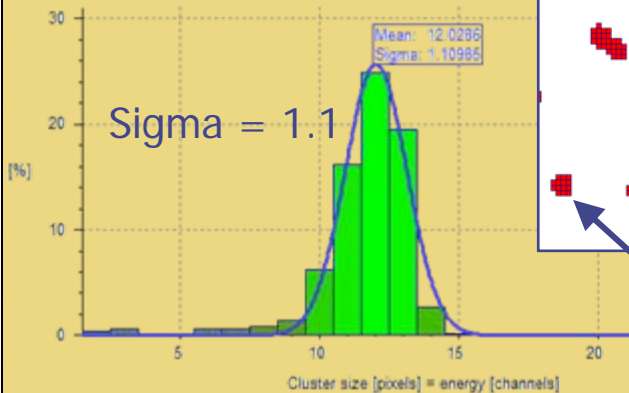
Several adjacent pixels can be incremented when a single particle is detected due to charge diffusion during charge collection.

Pixels incremented by a single particle form a **cluster**.



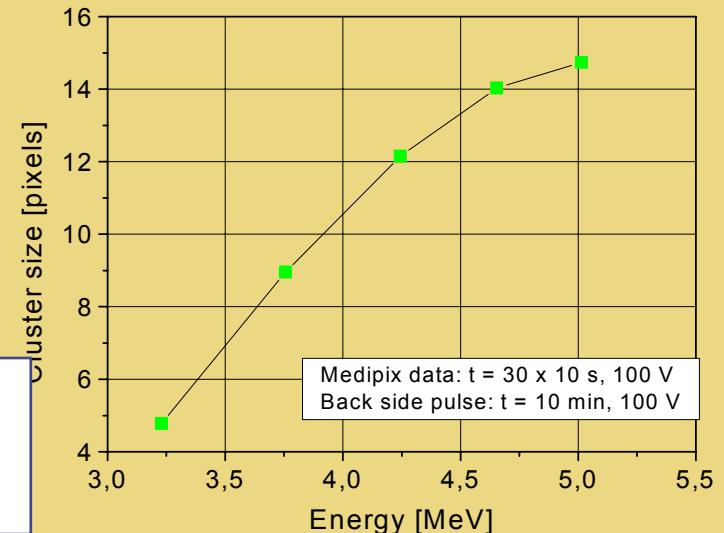
## Cluster size depends on particle energy

5.4 MeV alpha source at 24 mm (measured in air)



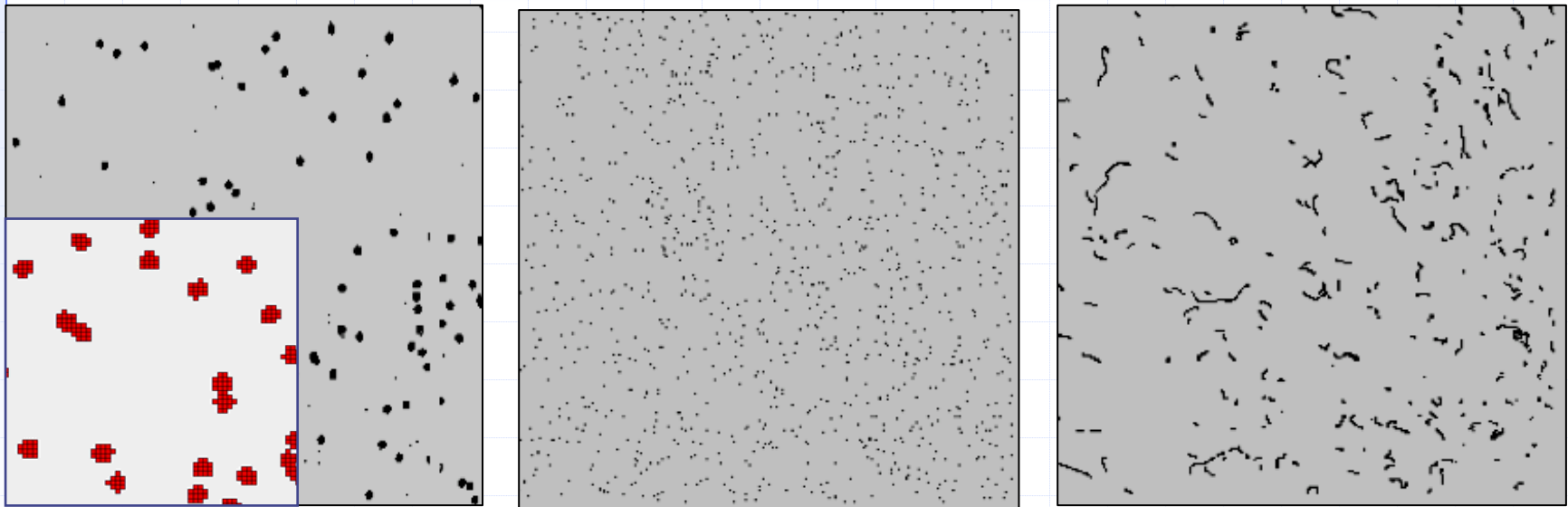
Signal by one alpha particle = cluster

Dependence of cluster size on alpha particle energy



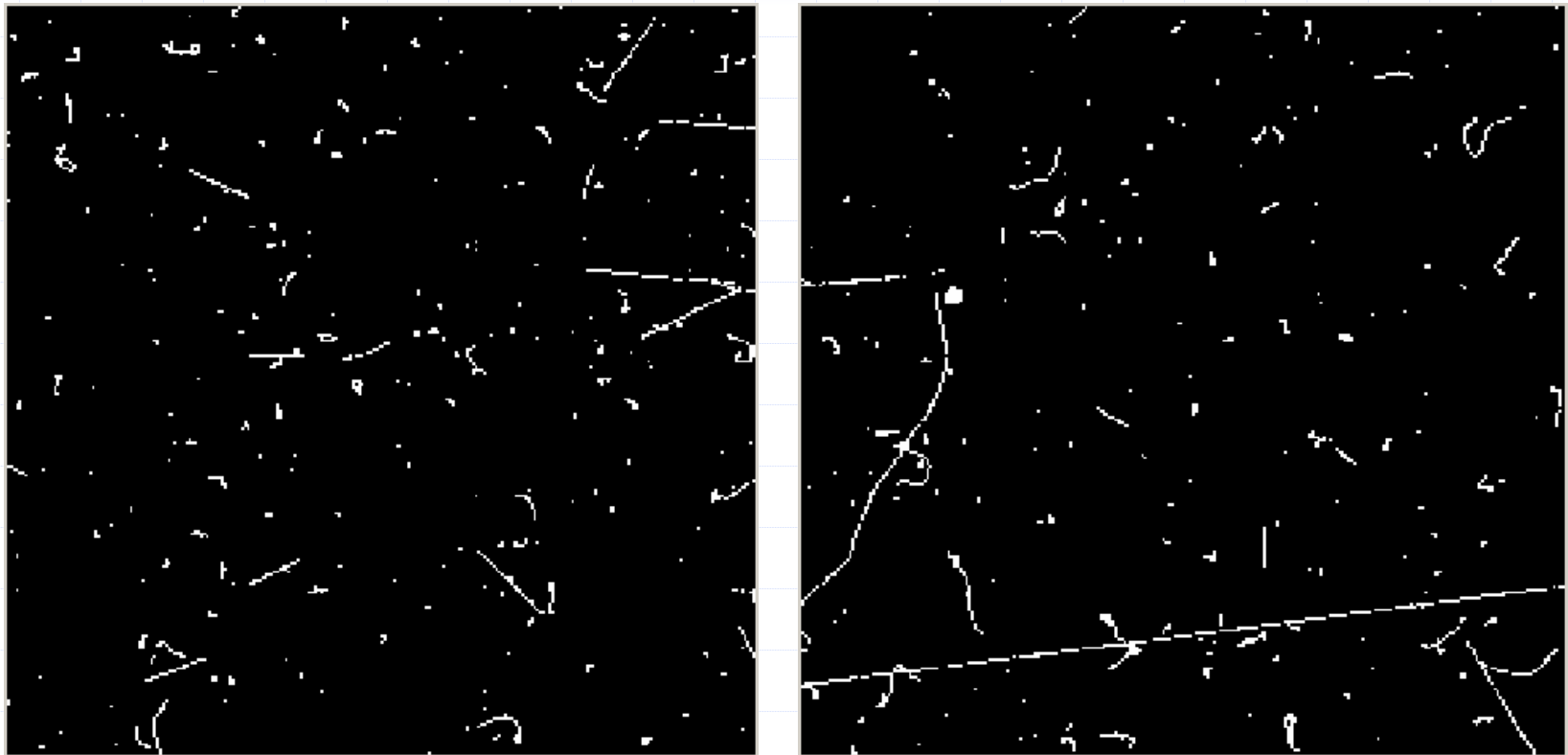
# Tracking mode of pixel detector

## (on-line imaging of tracks and traces of single radiation quanta)



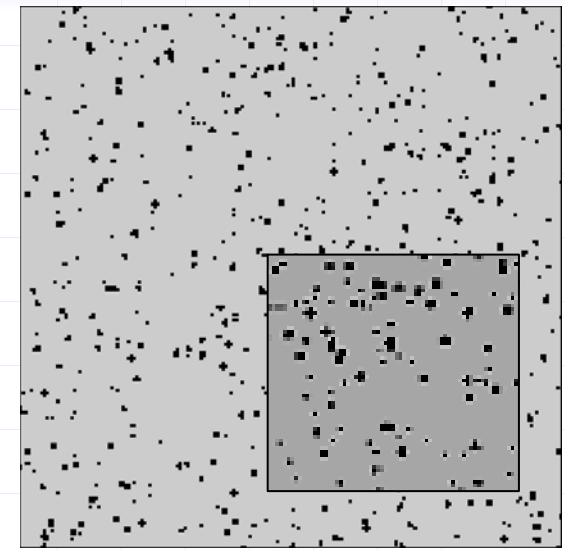
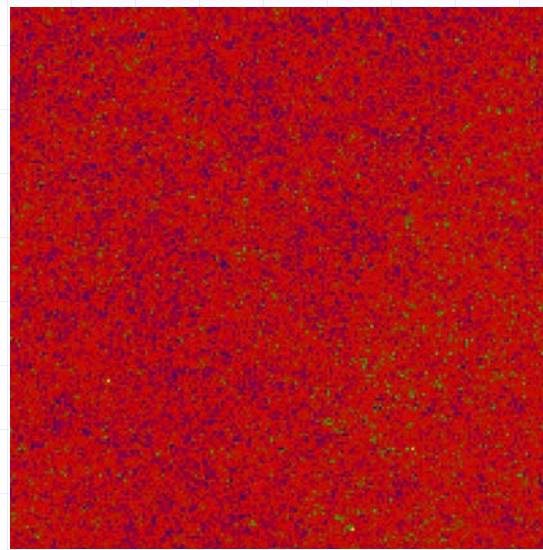
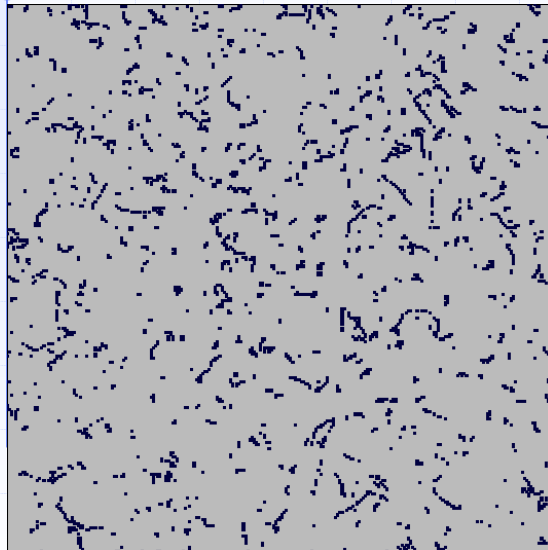
- ◆ 241Am alpha source gives clusters of  $\sim 5 \times 5$  pixels measured with the MEDIPIX-USB device and a 300  $\mu\text{m}$  thick silicon sensor. The clusters are shown in detail in the inset. The cluster sizes depend on particle energy and threshold setting.
- ◆ Signature of X-rays from a 55Fe X-ray source. Photons yield single pixel hits or hits on 2 adjacent pixels due to charge sharing.
- ◆ A 90Sr beta source produces curved tracks in the silicon detector.

# Natural background radiation



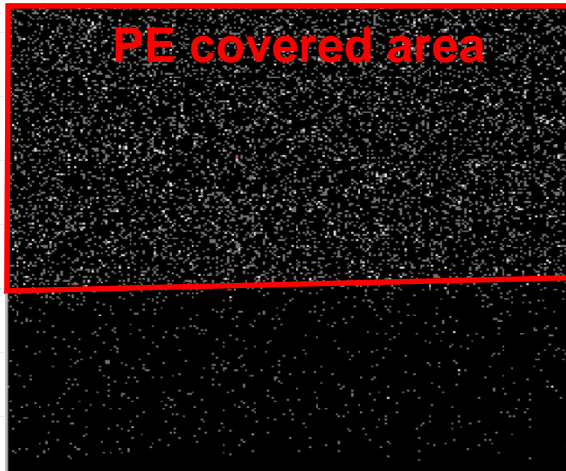
Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, ...

Measurements inside the “low power” light water reactor LR-0 (close to the active zone). The silicon sensor covered with a  ${}^6\text{LiF}$  converter 5 mg/cm<sup>2</sup> thick. The thermal neutron flux  $\sim 10^9$  n/(s.cm<sup>2</sup>)



- ◆ The measurements were done at different threshold settings to demonstrate the capability of the device to operate at extremely high count rate and to discriminate different components of radiation.
- ◆ Left: The reactor was off, image obtained at low threshold settings.
- ◆ Middle: The reactor was on – low threshold settings. Total count rate  $\sim 10^9$  counts/s.
- ◆ Right: The reactor was on – high threshold settings. One can clearly recognize, that all signals induced by gamma rays and electrons are discriminated (by corresponding tracks disappearance) and only neutrons are detected. It shows that the extremely high background contribution can be very effectively suppressed! ***See posters 10.9 – Josef Uher and 10.10 – Celine Lebel!***

# Background suppression by means of threshold high settings



1 mm thick PE sheet was mounted on Medipix2 device

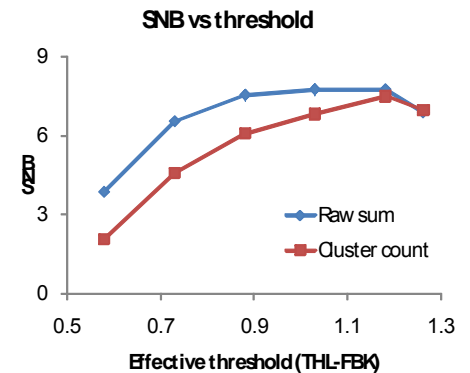
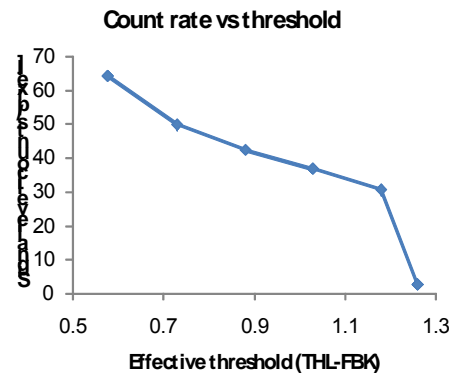
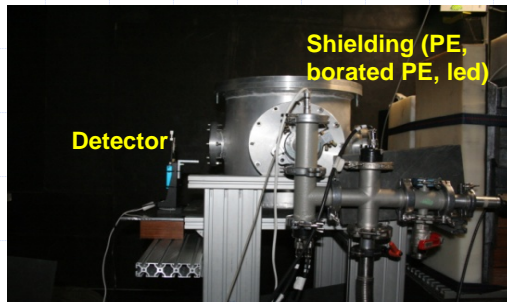


See also Poster 10.9 of Josef Uher!

Thresholds of individual pixel set high.  
Thresholds of individual pixel set low.  
Events in the events covered area are reduced significantly.

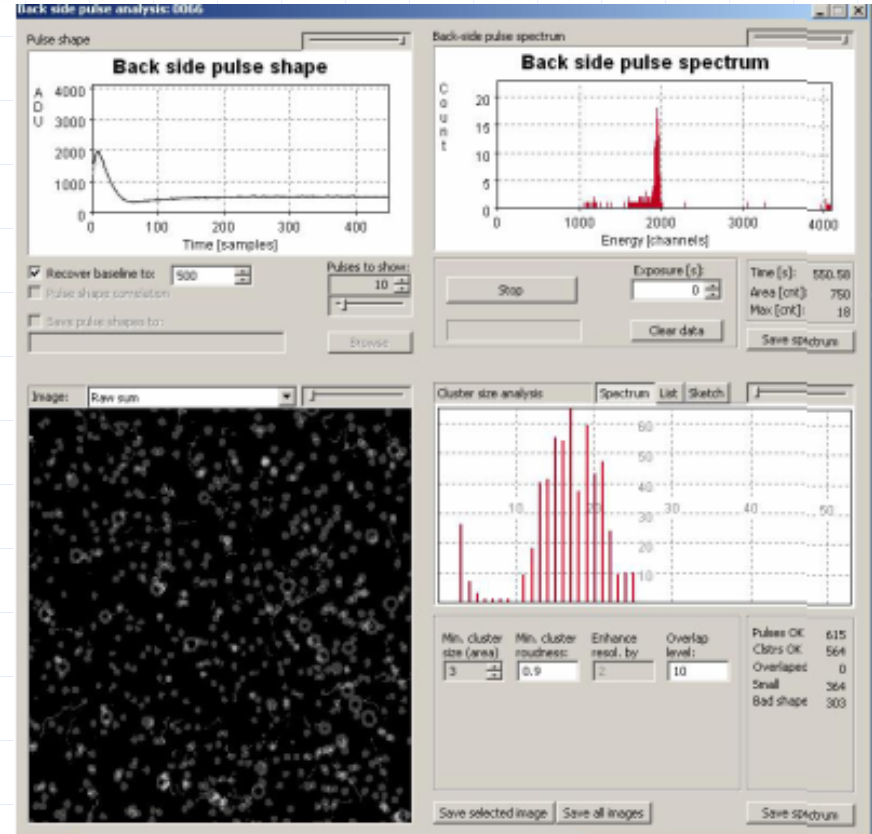
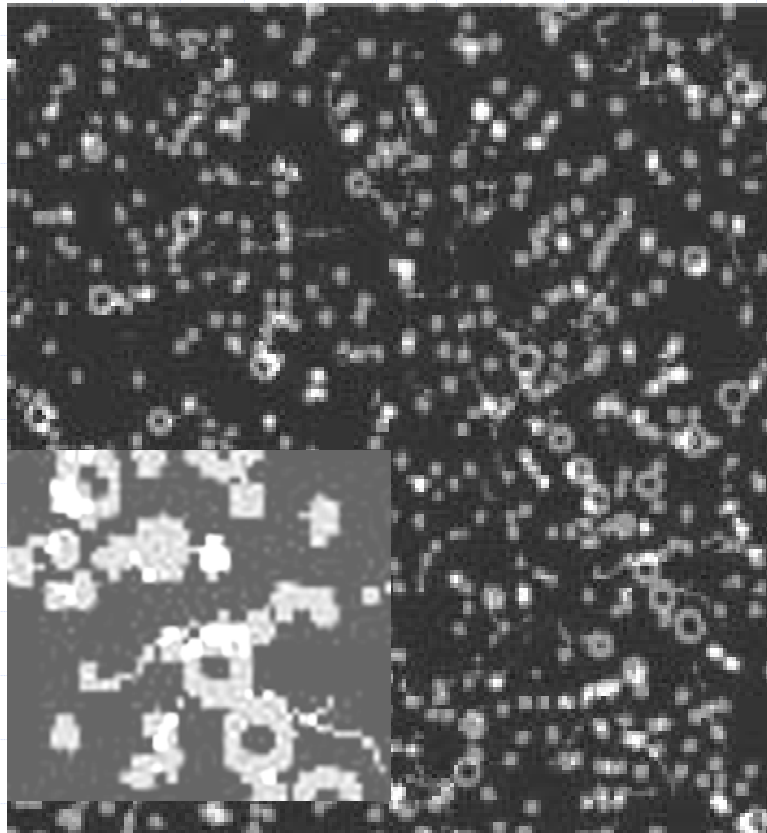
The measurements were performed at:

- neutron beam of the reactor Sparrow of the Czech Technical University in Prague
- neutron beam at Institut Laue-Langevin (ILL) in Grenoble



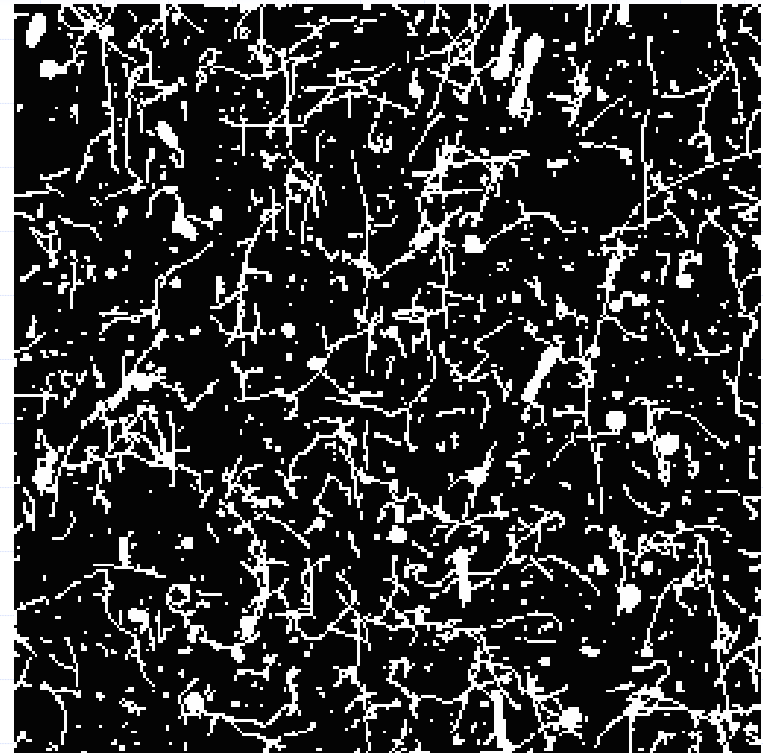
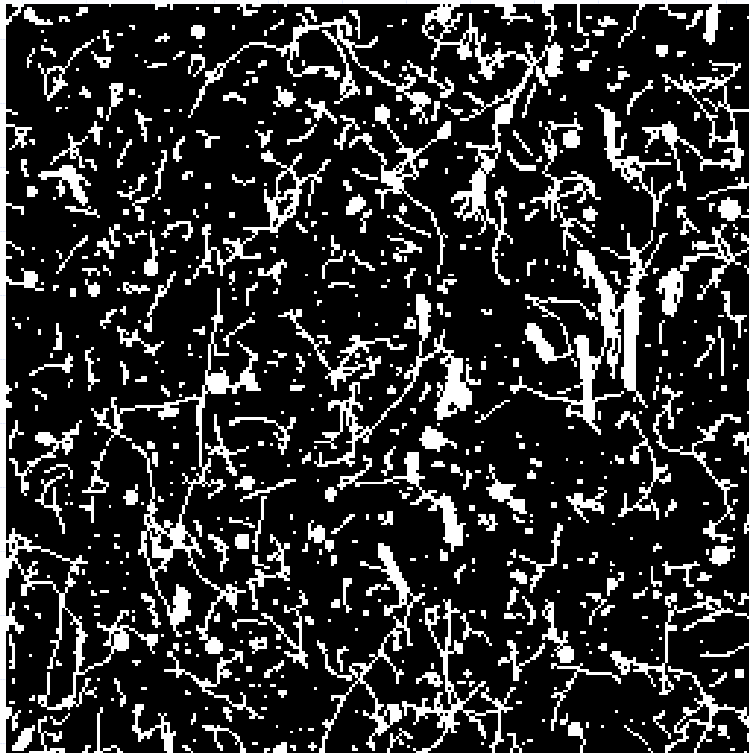
Measured count rate and SNB as functions of the effective threshold

# Detailed view on structure of clusters of fission fragments



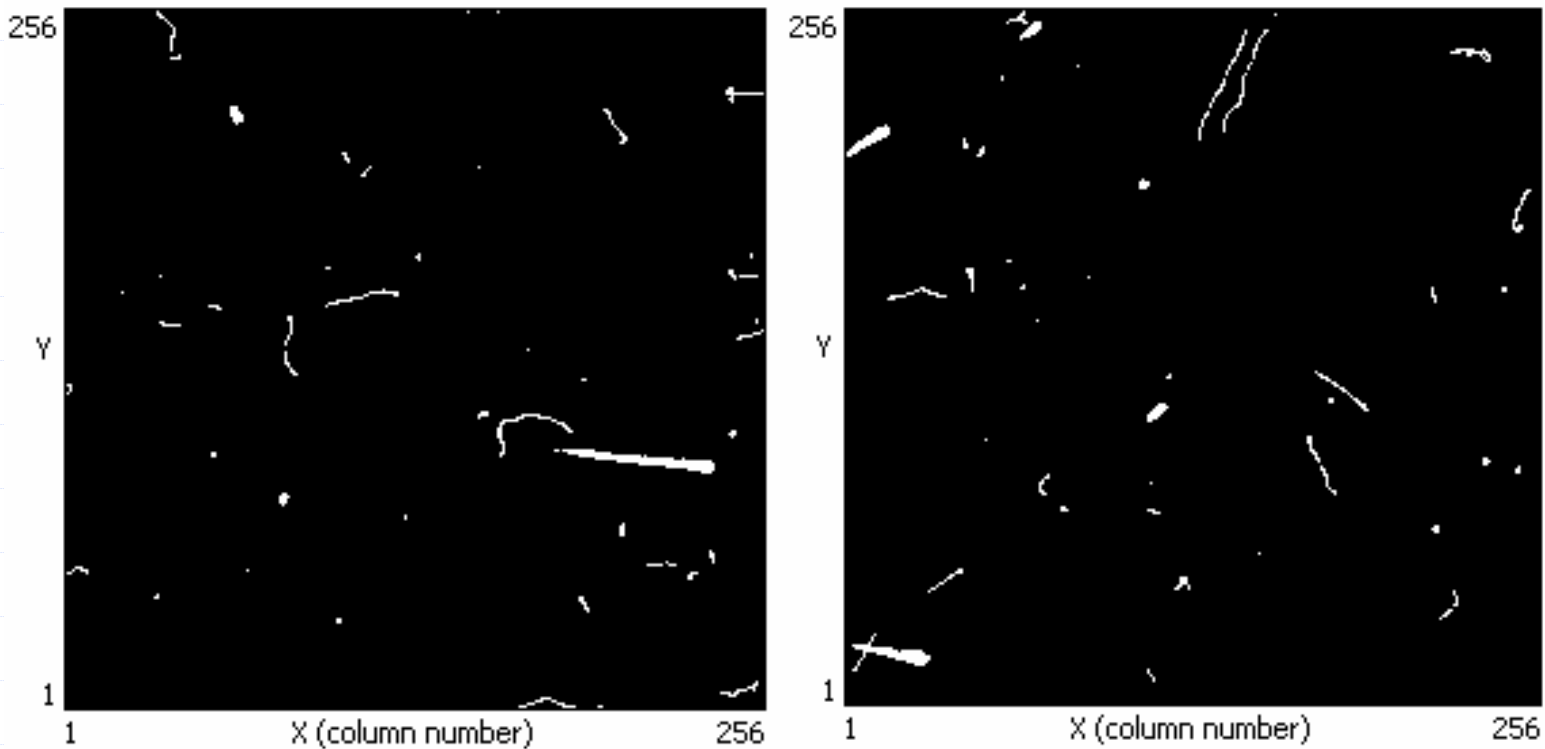
Clusters of alpha particles and fission fragments (up to 100 MeV energy) are clearly recognizable. Saturation of individual pixel electronics is displayed by a "ring" shape clusters. Pulse height spectrum (energy range > 3 MeV) obtained by the back-side pulse spectroscopy is also displayed (right).

# Examples of response of MEDIPIX-USB device to fast monochromatic neutrons (17MeV neutrons, flux about $10^4$ n/(s.cm<sup>2</sup>))



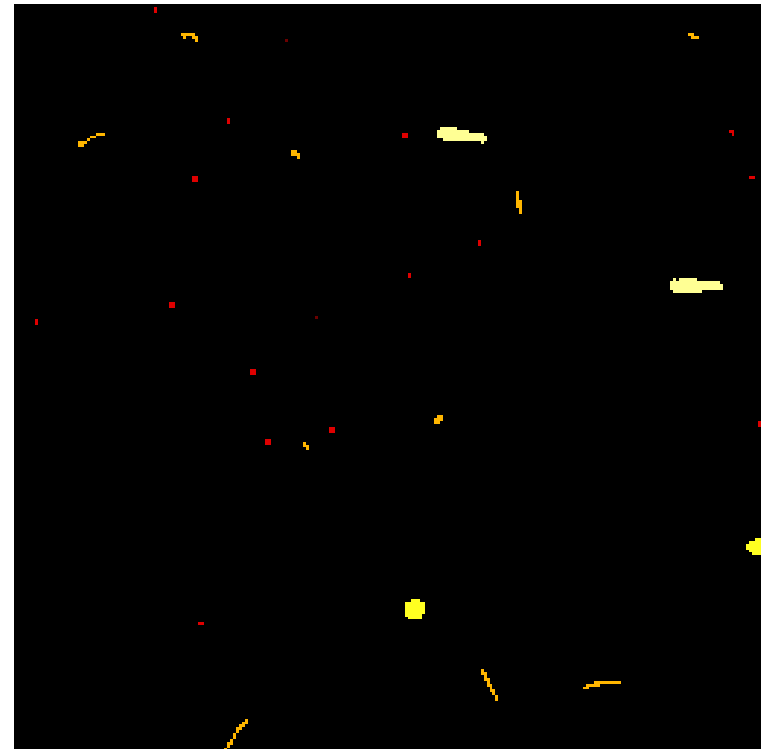
- ◆ The direction of the neutrons with respect to the image was upstream (from bottom to top). The huge background is due to gamma rays which accompany neutrons. Half of the sensor (the right-hand side) was covered with a CH<sub>2</sub> foil about 1.3 mm thickness.
- ◆ One can clearly recognize long and rather thick tracks of recoiled protons (up to 2 mm, vertically oriented) and big tracks and clusters generated via  $^{28}\text{Si}(n,\alpha)^{25}\text{Mg}$ ,  $^{28}\text{Si}(n,p)^{28}\text{Al}$  nuclear reactions in the body of the silicon detector. These events are displayed on the dense background caused by tracks and traces of electrons from interactions of gamma rays. One can even recognize that proton tracks shapes follows a Bragg law.

# Track visualization: recognition of interacting quanta and its energy



Medipix2 device with 700  $\mu\text{m}$  thick silicon sensor  
illuminated by fast neutrons (up to 30 MeV)

# Track pattern recognition



200 frames recognized in 1 sec on standard PC – see Poster 9.2 of Tomas Holy

# Effects to be considered to explain charge sharing in case of strongly ionizing particles (alpha particles)



## ◆ Plasma effect

- High free carriers density
  1. Carriers diffuse outwards of the column to reach equilibrium
  2. Electrons are faster than holes
    - Creation of two walls: outside negative, inside positive
  3. Distortion of the local electric field

## ◆ Erosion

- Walls created by the plasma effect are removed faster than by pure diffusion under the influence of the electric field in the detector

Important with high applied field

## ◆ Funneling

- Electric field distortion pushes the carriers towards their electrodes
  - ◆ More charge than expected is collected

Important for low applied fields

# Plasma Effect

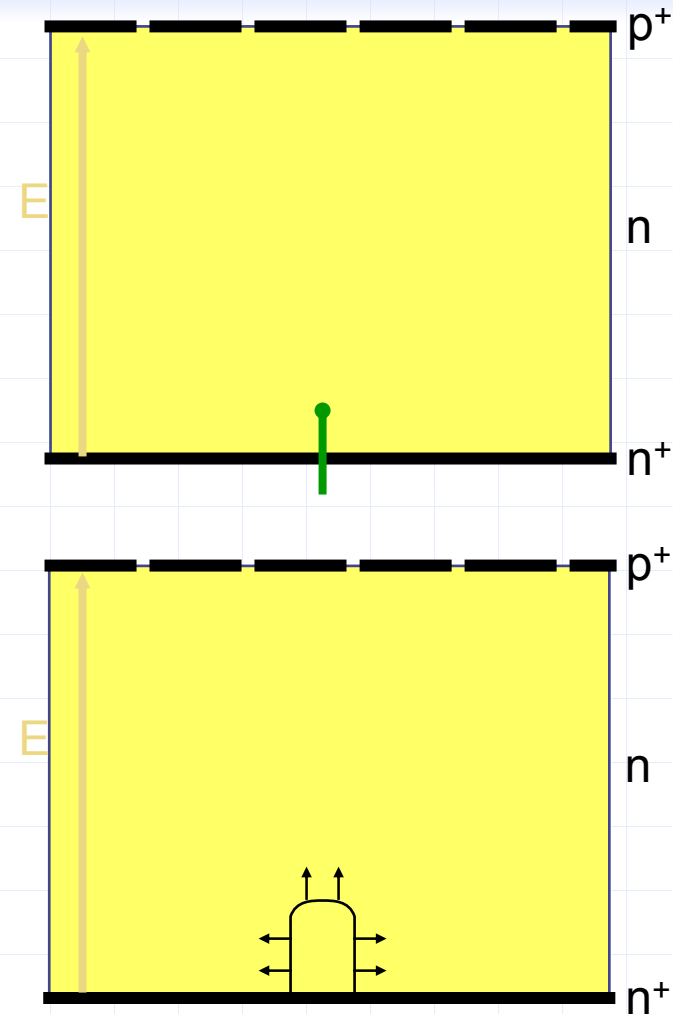
- ◆ Ionization along the track is sufficient to have a radius greater than the Debye length
  - Screening of the outside electric field
  - Conditions correspond to a plasma
- ◆ The plasma time is expressed as:

$$t_p = \frac{n_{lin}^2}{(4\pi\epsilon_0 E)^2 D_a}$$

where  $n_{lin}$  is the linear ionization density,  $E$  is the applied electric field and  $D_a$  is the ambipolar diffusion constant.

# In conditions of high applied electric field (over full depletion)

- ◆ The heavy charged-particle enters the detector through the back side:
  - Plasma of electrons and holes is created along the path
- ◆ The charge density is much higher in the column, the particles diffuse to less dense areas
  - Ambipolar diffusion



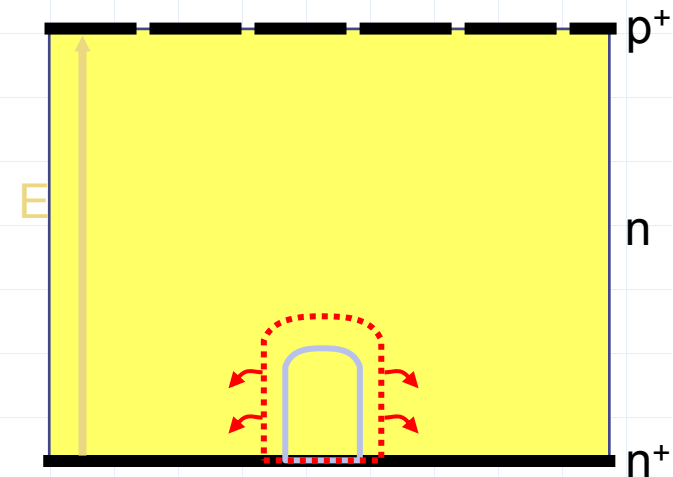
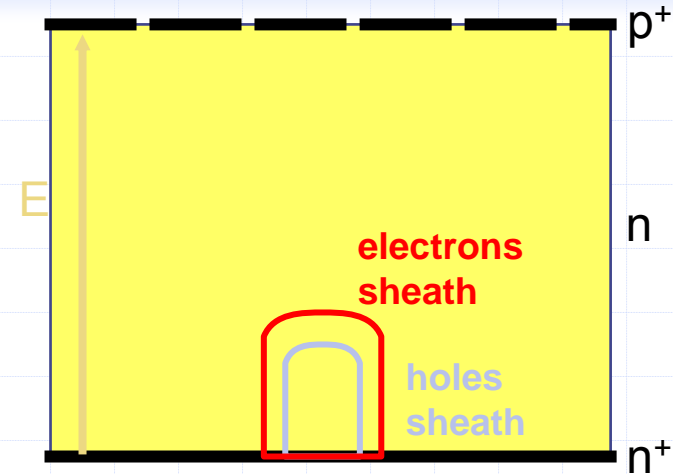
# In conditions of high applied electric field (over full depletion)

◆ Electrons move faster than the holes:

- Negative and positive sheaths are created in the column

◆ Carriers inside the column are shielded from the electric field but the electrons on the outside of the column feel it

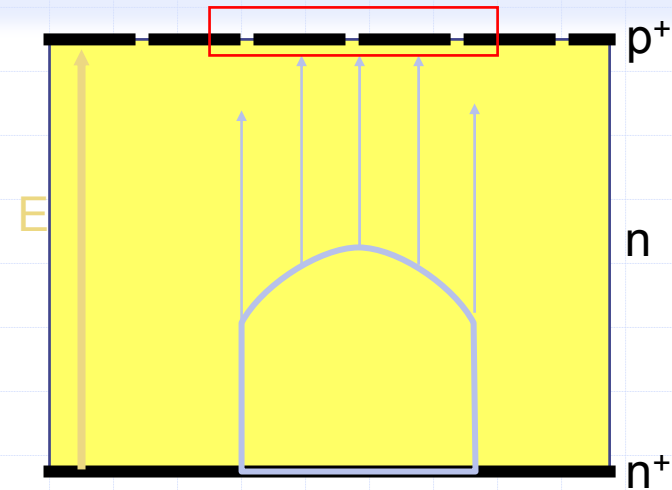
- Erosion begins



# In conditions of high applied electric field (over full depletion)

◆ Outside electrons are constantly removed. The column of holes expands up to a point where the plasma conditions no longer apply.

- Lateral expansion stops, charge is collected through drifting.



For low applied fields, the funneling effect, which pushes more carriers to the electrode than by pure diffusion, must be added. This case will not be discussed further.

# Cluster Size as function of $V_{\text{bias}}$

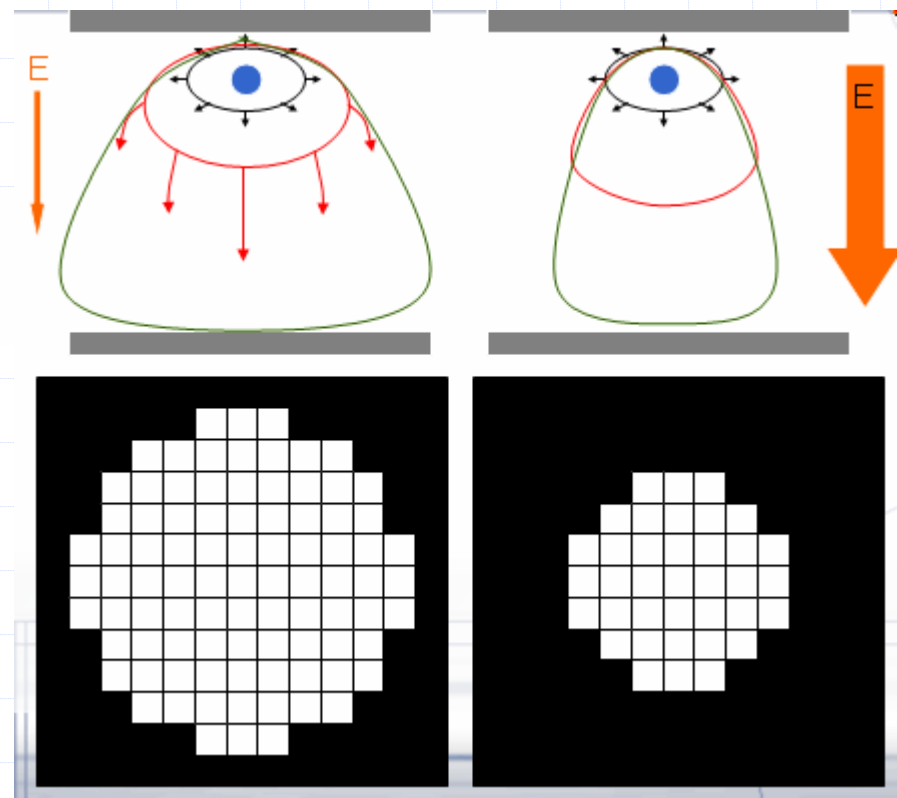
$$E_r(r) = \frac{-n_{lin}}{2\pi r \epsilon_0} \exp\left(\frac{-r^2}{4D_a t}\right)$$

$$E_z(z) = \frac{2V_{fd}}{w^2} (z - w) - \frac{V - V_{fd}}{w}$$

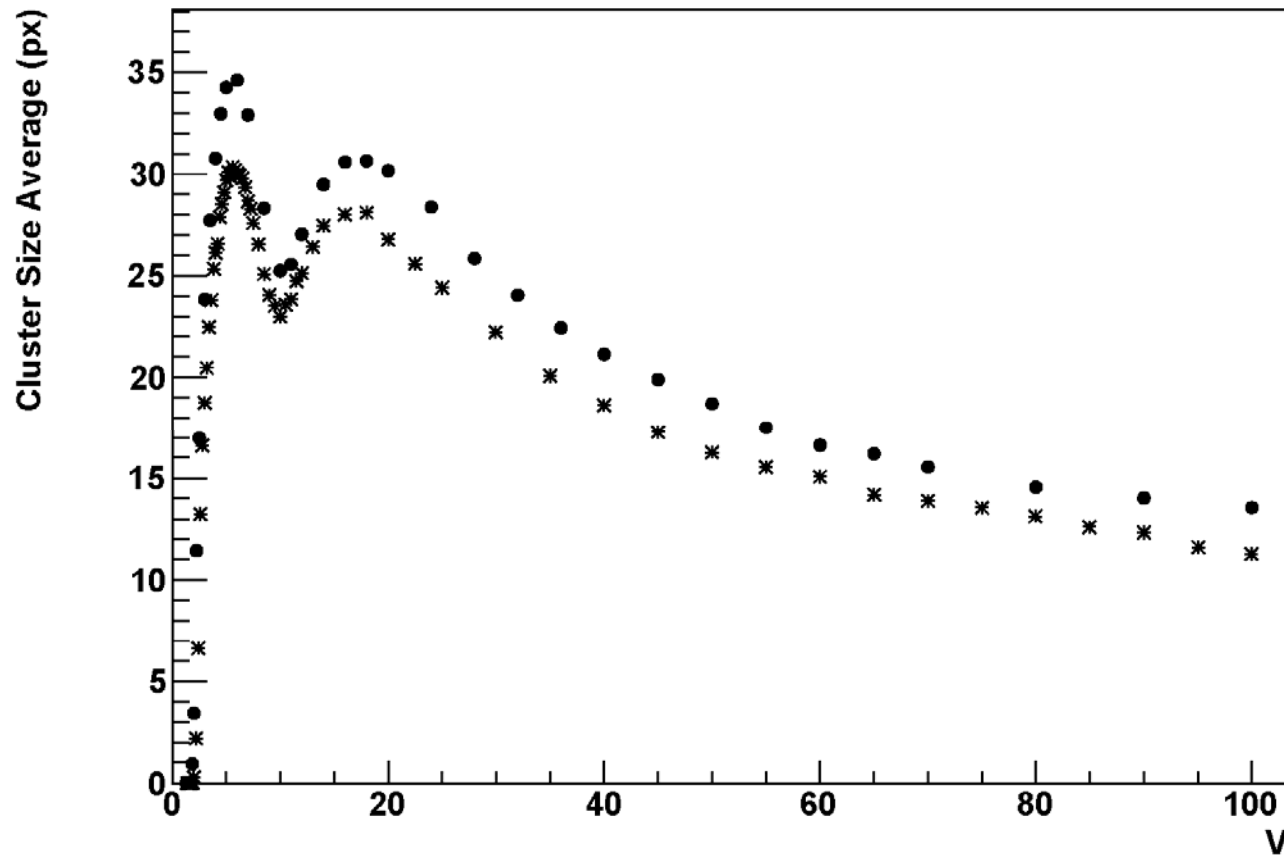
$n_{lin}$  is the linear density of electrons,  
 $D_a$  is the ambipolar diffusion coefficient,  
 $W$  is the detector thickness,  
 $V_{fd}$  is the full depletion voltage

The used values for calculations:

- Full depletion voltage: 25 V
- Initial plasma column length for alpha particles (12  $\mu\text{m}$  for 3 MeV and 19  $\mu\text{m}$  for 4.2 MeV) and radius (2.2  $\mu\text{m}$  for 3 MeV 1.85  $\mu\text{m}$  for 4.2 MeV)

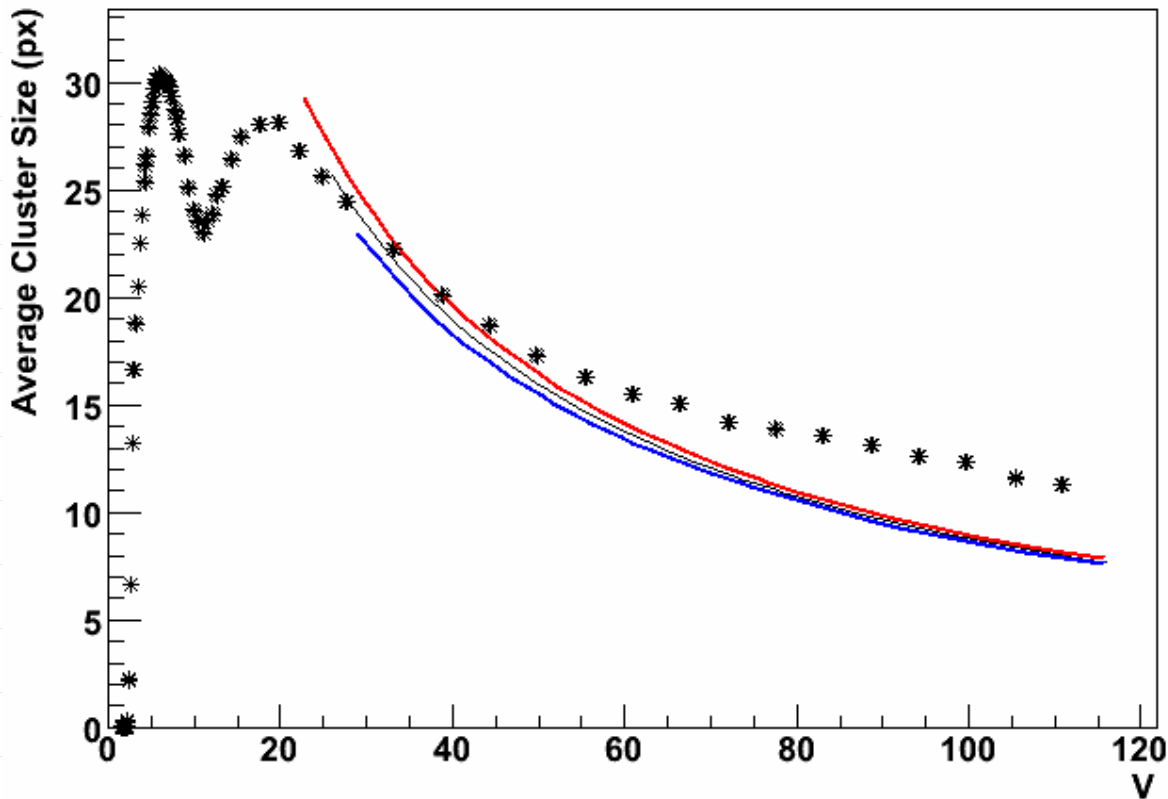


# Variation of alpha particle cluster size on applied bias



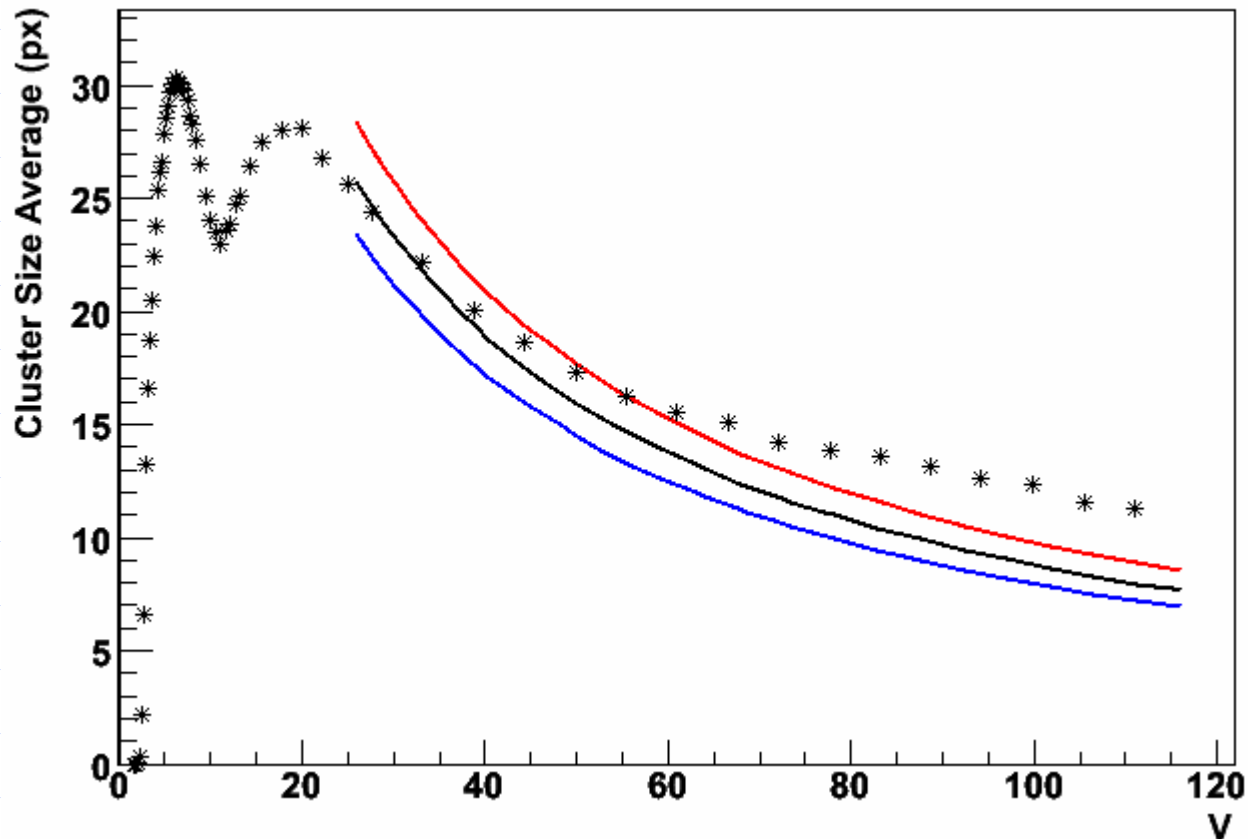
● for 4.2 MeV, \* for 3 MeV

# Variation of alpha particle cluster size as a function of applied bias for different $V_{fd}$



In red,  $V_{fd} = 22$  V, in black  $V_{fd} = 25$  V and in blue,  $V_{fd} = 28$  V.

# The influence of plasma column radius on charge sharing effect in case of alpha particles



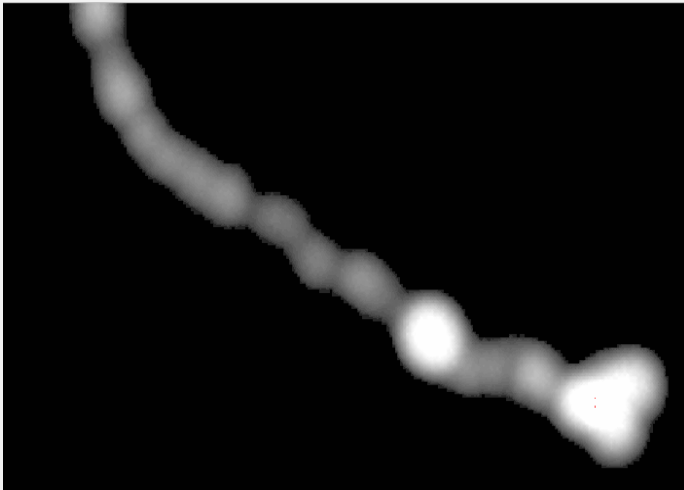
The plasma column size has a stronger influence since the radial field varies as  $1/r \cdot \exp(-r^2)$ . The influence of the plasma column radius on alpha particle cluster size: red: 2 μm, black: 2.2 μm, and blue 2.4 μm.

# New devices of Medipix family

## Timepix

Counter in each pixel can be used as

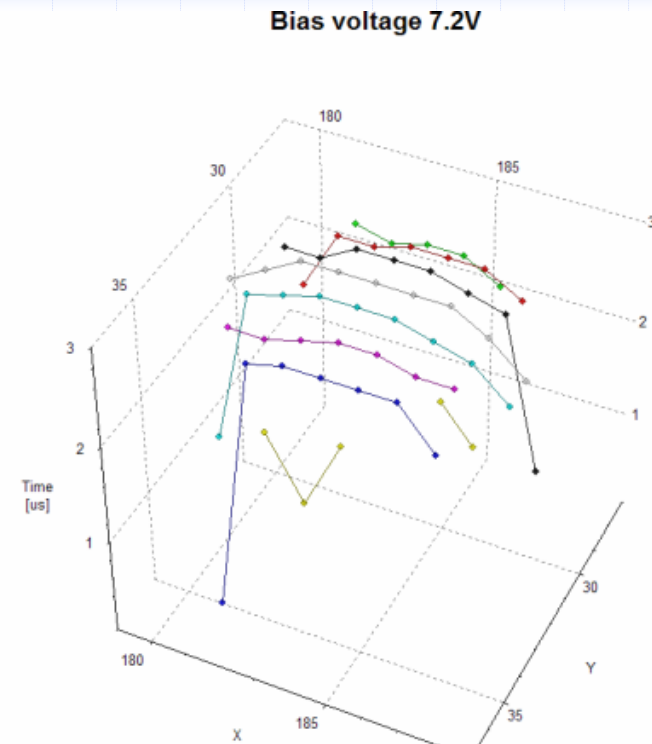
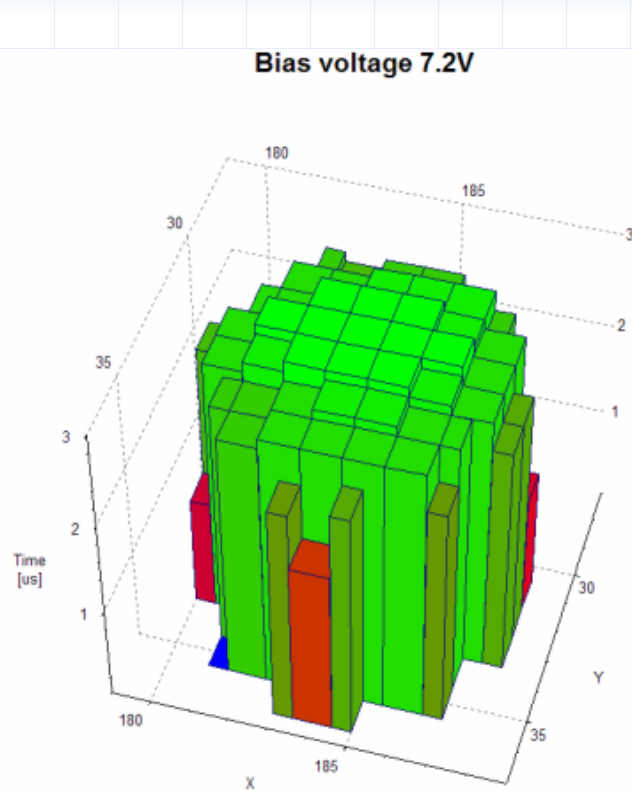
- ◆ **Timer** to measure detection time  
=> TOF experiments, TPC detectors
- ◆ Wilkinson type **ADC** to measure energy of each particle detected.  
Integral mode is also possible



## Medipix3

- ◆ **Two counters in each pixel** enabling
  - ◆ Continuous acquisition (no deadline due to data transfer)
  - ◆ Two "colors" imaging (two energy channels)
- ◆ **Charge summing scheme** => improved energy sensitivity
- ◆ **Four adjacent pixels can share their resources** => 8 counters allows 8 energy channels
- ◆ First "proof" chips exists so far

# Charge collection time in individual pixels - single alpha event



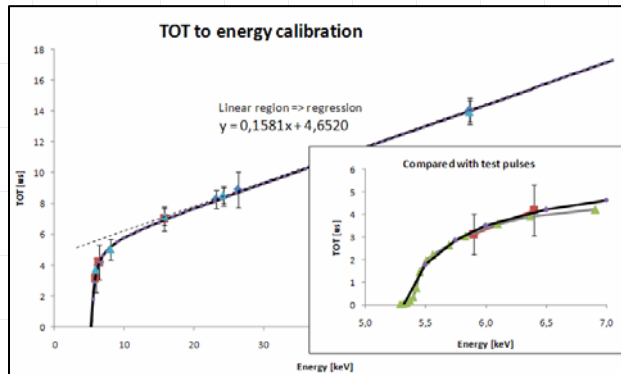
See also talk of Jan Jakubek on this conference!

New devices:

# First results with TimePix

Per hit energy measurement (TOT mode):

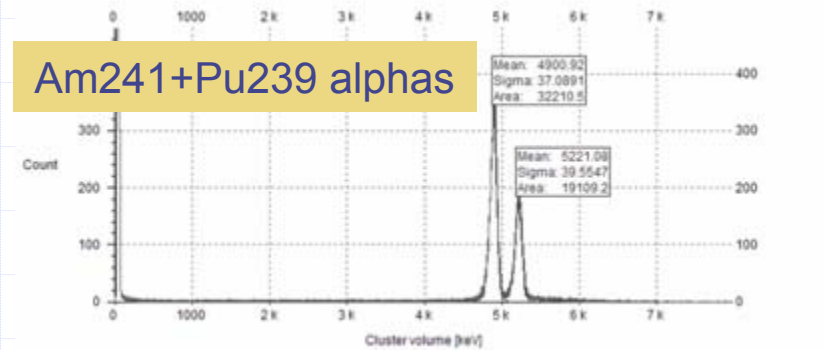
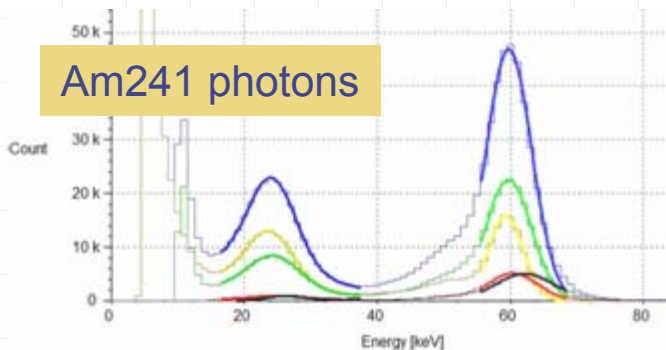
- ◆ Independent ADC is in each pixel => they have to be calibrated separately!



Not linear energy calibration!

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

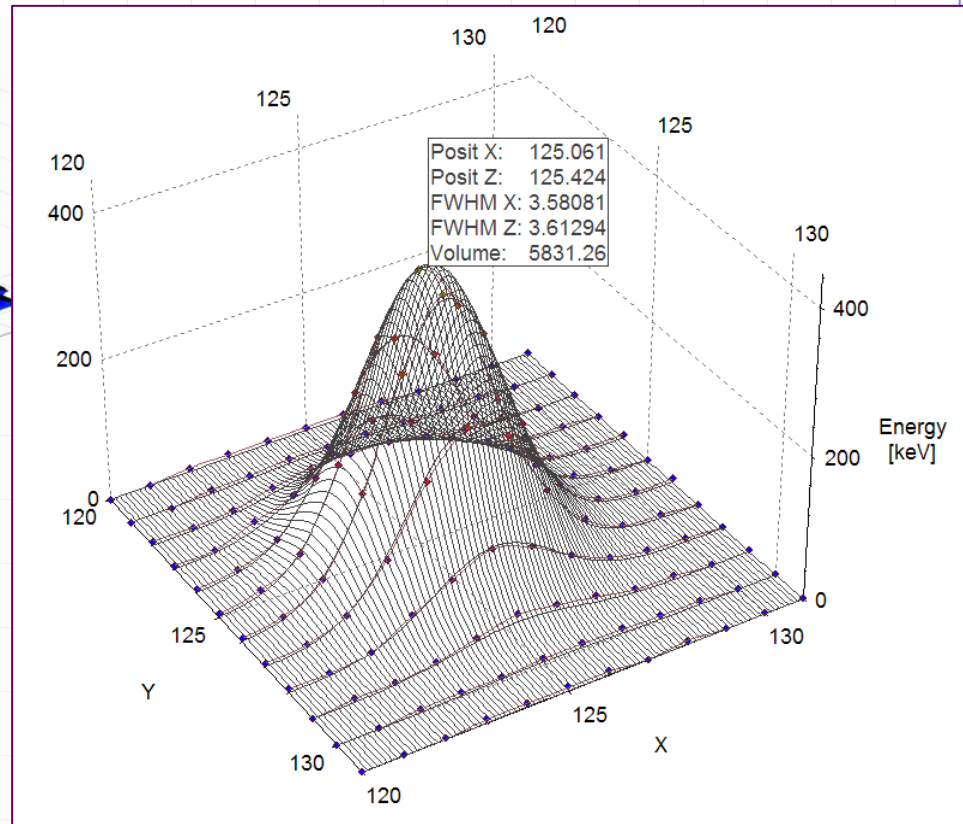
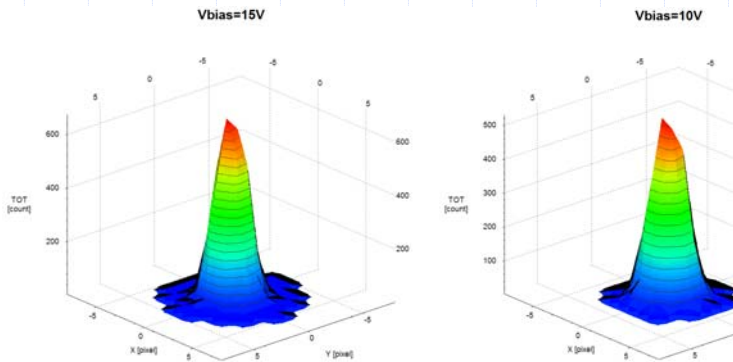
- ◆ Energy resolution for photons is about 3.3 keV (gaussian fit sigma)



First results with TimePix:

# Subpixel resolution

◆ Cluster shape depends on detector bias voltage. Can be Gaussian.

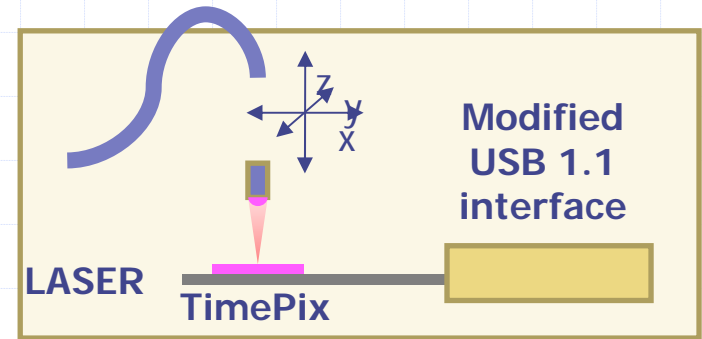


=> Subpixel resolution can be reached by Gaussian fit.

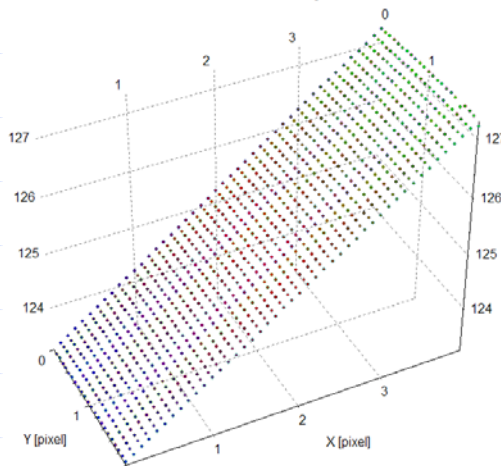
## First results with TimePix:

# Subpixel resolution test

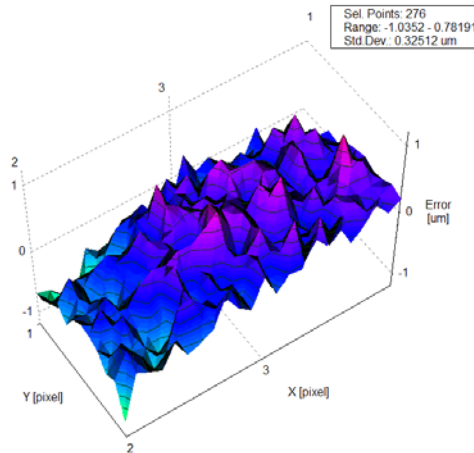
- ◆ Alpha particles simulated by red LASER pulses
- ◆ Laser spot positioned with 1 $\mu$ m accuracy
- ◆ Area of 3 x 2 pixels scanned with step of 1.25  $\mu$ m. Just single shot evaluated in each position.



Laser scan, step 5 $\mu$ m  
Measured cluster X position



Difference of measured and set X position



Standard deviation  
of position  
determined by fit is  
**0.32 $\mu$ m**

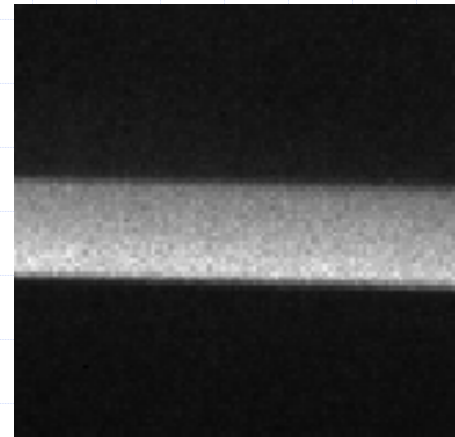
⇒ Each pixel can be  
divided to 100 x  
100 subpixels  
⇒ **655 Megapixels!**

# Dependence of cluster size on depth of interaction



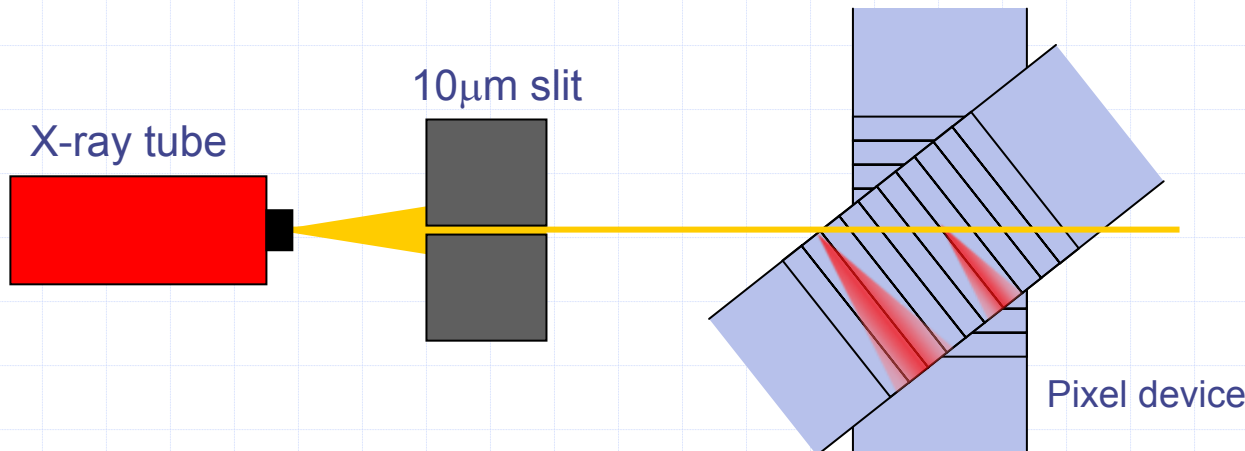
## How to create defined charge in single point defined depth?

- Charged particles are creating tracks of statistical nature
- Photo-effect is localized, amount of charge is well defined



Direction under projection:

Depth of interaction determined easily. => Hard to process data

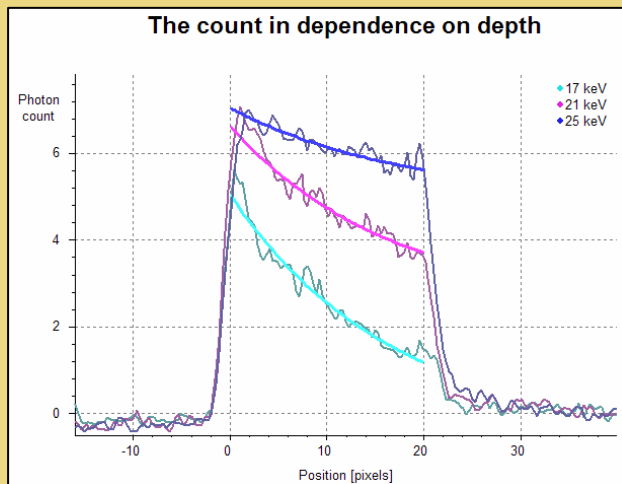


# Dependence of cluster size on depth of interaction

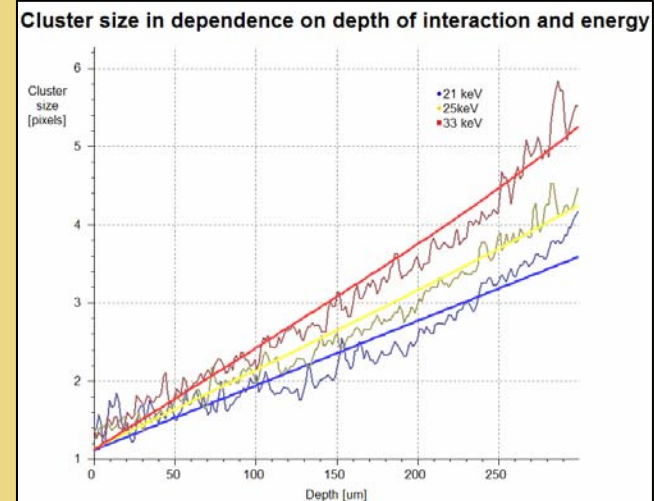


## Measurement:

- X-ray tube settings: 60kV, 1 $\mu$ A
- 5069 frames with short exposure time were taken by **TimePix** device in TOT mode (to see individual clusters). Threshold is set just above the noise ( $\sim$ 3keV).
- 570 663 clusters identified.
- Volume of each cluster reflects the photon energy
- Just clusters of given energy are processed.



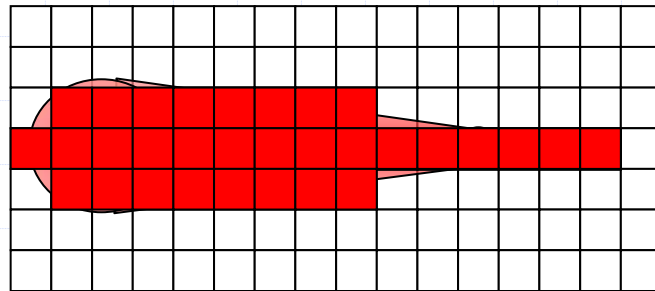
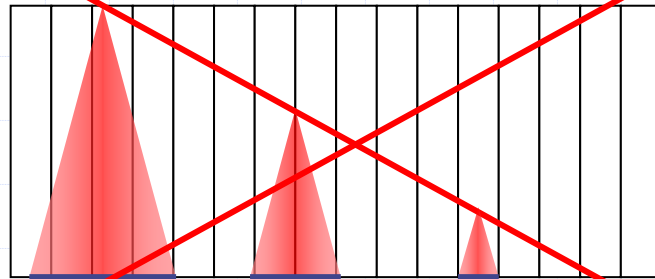
**Exponential attenuation** confirms method of energy determination using cluster volume (The device has to be calibrated)



**Dependence of cluster size on the depth is almost linear.** Cluster size can be even 8 pixels and more for higher photon energies.

Charge sharing effect:

# Tracks of MIP particles

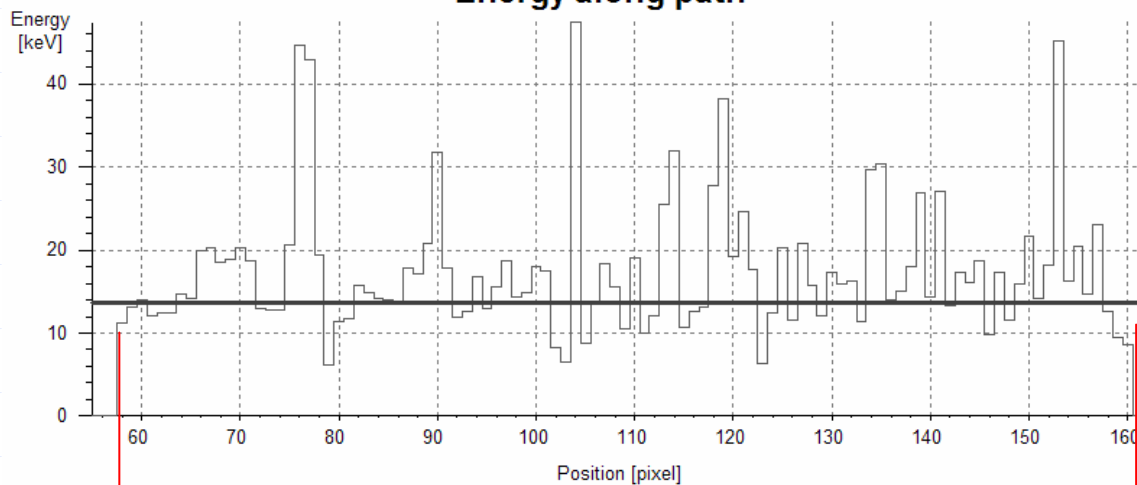


- Ionization by MIP particles doesn't depend on depth and follows Landau distribution
  - Charge sharing effect is more significant if charge is generated near the surface
- => Charge sharing brings more information in tracking mode

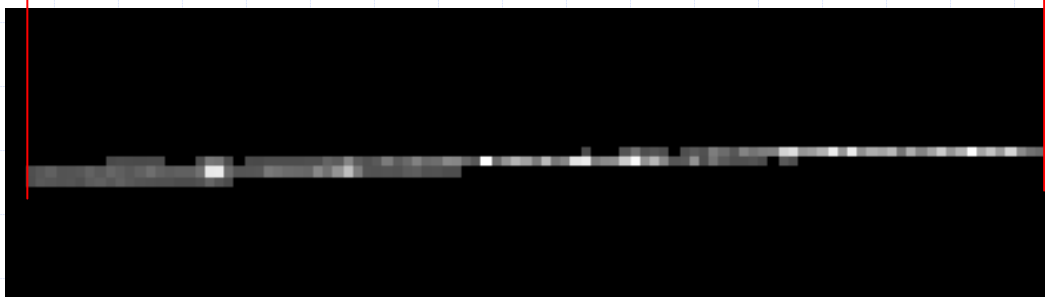
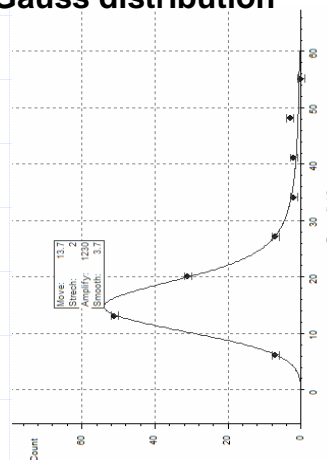
# Tracks of MIP particles – Cosmic muons



Energy along path



Energy distribution fit by convolution of Landau and Gauss distribution



The muon track recorded by TimePix device

# Conclusion and future

- ◆ The amount of information which can be obtained from pixels is essential => future chips will provide more information:
  - **Timepix** – direct measurement of particle energy or its interaction time in each pixel.
  
- ◆ **Event by event measurement mode is very powerful tool.** However
  - data read out and analysis increases dead time
  - => Implementation of data compression directly into ASIC chip.
  - => hardware have to be optimized for ROI read out and for on-line data evaluation (FPGA + DSP).
  
- ◆ **New interfaces (portability, performance)**



# Thanks for your attention