TRAINING COURSE ON RADIATION DOSIMETRY:

Instrumentation 2 – Solid state detectors

Tracking and radiation field measurement with pixel detectors

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Thu. 22/11/2012, 11:30 – 12:30 am

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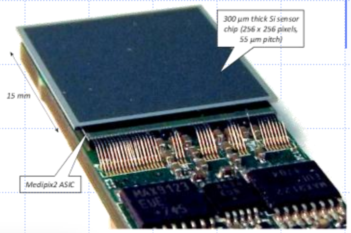
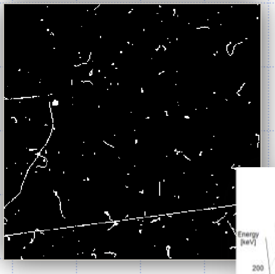
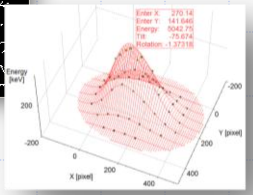
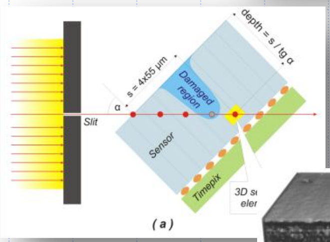
Outline

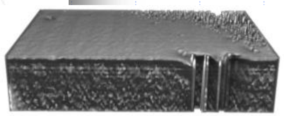
- Radiation detection
  - What information on surrounding radiation field we can get?
  - What we can use to get the information?
- Evolution of the detectors from Medipix family
  - Medipix 1
  - Medipix 2 / Timepix
  - Medipix 3
- Radiation measurement with the solid-state detectors
  - Integration x tracking
  - Threshold based background suppression
  - Cluster analysis
  - Energy information
  - Time of arrival information
- Characterization of the detector properties
  - 3D scanning of pixelated sensor with X-rays
  - Scanning of pixelated sensor with protons and alpha particles











Radiation detection

What information we can get (and what effect we are figting against)?

- Position - 1D, 2D, 3D (technological limitations)
- Energy (charge sharing effect)
- Time of arrival (delay, jitter)
- Particle identification (count rate and data handling)

- High dynamic range (dark current)
- Signal to noise/background ratio (detection efficiency)

What we can use to get the information?

- Strip/Pixel/Voxel detectors
- Clever pixels - charge summing on the level of analog electronics
- Advanced electronics on both detector and computer side

- Single particle counting devices instead of integrating devices
- Different sensor materials, pattern recognition of individual particle traces, threshold

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Hybrid single particle counting semiconductor pixel detectors are excelent choice for this purpose

Principle of single particle counting pixel detector

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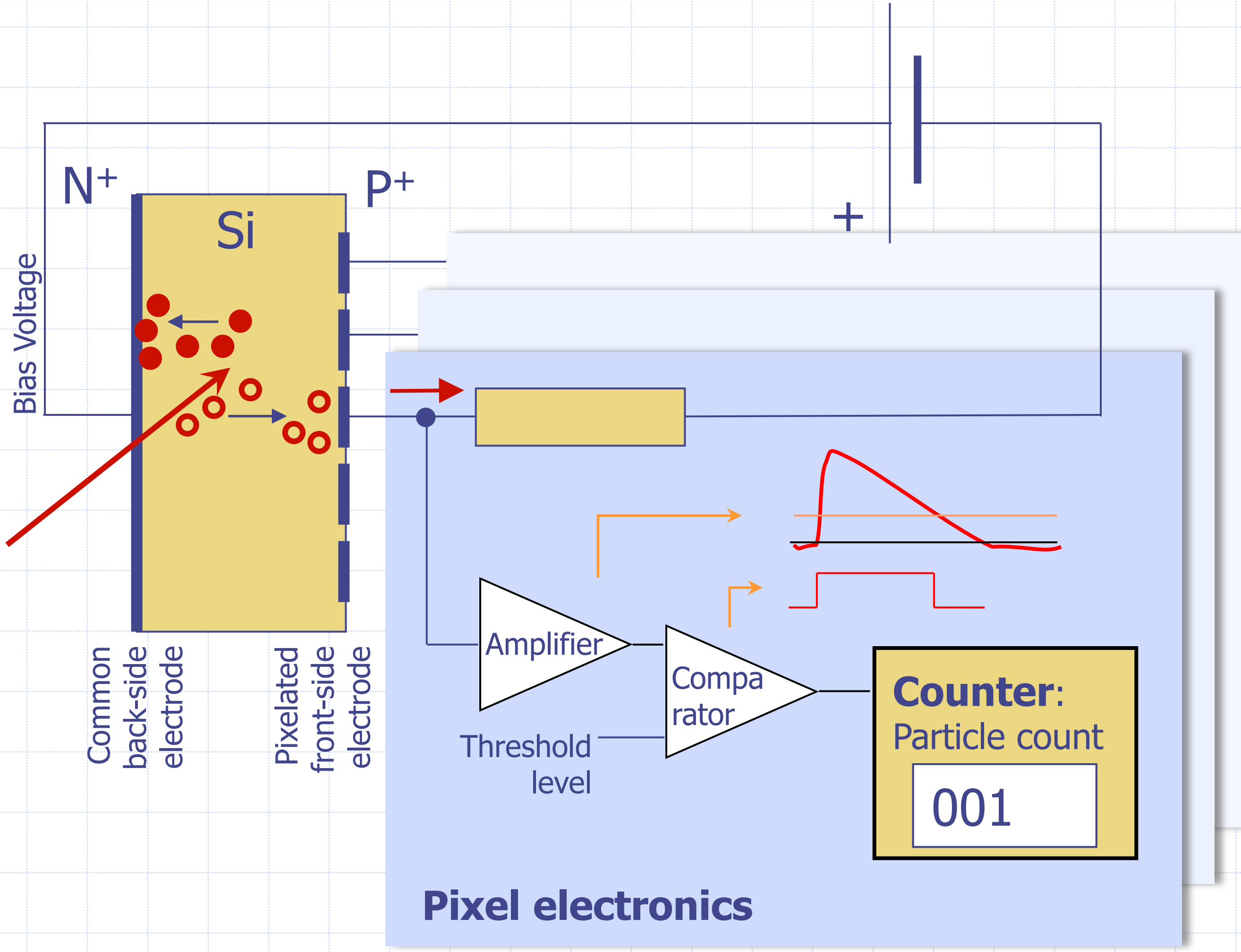

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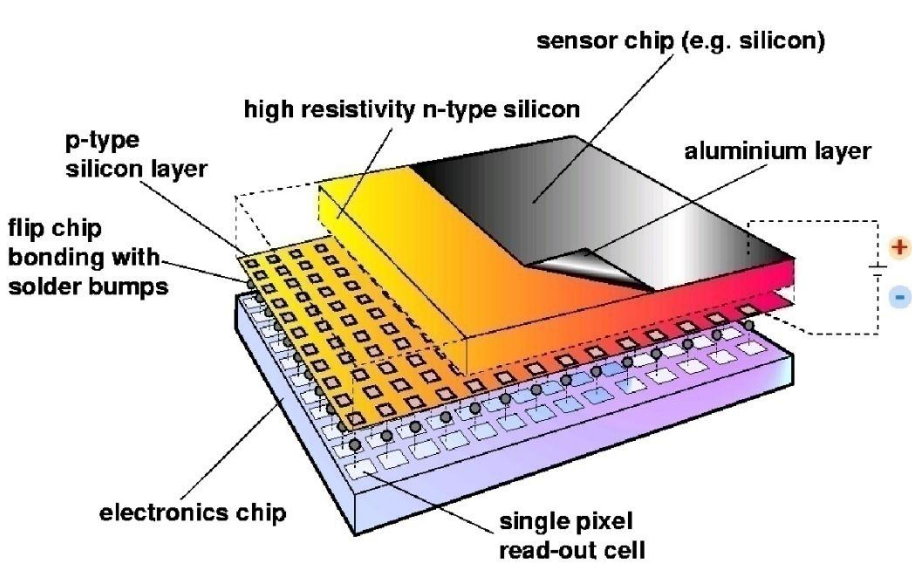
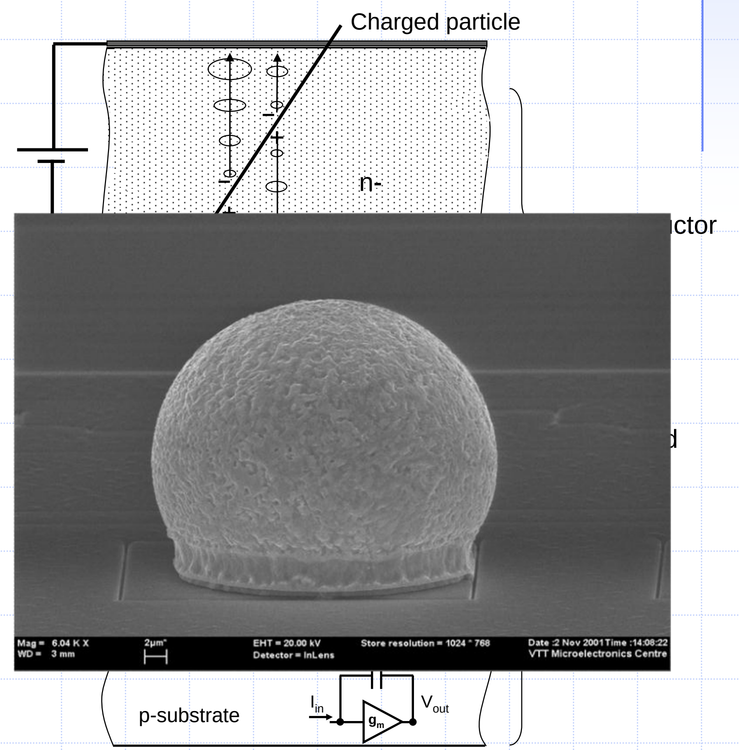
Principle of hybrid pixel detectors





- Hybrid technology allows to use different semiconductor sensors (Si, CdTe, GaAs,…)
- Pulse processing electronics provides simultaneously fast and noise free images

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Medipix: an example of a hybrid pixel detector

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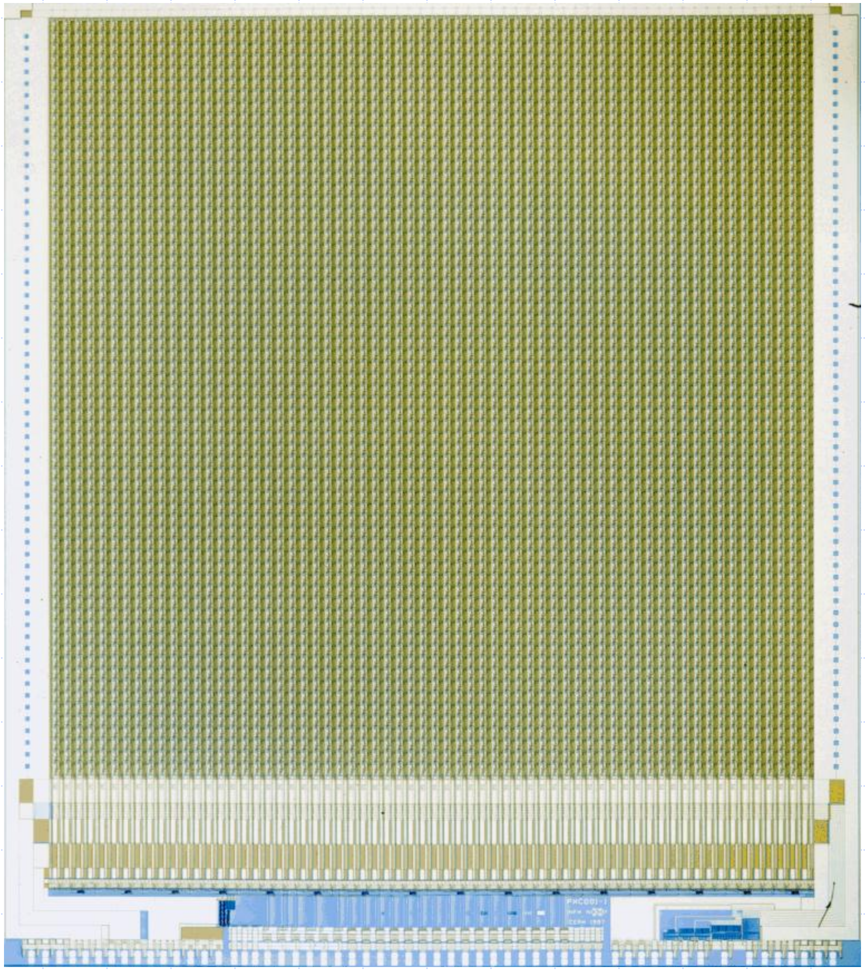
Medipix1 detector:

Evolution of the detectors from Medipix family (1997)

- 64 x 64 square pixels of 170 μm side-length.
- Active area of the chip: ~1.2 cm^2.
- Sensitive to positive charge. Leakage current compensation at the input.
- Maximum countrate: ~2 MHz.
- 1 comparator per pixel with 3 bits fine tuning for a homogeneous threshold distribution within the pixel matrix.
- Minimum threshold ~1500 e (~5.5 keV charge deposition in a Si sensor).
- 15 bit counter per pixel to store up to 32767 single events.
- Variable acquisition time.
- 1 μm CMOS, 2-metal, 1.6 M transistors.



www.cern.ch/medipix

Medipix2 detector:

Evolution of the detectors from Medipix family (2002)

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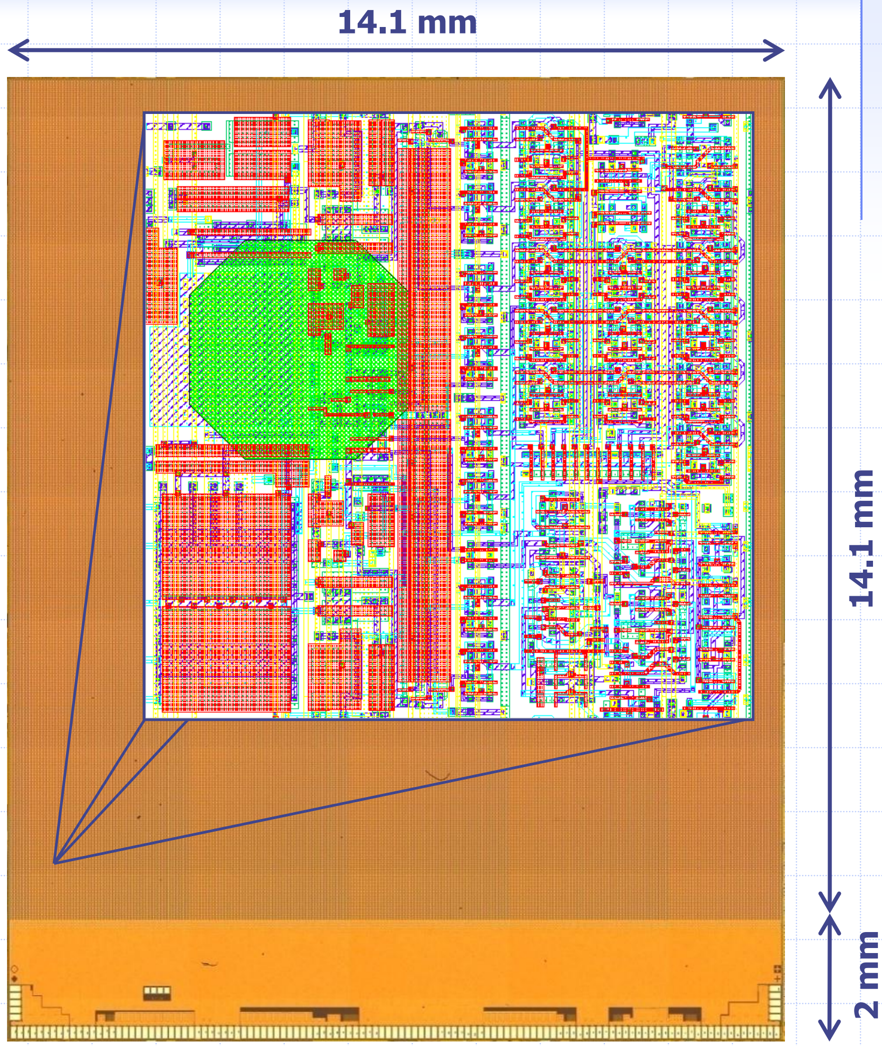
- 256 x 256 square pixels of 55 µm in size.
- Sensitive area of ~2 cm² (87% of chip).
- The chip is designed to accept either positive or negative charge input in order not to restrict the choice of the sensor material (Si, GaAs, CdZnTe,...).
- Maximum countrate: ~100 kHz per pixel
- Amplifier, two discriminators and a 13-bit counter in each pixel cell. It is possible to select a window in energy. Upper and lower threshold can be adjusted pixelwise with 3 bits.
- Parallel and serial read-out.
- 3-side buttable for fesible large area coverage.
- 0.25 µm CMOS, 6-metal, 35 M transistors



Timepix detector:

Evolution of the detectors from Medipix family (2006)

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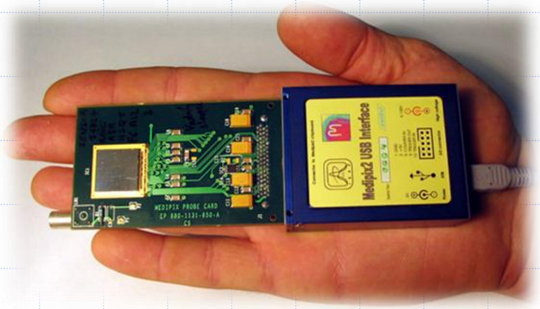
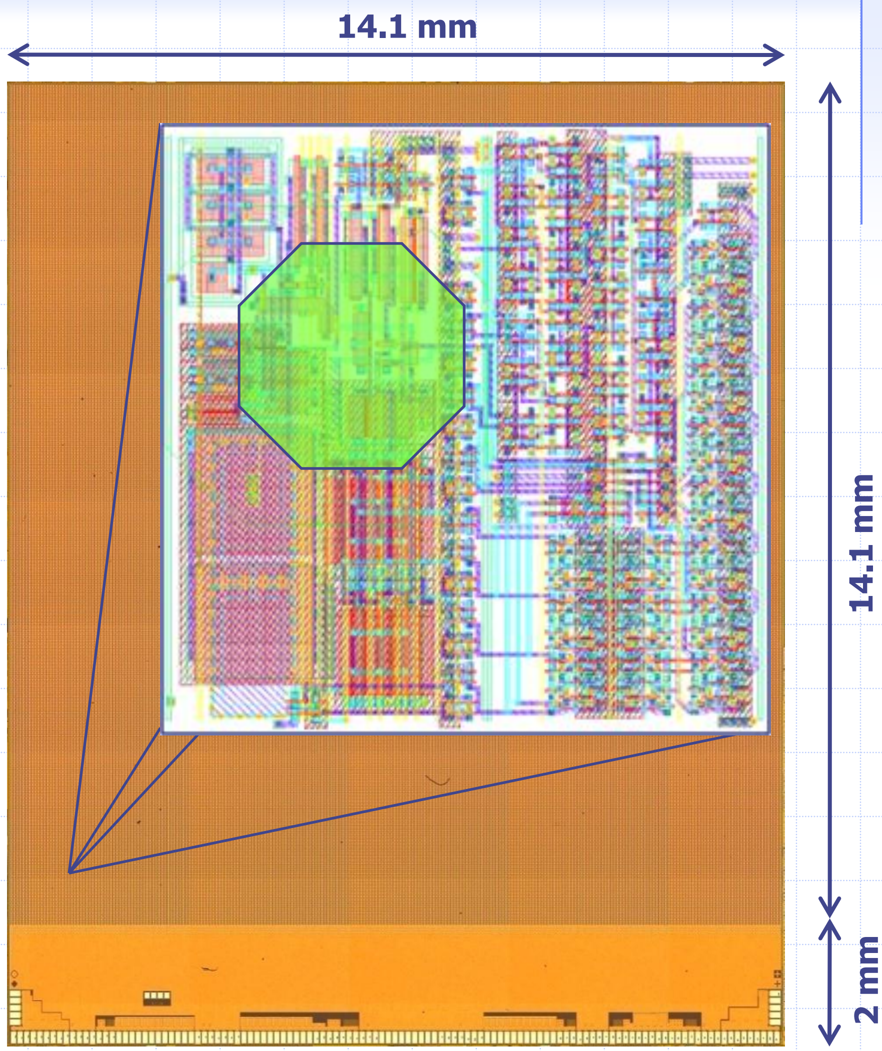
- 256 x 256 square pixels of 55 μm in size.
- Timepix has a single energy threshold. The threshold can be adjusted pixelwise with 4 bits.
- Each pixel can be programmed to work on one of 3 modes: Single particle counting, Time over Threshold or Arrival time mode.
- Exposure times can be chosen arbitrarily. Data is accumulated in a 13-bit counter per pixel. The pixel overflows at 11810 counts. In single particle counting mode each pixel can handle count rates of about 100 kHz of randomly arriving particles.
- Parallel and serial read-out are realized.
- 0.25 μm CMOS, 6-metal, 36 M transistors.





Timepix detector:

Direct measurement of particle *energy* or its *arrival time*

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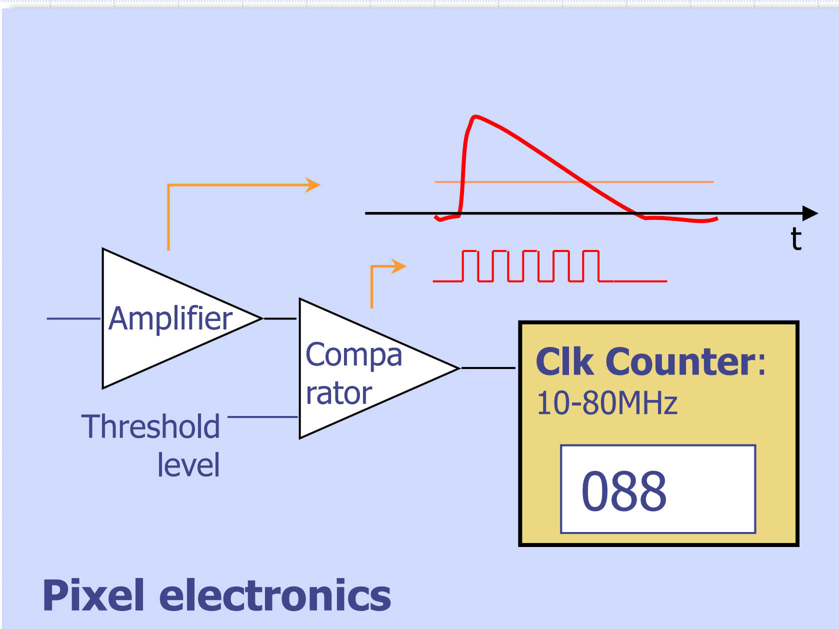
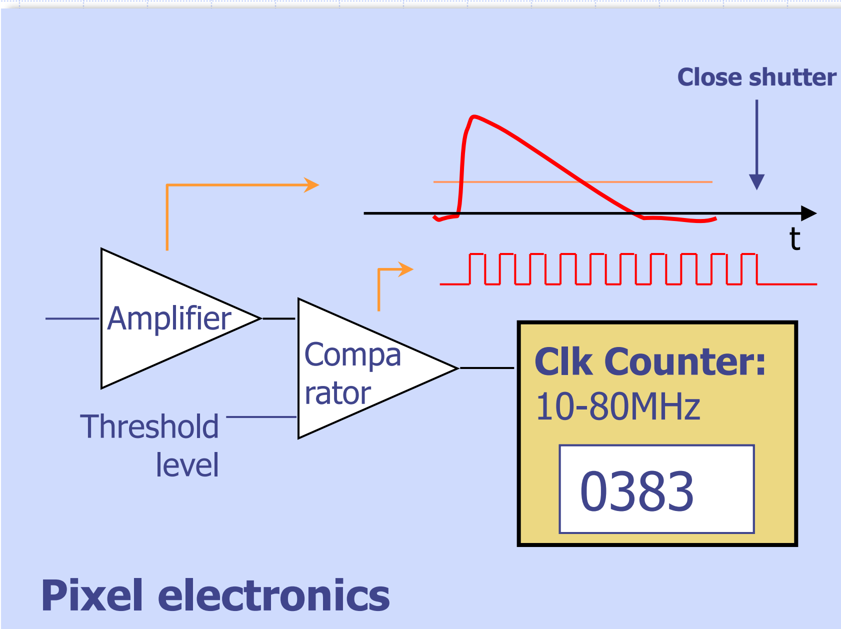
Operation Modes

Time-over-Threshold



Counter value ~ Energy

Arrival Time



Counter value ~ Arrival time

Medipix3 detector:

Evolution of the detectors from Medipix family (2009)

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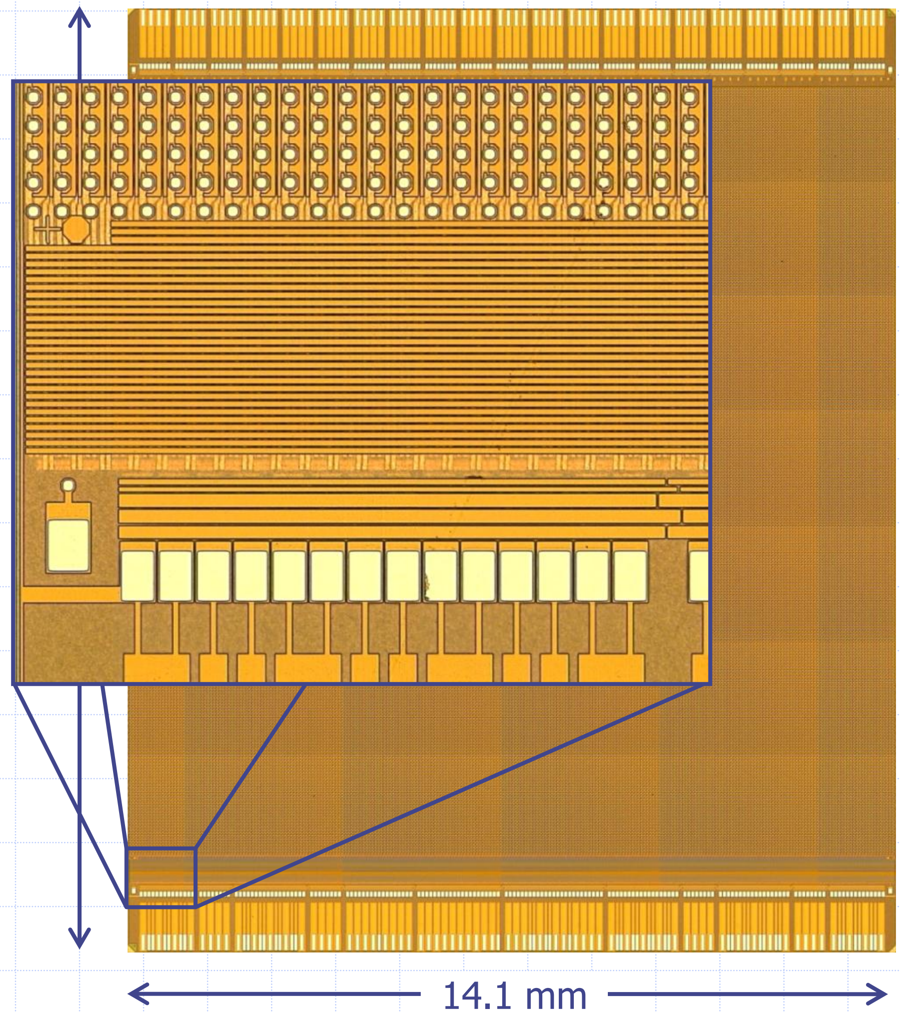
- Matrix of 256 x 256 pixels, 55 μm each
- The Medipix3 architecture allows pixels to operate either in single pixel mode or in charge summing mode.
- Each Medipix3 pixel have 2 thresholds and 2 counters.
- User may configure the chip to work eith in continuous read/write mode (one cour r is read out while the other counts) or in sequential read/write mode with 2 differe thresholds.
- Variable counter depth (1, 4, 12, 24 bits) to reduce readout time.
- It is also possible to bump bond only 1 pixel in 4 increasing the sensor pixel pitch from 55 μm to 110 μm while having 8 counters per pixel. This is called color mode and permits either 4 separate thresholds in simultaneous read/write mode or 8 thresholds in sequential read/write mode.
- 0.13 μm CMOS, 8-metal, 72 M transistors.



Medipix3 detector:

Charge summing and allocation concept

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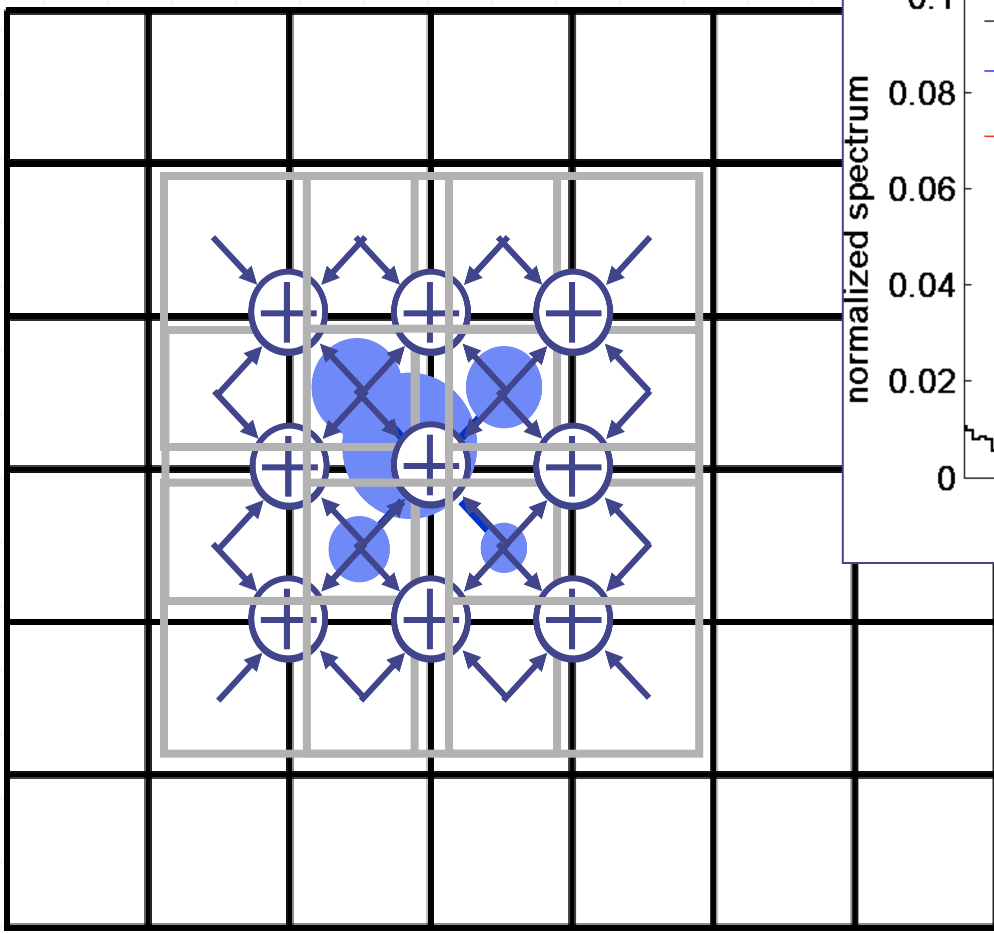

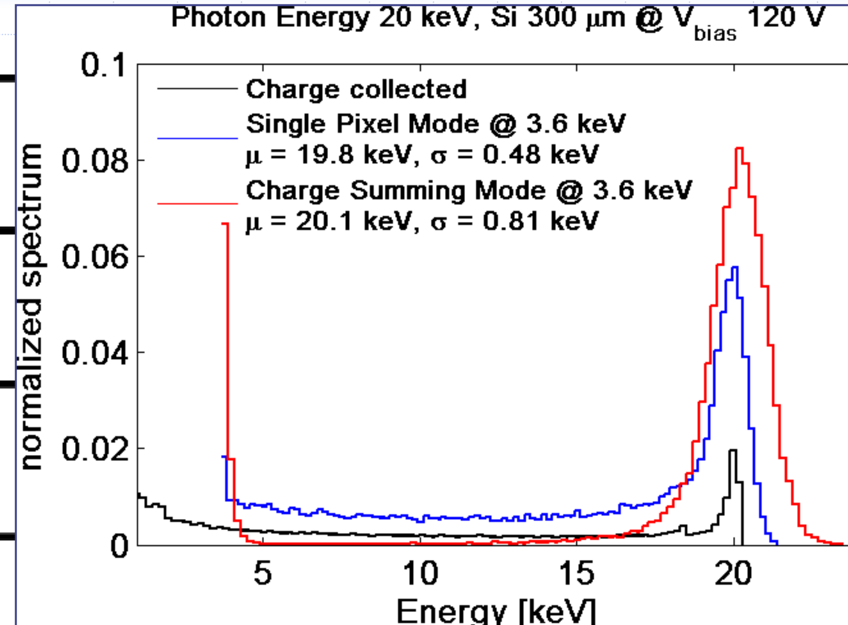

- Pixel spectrum is reconstructed
- Immune to threshold variations

55 µm

Back-side signal processing:

Trigger the measurement by the heavy particles

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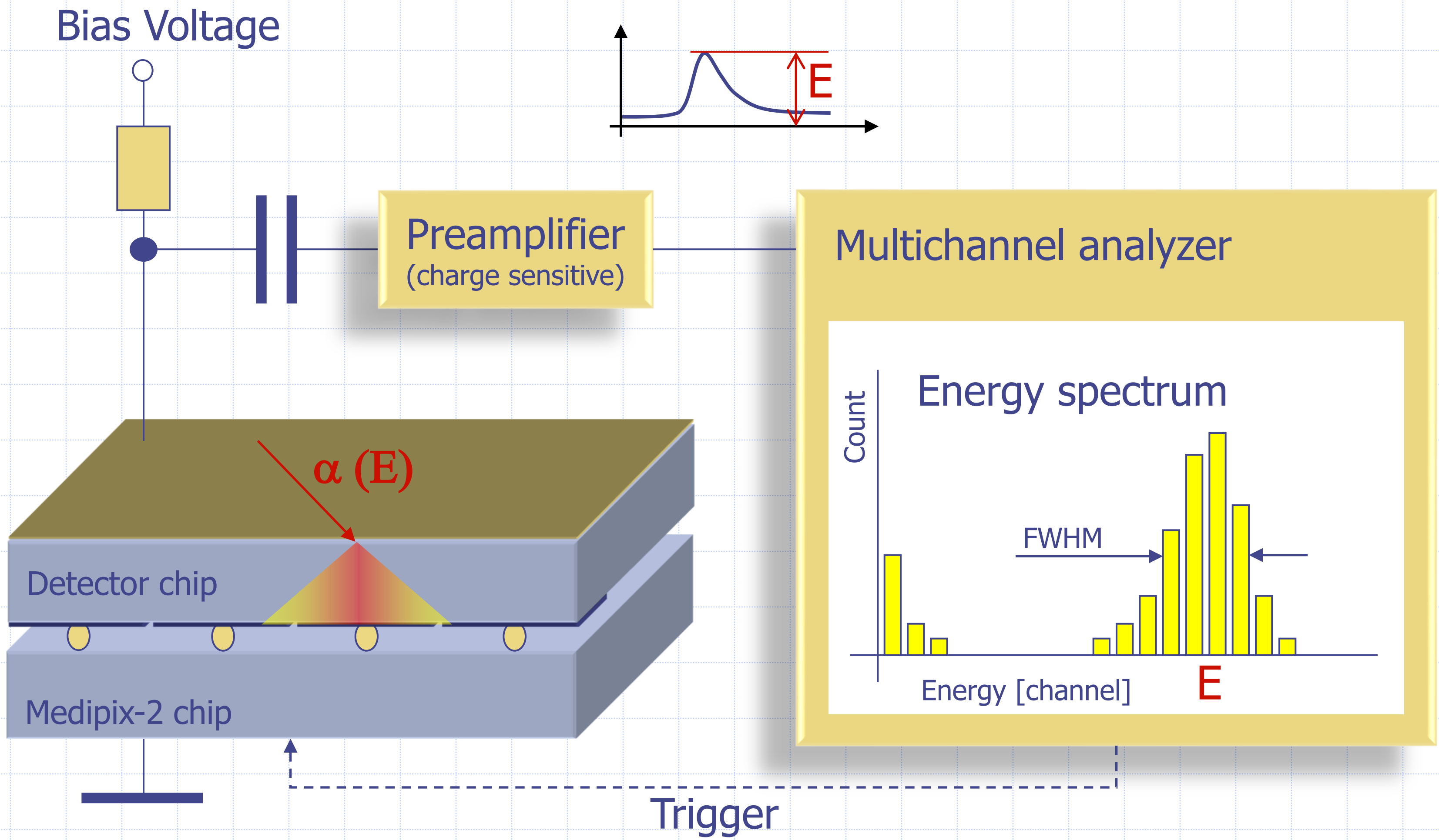
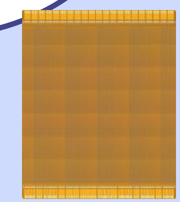


Evolution of the detectors from Medipix family

Position resolution → **Energy response** → **Functionality**

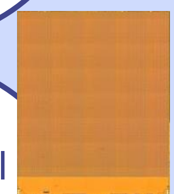
2009

Medipix 3
256 x 256 pixels
55 x 55 µm
~1100 transistors



2006

Timepix
256 x 256 pixels
55 x 55 µm
~550 transistors

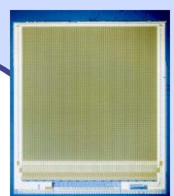


2002

Medipix 2
256 x 256 Pixel
55 x 55 µm
~520 transistors

1997

Medipix 1
64 x 64 pixels
170 x 170 µm
~400 transistors



Medipix 1	Medipix 2 / Timepix	Medipix 3
1 µm CMOS, 2-metal, 1.6 M transistors	0.25 µm CMOS, 6-metal, 36 M transistors	0.13 µm CMOS, 8-metal, 72 M transistors

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Tracking and radiation field measurement with solid-state pixel detectors

Radiation measurement with the solid-state pixel detectors

Detected particle types (for 300 µm thick Si sensor):

- All charged particles with energy above 5 keV (minimal threshold level)
- Other particle types have to be converted into secondary charged particles first

Efficiency of the detection (for 300 µm thick Si sensor):

Efficiencies for noncharged particles are reduced by the conversion efficiency to detectable charged particles and geometry factors to following:

- Charged particles (above 5keV): 100%
- X-rays (5keV – 10keV): ~100%
- Gamma-rays (from 1MeV): ~0.1%
- Thermal neutrons (energy < 1eV): ~5% (with LiF converter)
- Fast neutrons (MeV range): ~0.5% (with PE converter)

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Radiation measurement with the pixel detectors:

Integration x tracking

Description of the modified Medipix2 detector

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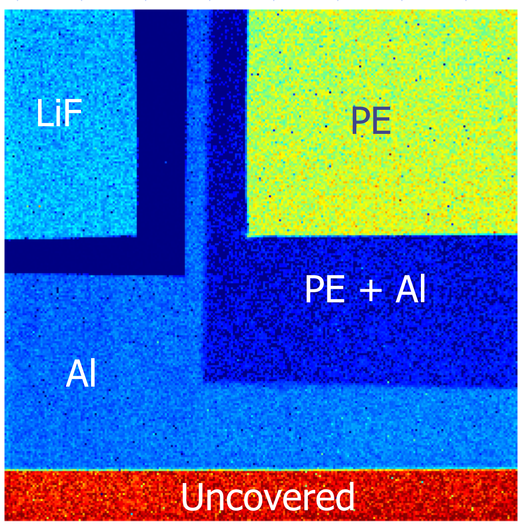
Medipix2 with 300µm Si sensor + USB interface

Neutron conversion structures:

1) LiF+50µm Al foil area
2) 100µm Al foil area
3) PE area
4) PE+50µm Al foil area
5) Uncovered area

X-ray image of conversion layers



Counting x Tracking operation mode

The Medipix device can operate in two "modes" chosen by selecting appropriate acquisition time for given particle flux.

Counting mode:

a) Acquisition time is relatively long, so the signal from the individual particles is overlaped.

b) Overlaping limit is given by the depth of the Medipix2 pixel counter to 11810.

c) Negligible dead time.

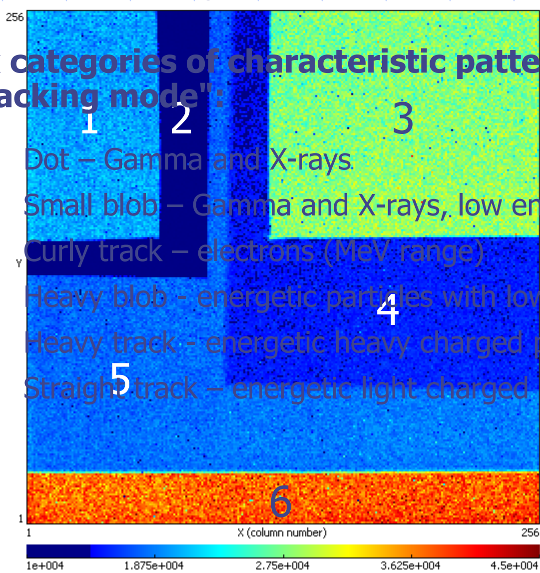
Tracking mode:

a) In the same field conditions the acquisiton time has to be ~1E6 times lower than in counting mode.

b) Identification of the particle type and energy from it's characteristic track.

c) Dead time can significantly increase because of data transmission -> fast readout is needed

X-ray image of conversion layers



Six categories of characteristic patterns were introduced in "tracking mode":

1) Dot – Gamma and X-rays

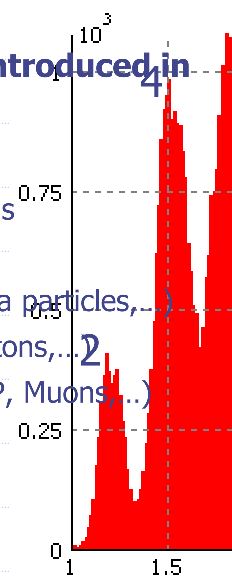
2) Small blob – Gamma and X-rays, low energy electrons

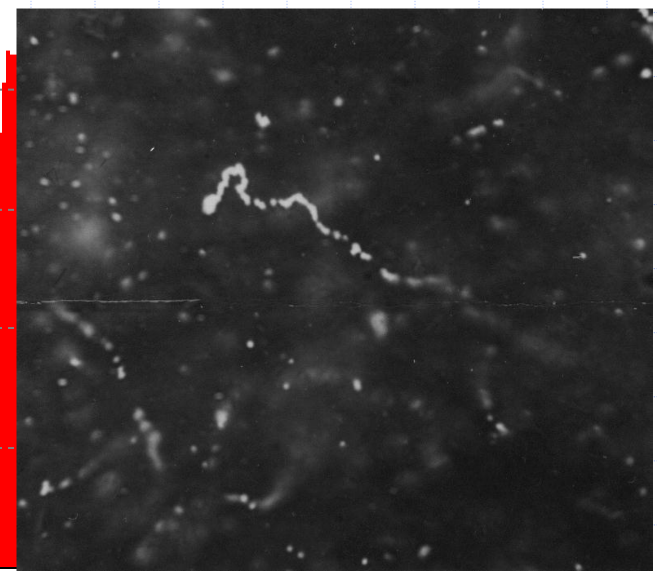
3) Curly track – electrons (MeV range)

4) Heavy blob – energetic particles with low range (alpha particles,…)

5) Heavy track – energetic heavy charged particles (protons,…)

6) Straight track – energetic light charged particles (MIP, Muons,…)





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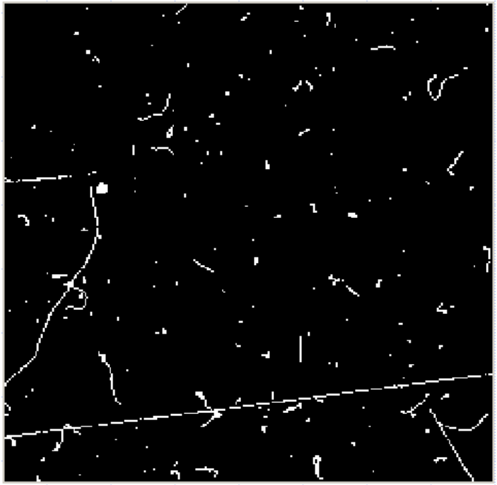
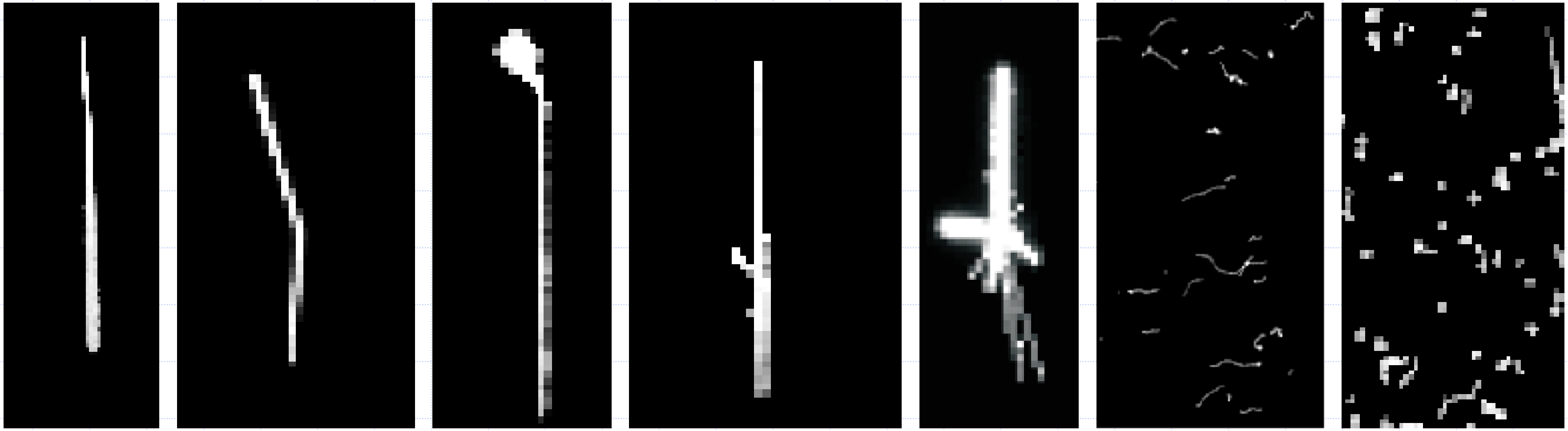
Several examples of the recorded particle tracks

- Primary proton tracks (keeping direction)
- Scattered protons (change of directions)
- Tracks of recoiled nuclei
- Delta electrons
- Fragmentation
- Electrons
- Low energy electrons and X-rays



Natural radiation background



Charge sharing effect

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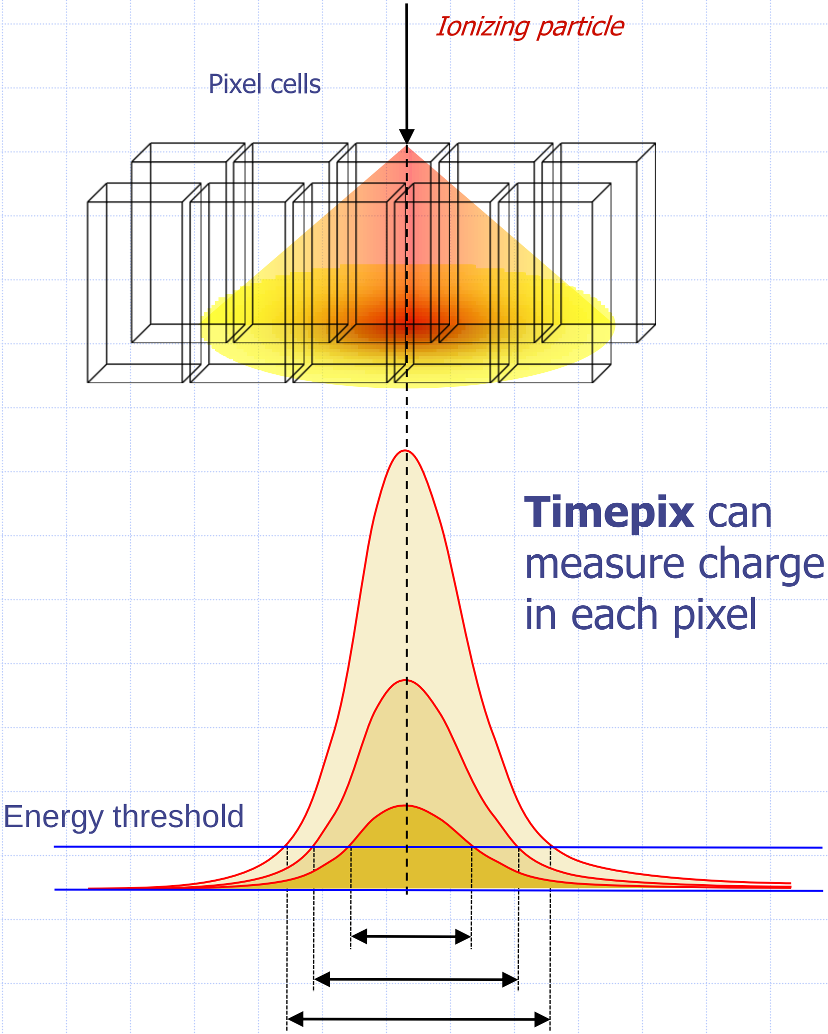
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => CLUSTER
- Pixels in a cluster will detect the charge if it is higher then certain threshold

The Cluster size depends on:

- Particle energy
- Depth of interaction
- Detector bias voltage
- Local material properties



Timepix can measure charge in each pixel

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Radiation measurement with the pixel detectors:

Threshold based background suppression

Low x High Threshold:
Example with 252Cf neutron source

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Two general threshold levels can be used with respect to the kind of radiation we want to study:

Low threshold: energy of 10 keV

a) Necessary for measurement of X-ray and gamma radiation, electrons and MIPs.

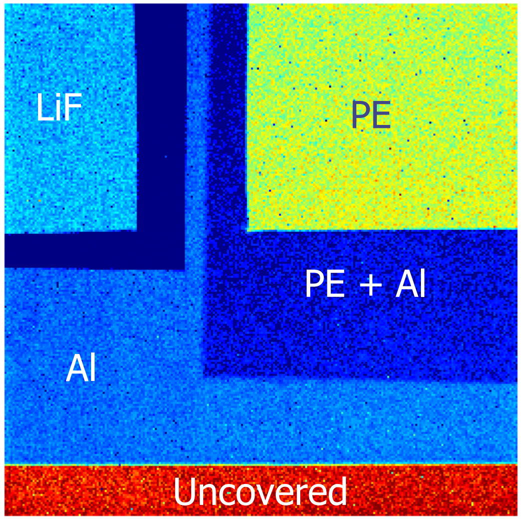
b) Shorter acquisition times are needed for cluster separation.

High threshold: energy of 230keV

a) Advantageous for neutron measurements because of low detection efficiency compared to the signal from primary or secondary electrons.

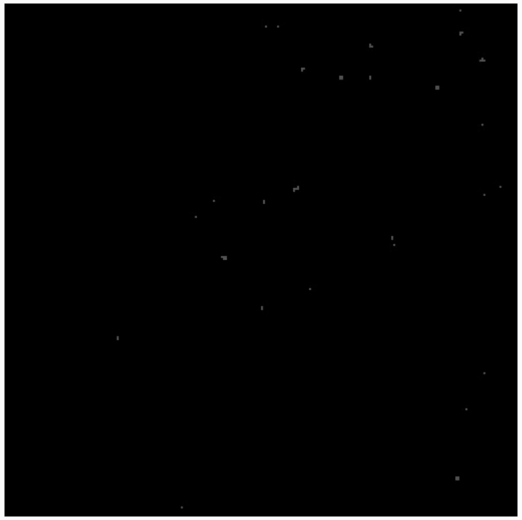
b) Allows using of longer acquisition times and keep the benefit of tracking mode of operation.

X-ray image of conversion layers



Low Threshold 252Cf – 1s

High Threshold 252Cf – 2000s



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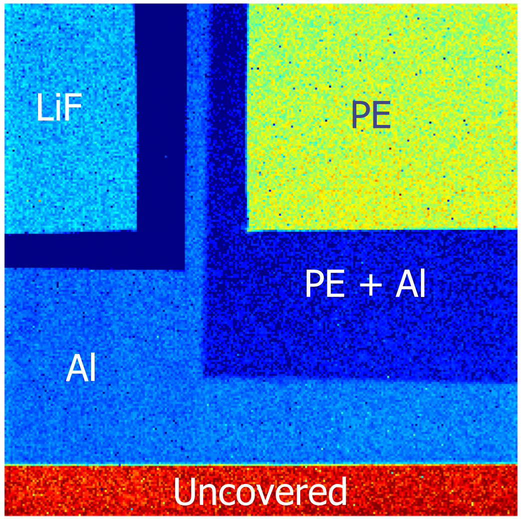
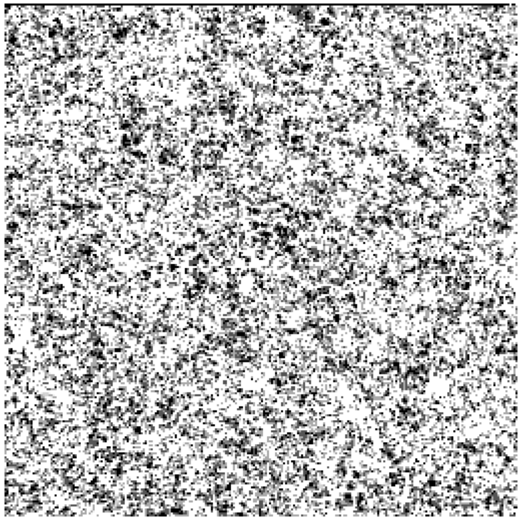
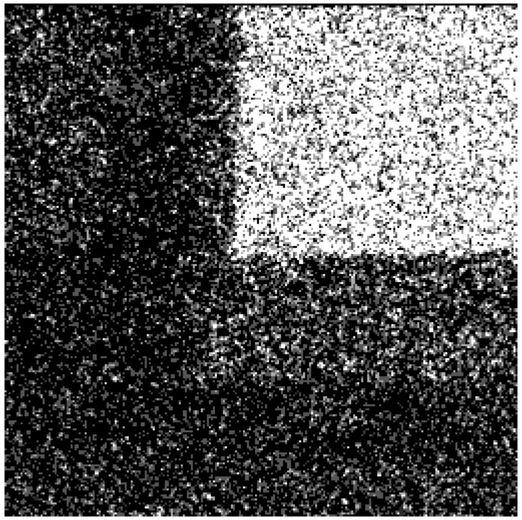


Low Threshold 252Cf – 1s



High Threshold 252Cf – 2000s



High threshold measurement in different neutron fields

Efficiency:

Thermal n: 1.41E-2 ± 7.11E-4 $cm^{-2}s^{-1}$

252Cf: 1.19E-3 ± 1.89E-5 $cm^{-2}s^{-1}$

241AmBe: 2.86E-3 ± 5.46E-5 $cm^{-2}s^{-1}$

Fast n: 7.23E-3 ± 5.81E-4 $cm^{-2}s^{-1}$

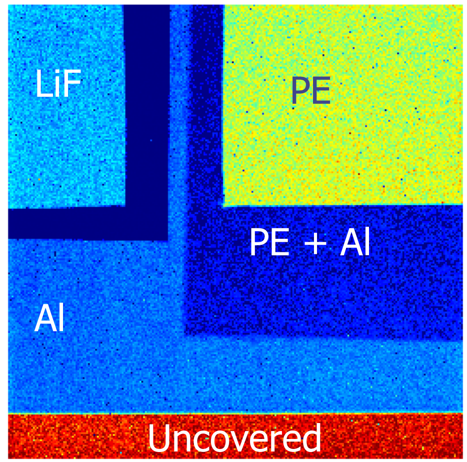
PE / PE+Al cluster count ratio:

252Cf: 10.70 ± 0.04

241AmBe: 5.18 ± 0.03

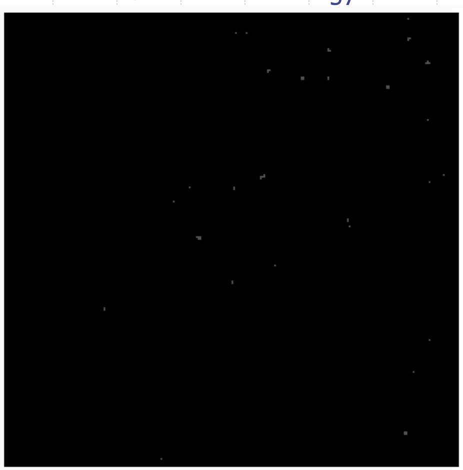
Fast n: 2.51 ± 0.03

X-ray image of conversion layers

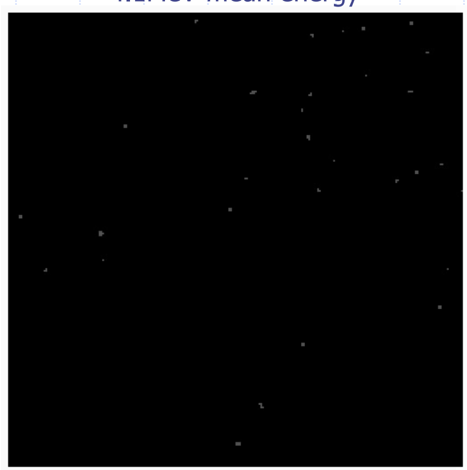


Thermal – 500s, 2.5E6 neutrons, 25meV energy

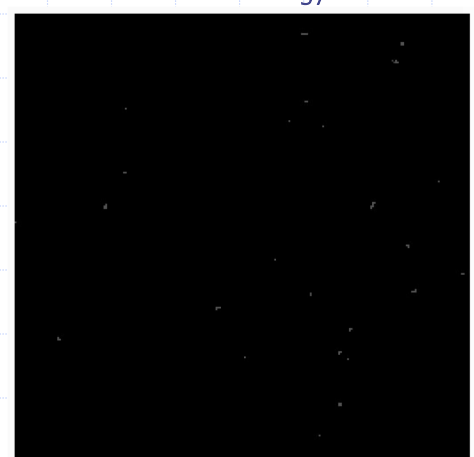
252Cf – 2000s, 1E8 neutrons, 2.3MeV mean energy



AmBe – 2000s, 4E7 neutrons, 4.1MeV mean energy



VDG – 1000s, 1E7 neutrons, 14MeV energy



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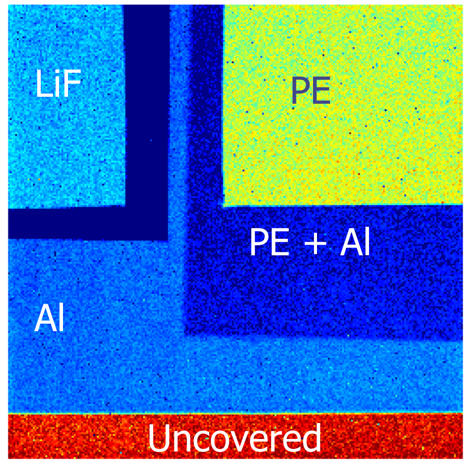
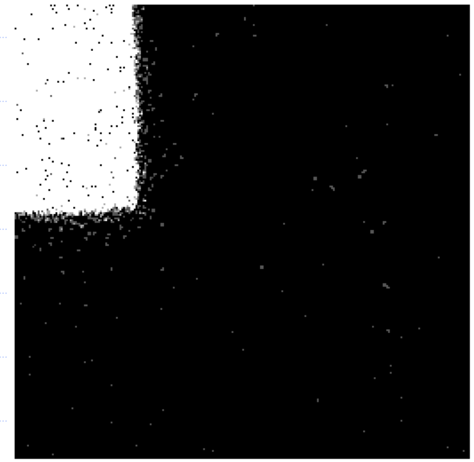
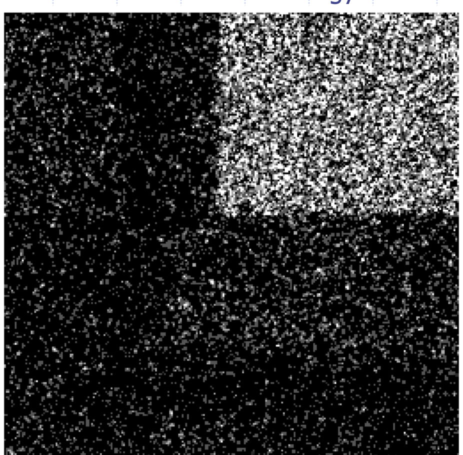


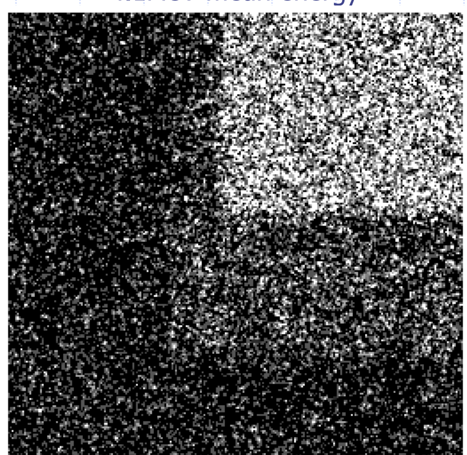
Thermal – 500s, 2.5E6 neutrons, 25meV energy



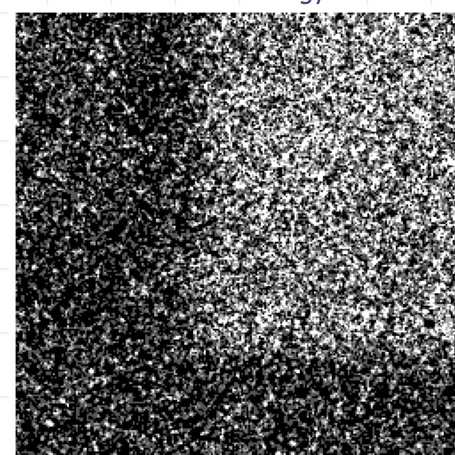
252Cf – 2000s, 1E8 neutrons, 2.3MeV mean energy



AmBe – 2000s, 4E7 neutrons, 4.1MeV mean energy



VDG – 1000s, 1E7 neutrons, 14MeV energy



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Radiation measurement with the pixel detectors:

Cluster analysis

Cluster analysis in tracking mode of operation

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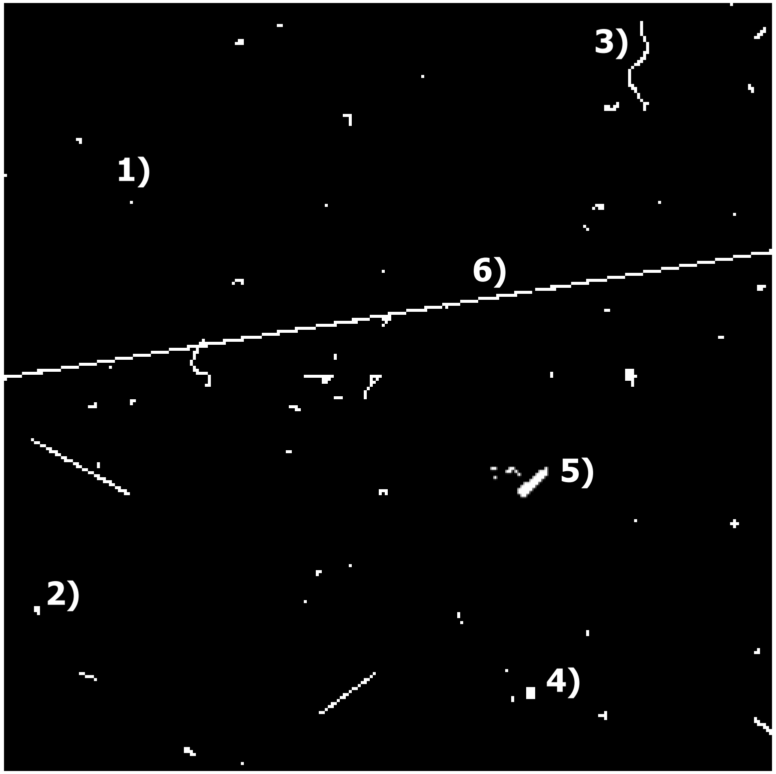
Each particle depositing energy above the preset threshold in the sensitive volume of the detector is visualized as it‘s characteristic track.

Set of criteria can be established in order to resolve those different shapes:

- Area (number of pixels) in the cluster
- Roudness (surface compared to length of the border)
- Linearity (possibility to interleave track with line)
- Thickness of the straight track

Six categories of characteristic patterns were introduced in "tracking mode":

1) Dot – Gamma and X-rays
2) Small blob – Gamma and X-rays, low energy electrons
3) Curly track – electrons (MeV range)
4) Heavy blob - energetic particles with low range (alpha particles,…)
5) Heavy track - energetic heavy charged particles (protons,…)
6) Straight track – energetic light charged particles (MIP, Muons,…)



Cluster analysis with different thresholds

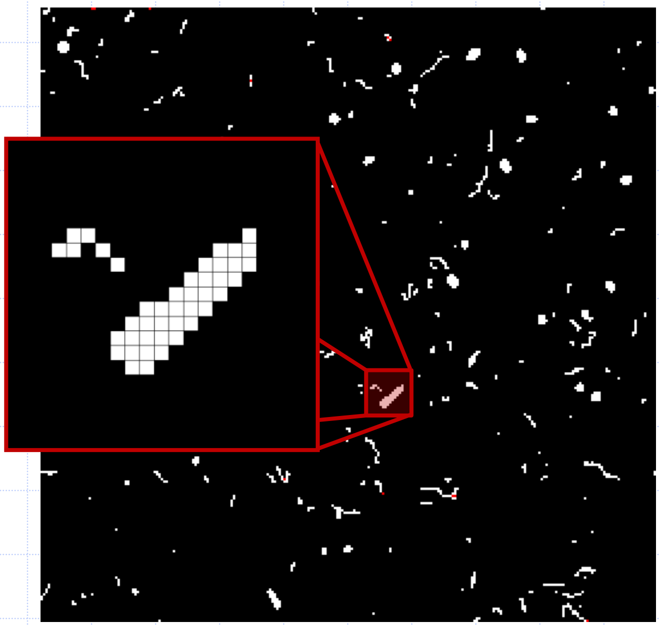
Device irradiated perpendicularly by fast neutrons (14 MeV neutrons from Van der Graaff accelerator) and accompanying radiation. Surface was covered with PE – detection of the recoiled protons. Change of the detection threshold influence the shape of the tracks characteristic to the different ionizing particles.

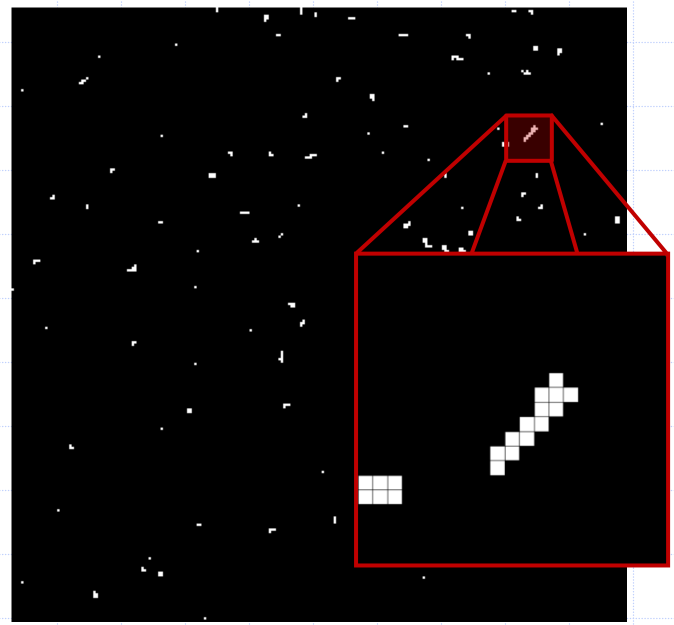
Low threshold:

- Threshold energy of 10 keV
- 1 s acquisition time

High threshold:

- Threshold energy of 230keV
- 5 s acquisition time
- Low energy tails of the individual tracks are suppressed





Radiation measurement with the pixel detectors (Timepix):

Energy information

Timepix ToT capability:
Energy (volume – 3D) information

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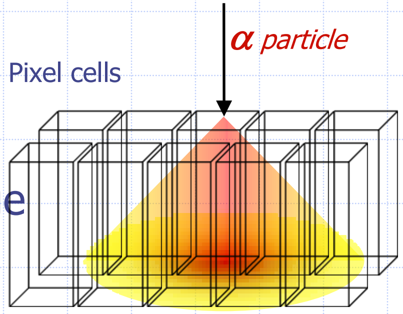
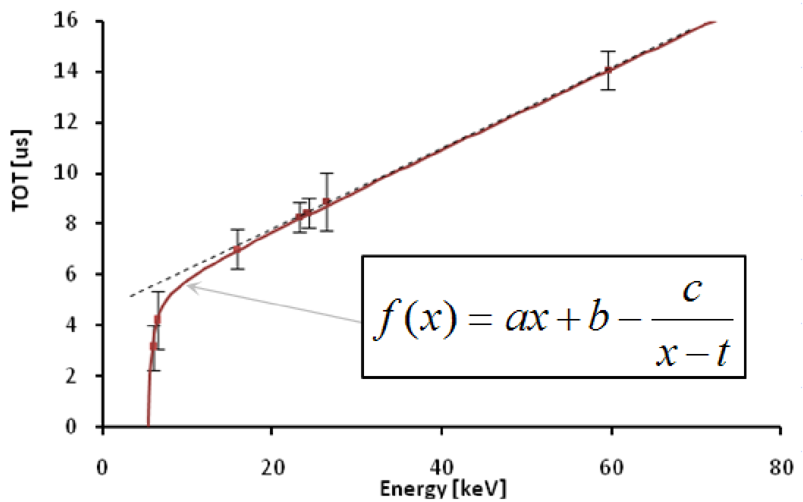
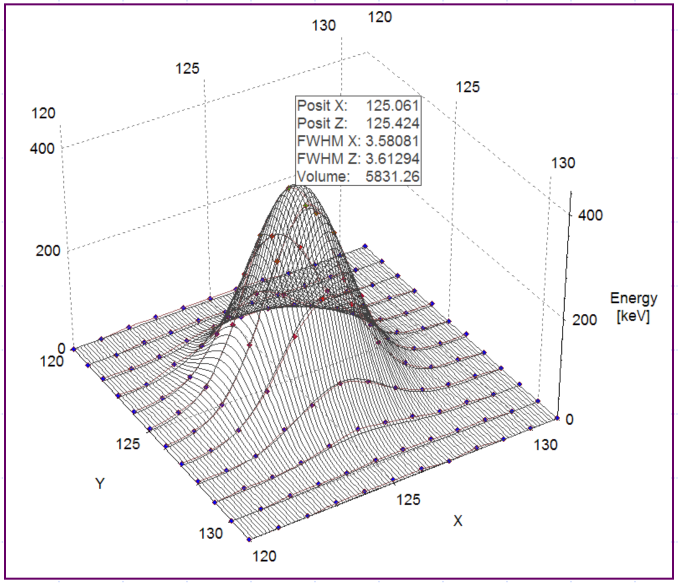
- Charge difussion during the collection in sensor (charge sharing)
  - Several neighboring pixels shows response
- Per pixel energy calibration for precise reconstruction of charge
- Analysis of the cluster shape (volume) provides us with the additional information
  - On position
  - On direction – with high energies or low mass







Subpixel resolution below 1 μm can be reached by Gaussian fit.

Highly ionizing interactions

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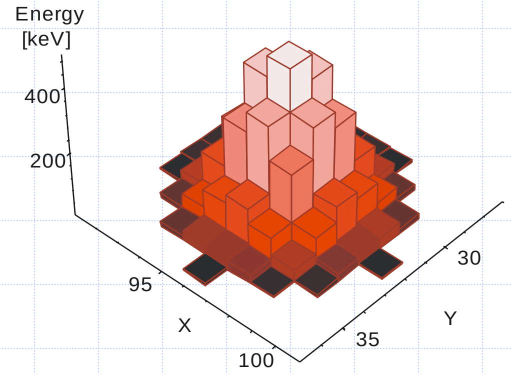
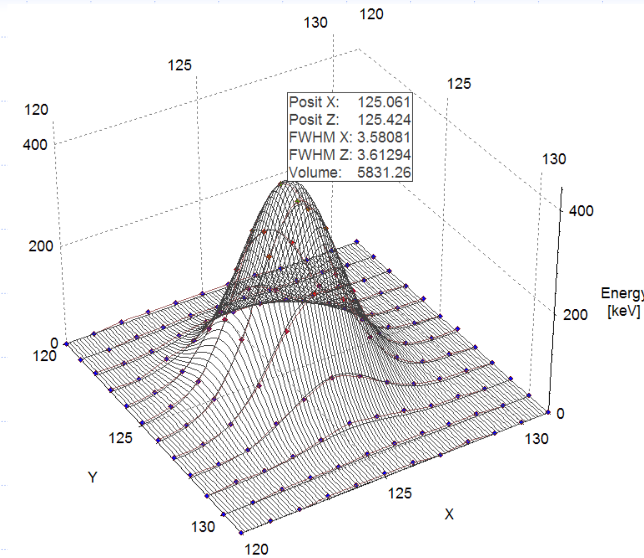
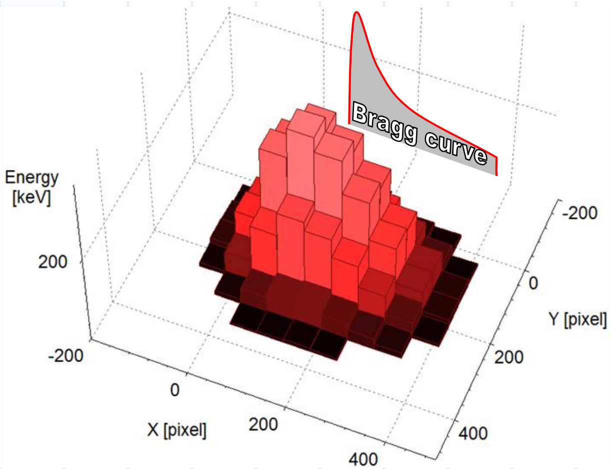
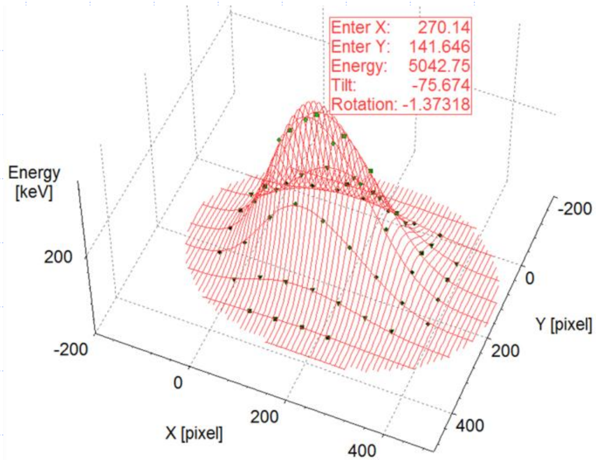
Alpha particles:

- ^{241}Am alpha source
- 5.48 MeV alpha particles
- 28 µm range in silicon
- Spatial resolution below 500 nm









Protons:

- Energy of 4.9 MeV
- Angle 76 deg
- 220 µm range in silicon
- Incident angle determination with precision of about 1°

JINR Dubna - Nuclotron

ARDENT

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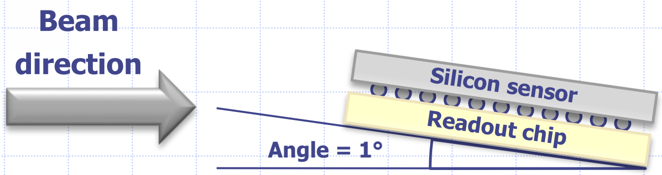
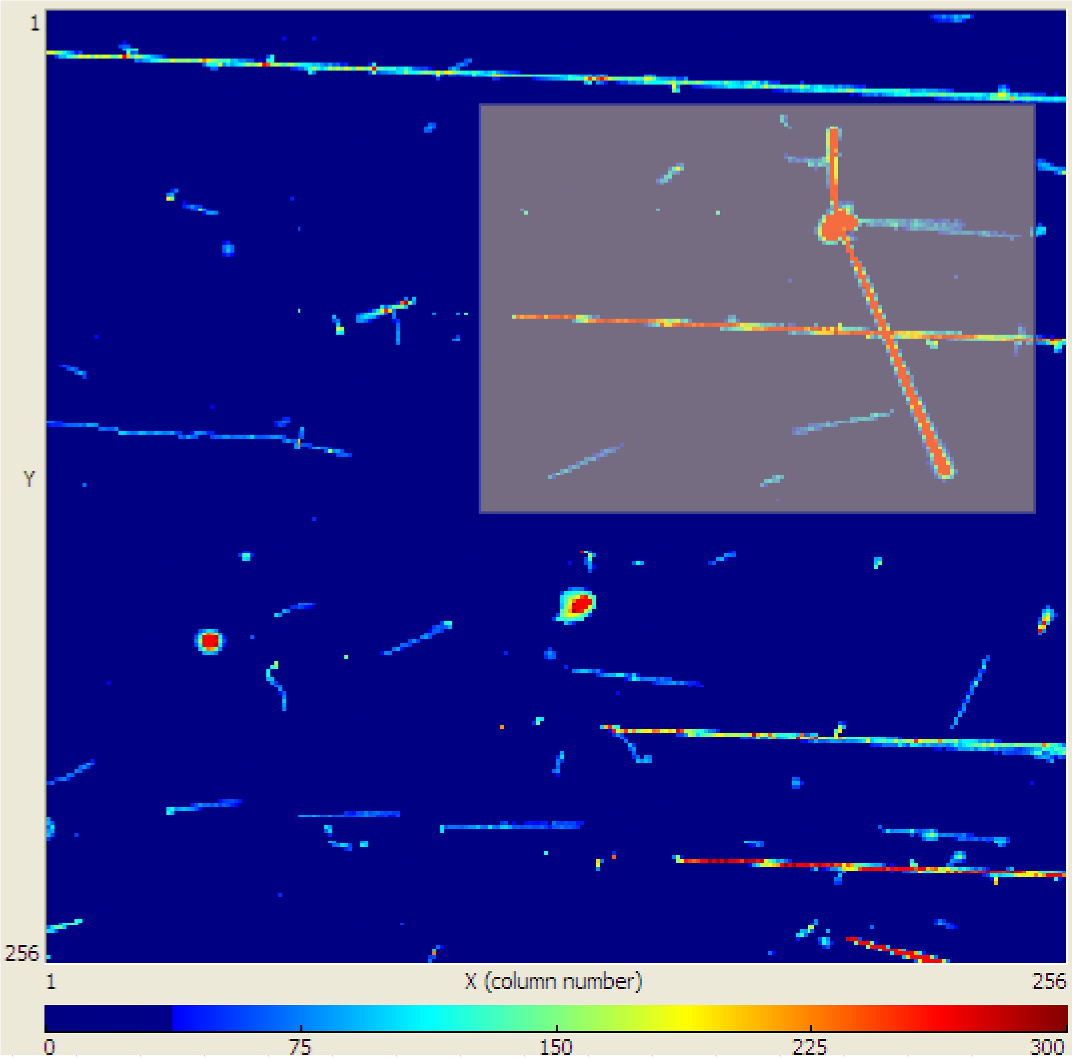
^{6}Li @ 14 GeV ions:

Sensor surface oriented almost in parallel to the beam

- ^{6}Li energetic ions
- Relativistic energy
- MIP tracks
- Direct observation of nuclear reactions in silicon





^{6}Li @ 2.3 GeV ions:

Sensor surface oriented in parallel to the beam

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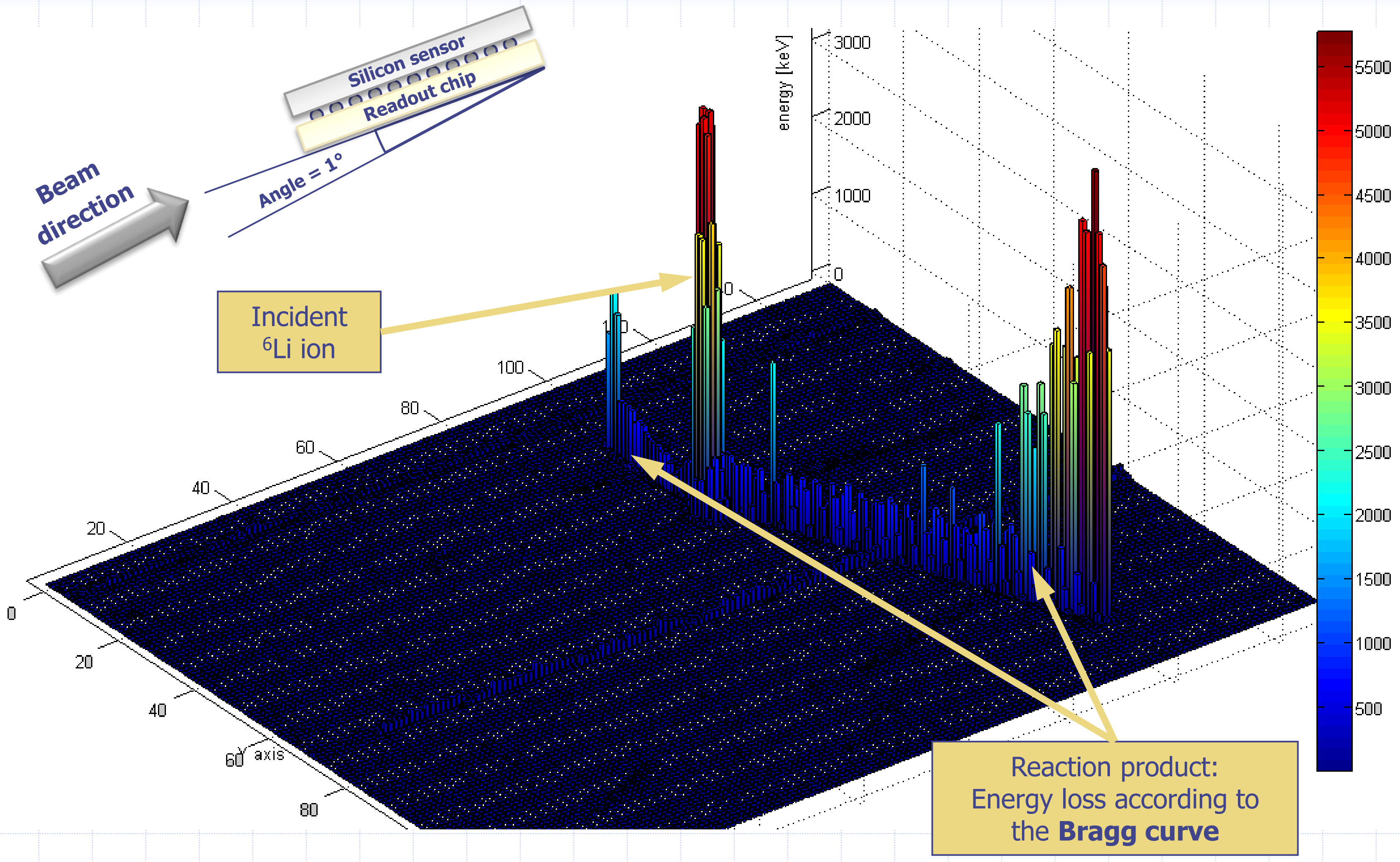

^{2}H @ 2 GeV and ^{6}Li @ 14 GeV ions:

Sensor surface oriented perpendiculary to the beam

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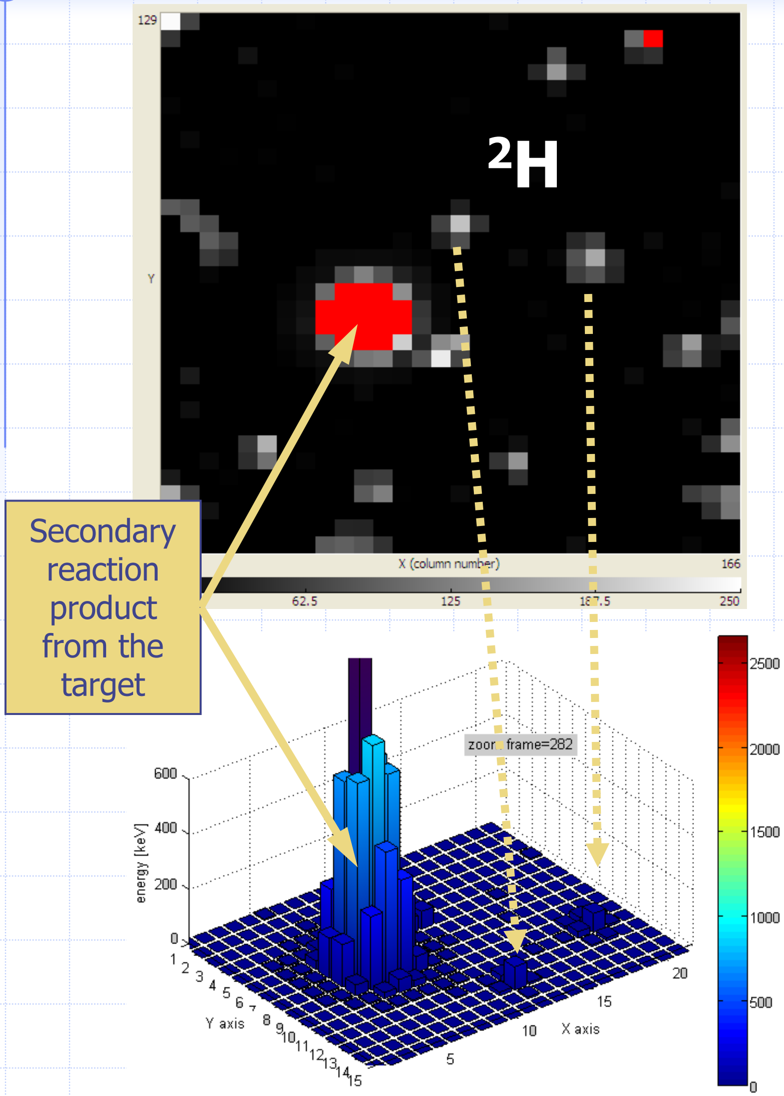

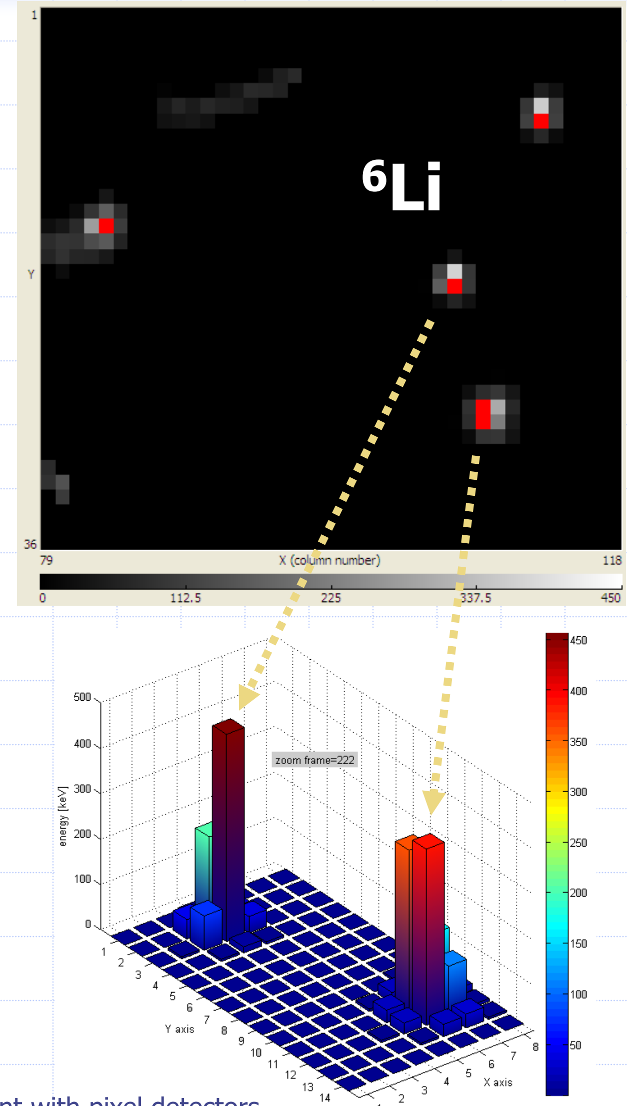

^{6}Li @ 2.3 GeV ions:

Relativistic energy – MIPs behaviour

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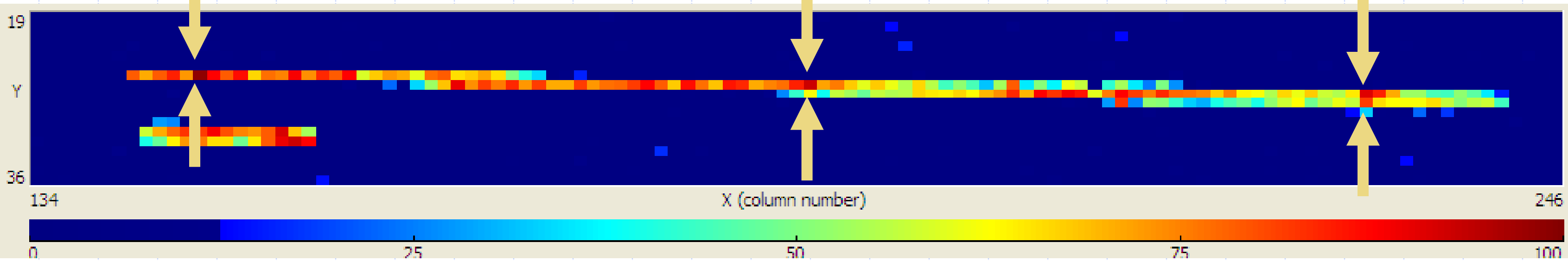

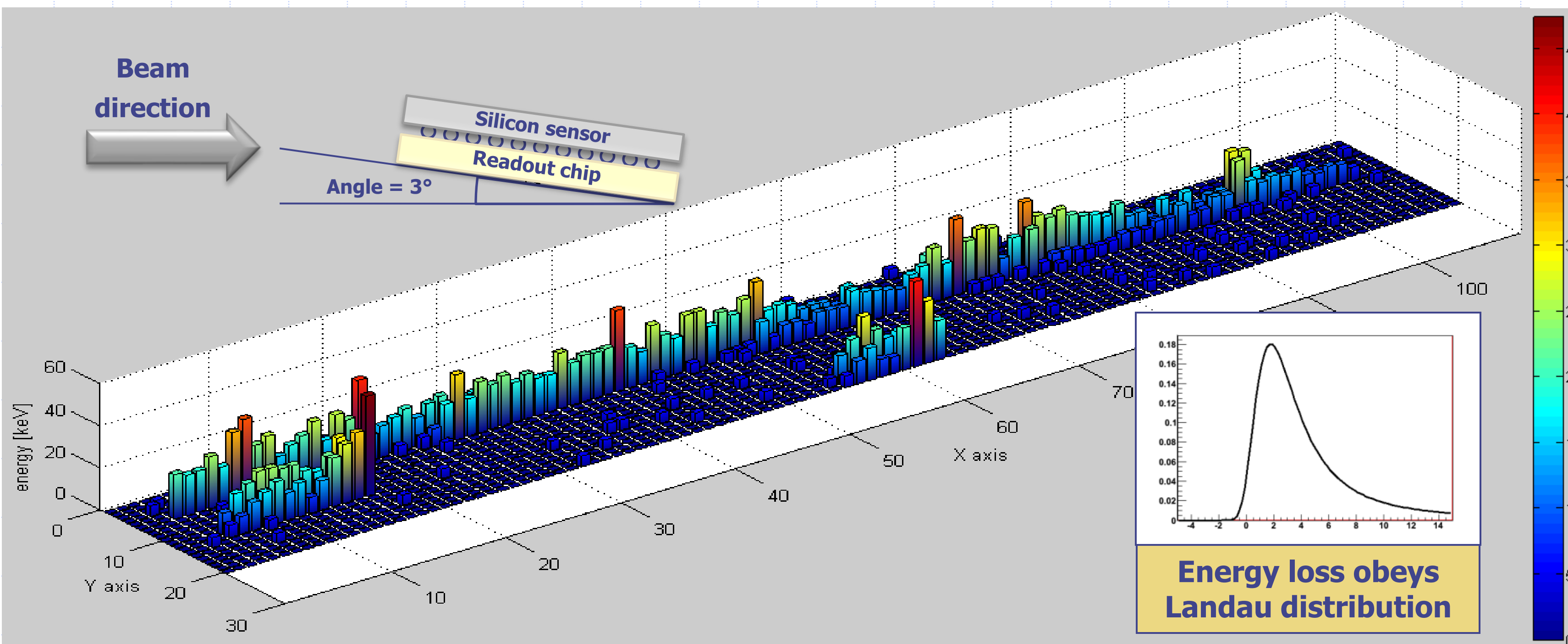

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Radiation measurement with the pixel detectors (Timepix):

Time of arrival information

Measurement of the single ^{8}He ion decay sequence

LOHENGRIN - ILL Grenoble

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Decays of some exotic fission fragments from the Lohengrin mass separator are measured by Timepix.

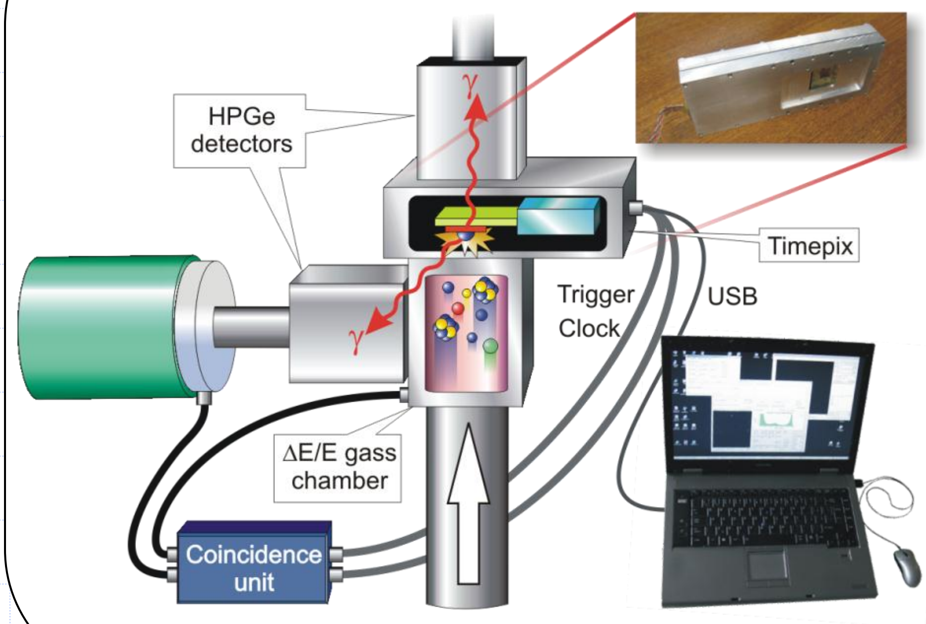
The primary particle is recognized by $\Delta E/E$ gas detector and generates a trigger (shutter) for Timepix. Timepix runs in Timepix mode recording the decay

Temporal and Spatial coincidence technique => suppressing of the background

Very high selectivity of the method (background suppression $>10^4$)

Can measure decay times in range from microseconds to seconds (and longer).

Experimental setup



Single ^{8}He ion decay sequence recorded by Timepix

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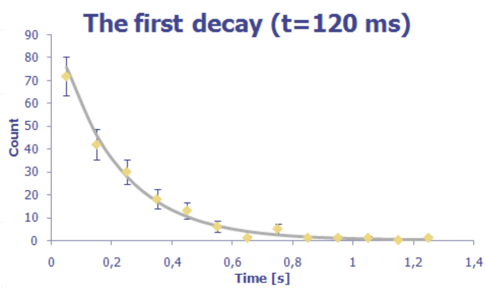
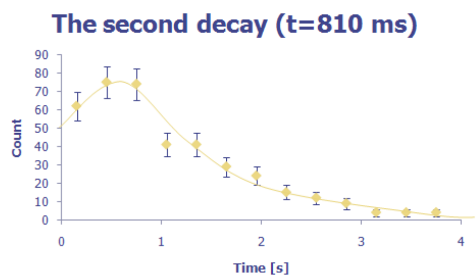
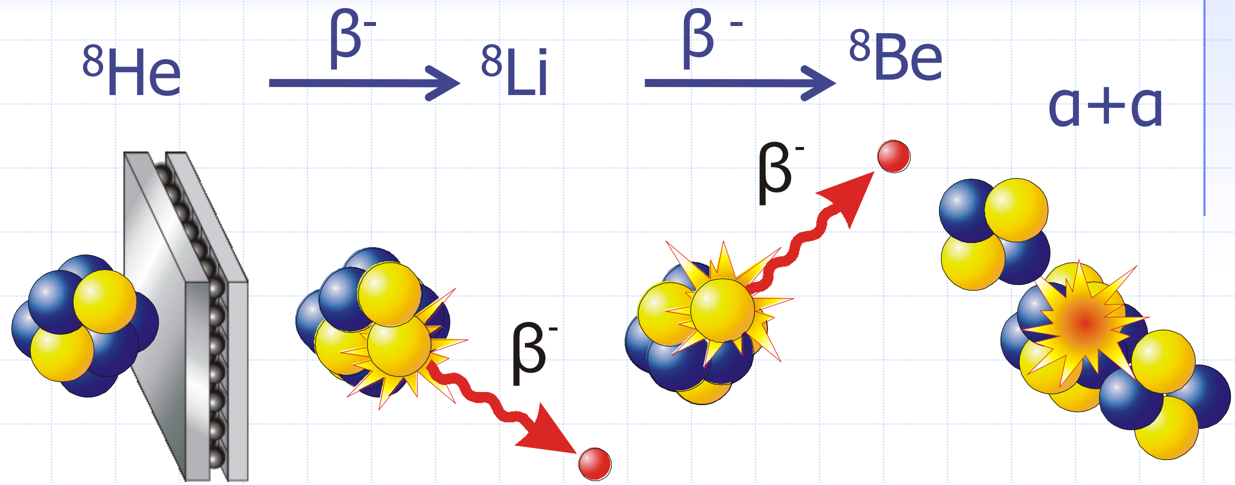
Ion hits the Timepix

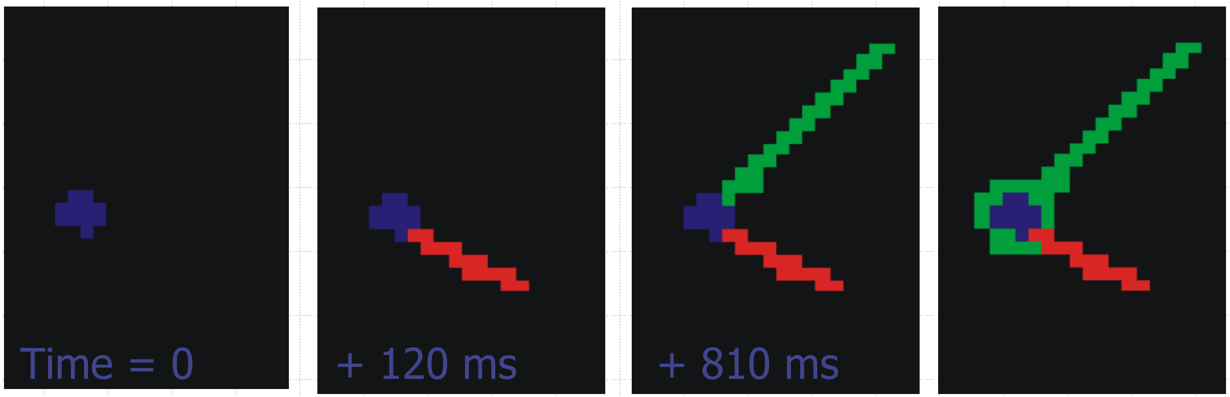
First β-decay

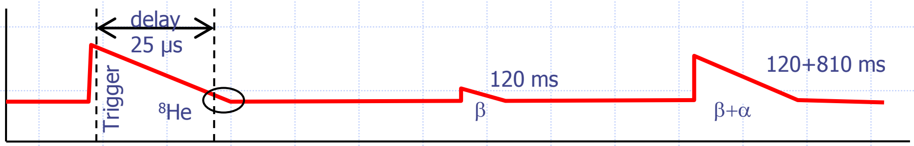
Subsequent decay of the daughter nucleus by emission of one beta and two alpha particles.











Single ^{8}He ion decay sequence:

Measured events

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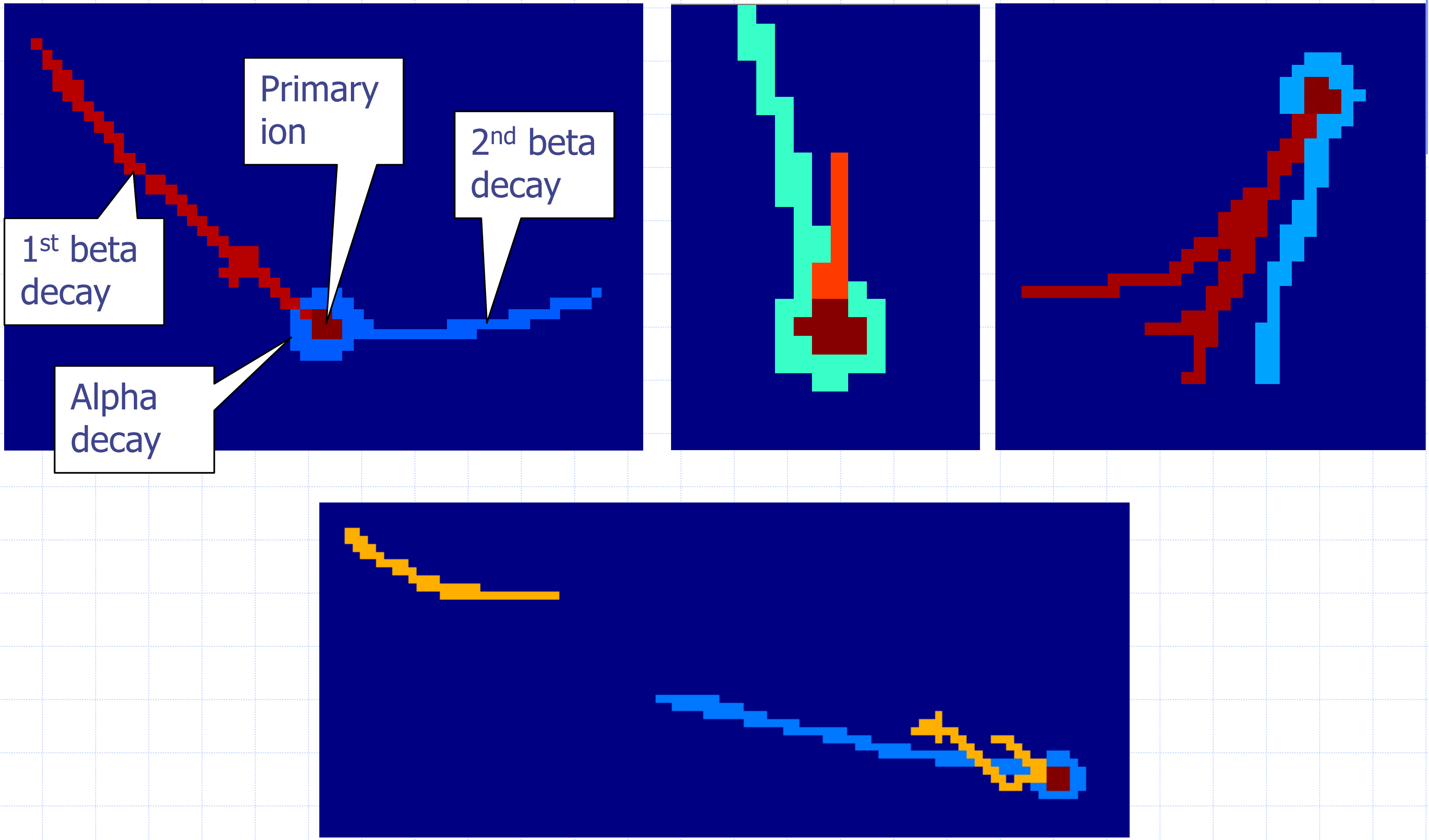

Characterization of the detector properties

Characterization of the sensor properties

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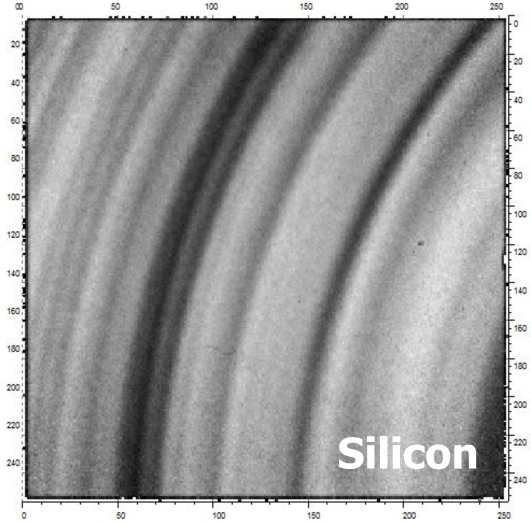
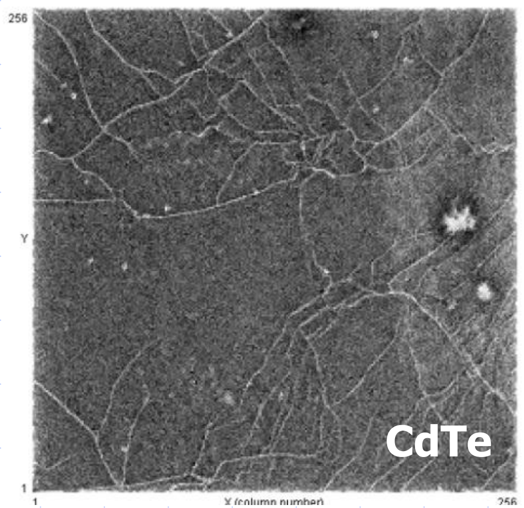
- Good level of charge sharing improves tracking precision and provide additional information on interaction position and direction but it has to be well described, predictable, homogenous and stable in time.
- Inhomogeneity of the sensors bump-bonded to Timepix device was observed in dependence on material type, bias voltage, temperature, radiation damage…

Local cluster size (alphas 5.5 MeV)



Local cluster count (X-rays)



Idea: Use Timepix detector as the multichannel microprobe to measure local performance of sensor material preferably in 3D using specific particles

Application: Detector homogeneity, material quality, radiation damage,…

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3D scanning of pixelated sensor with X-rays

Experimental setup for 3D scanning of pixelated sensor

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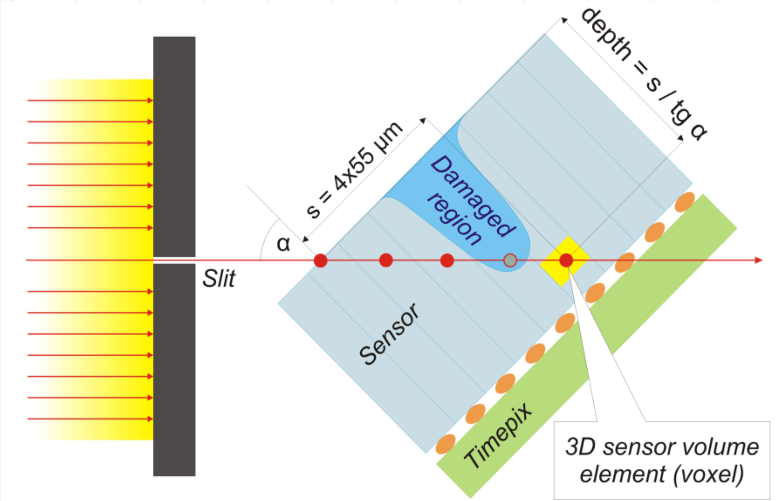
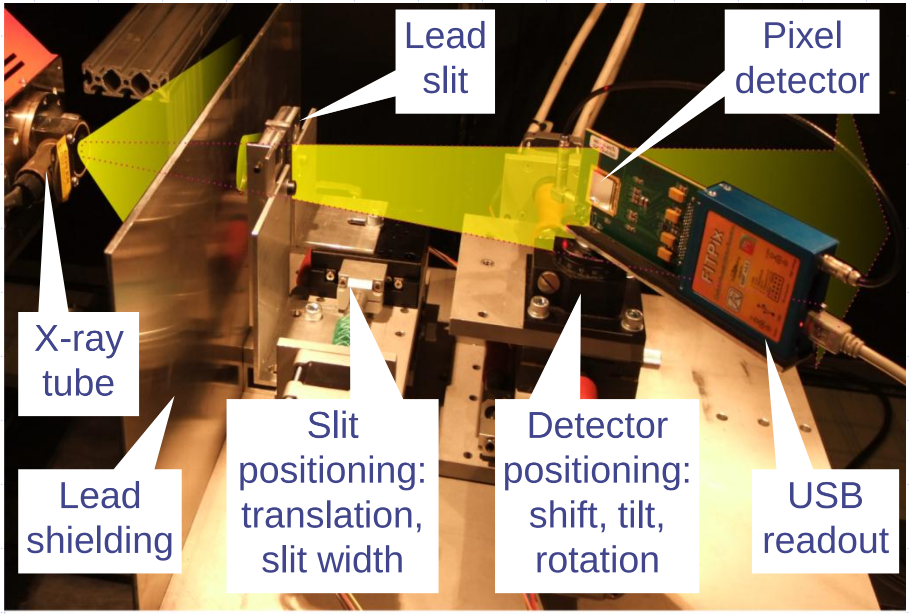
- System use narrow collimated X-ray beam 10 μm wide
- The beam can be sent on to detector at a shallow angle
- The depth of interaction can be determined for each pixel along the beam path
- Shifting the detector along the axis perpendicular to the plane of the beam (hitting other columns) we can obtain a 3D map of the sensor response



(a)



(b)

Principle of the method

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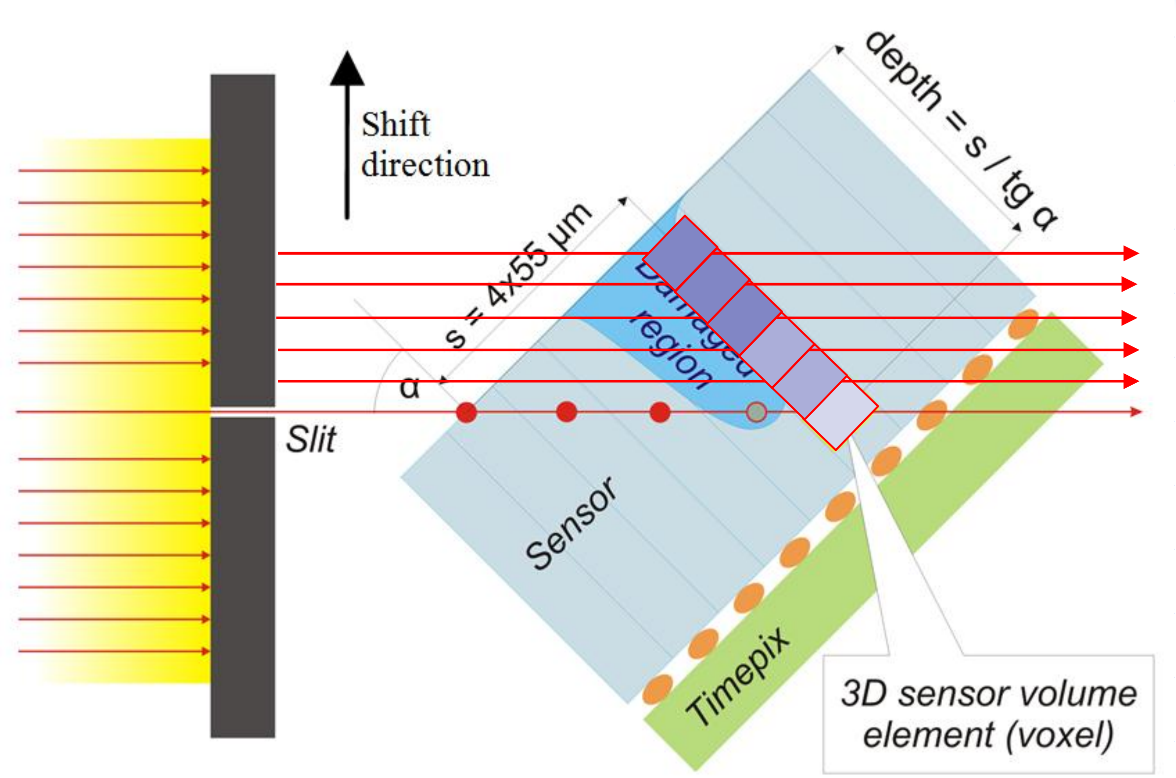

Why X-rays:

- Each photon deposits all the energy in single point (photo effect)
- No deconvolution needed
- Negligible radiation damage

For each X-ray photon we record:

- 3D Position
- Energy => Local charge collection efficiency
- Charge sharing => Local charge diffusion

Sensor Damaged by Proton beam

Energy of 3 resp. 4.9 MeV (range of 93 resp. 220 µm)

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Bias voltage 60 V

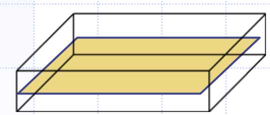
- detector is fully depleted
- well homogeneous response
- the response is shown in depth of 8 µm

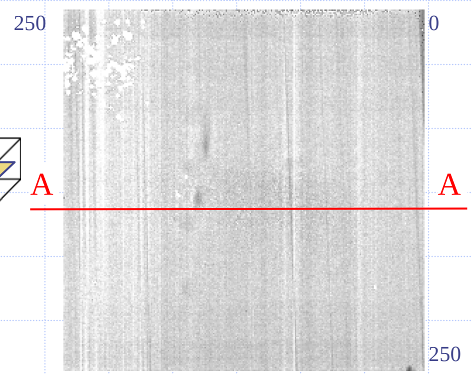
Bias voltage 12 V

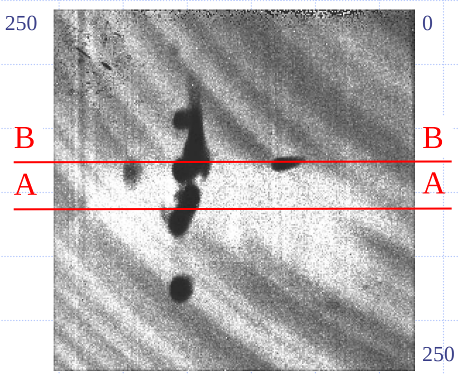
- depleted volume is 240 µm thick
- the damaged regions appeared
- the response is shown in depth of 20 µm

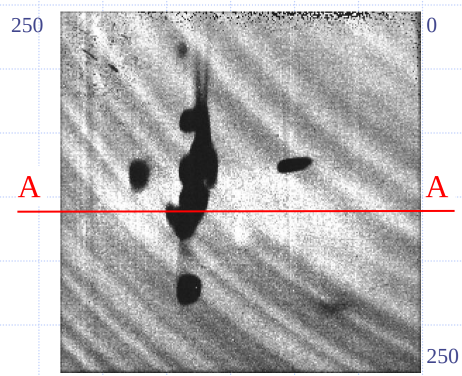
Bias voltage 6 V

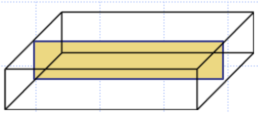
- depleted volume is 160 µm thick.
- the response is shown in depth of 120 µm



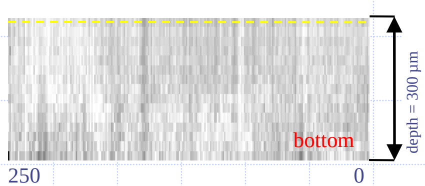




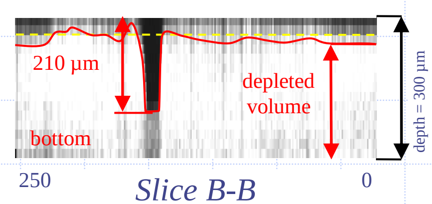




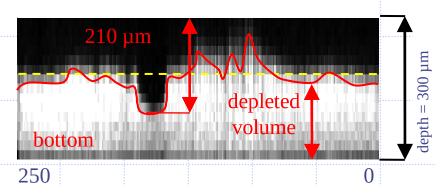
Slice A-A



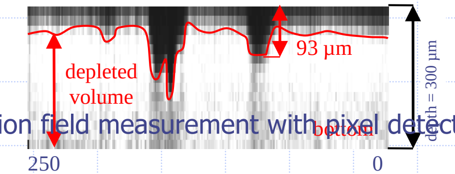
Slice A-A

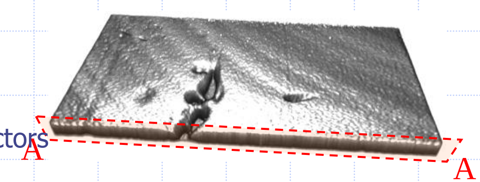


Slice A-A



Slice B-B





Test of the new 300 µm thick silicon sensor

Bias voltage 60 V

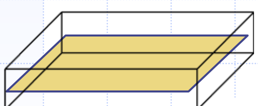
- detector is fully depleted
- nicely homogeneous response
- the response is shown in depth of 8 µm

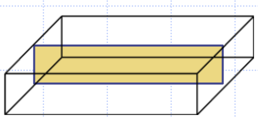
Bias voltage 12 V

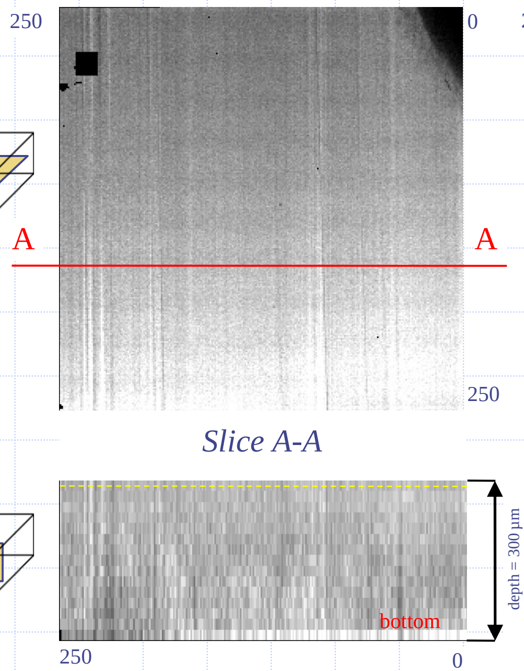
- depleted volume is 220 µm thick with variations caused by local variations of E field
- the response is shown in depth of 60 µm

Bias voltage 6 V

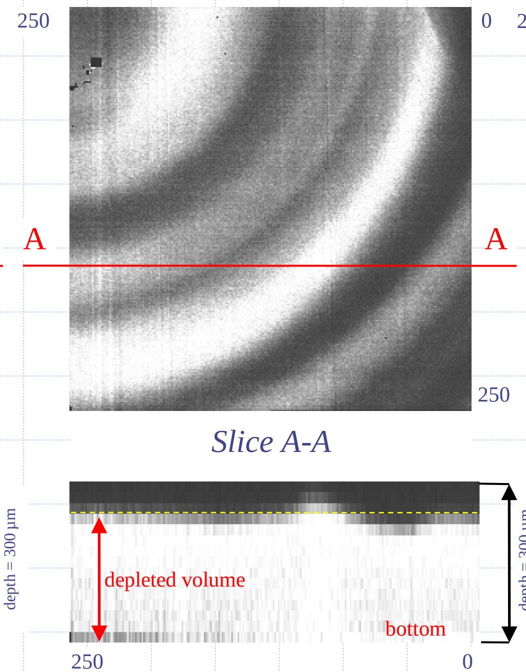
- depleted volume is 170 µm thick.
- the response is shown in depth of 120 µm



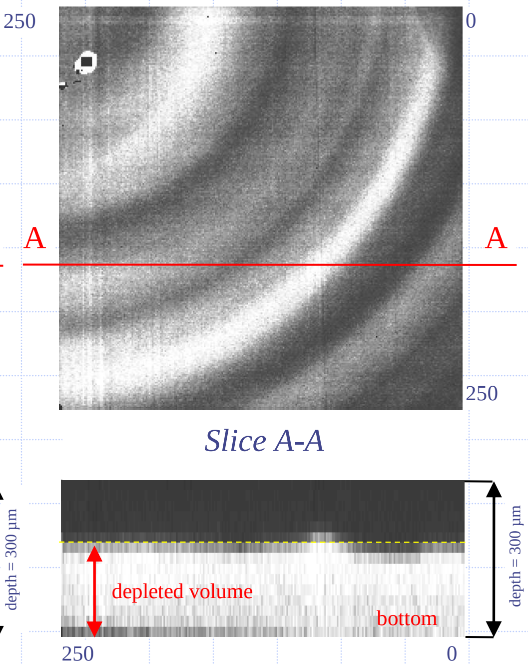




(a)



(b)



(c)

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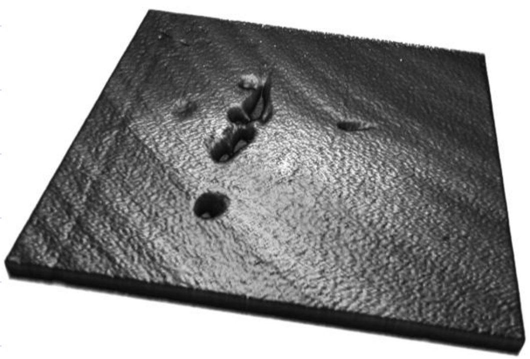
Surface of depleted volume rendered in 3D

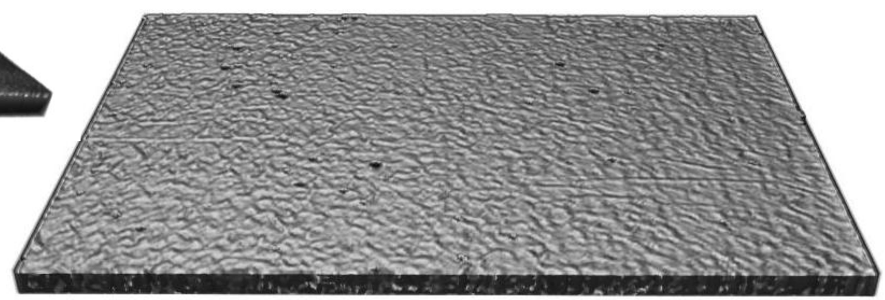
Si (G09-W0015) Radiation damaged

- Bias +6 V (partially depleted)
- 300 μm thick
- 256 x 256 pixels
- 55 μm pixel pitch



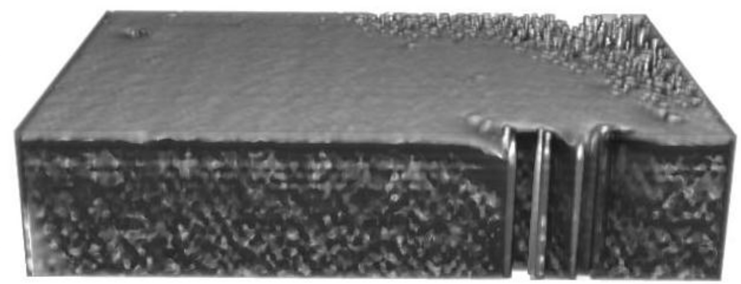
GaAs (H11-W0087)

- Bias -200 V
- 300 μm thick
- 256 x 256 pixels
- 55 μm pitch



CdTe (C04-W0083)

- Bias -200 V
- 1000 μm thick
- 128 x 128 pixels
- 110 μm pitch



3D X-ray scanning - conclusions

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- Described method allows to generate a 3D map of charge collection efficiency in dependence on various detector parameters such as: bias voltage, detector temperature and radiation damage.

- The spatial resolution of 3D mapping is determined by pixel size (lateral) and width of the slit (depth). Results were demonstrated for 55 x 55 x 10 μm. The minimal slit width is 3 μm.

- The energy of X-rays can be chosen combining X-ray tube target material and filter (semi-monochromatic beam). Standardly we use W target and W filter => 59 keV.

- This method is not ideal for thick or heavy sensor material (CdTe) because of high photon absorption. More energetic X-rays are not suitable for this method because the Compton scattering predominates photo effect.

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Scanning of pixelated sensor with protons and alpha particles

Protons used as 3D microprobe

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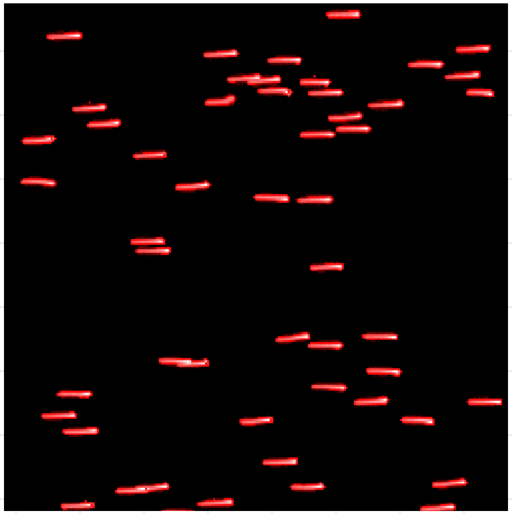
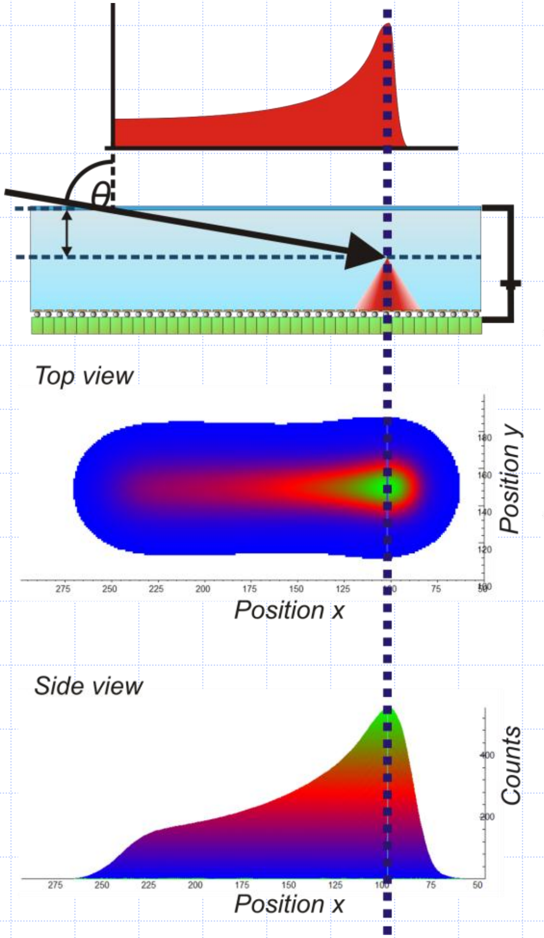
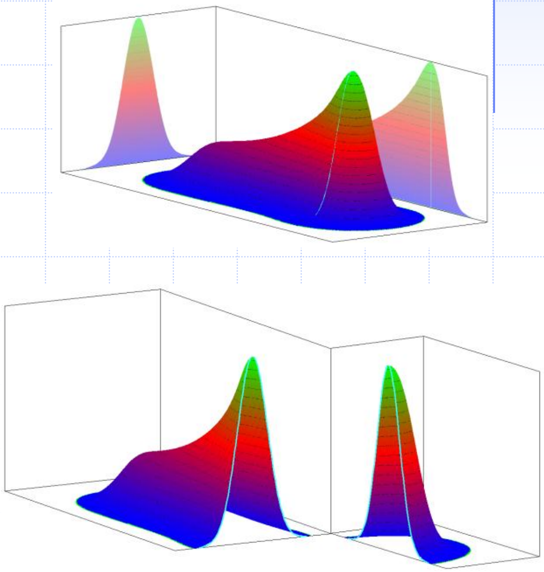
- Large charge deposition in specific sensor depth according to the Bragg law.
- CCE and electric field properties can be studied from the differences in average cluster shape over the sensor surface.

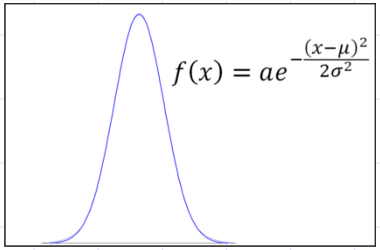


11 MeV protons under 85° in 300 μm thick silicon sensor

11 MeV protons under 85° - measured average cluster shape







Fit of the average cluster shape in it's maximum

Charge diffusion map scanned with protons and alpha particles

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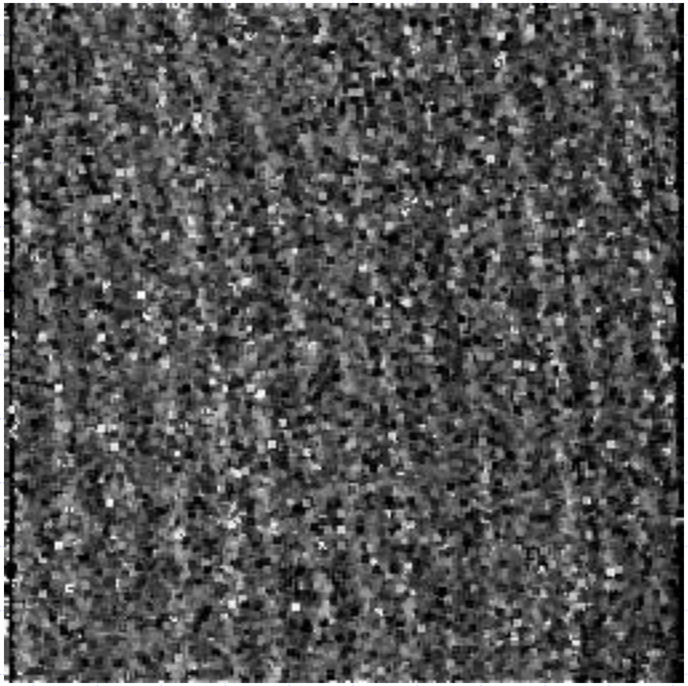
- New silicon sensor; 300 µm thick; 55 µm pixel pitch; Bias = 7.5 V

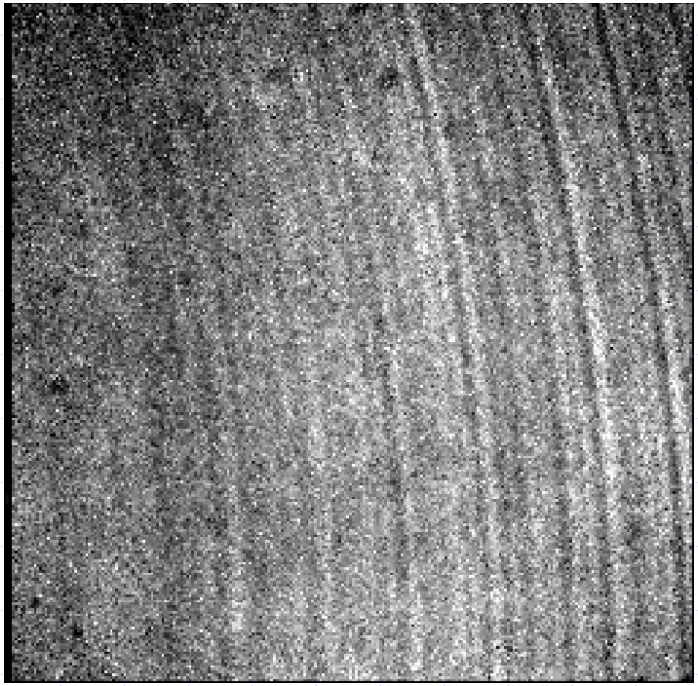
Protons:

Energy: 3.5 MeV
Incident angle: 85°
Penetration depth: 10 µm
Number of events: 40 000



Alpha particles:

Energy: 5.5 MeV
Incident angle: 0°
Penetration depth: 28 µm
Number of events: 400 000



Proton and alpha particle scanning - conclusions

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- Described method allows to generate a 3D map of charge collection efficiency in dependence on various detector parameters such as: bias voltage, detector temperature and radiation damage.
- Electric field is mapped by means of differences in the charge diffusion.
- Suitable also for thick and heavy sensors (CdTe, GaAs).
- Potentially destructive – Bragg peak scan in several depths by many particles in each pixel => possible radiation damage during the scan

Summary

- Semiconductor pixel detectors are excelent tools for radiation field characterization:
  - Using imaging of the specific sample by surrounding radiation
  - Using event by event analysis in tracking mode
- The charge sharing effect provides additional information on:
  - Position of the interaction
  - Incident angle of interaction
- Energy threshold can be used for effective background suppression but some information will be lost.
- Timepix detector can be used as an multichannel microprobe to measure local performance of different sensor materials in 3D.
- The charge sharing effects enables possibility of 3D-mapping of electric field inside the sensor volume.
- Sensor response can be analyzed by different particles:
  - X-rays
  - Ions (protons, alpha particles)
  - MIPs