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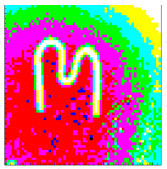
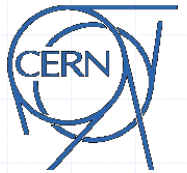
Application of semiconductor pixel detectors for high resolution X-ray and neutron imaging, particle tracking and in space

Stanislav Pospíšil

on behalf of former and present Medipix/Timepix team
of the Institute of Experimental and Applied Physics
Czech Technical University in Prague





Main goals of the lecture

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- To describe shortly family of ***Medipix2, Timepix and Timepix3 semiconductor pixel detectors*** including corresponding R/O electronics.
- To document ability of Timepix pixel detector to ***visualize individual particle tracks in solid state*** similarly to nuclear emulsions, cloud chambers, bubble chamber, Micro-Pattern Gaseous Detectors etc.
- To demonstrate capability of the devices for ***high resolution (micrometric and nearly nanometric) radiography, nondestructive testing and 3D imaging*** by means of ***X-rays and neutrons.***
- To present results of investigation of ***neutron interactions in silicon*** sensors in a broad energy range (500 keV up to GeV region) by means of ***Time-of-Flight (ToF) technique.***
- To show examples of broad ***applications*** of the Timepix detectors for ***measurements of composition and spectral characteristics of mixed radiation fields around physics experiments, in medicine and in space research.***

Medipix/Timepix hybrid pixel detector device

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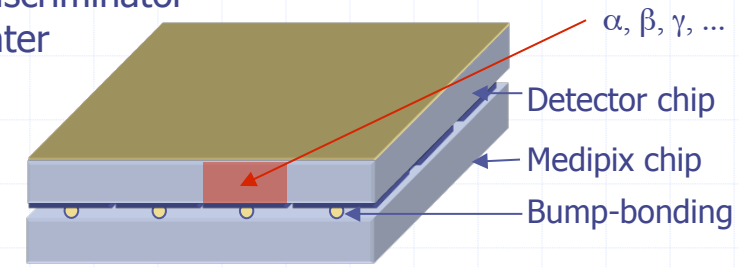
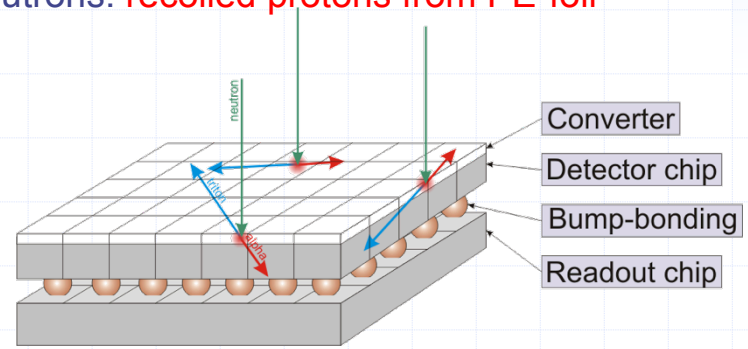
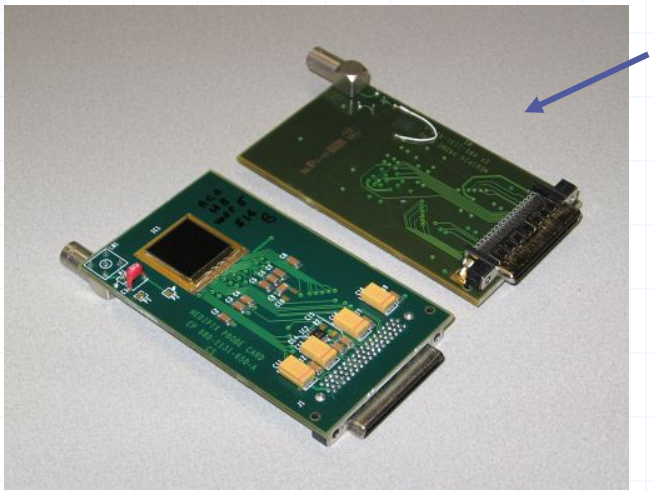
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000μm)
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter

- Converter materials to detect
  - thermal neutrons: 6Li(n,α)T, Q=4.78MeV
    10B(n,α)7Li, Q=2.78MeV
  - fast neutrons: recoiled protons from PE-foil

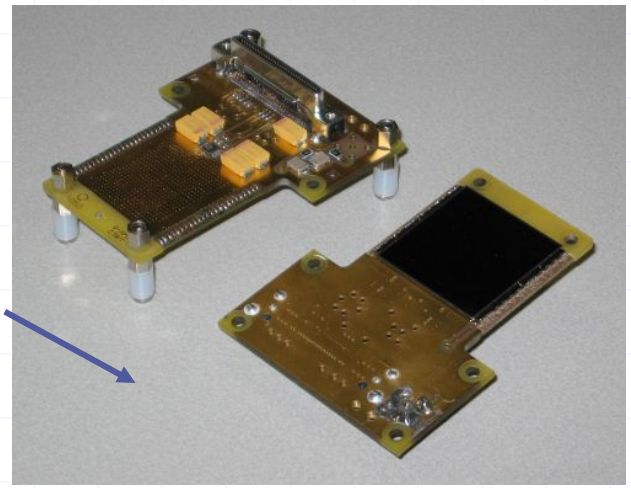






Medipix2/Timepix
Pixels: 256 x 256
Pixel size: 55 x 55 μm²
Area: 1.5 x 1.5 cm²

Medipix2/Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm²
Area: 3 x 3 cm²



TIMEPIX3

The pixel device permitting simultaneous measurement of Time over Threshold (ToT - collected charge) and Time of Arrival (ToA) of the signal in every pixel with resolution 1.6 ns.

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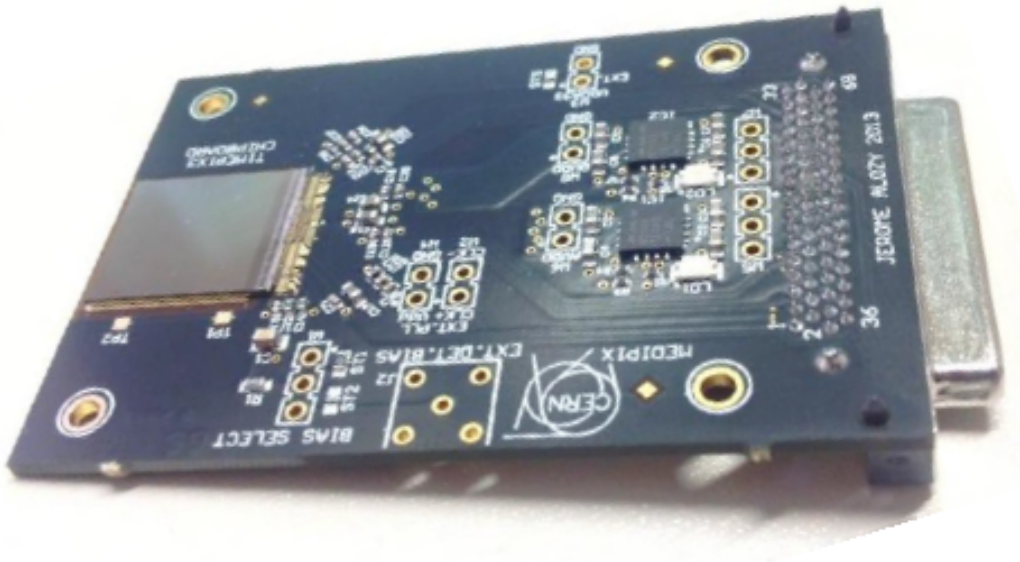
It can be effectively used for simultaneous measurement
- of Time-of-Flight of detected particle,
- Energy of this particle deposited in the sensor and
- a drift time of charge in the sensor

- Thickness: 300μm
- Bias: 90 V
- Triggered
- Data driven mode
- T0 synch when trigger signal was received



Timepix3 CERN chip board

About development of R/O interfaces for Medipix/Timepix devices

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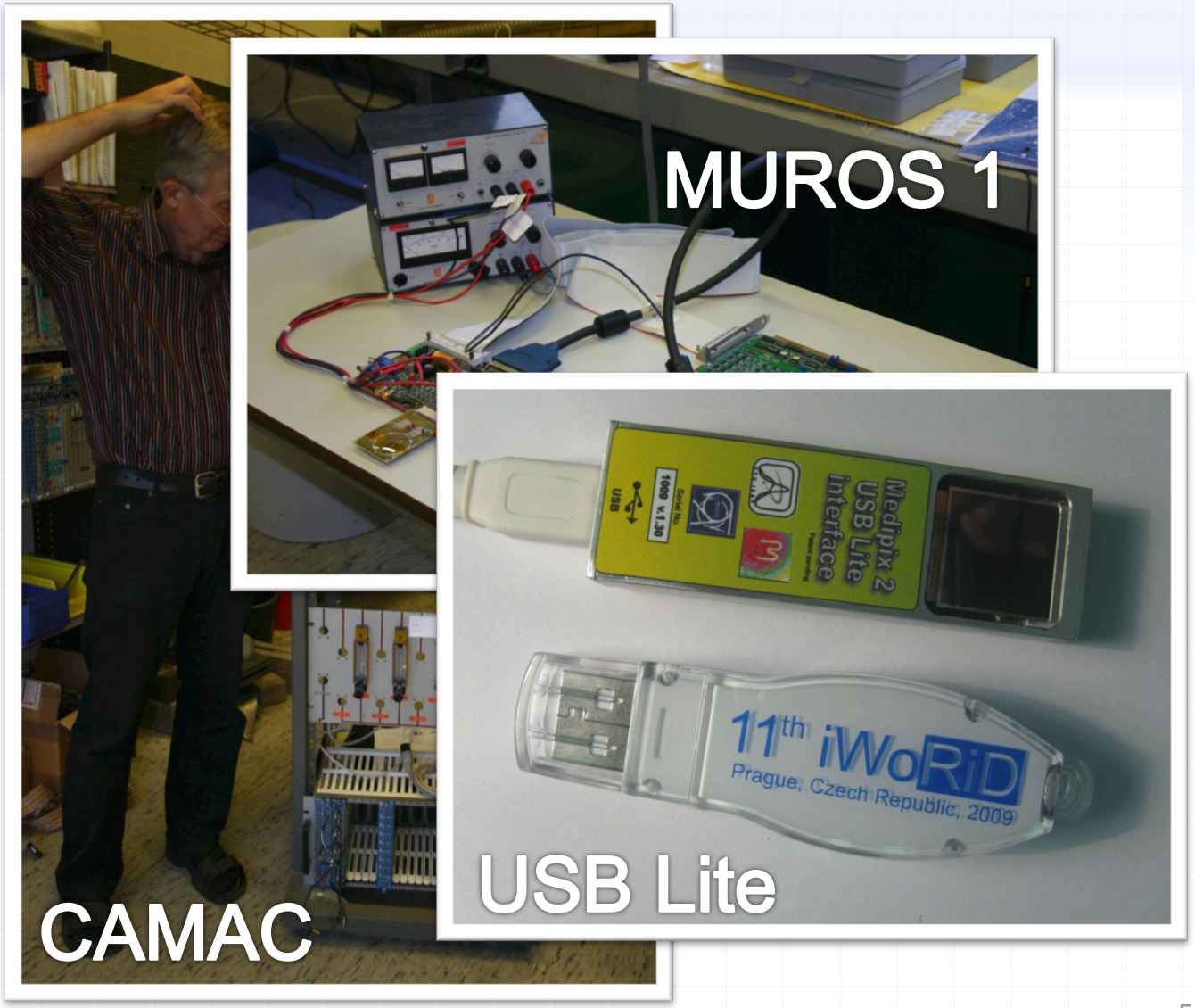
HISTORY
1995-2011:

MAMOGRAPHY

- **CAMAC/VME**
- **MUROS (NIKHEF)**
- **USB1 (IEAP)**
- **USB Lite (IEAP)**
- **RUIN (IEAP)**
- **MARS (NZ)**
- **USB2 (IEAP)**
- **TPX Lite (IEAP)**



Timepix pixel device

operating as single particle counting pixel detector

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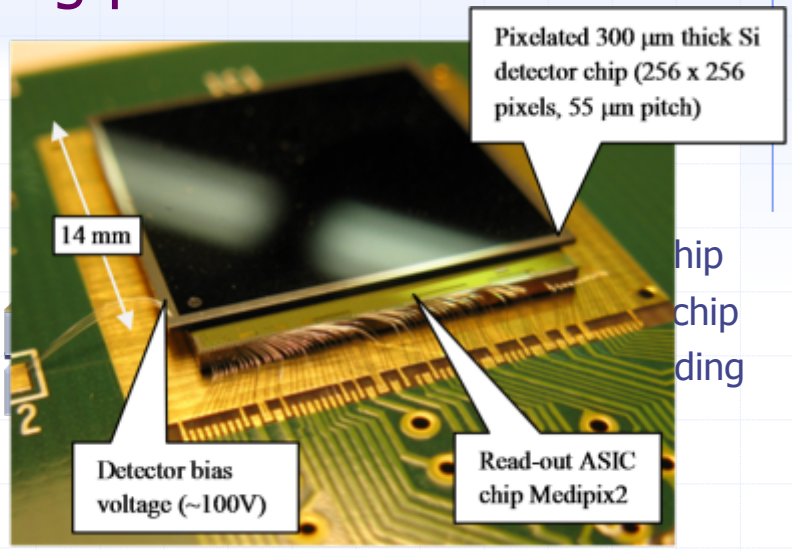
- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or ADC or **Timer**
- Multichip assemblies with common sensor: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)
- Multichip detectors with edgeless sensors: **WidePIX$_{10x10}$** (143x143 mm)



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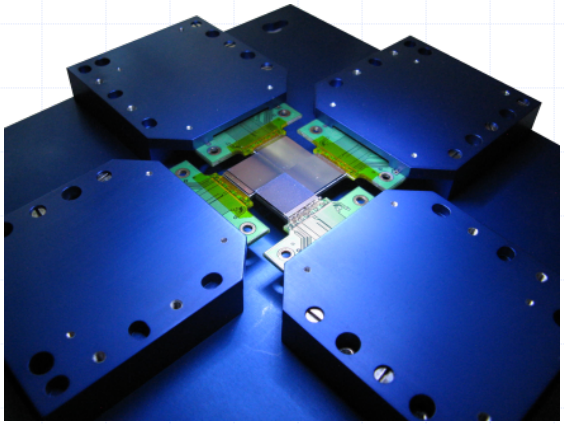
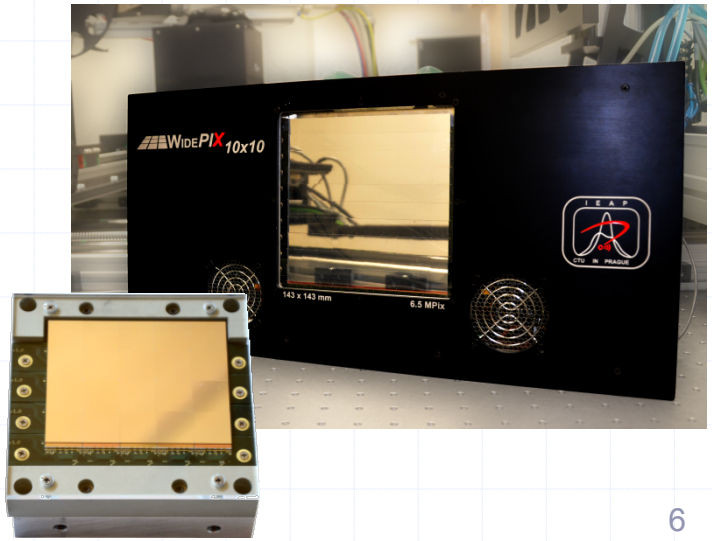
Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2





Response of Medipix2 device to natural background radiation

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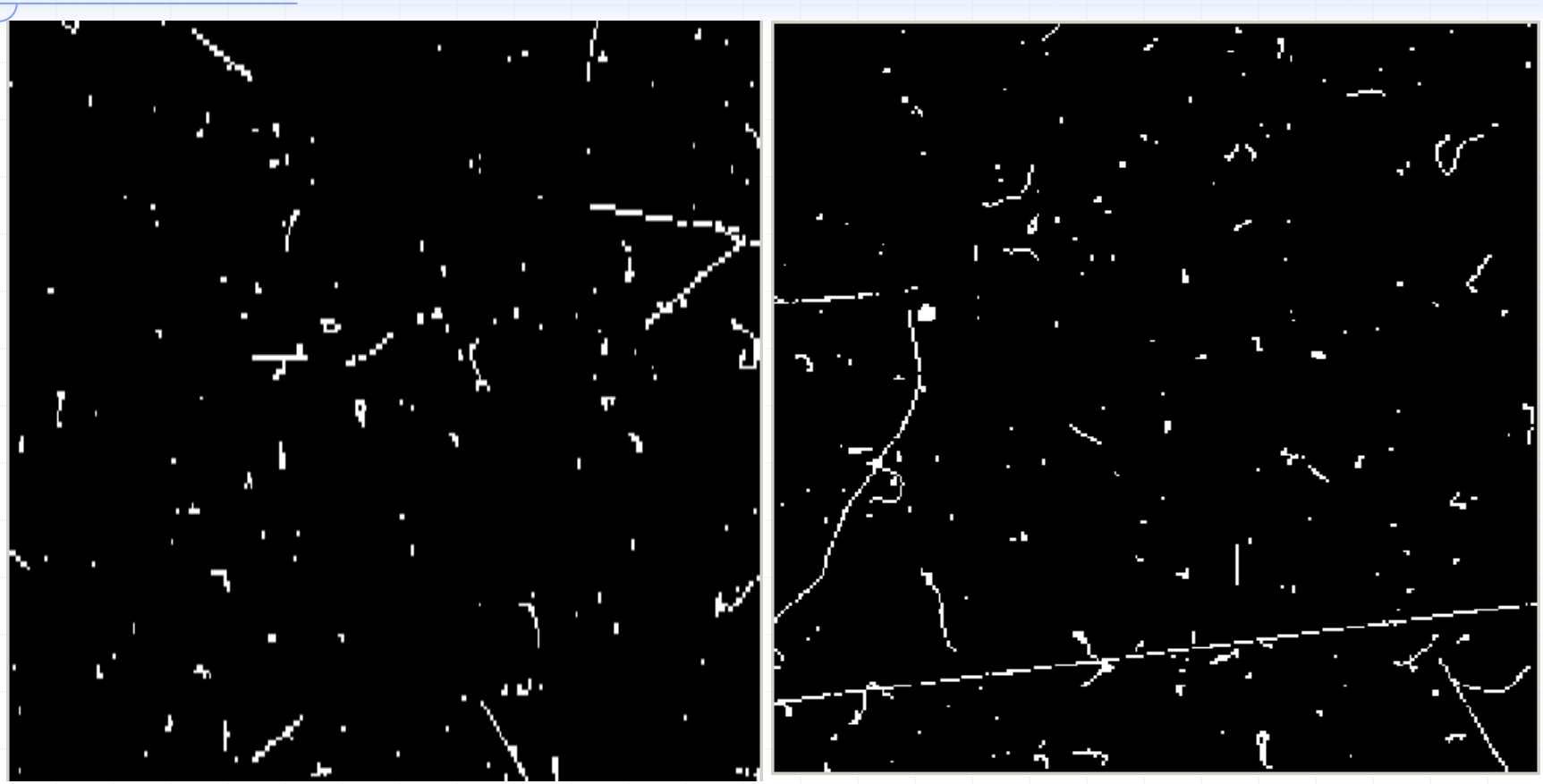

Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, … . Muon tracks can be recognized by submicrometric precision.

Noiseless particle detection
Tracking mode of pixel detector operation
(On-line imaging of tracks and traces of single radiation quanta)

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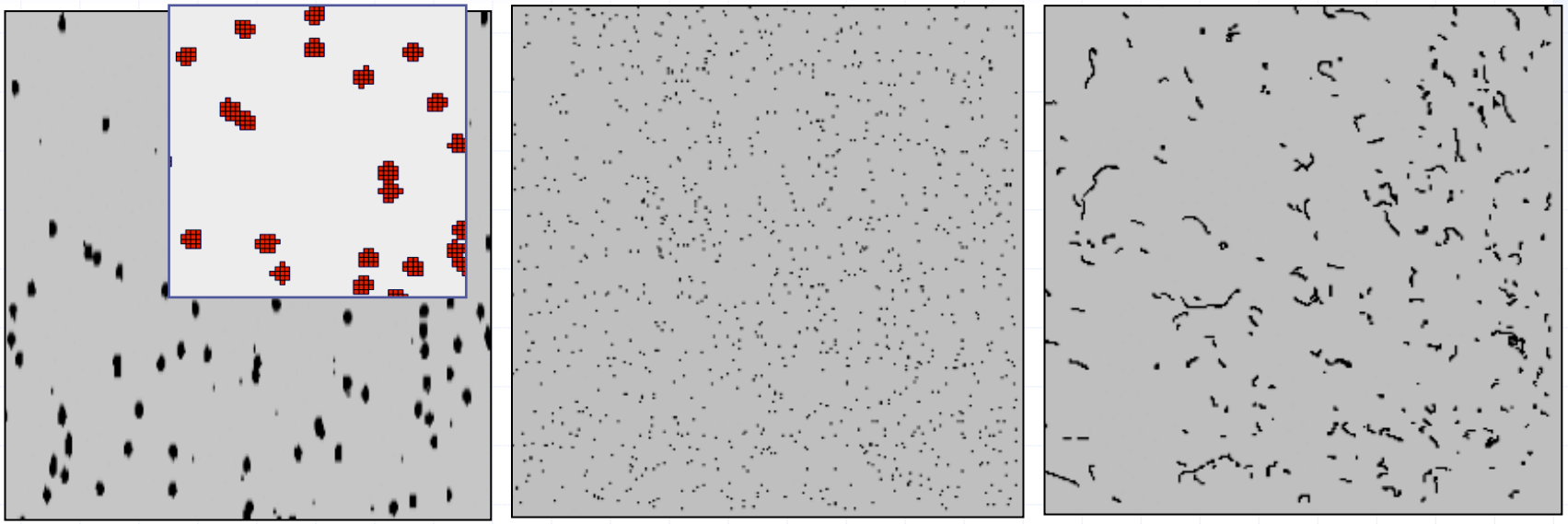

- ^{241}Am alpha source gives clusters of ~5x5 pixels measured with the MEDIPIX-USB device and a 300 μm thick silicon sensor. The clusters are shown in detail in the inlet. The cluster sizes depend on particle energy and threshold setting.
- Signature of X-rays from a ^{55}Fe X-ray source. Photons yield single pixel hits or hits on 2 adjacent pixels due to charge sharing.
- A ^{90}Sr beta source produces curved tracks in the silicon detector.
- A pixel counter is used just to say "YES" if individual quantum of radiation generates in the pixel a charge above the pre-selected treshold.

Charge sharing effect - clusters

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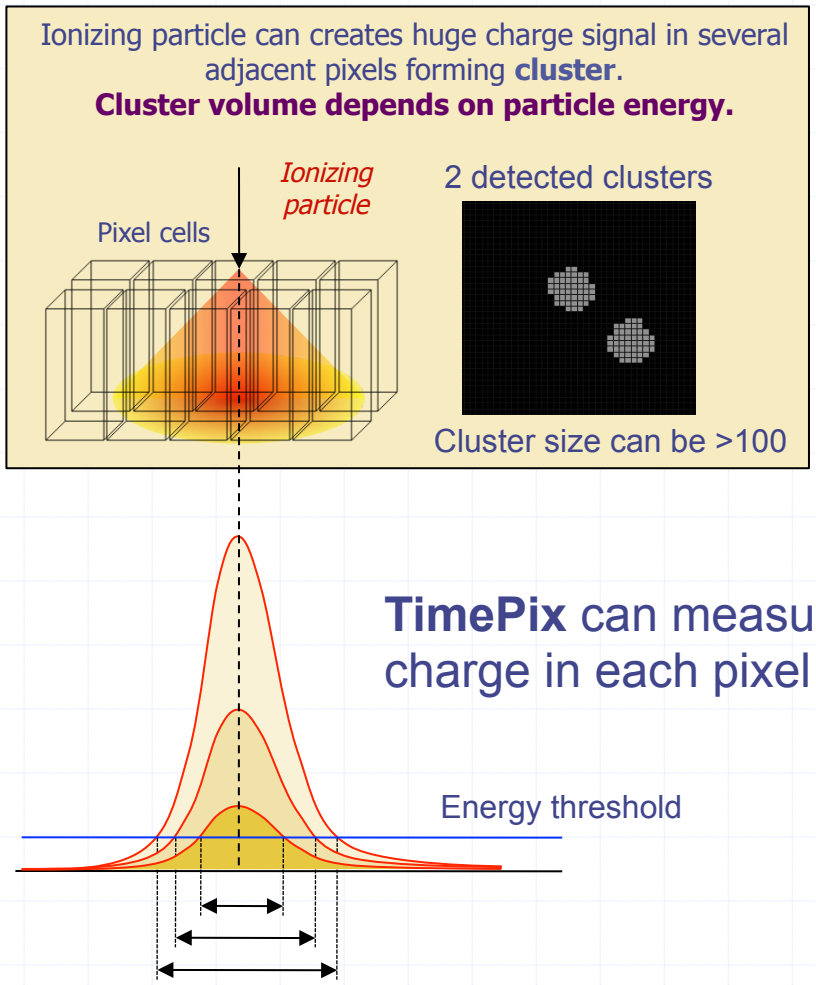
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => **CLUSTER**
- Pixels in a cluster will detect the charge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

The Cluster size depends on:

- Particle energy and range
- Depth of interaction
- Detector Bias Voltage
- Local CCE (e.g. due to a material inhomogeneities and radiation damage)



Dependence of cluster size on applied bias (on electric field in semiconductor)

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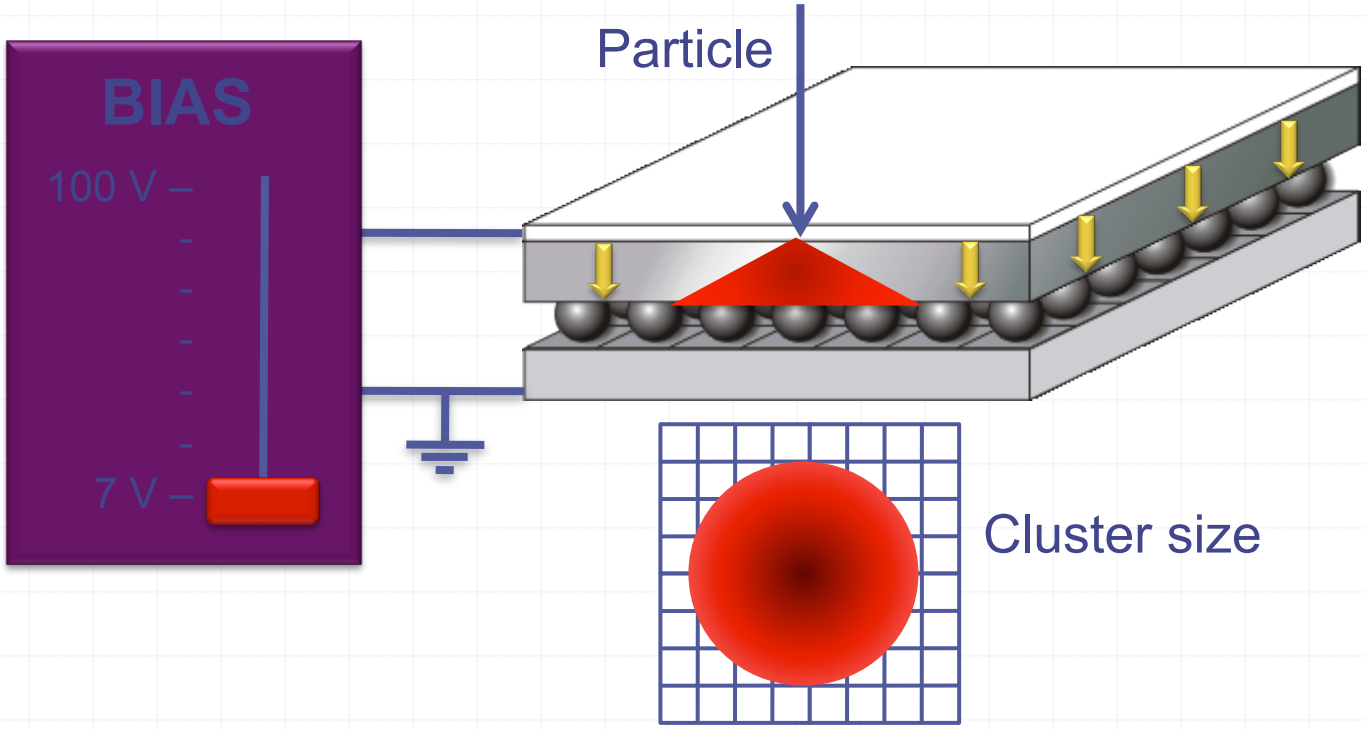

3D-visualization of proton tracks in Timepix silicon pixel detector. Illumination under different applied biases

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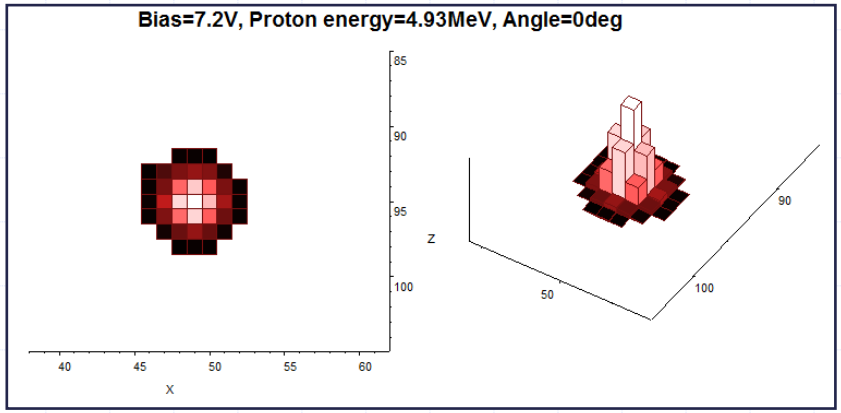

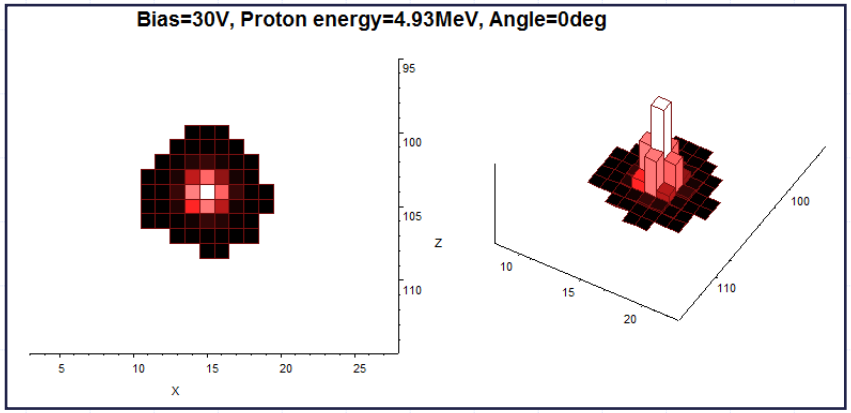

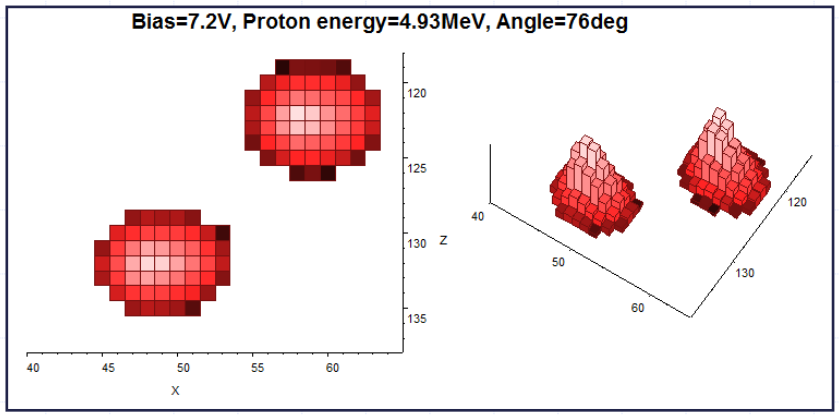

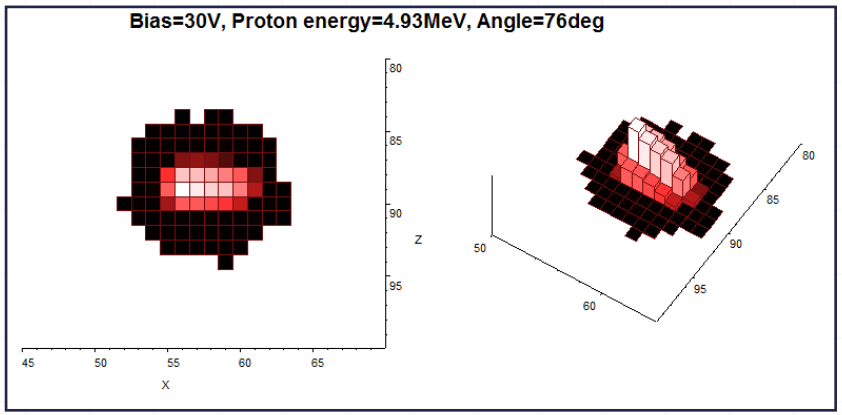

What is the spatial resolution? X- and Y-coordinates are determined with a precision of about 500nm. Determination of angle is with a precision of about 1°. It needs additional experiments.

Flock of 11 MeV protons entering the silicon sensor under 85°

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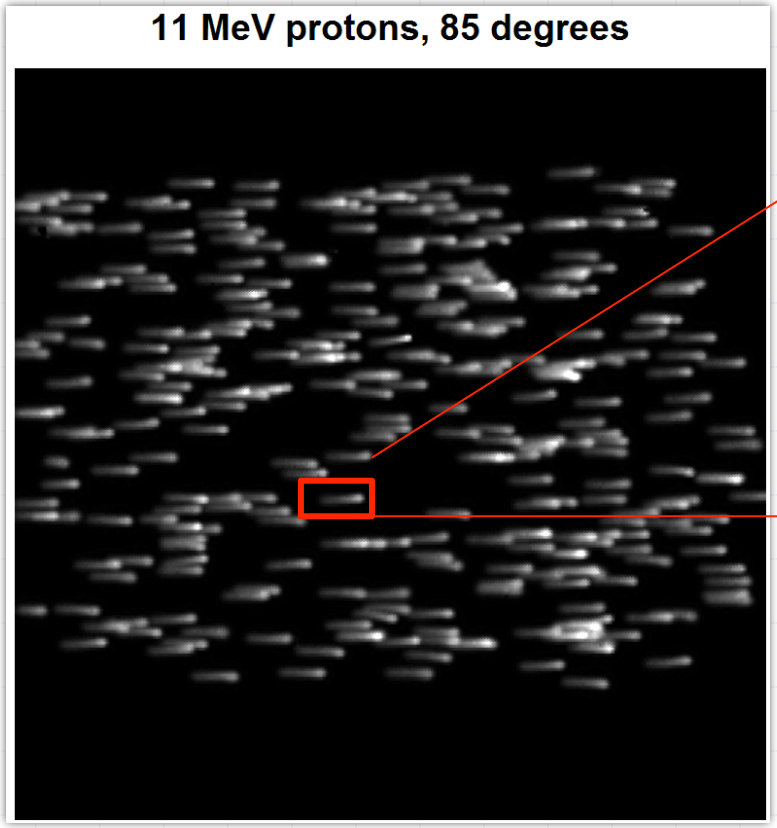
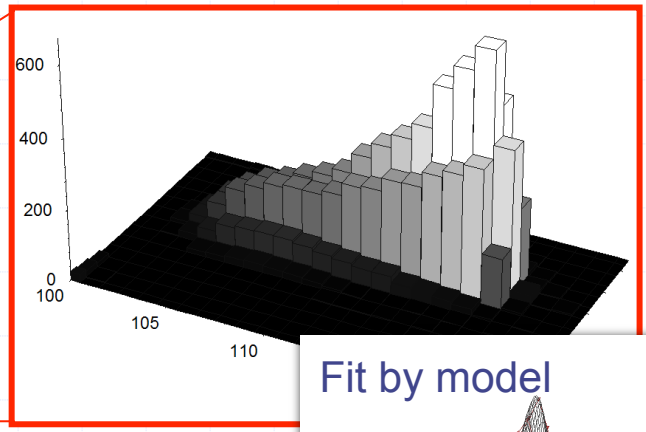
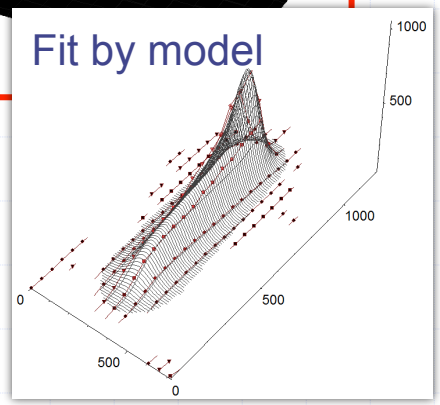


ΔE/Δx Bragg profile nicely pronounced, proton range about 960 μm





Typical observed tracks of particles used for hadron therapy beam

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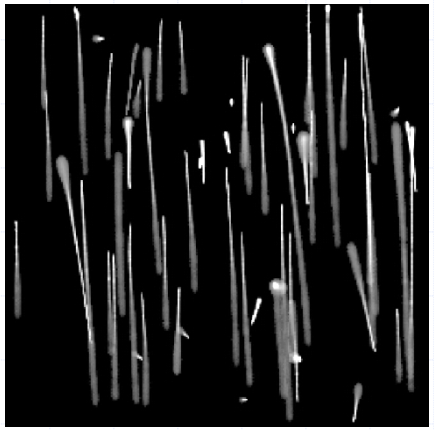
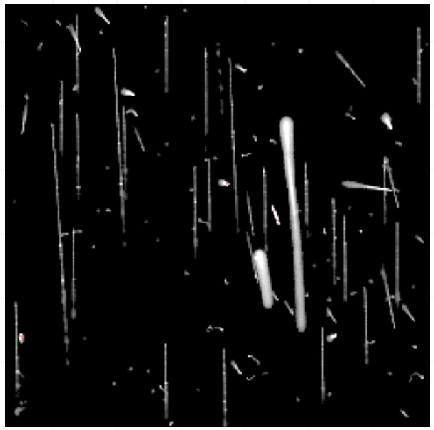
Protons 48 MeV



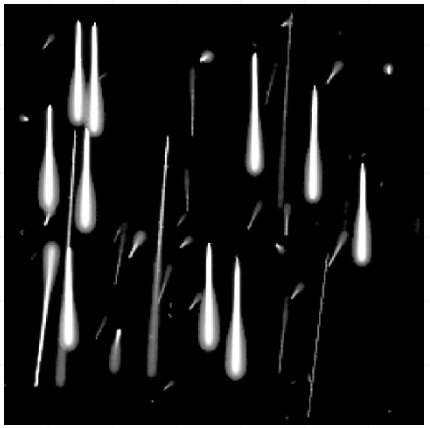
Only protons and their scattering, no secondaries.

Protons 221 MeV



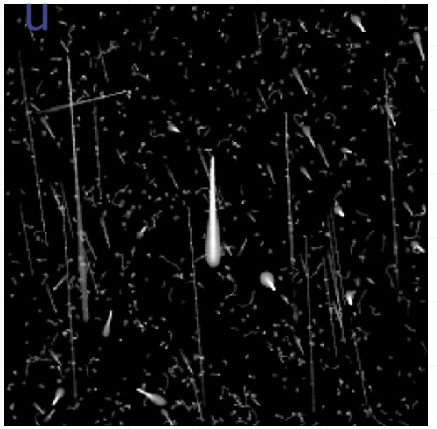
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u



Carbons and many secondaries.

Track of MIP particle – cosmic muon

Charge sharing effect helps to determine all three track coordinates with quite high resolution (deeply submicrometric in case of x and y)

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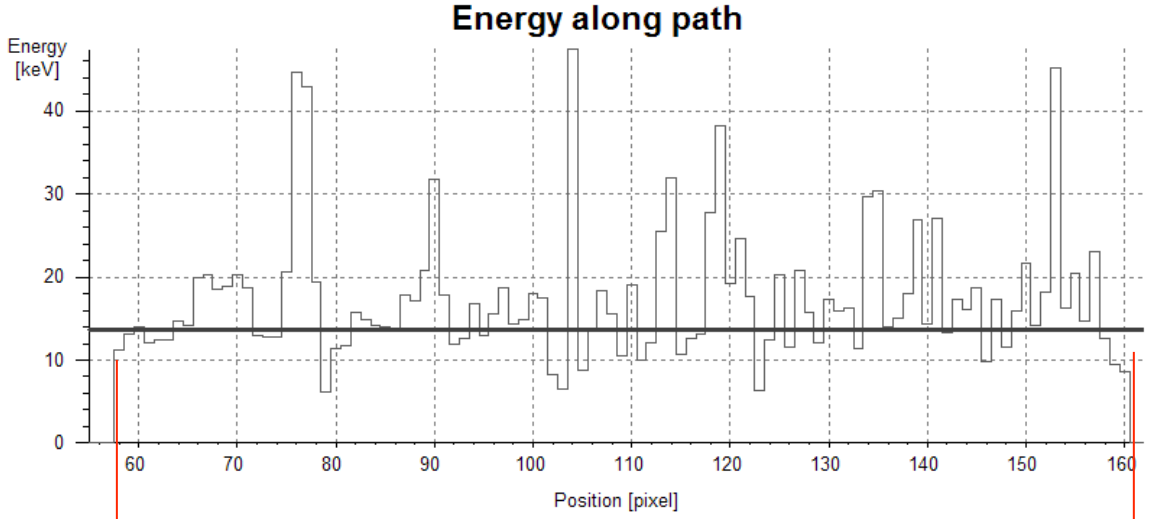
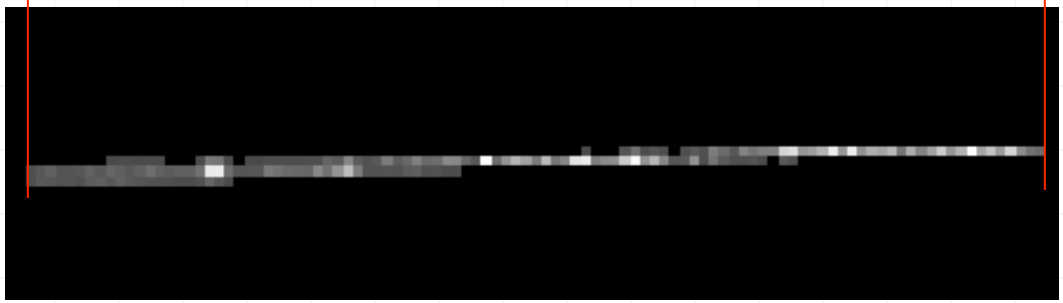
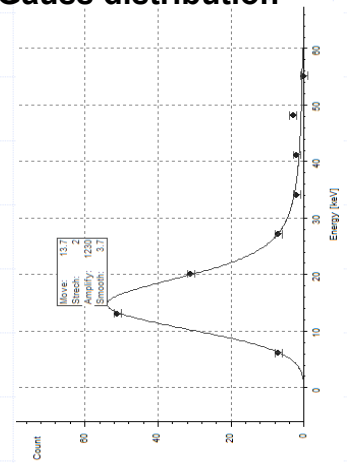
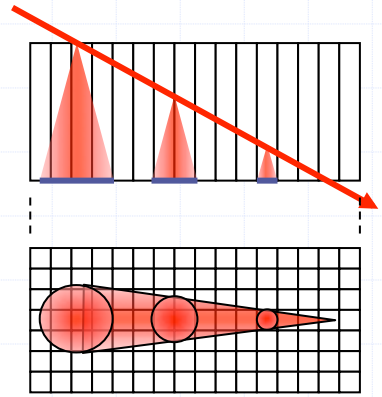




Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





Review of the characteristic patterns
Event by event processing

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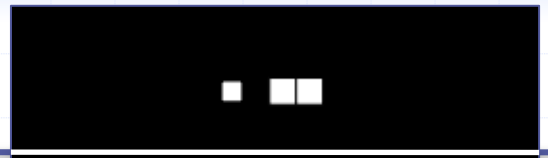
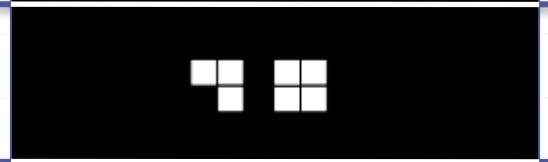
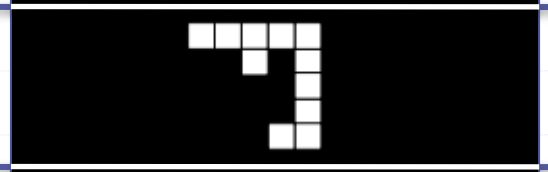
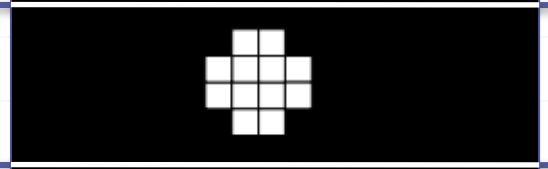
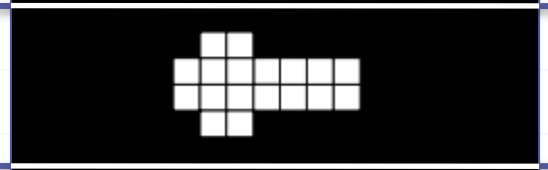
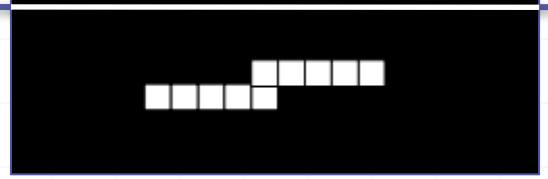
1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with low range (alpha particles,…)
5) Heavy track		Heavy ionizing particles (protons,…)
6) Straight track		Energetic light charged particles (MIP, Muons,…)

X-ray imaging

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Experimental setup

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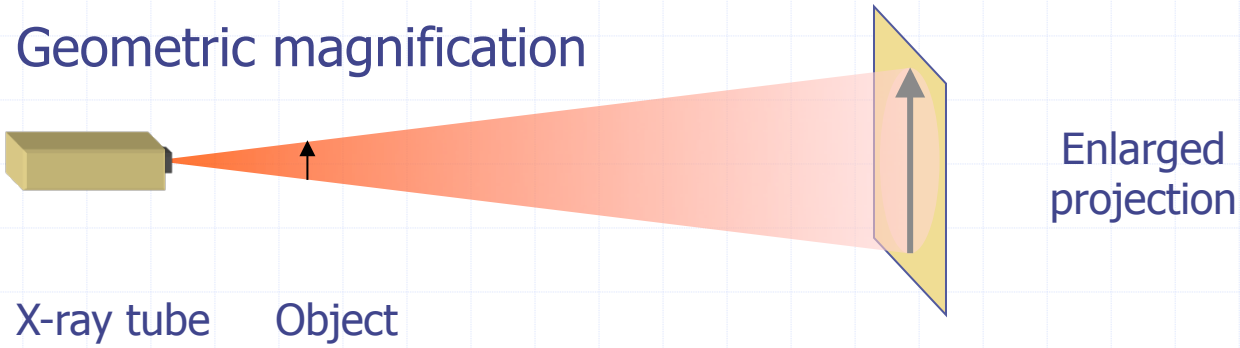
Requirements:

- Microfocus X-ray source to enable geometrical magnification
- Adjustable object holder (three translations + rotation)
- Sample stabilization (temperature, humidity)
- Equipment for automatic calibration of pixel responses
- Detector holder and detector stabilization (temperature, condensing point)



Mouse Kidney Tomography

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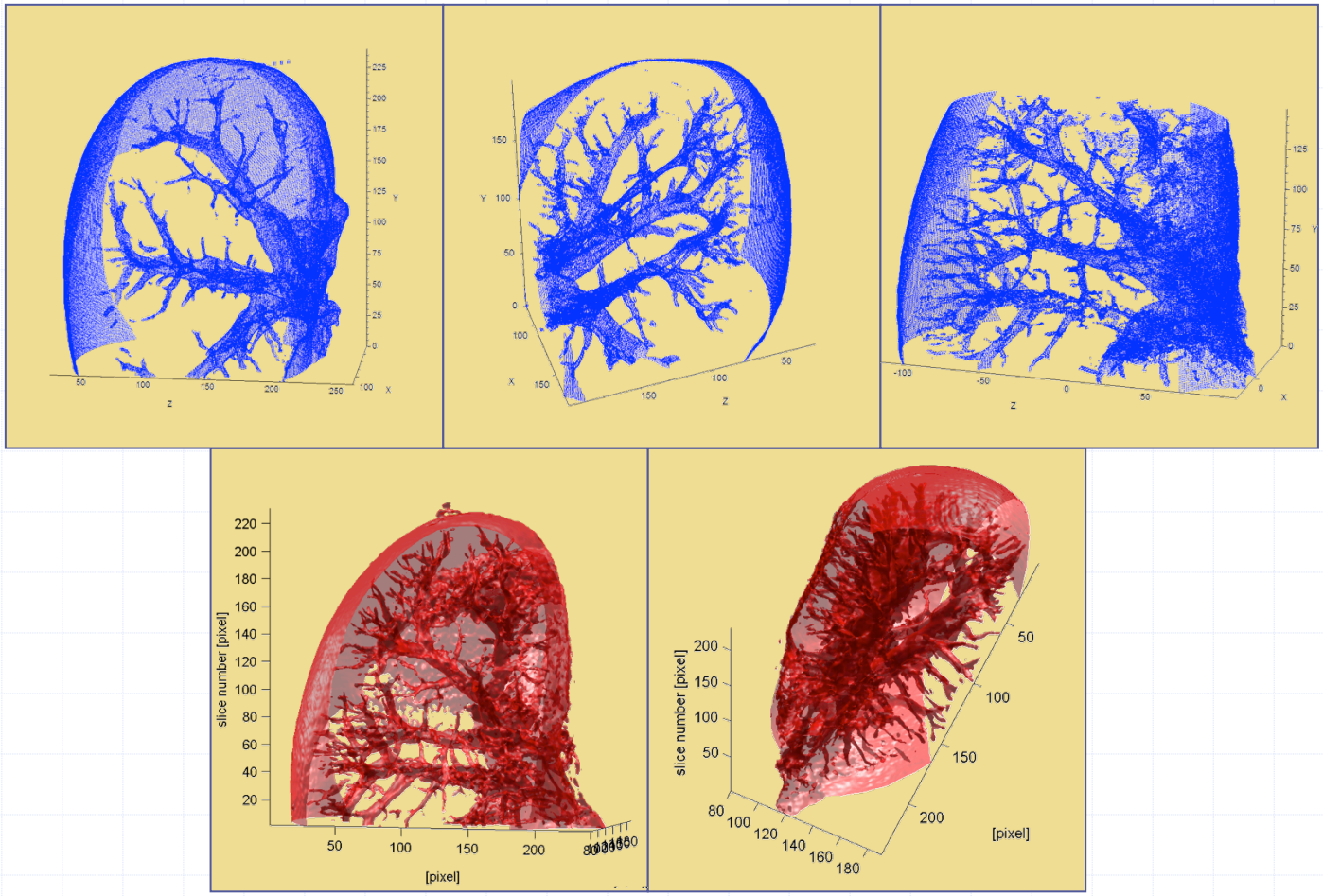
Missing angles => Iterative algorithm instead of Filtered back projection (3 iterations in OSEM 5)



High resolution X-ray radiography:

Imaging of Termites

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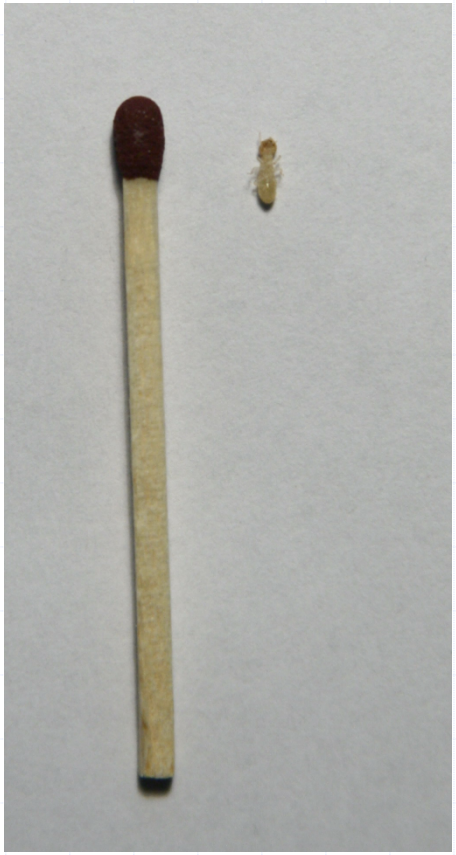


The imaging of termites as a model **soft tissue organism** is particularly difficult due to their **poorly sclerotized** cuticle making difficult to observe the anatomic structures with an optimal contrast.

Moreover, they are vulnerable to damage when they are manipulated or treated during sample preparation.

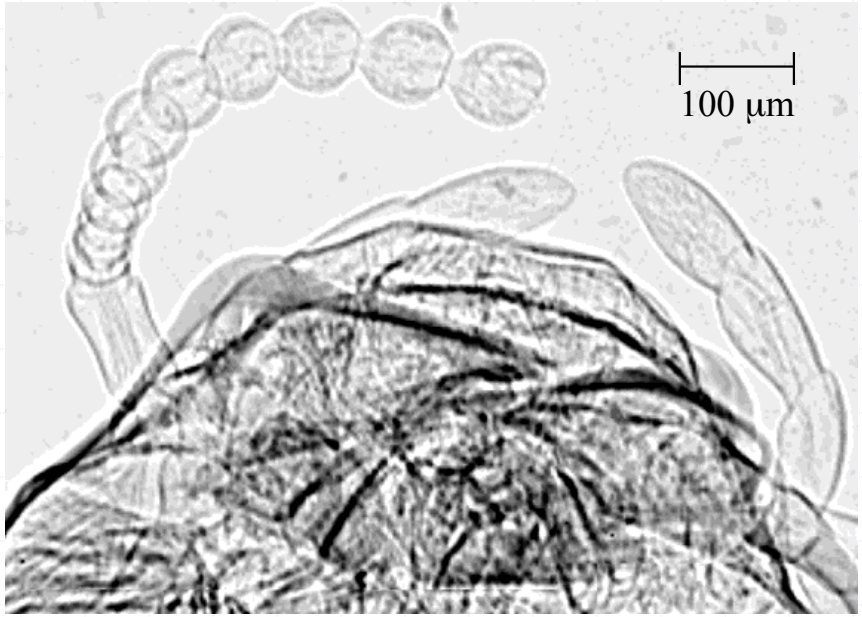
Thus, the termites represent an ideal model to optimize the accuracy and sensitivity of the developed method.

High resolution X-ray radiography:

Imaging of Termites

X-ray transmission image of termite worker body (left) and detail of its head (bottom). Even fine internal structure of the antennae is recognized.

(Magnified 15x, time=30s, tube at 40kV and 70μA)



Imaging of Living Termites

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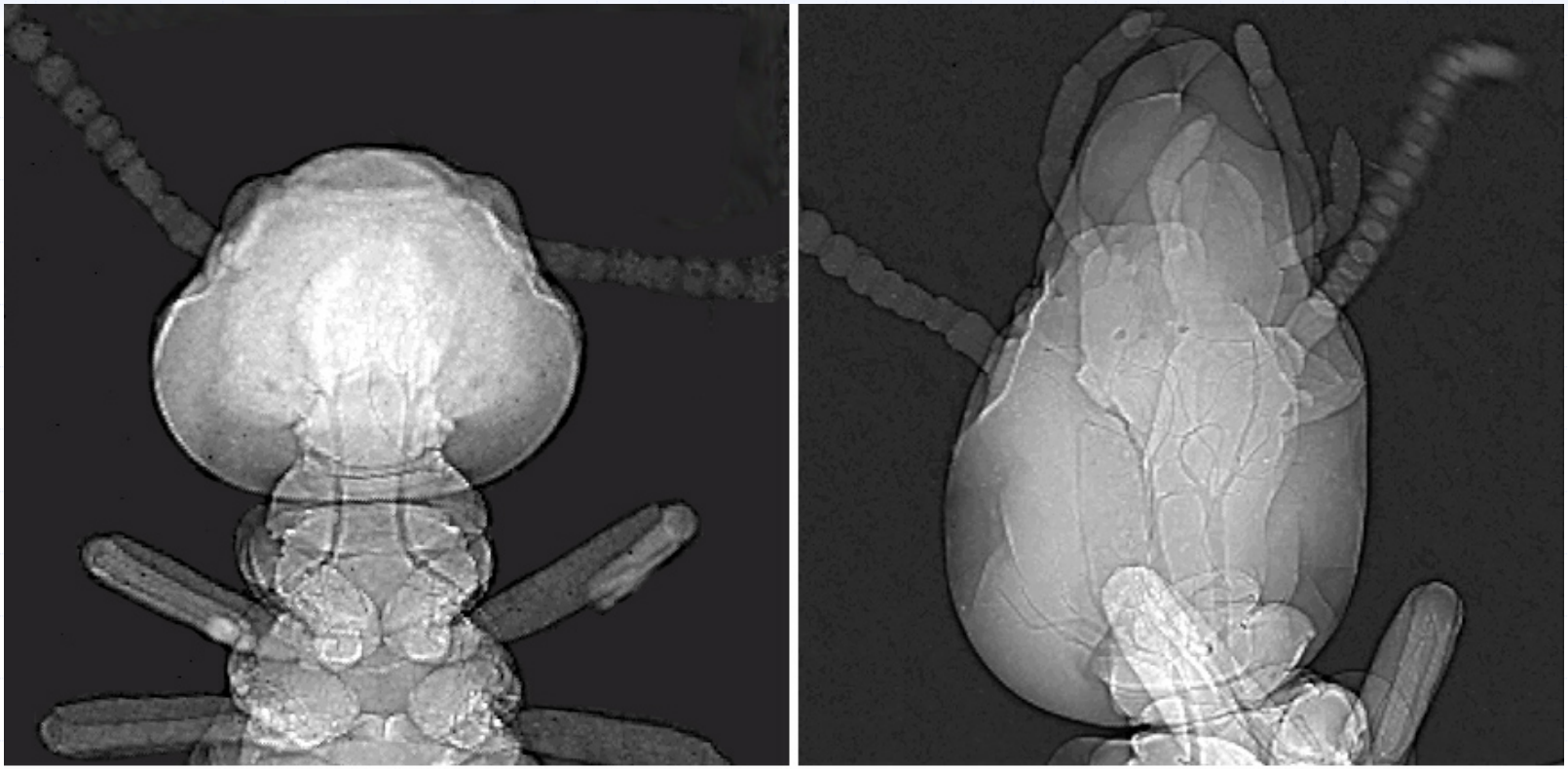

Images of a termite worker before (left) and after (right) its metamorphosis toward the soldier caste (5s exposure ~ 0.7mGy dose)

About neutrons

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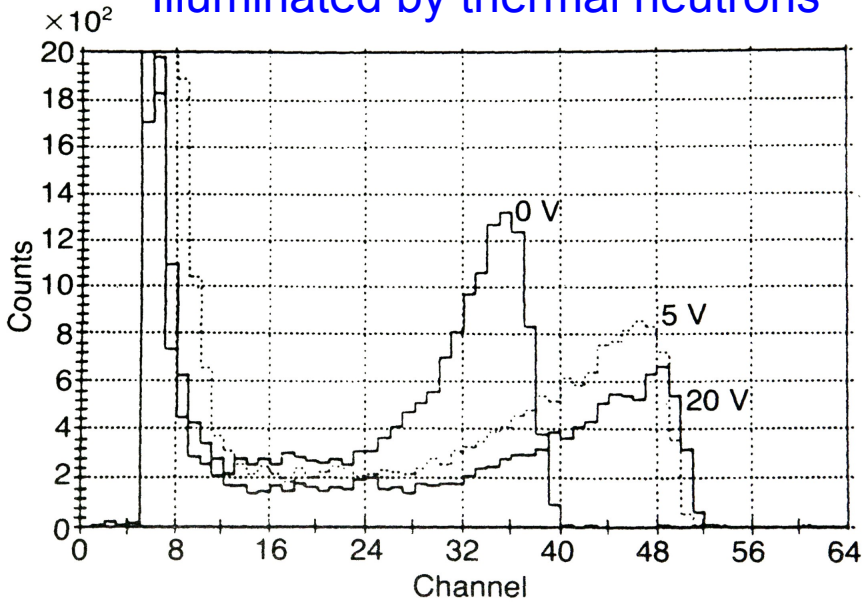
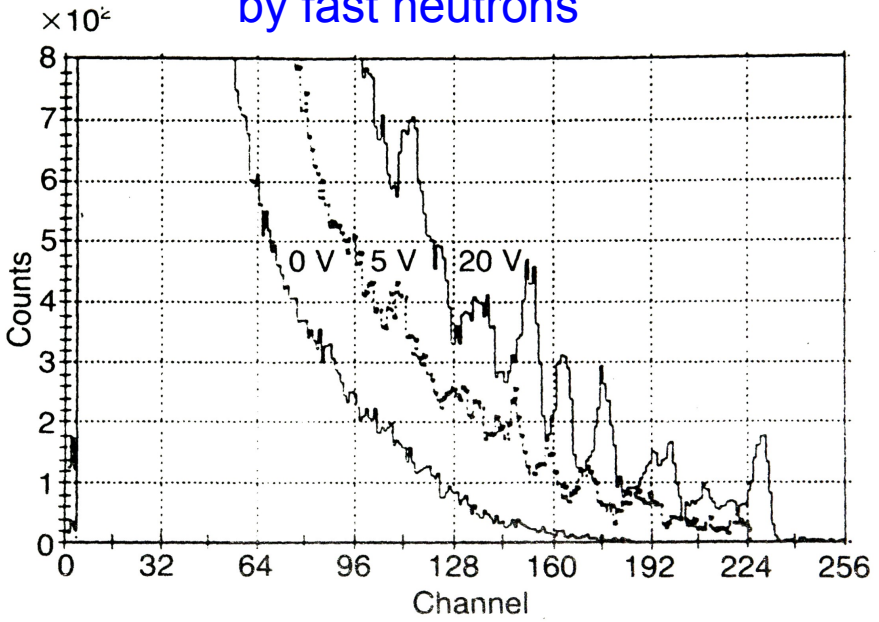
Responses of silicon detetcors to neutrons

Silicon diode + ^{6}LiF converter
Illuminated by thermal neutrons



Pulse height distributions of neutron detector on thermal neutrons at different bias (0, 5, 20 V). Detector operates well in the self-biased regime.

Silicon diode illuminated
by fast neutrons



Pulse height distributions of neutron detector when illuminated by fast neutrons (14.8 MeV) at different bias (0, 5, 20 V). Peaks from interaction of fast neutrons with ^{28}Si are clearly seen

Response of silicon diode with CH2 converter to protons recoiled by 3.8 and 4.2 MeV neutrons

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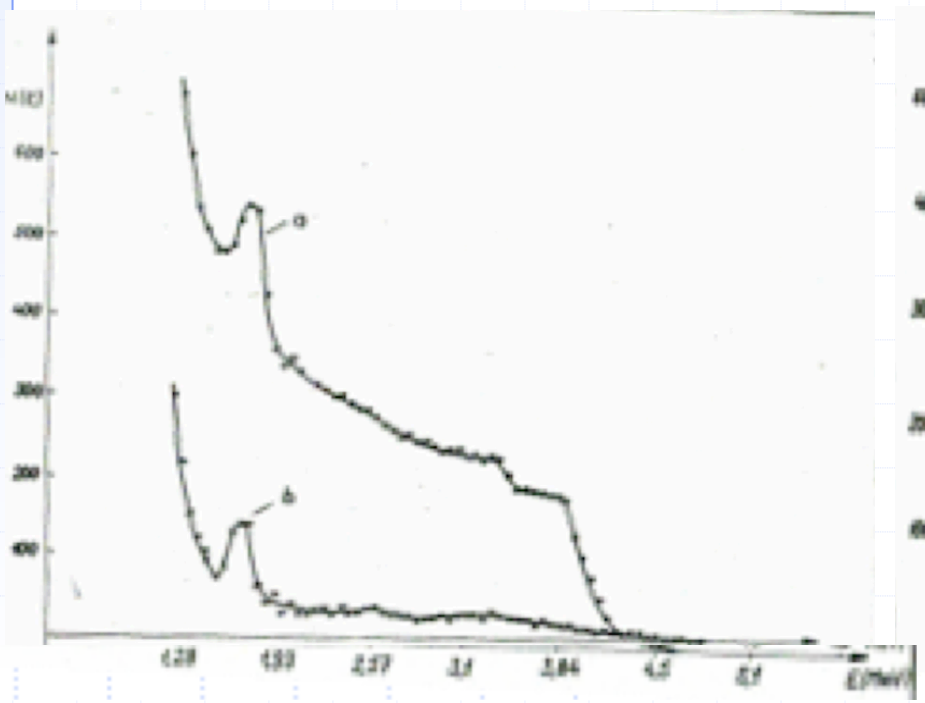

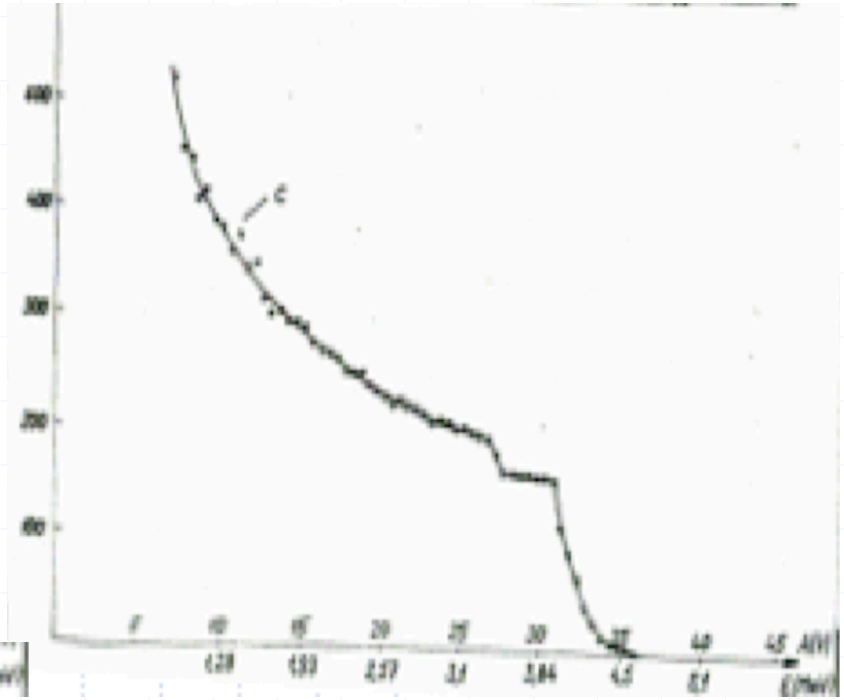

a) PH spectrum measured by the diode with CH2 converter (up)
b) PH spectrum measured by the diode without CH2 representing background caused by $^{28}Si(n,\alpha)^{25}Mg$ (down)

c) Pure spectrum of recoiled protons (background subtracted

Response of MEDIPIX-USB device with polyethylene converter (on the right hand side) to fast monochromatic neutrons (17MeV)

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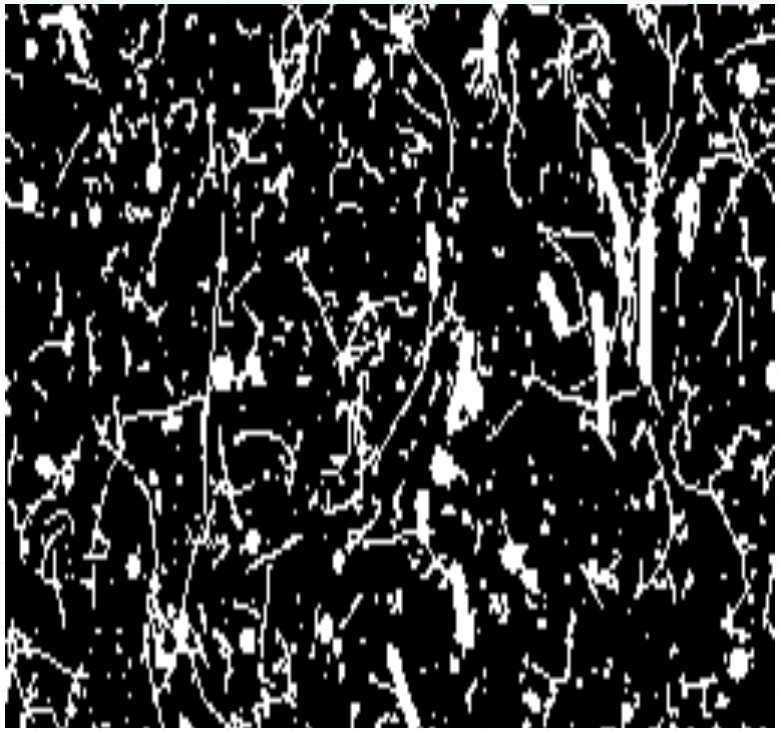

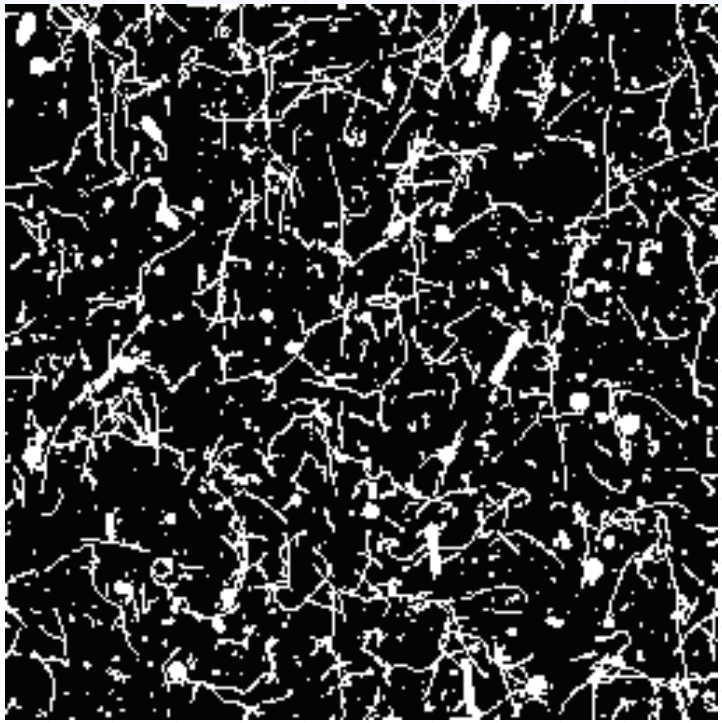

- The direction of the neutrons with respect to the image was upstream (from bottom to top). The huge background is due to gamma rays which accompany neutrons. Half of the sensor (the right-hand side) was covered with a CH2 foil about 1.3 mm thickness.
- One can clearly recognize long and rather thick tracks of recoiled protons (up to 2 mm, vertically oriented) and big tracks and clusters generated via 28Si(n,α)25Mg, 28Si(n,p)28Al 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.

Detail view on conversion layers

added for a neutron detection in mixed radiation fields

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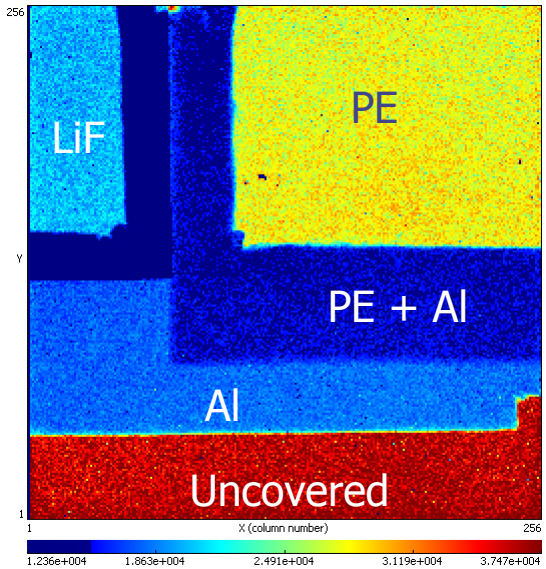
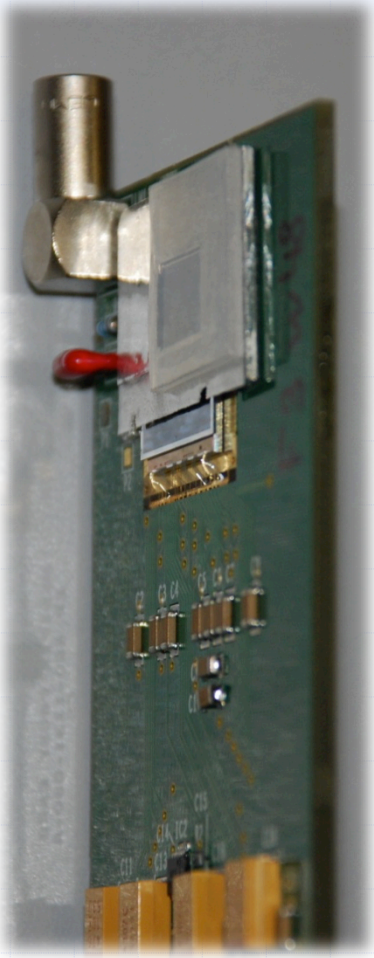
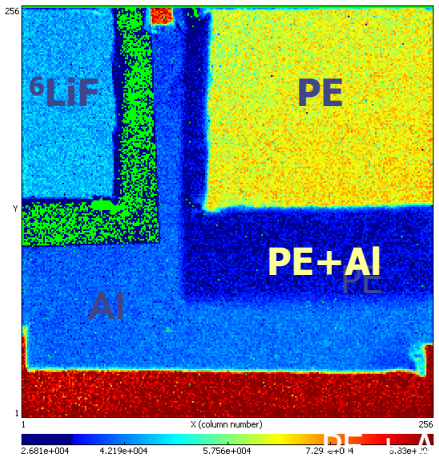
Several different regions:

- LiF+50μm Al foil area
- 100μm Al foil area
- PE area
- PE+50μm Al foil area
- 50μm Al foil area
- Uncovered area



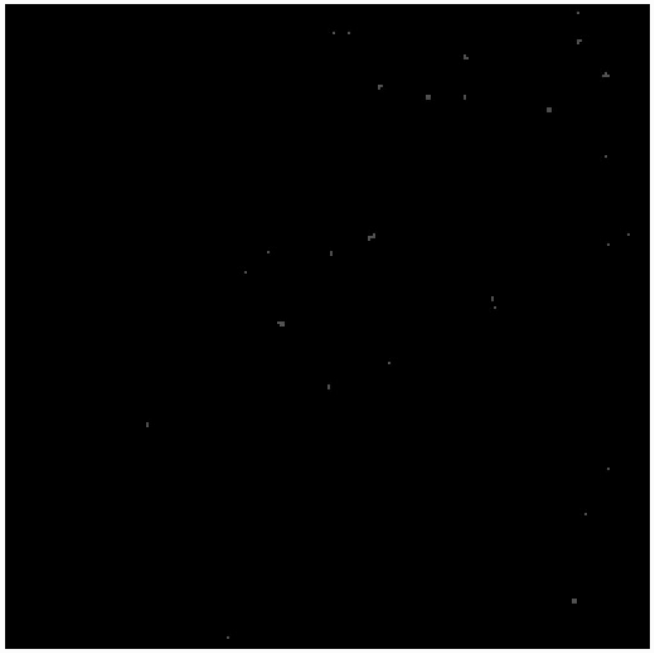


^{252}Cf neutrons measured in counting mode of operation at different thresholds



252Cf, low threshold (8 keV)

252Cf, high threshold (300 keV)



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Responses to neutrons of different energies measured at high threshold in counting mode

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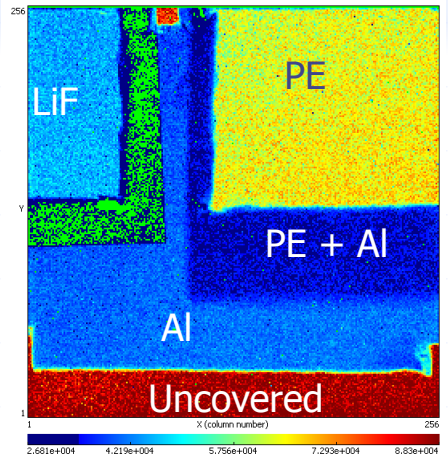
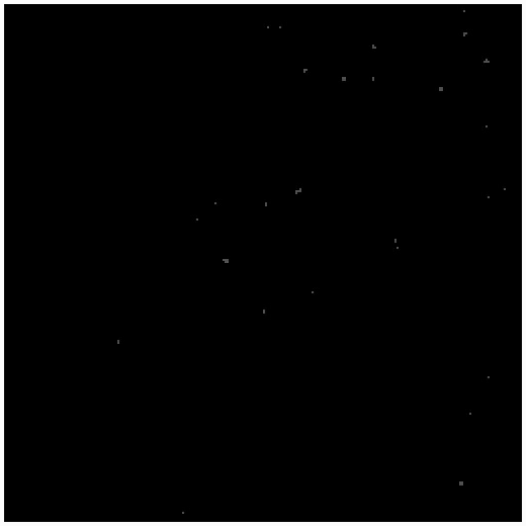
Identification of spectral composition of incoming neutron radiation can be done by comparing responses of different sensitive regions.

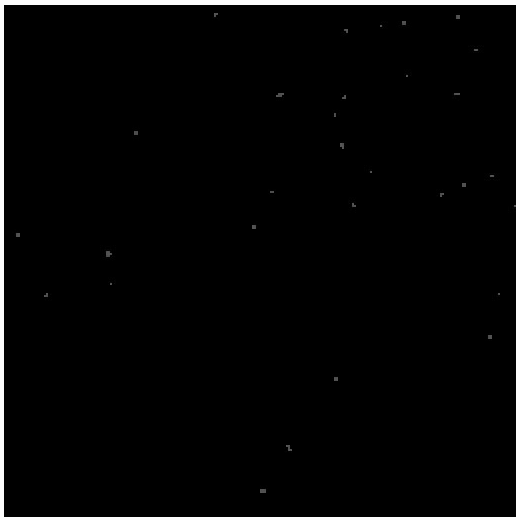
Thermal neutrons – 500s



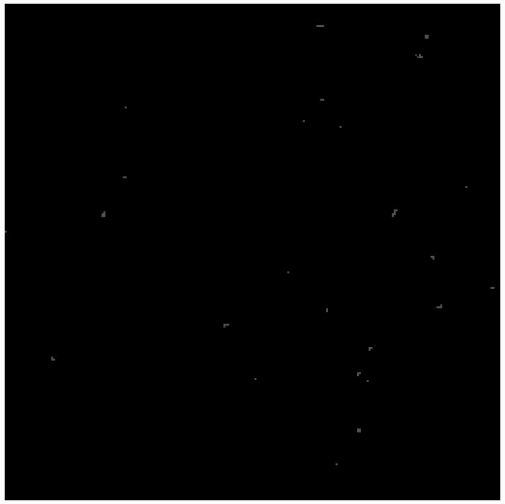
252Cf – 2000s



AmBe – 2000s



17 MeV neutrons at 0°



Neutron imaging

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Motivation – neutron radiography

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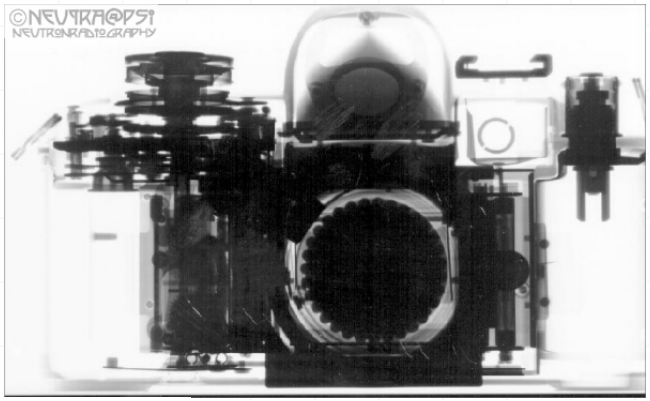
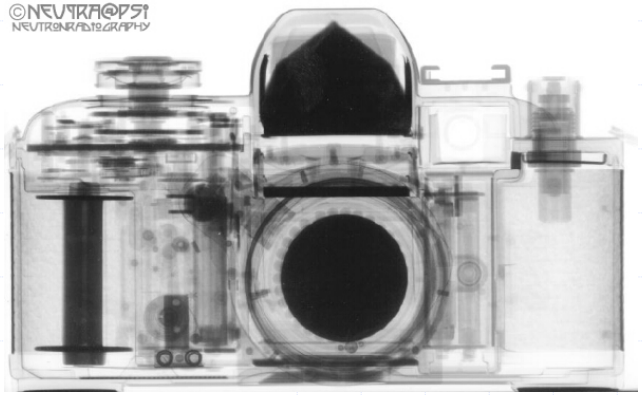
- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



X-rays



Neutrons

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts (Courtesy of E. Lehmann, PSI)

The Neutronography based on

$^{6}Li(n,\alpha)T$, Q=4.78MeV and $^{10}B(n,\alpha)^{7}Li$, Q=2.78MeV

(energetic charged products define interaction with deeply subpixel resolution)

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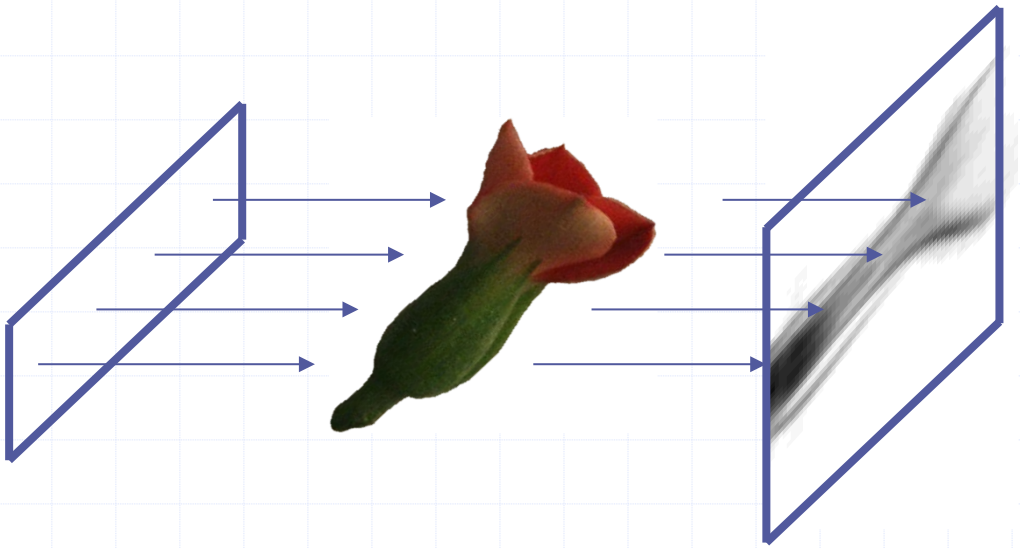
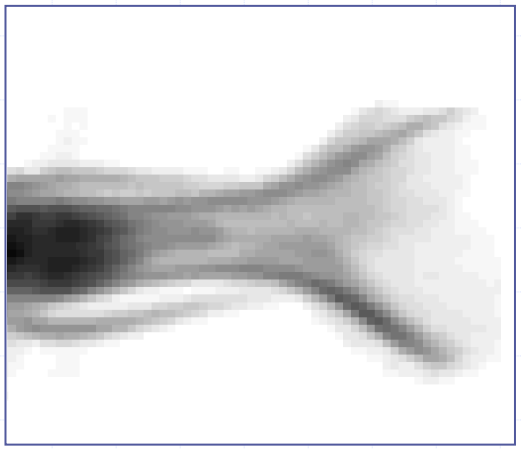


Parallel beam of thermal neutrons

Specimen attenuating the beam

Shadow on detector plane



Neutronogram

Flower behind Al plate

Look through metal with thermal neutron beam at NPI Rez

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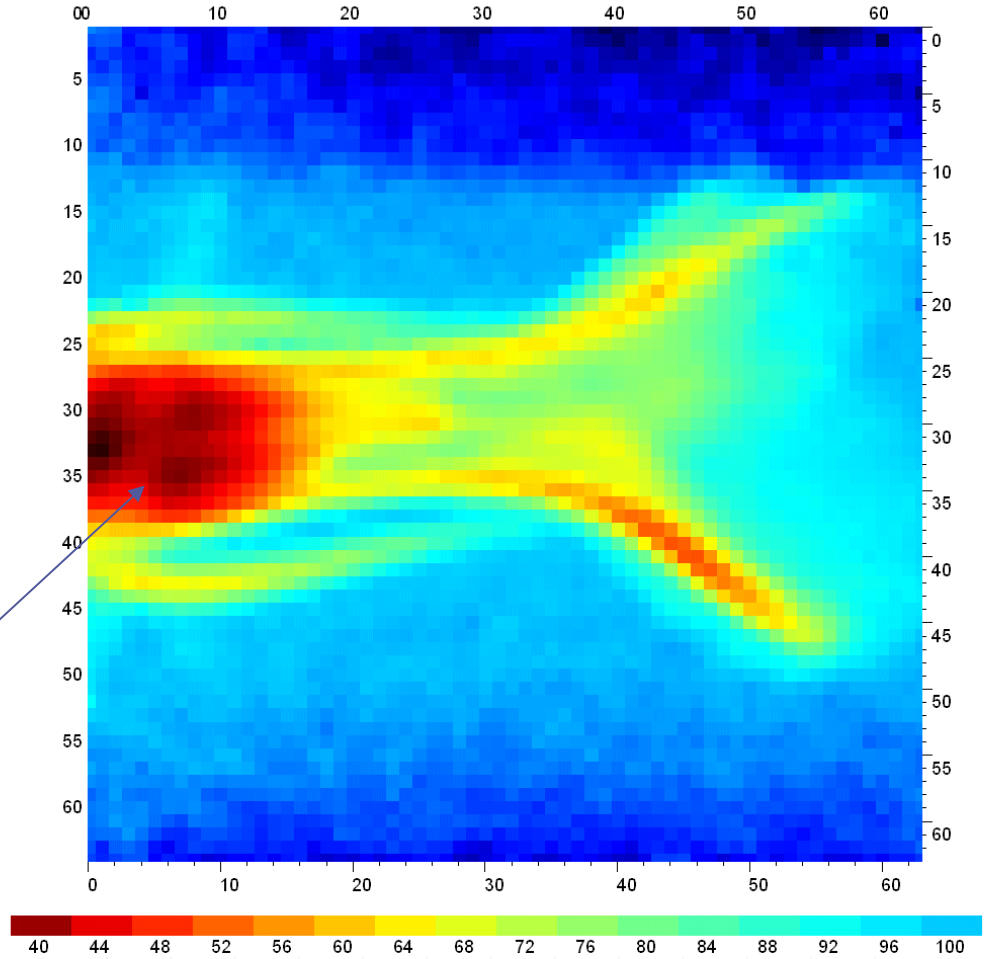

Glued Al pieces
(measured at NPI Rez)

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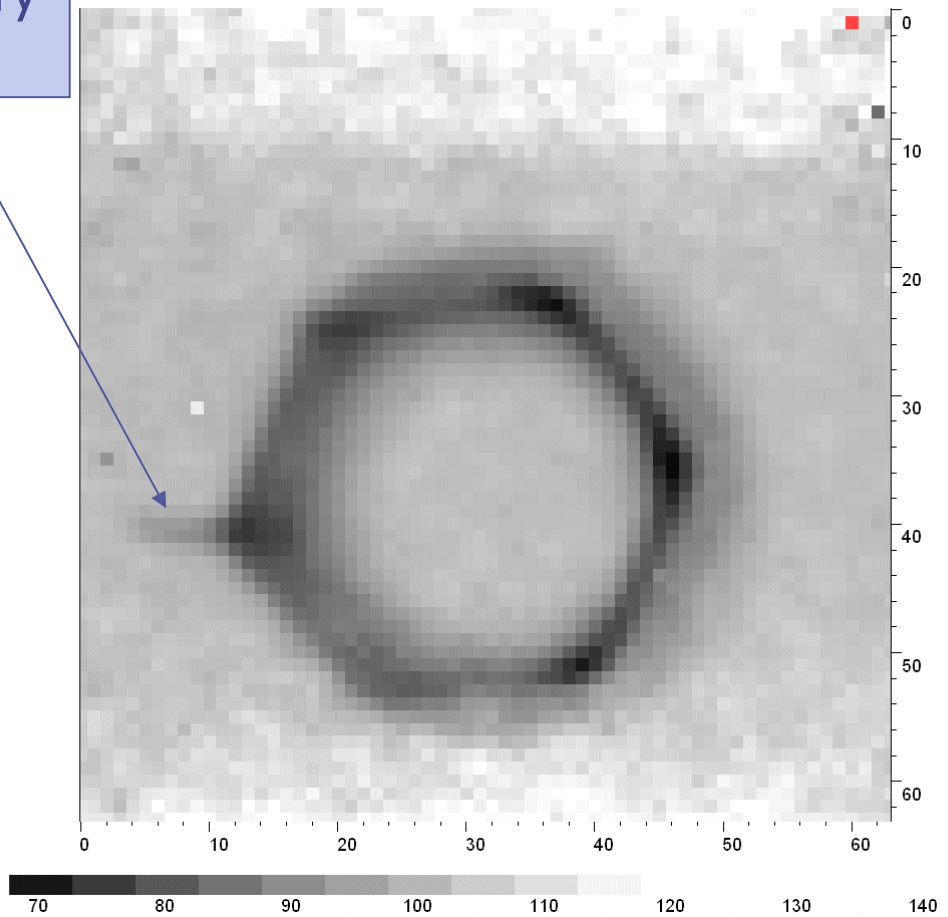
Glue raised through capillary attraction



Neutron radiography with Medipix coated by ^{6}LiF: Blank cartridge. Look through metals!

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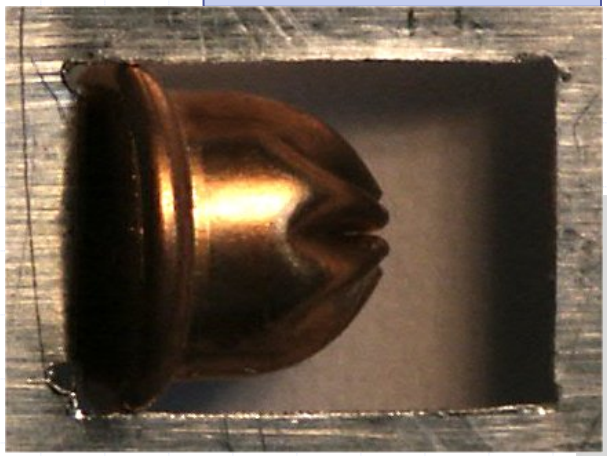
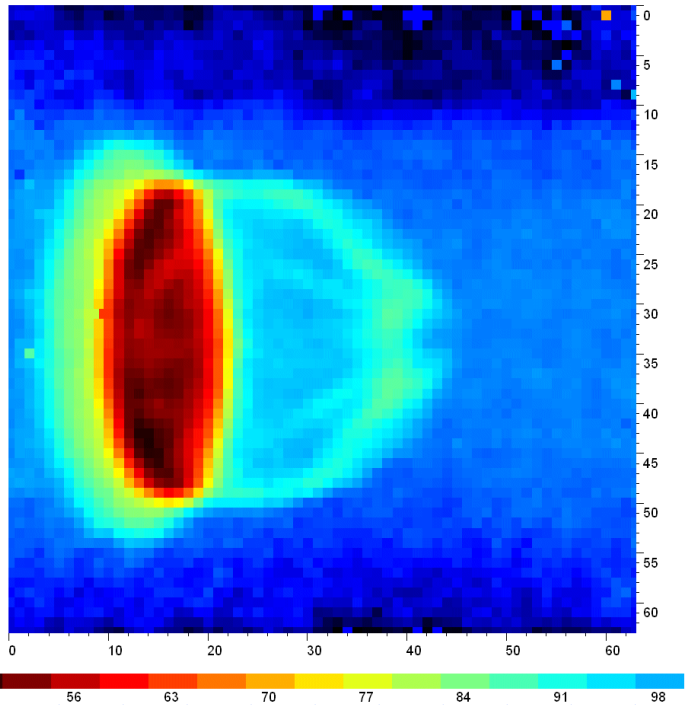
Photography



Roentgenogram



Blank shell (cartridge)

Explosive filling

3D neutron tomography

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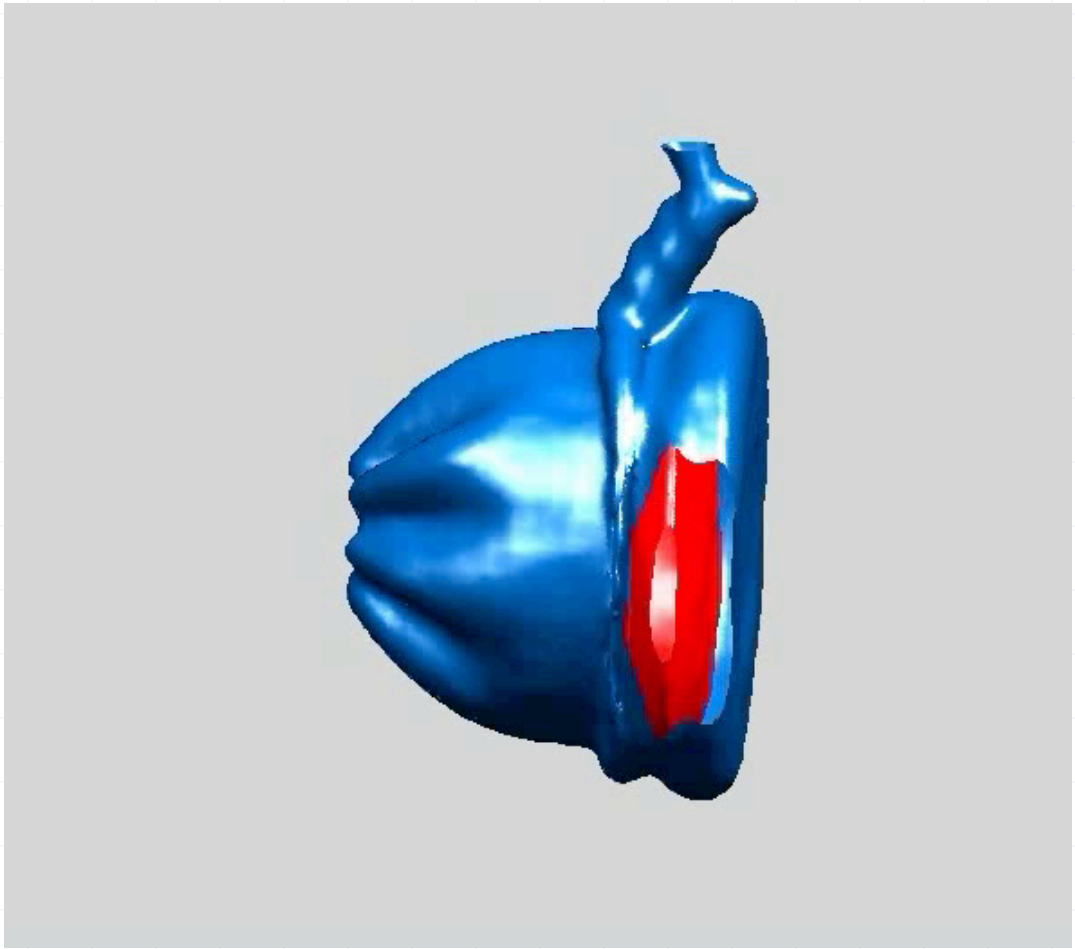
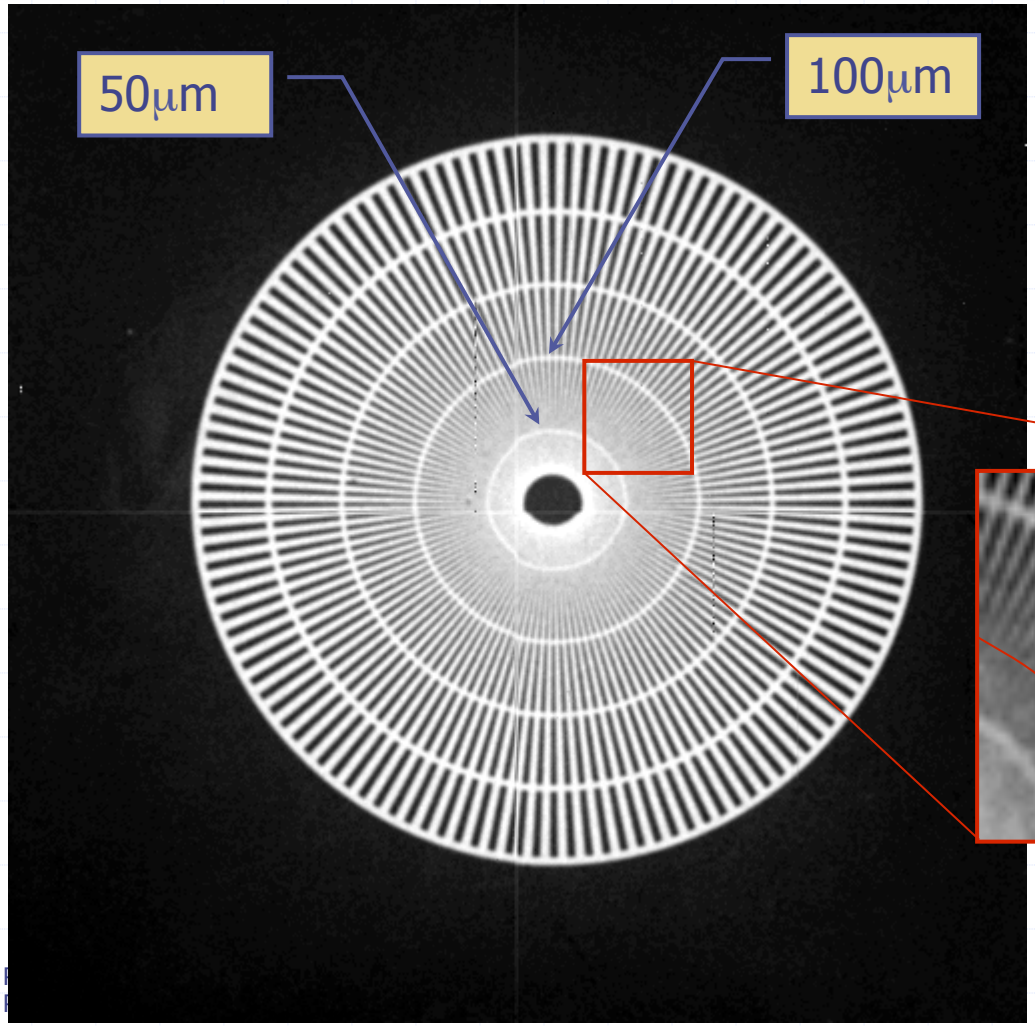
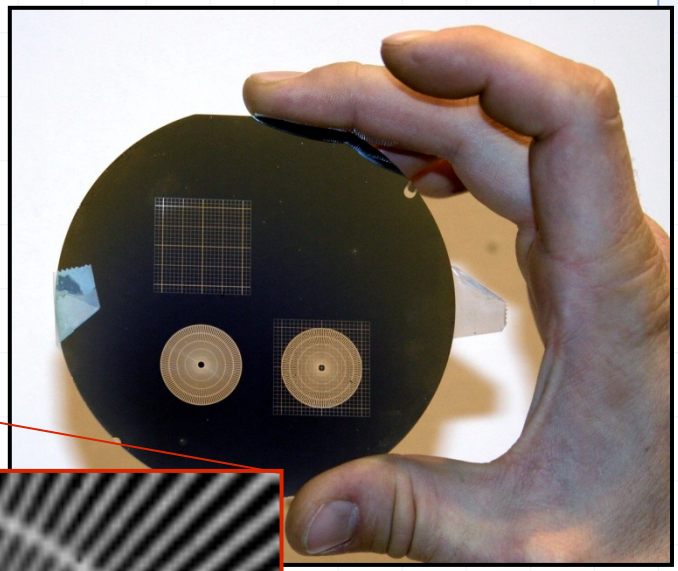


Neutron transmission radiography (counting mode)
Test of Spatial Resolution
(Medipix2 Quad system and cold neutrons)





=>Resolution about 65μm!

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Cold neutron radiography performed at PSI
Wrist watch

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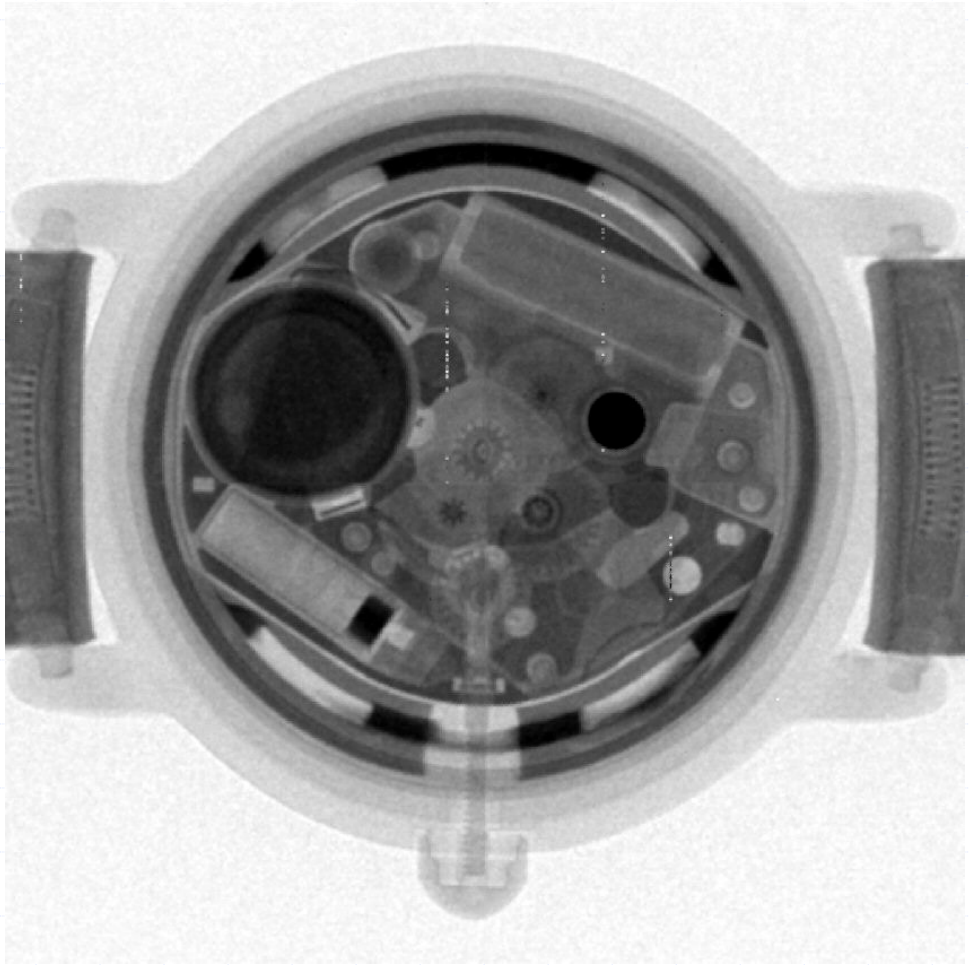
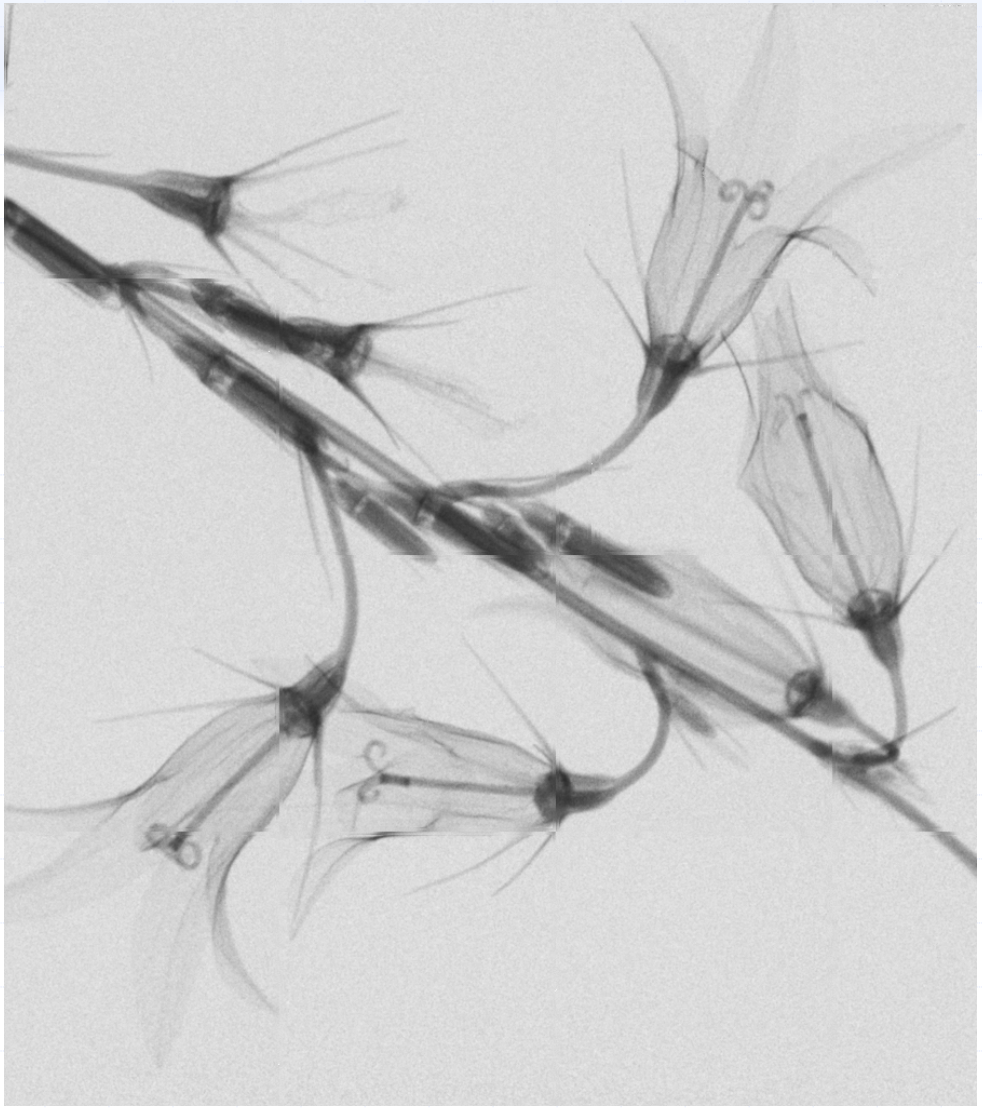


Bellflower



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About detection efficiency and position resolution Monte-Carlo simulations and experiments

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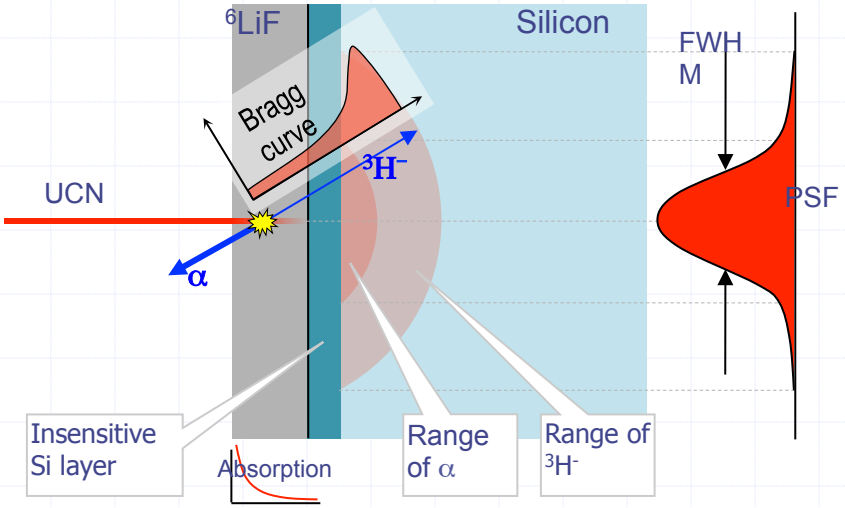
- Simulations performed using MCNP, SRIM and Matlab
- Aim: To estimate detection efficiency and spatial resolution



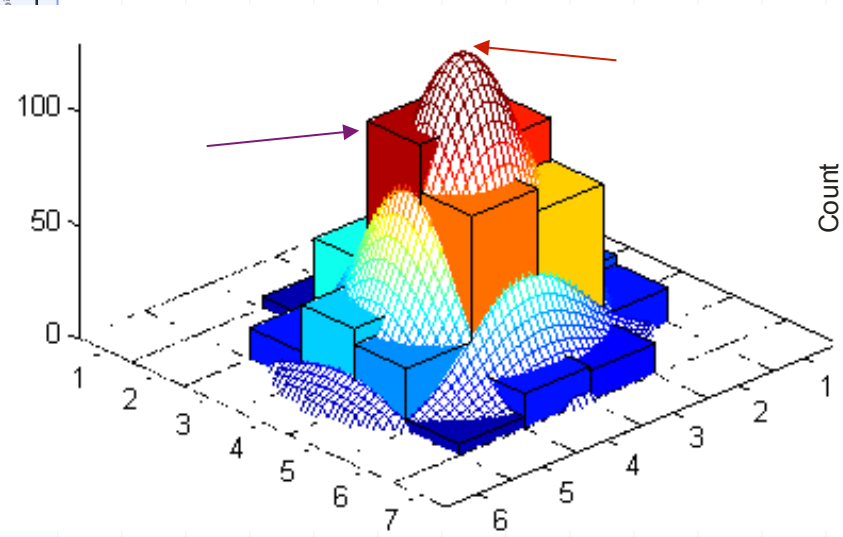
Geometry used in simulations

Expected UCNs velocity: 500 cm/s. For such neutrons the cross section of ^{6}Li increases to **0.34 Mbarn**. The cross section of ^{10}B reaches **1.67 Mbarn**.

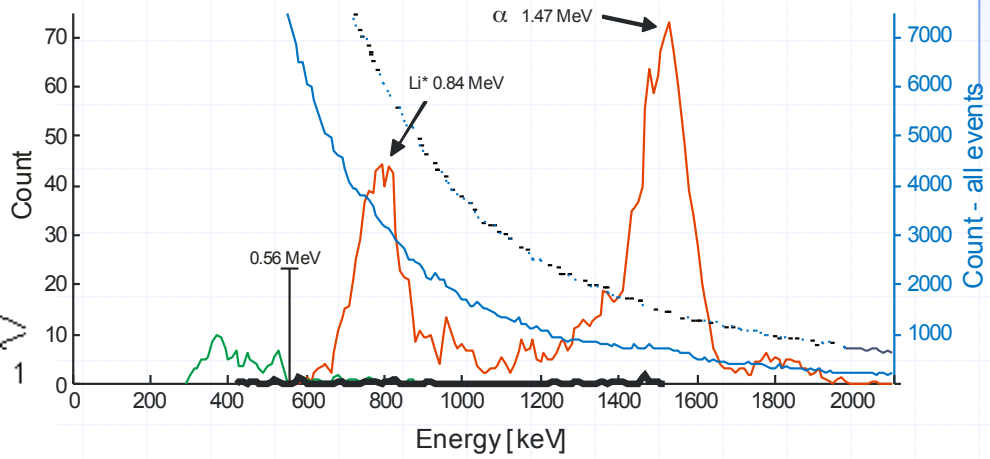
50% of such UCNs are fully absorbed in ^{6}LiF layer of 85 ug/cm^2 (~ 320 nm thickness). For ^{10}B it is layer of 7 ug/cm^2 (~ 30 nm thickness).

Used ^{6}LiF density of 2.65 g/cm^3 and ^{10}B density of 2.35 g/cm^3.

Detail view on individual clusters resulting from (n,α) reaction in ^{10}B converter (tracking mode applicable for neutron imaging)

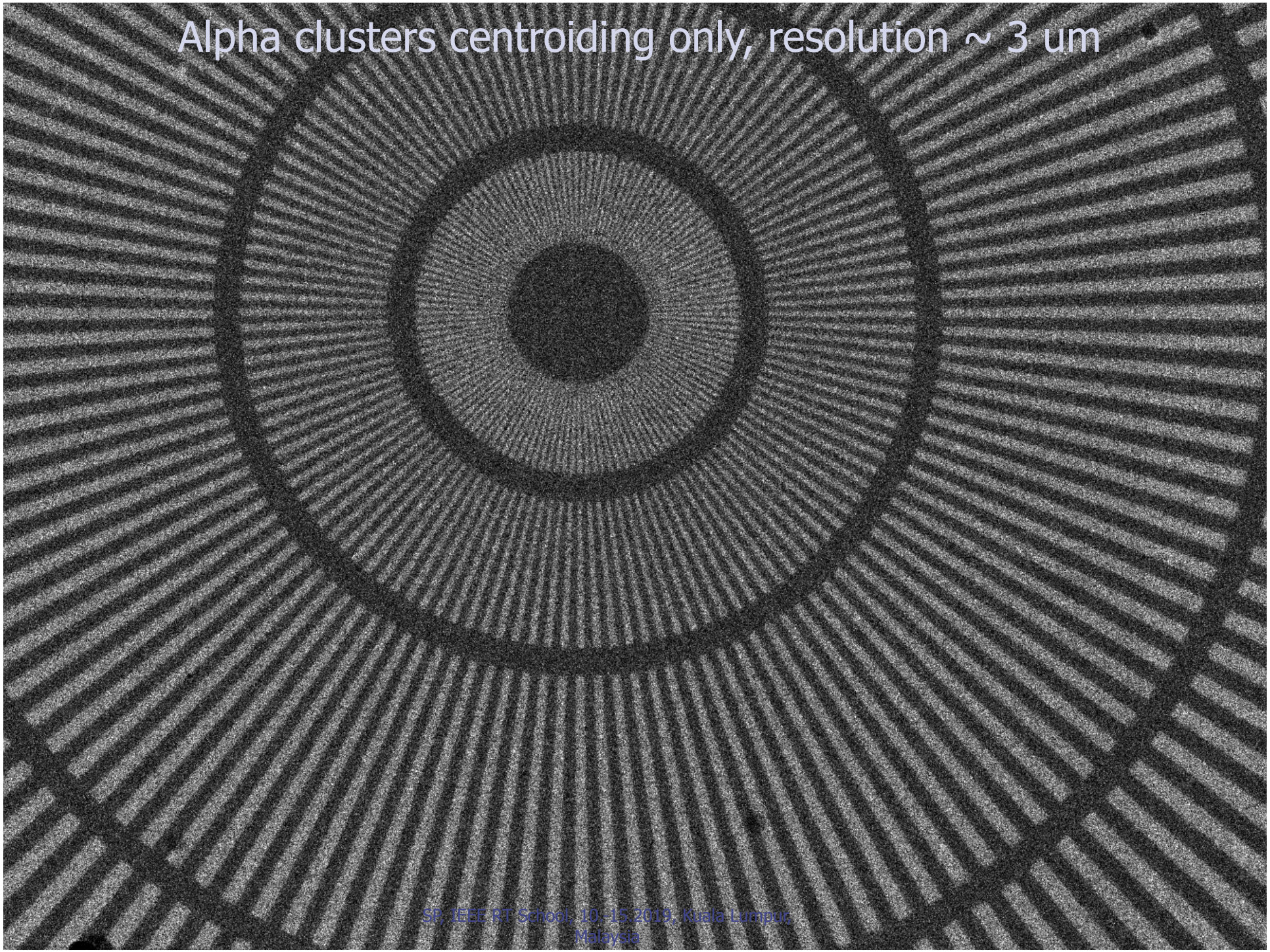


Pixel detector response to every charged article (alpha and 7Li) in a form of 3D-cluster with a shape corresponding to convolution of Gaussian and individual pixel responses



Corresponding amplitude spectrum measured by integration of cluster volumes. ^{10}B converter thickness 1.8 ug/cm^2 (~ 36 nm)

Alpha clusters centroiding only, resolution ~ 3 um



Alpha radiography

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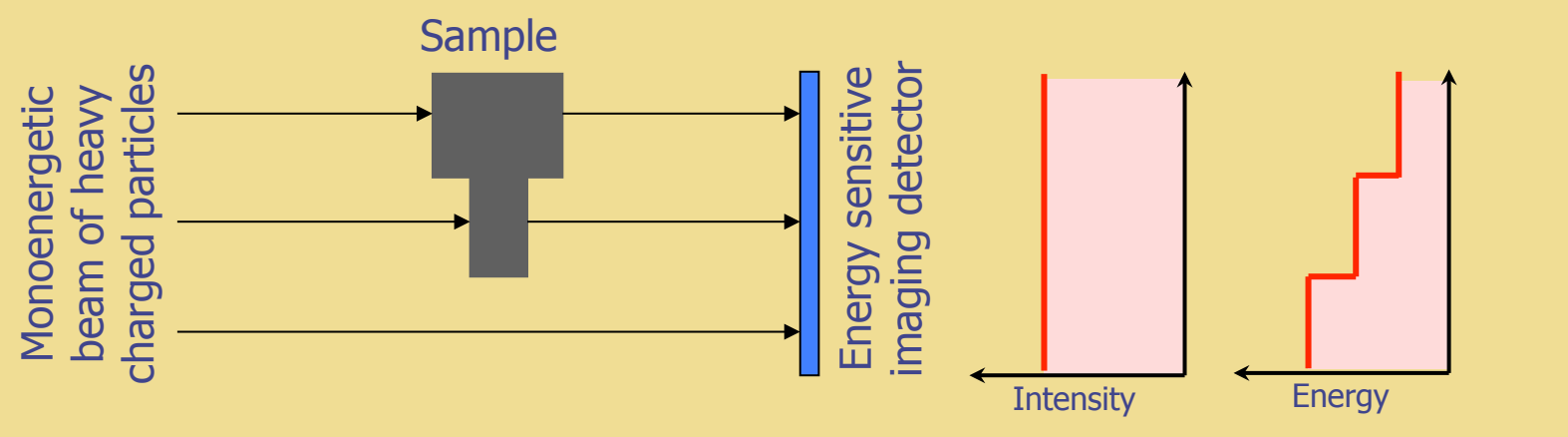
Application:

Radiography with highly ionizing particles



- **Heavy charged particles** (protons, deuterons, tritons, alphas, ions) can be used (impossible with photons, difficult with electrons due to huge change of direction).
- Instead of transmitted beam intensity the **energy losses** of individual particles are measured.
- Just single particle is needed to measure material "density".
- With common sources of heavy charged particles (isotopes, ion beams) it is feasible to inspect just small (thin) objects (thin layer, foils, cellular structures)
- **Precision of thickness measurement can be in nanometer scale**.

Radiography with heavy charged particles with Medipix2

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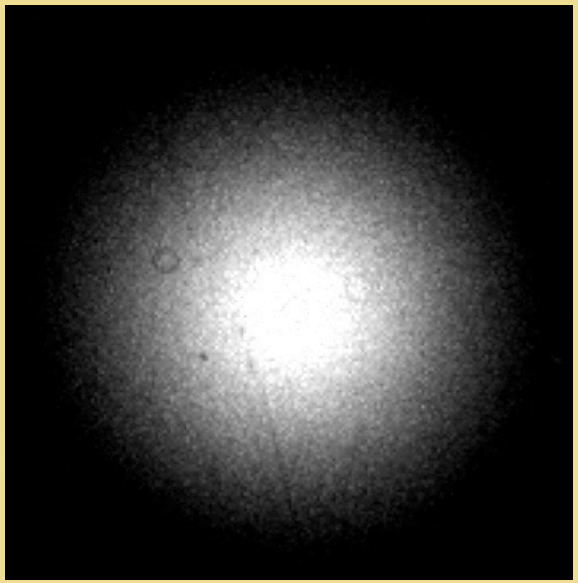
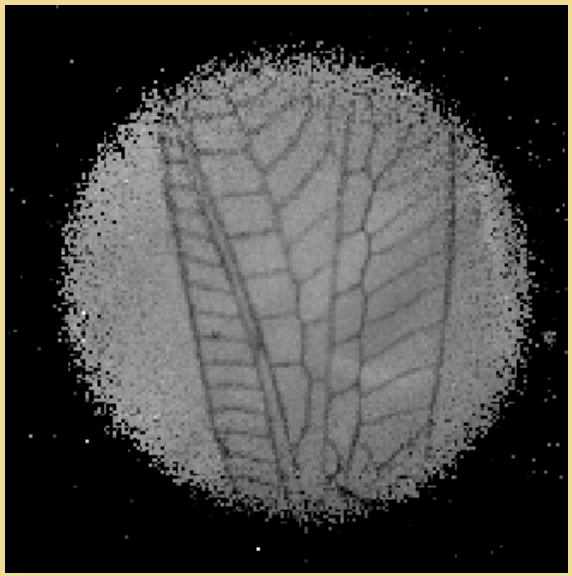
By cluster analysis it can be determined:
- **Centroid** to increase spatial resolution (subpixel resolution)
- **Size** as a measure of particle energy

Wing of fly
(less than 20 particles per pixel)

Photo



Intensity



Energy

Single ^{8}He ion decay sequence recorded by Timepix operating in ToA mode

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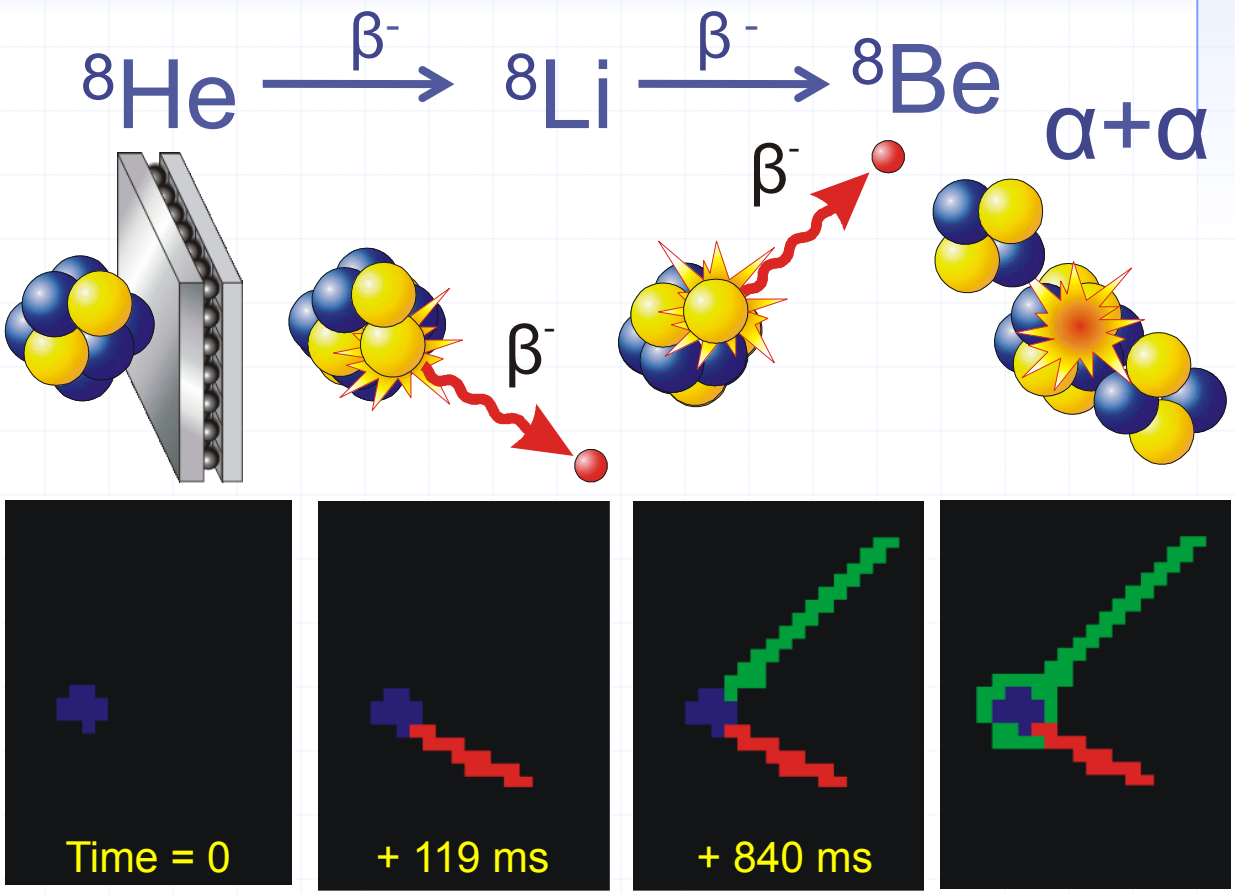
^{8}He ion hits the Timepix sensor where undergoes β-decay

Subsequent decays of the daughter nuclei by emission of one beta and two alpha particles follows



About use of Timepix pixel detectors for measurement of composition and spectral characteristics of complex radiation fields

Calibration of detector responses to all available particles is required!

Protons with different energies: 90 degree

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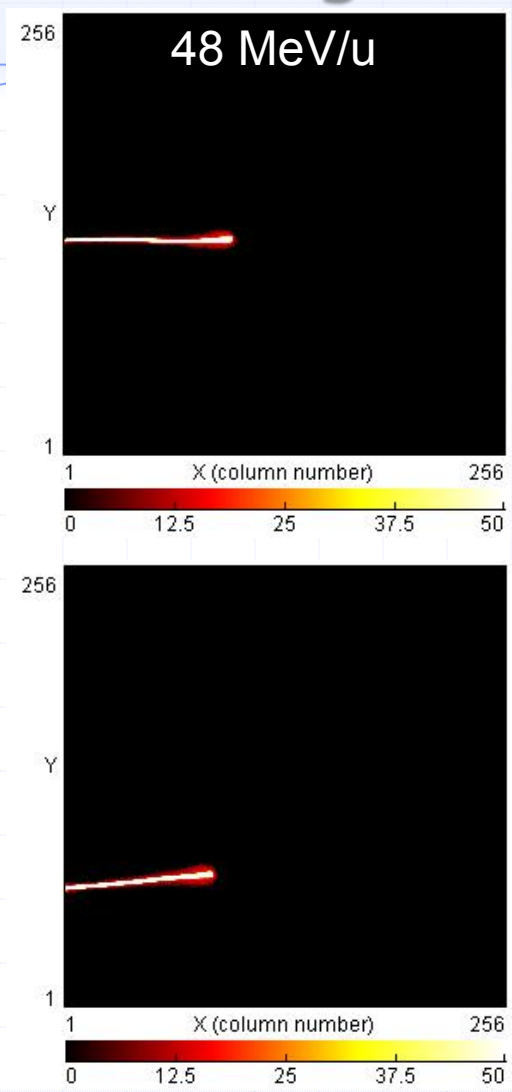

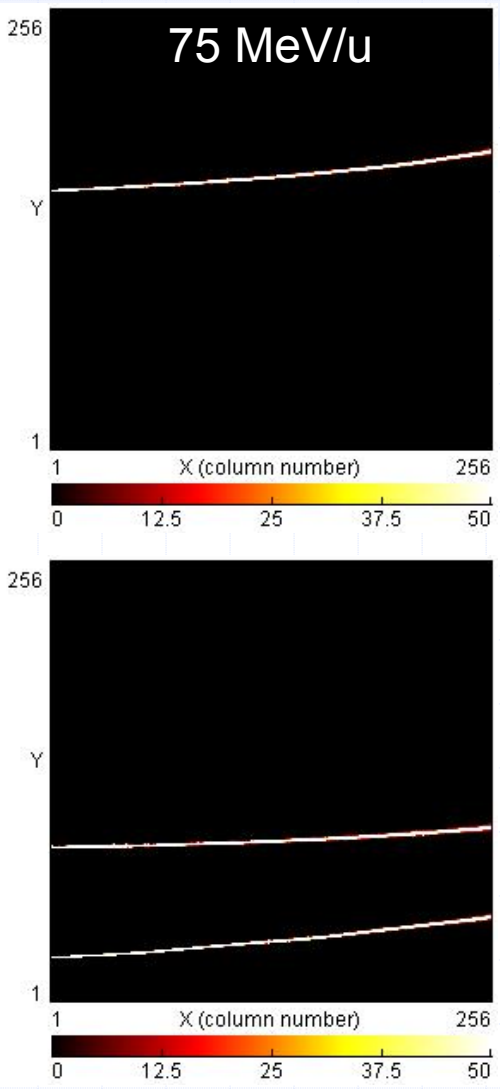

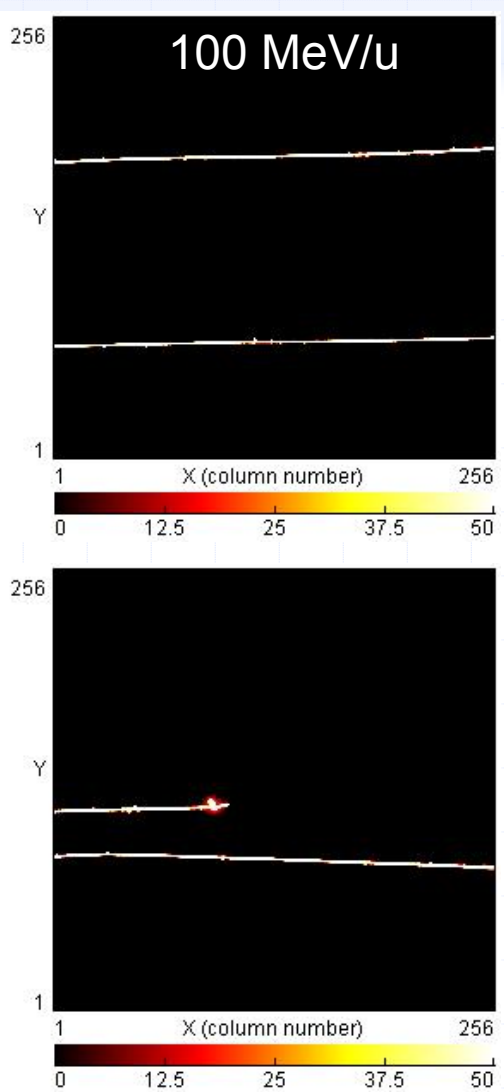

Carbon ions with different energies: 90 degrees

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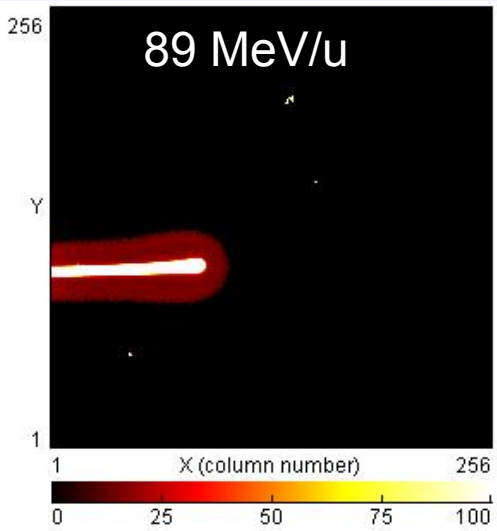
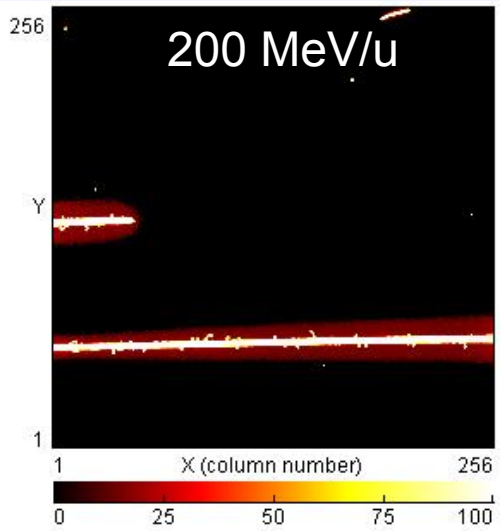
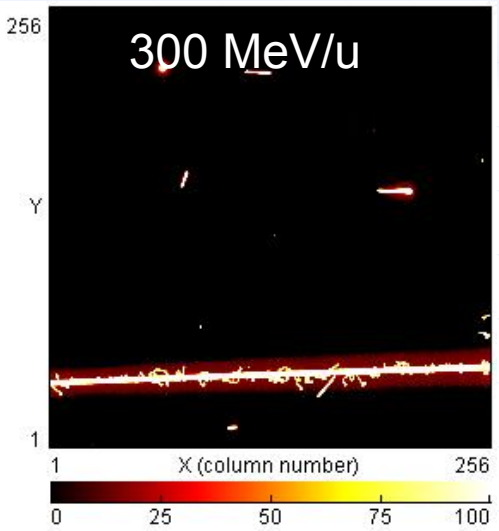
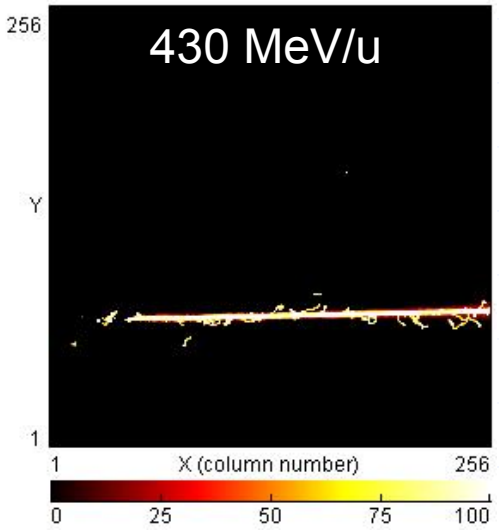


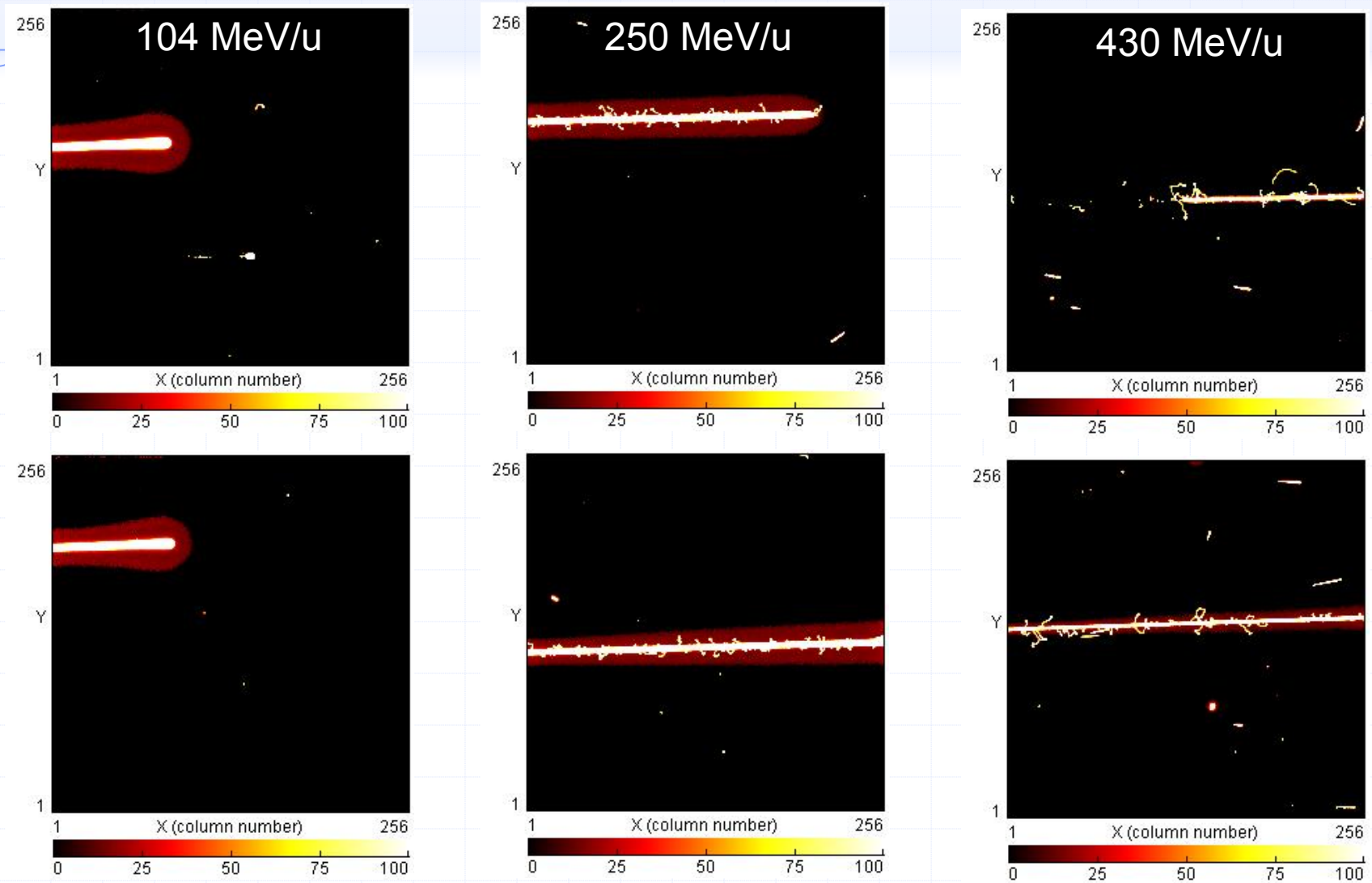






- Halo of pixel with low energy deposition around track - less pronounced for higher energies.
- Number of delta rays increases with increasing energy.

Oxygen ions with different energies: 90 degrees



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Alphas with different energies: 90 degrees

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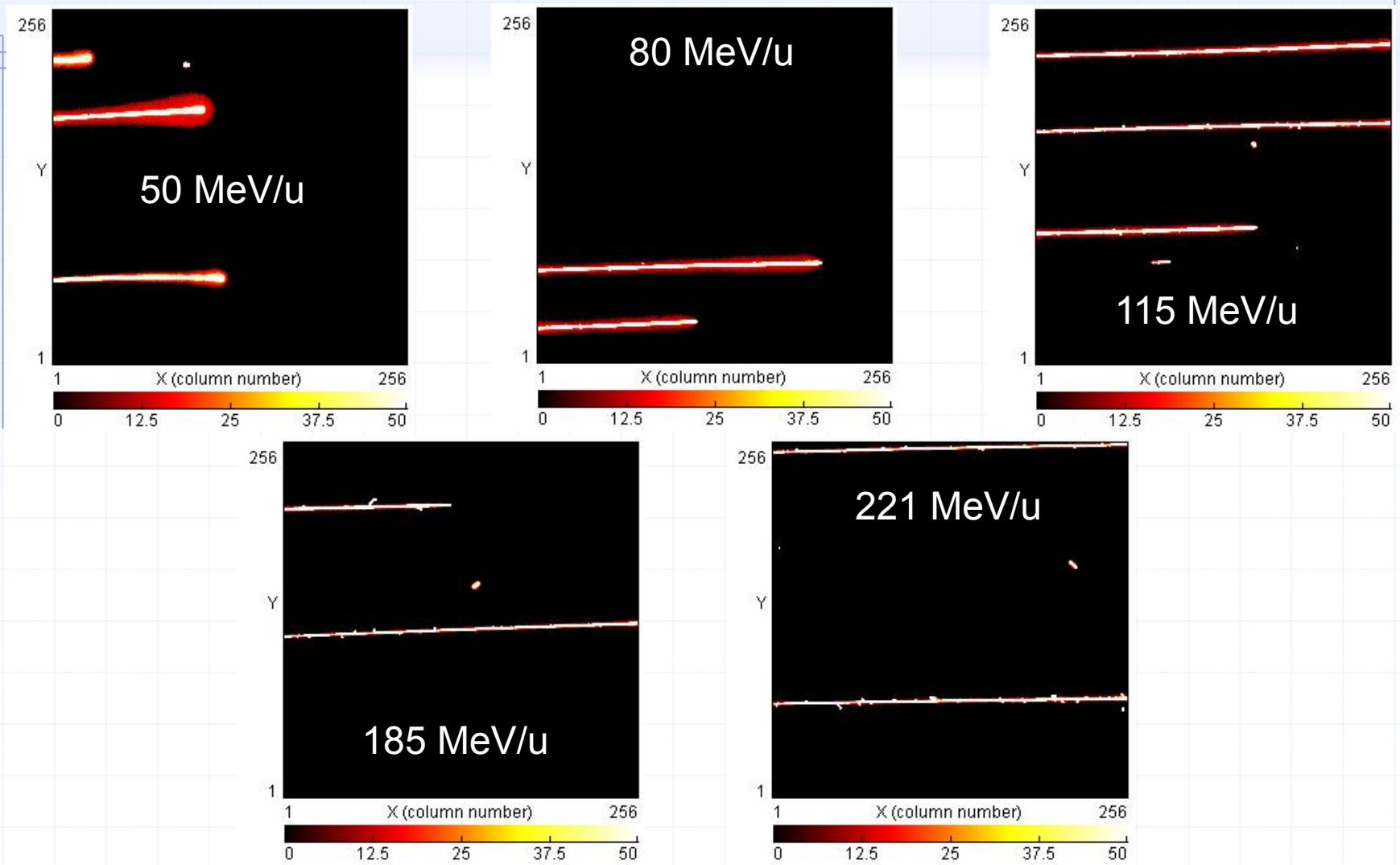
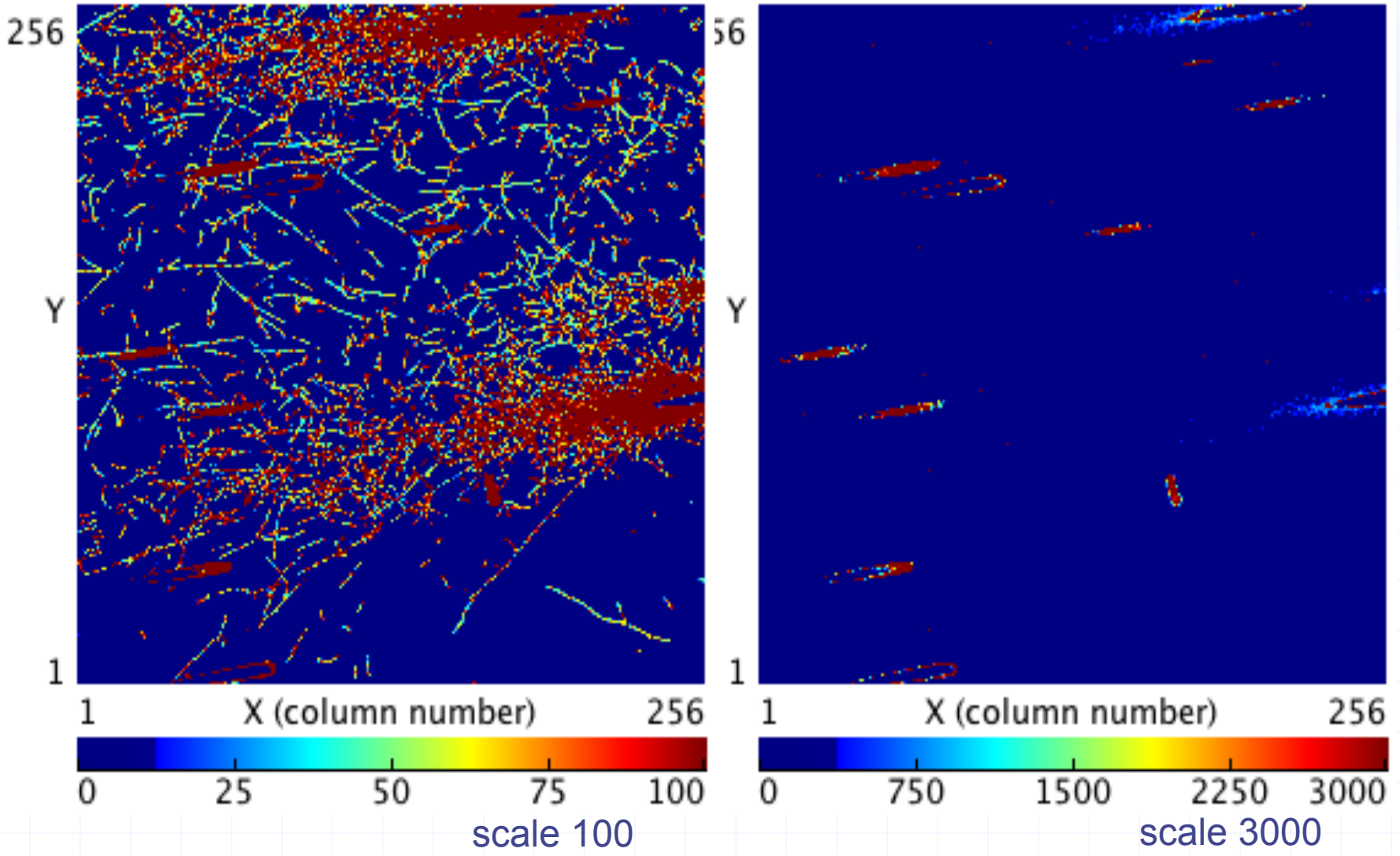


Tracks of Pb ions as measured on SPS beam at CERN (rear-side glancing angular incidence about 4.1 degree)



Imaged with low threshold on the left and with high threshold on the right

Online miniaturized Timepix Quantum Dosimeter

Single particle visualization & tracking

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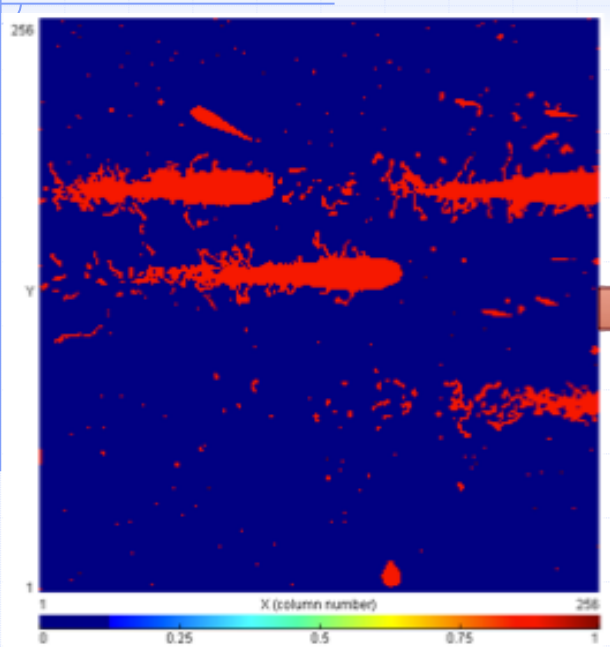
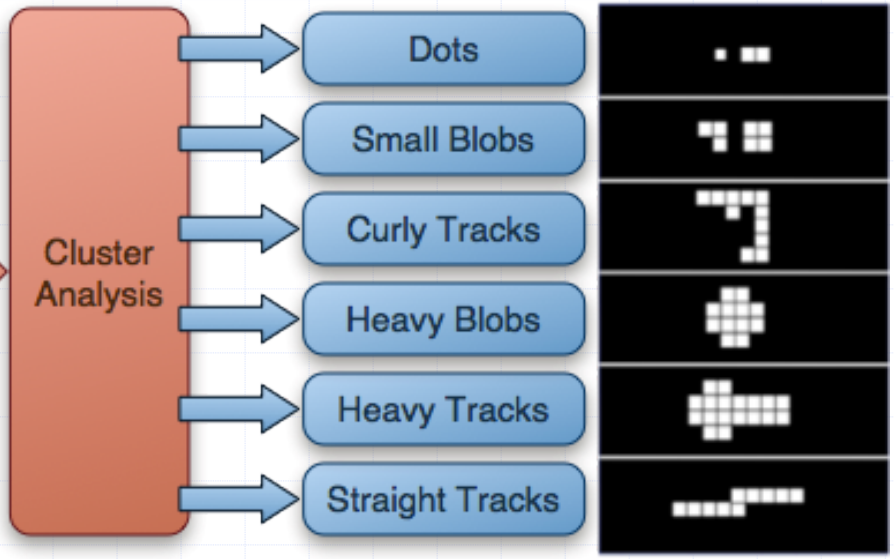
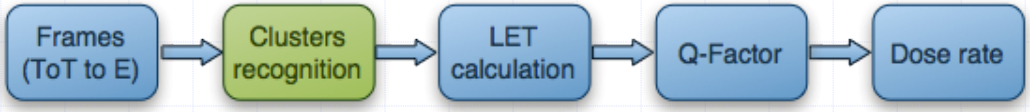


Frame containing 400 MeV 56Fe, 85°, measured at HIMAC, Japan



Cluster analysis algorithm is successfully working in ATLAS-MPX network



Fast neutron ToF measurement with TIMEPIX

LANSCE neutron sources and nuclear science flight paths

(combined ToA and ToT modes)

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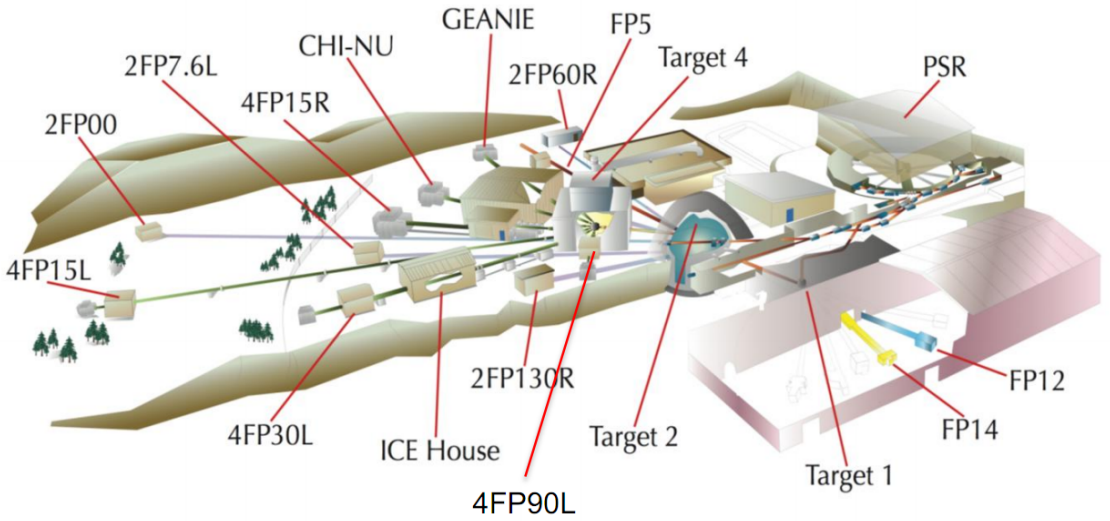
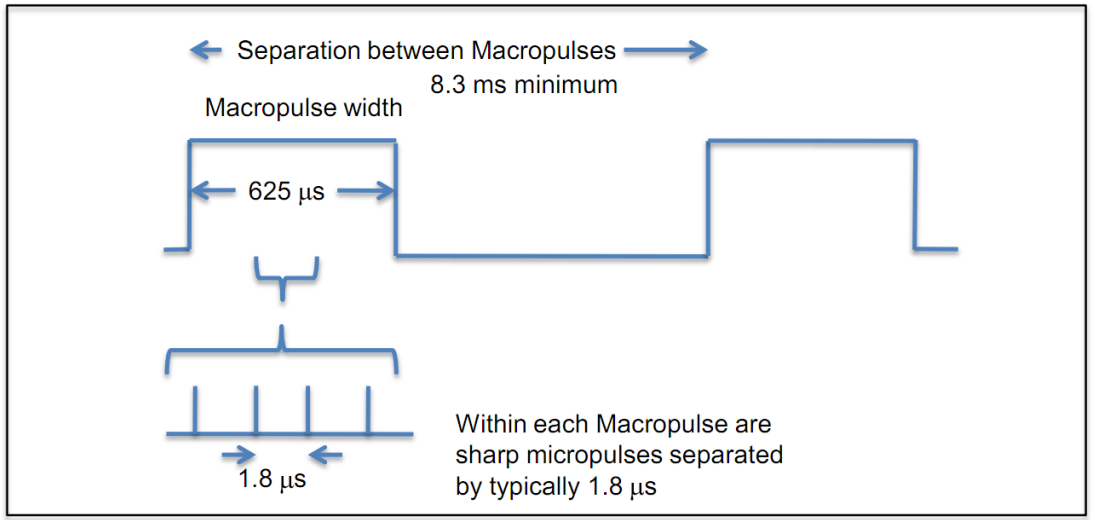
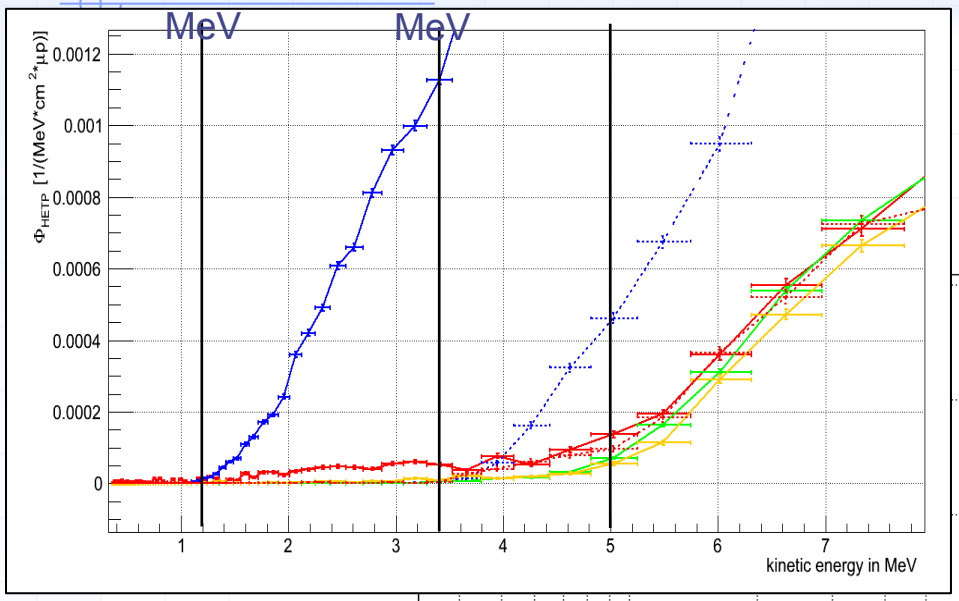
The layout of the LANSCE neutron sources and Nuclear Science flight paths



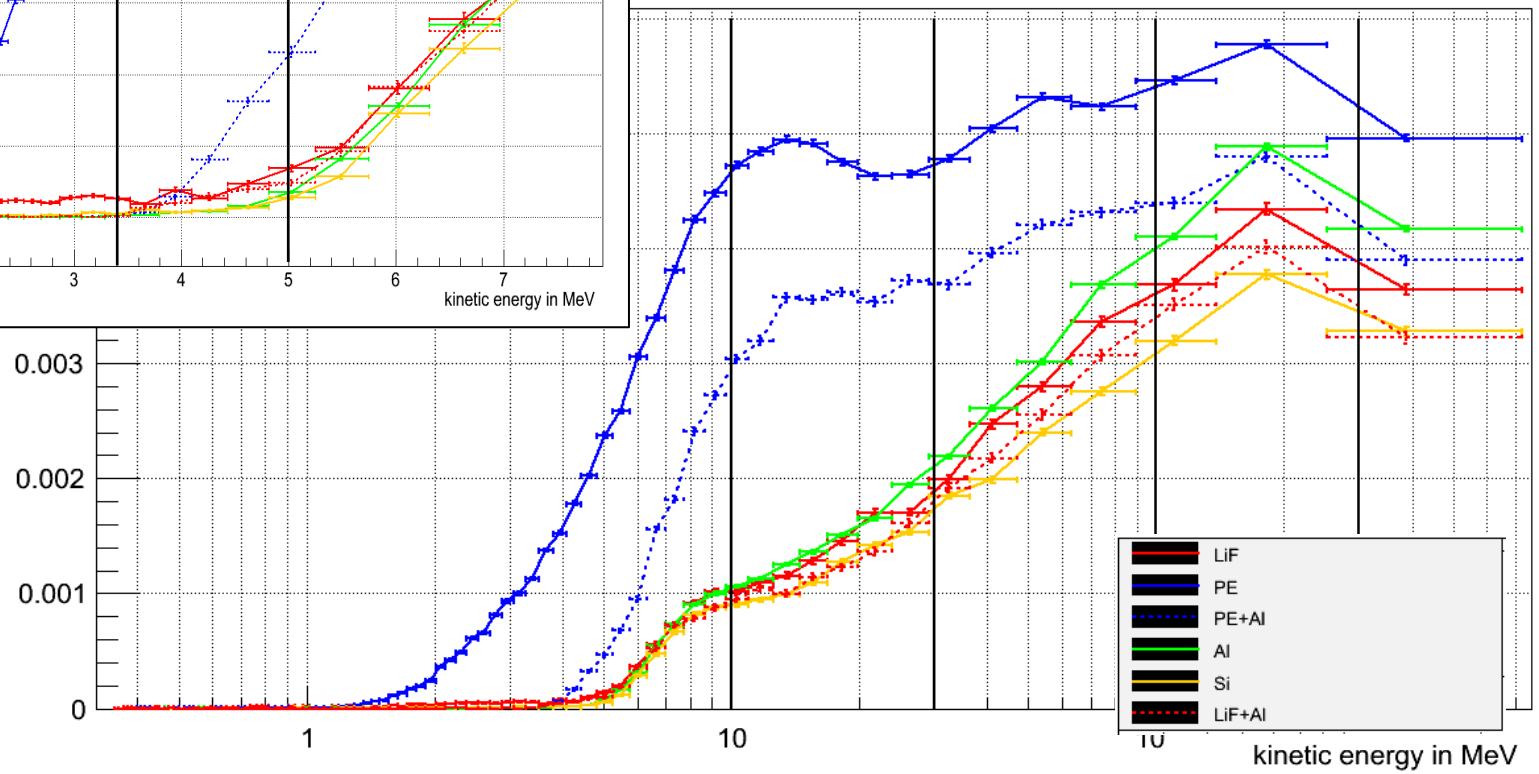


Fluences below different conversion layers



In the lower energy region responses below LiF, PE, PE+Al seem to be a good indicator for neutron energies

- Threshold for PE+Al at ~ 3.4 MeV
- Enhanced signal below LiF up to 4 MeV
- Recoiled protons visible above 1.2 MeV



Response of Timepix:
Energy region 0.4 – 1.2 MeV

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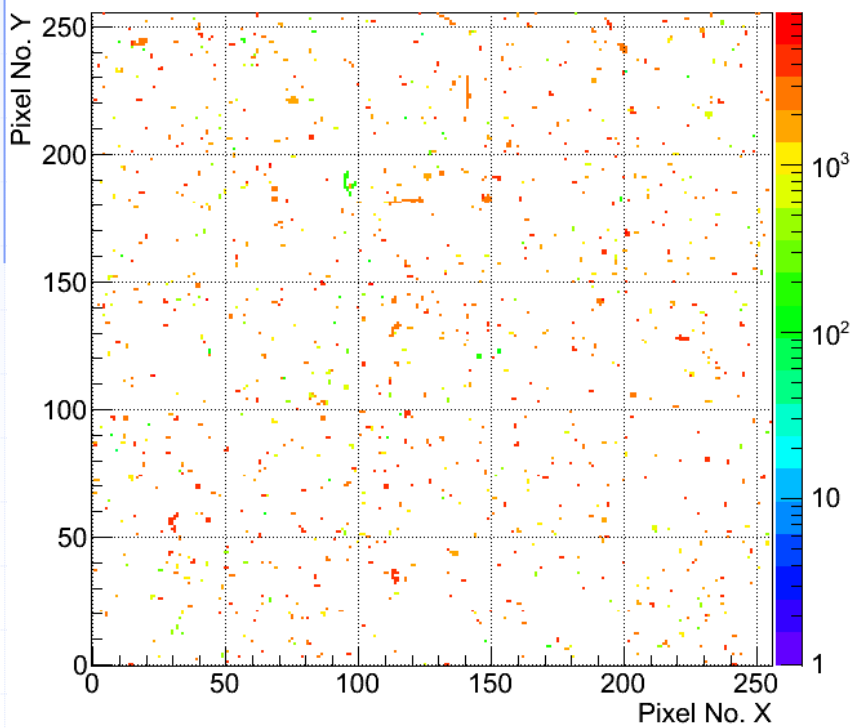
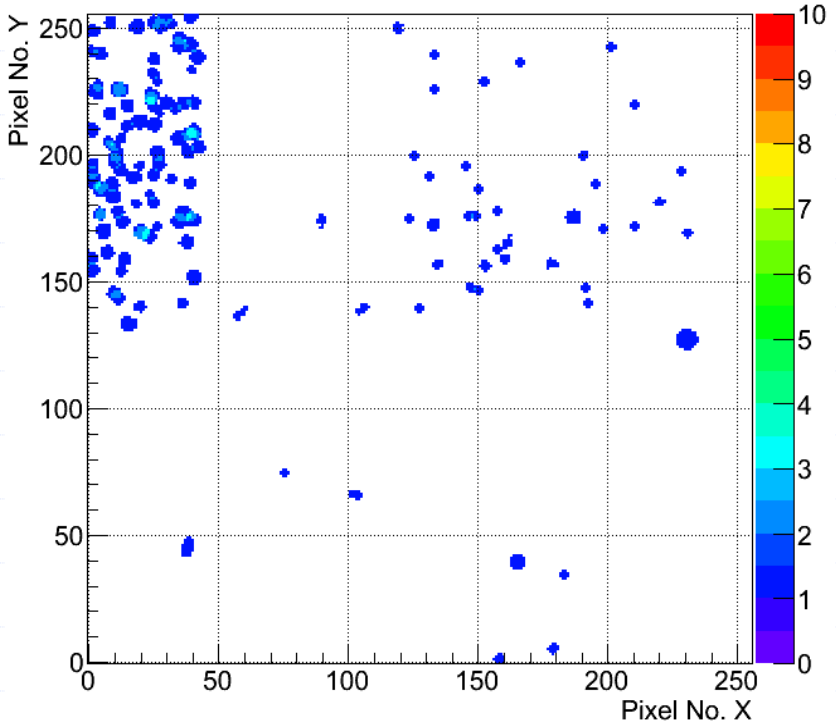
- Mainly dots, curly tracks are found in this energy region
- Heavy blobs below LiF indicate presence of slow/thermal neutrons
- Also PE region shows slightly enhanced count rate



All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (139 events were found)

Response of Timepix:
Energy region 1.2 – 3.4 MeV

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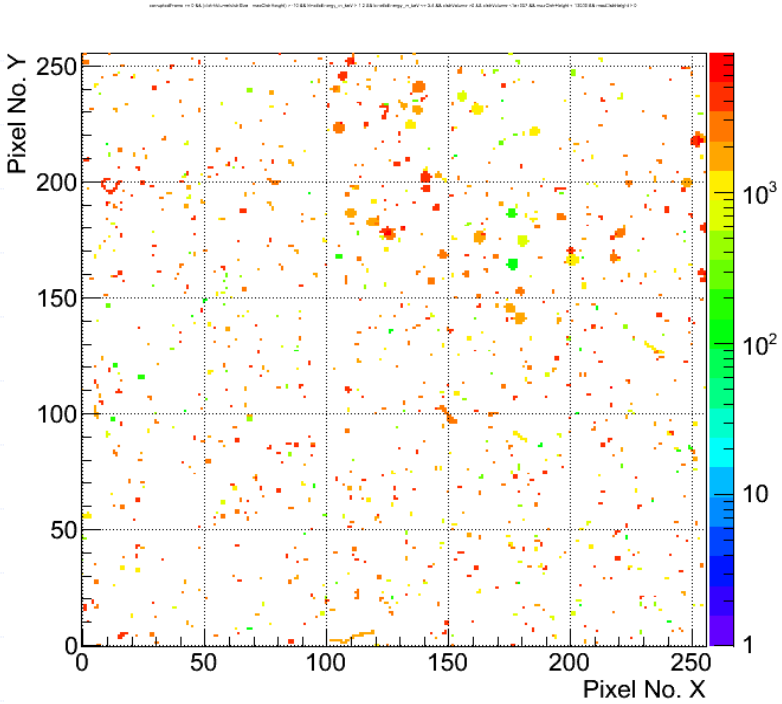
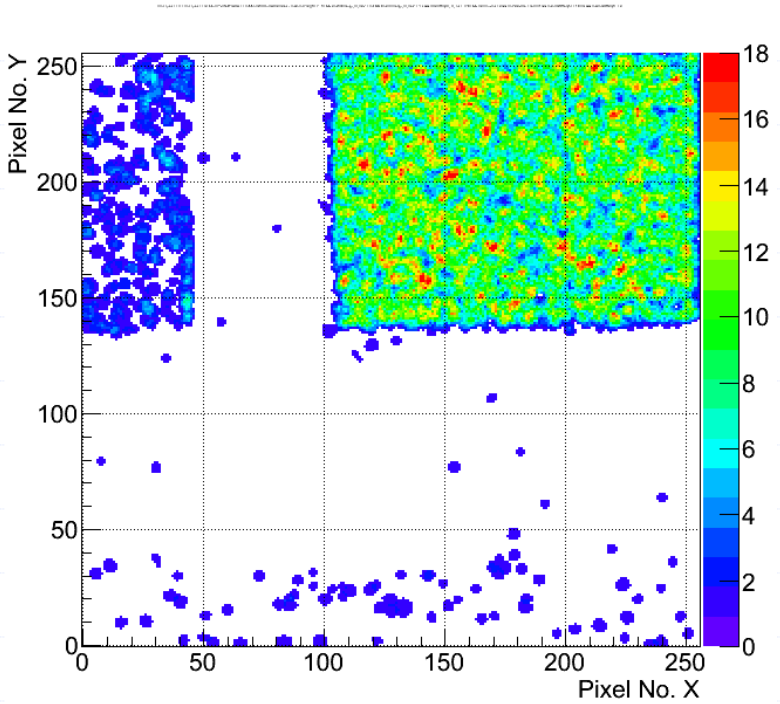
- Heavy blobs below LiF indicate presence of slow/thermal neutrons
- Clear signal of High Energy Transfer Particles (HETP) below PE
- uncovered area shows also a few events



All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (full statistics - 10259 events were found)

Response of Timepix:
Energy region 3.4 – 5.0 MeV

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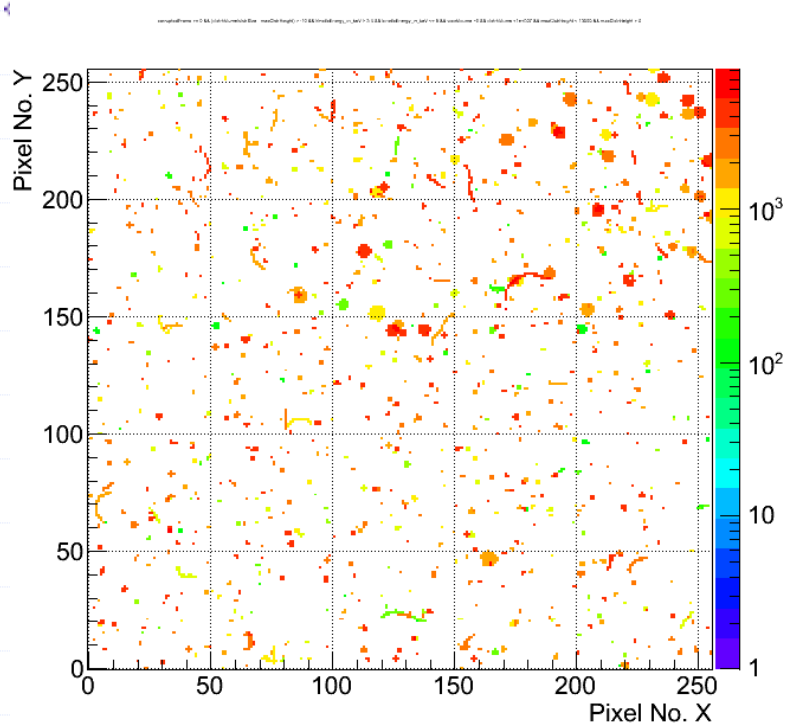
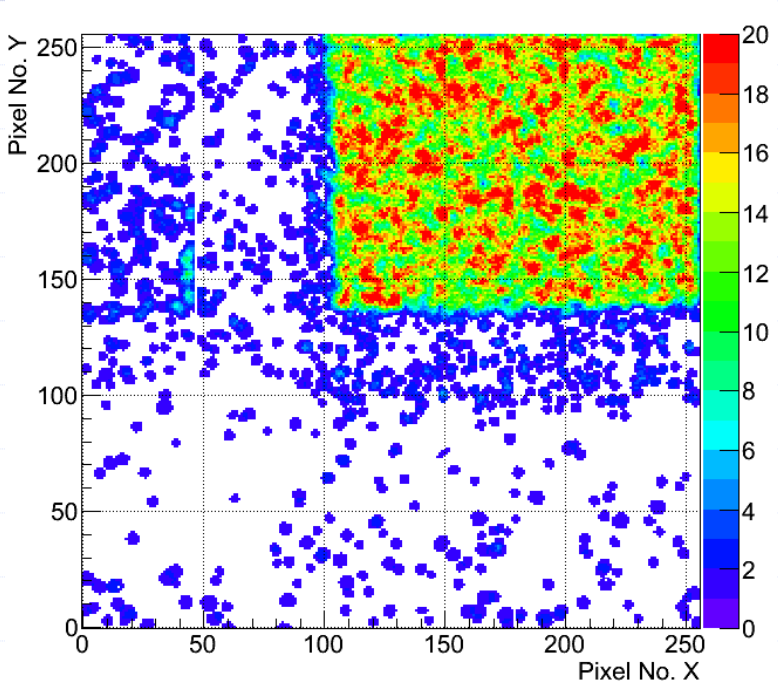
- Clear signal of HETP below PE
- Also in PE : Al region h



All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (full statistics – 13406 events were found)

Response of Timepix:
Energy region 100 – 300 MeV

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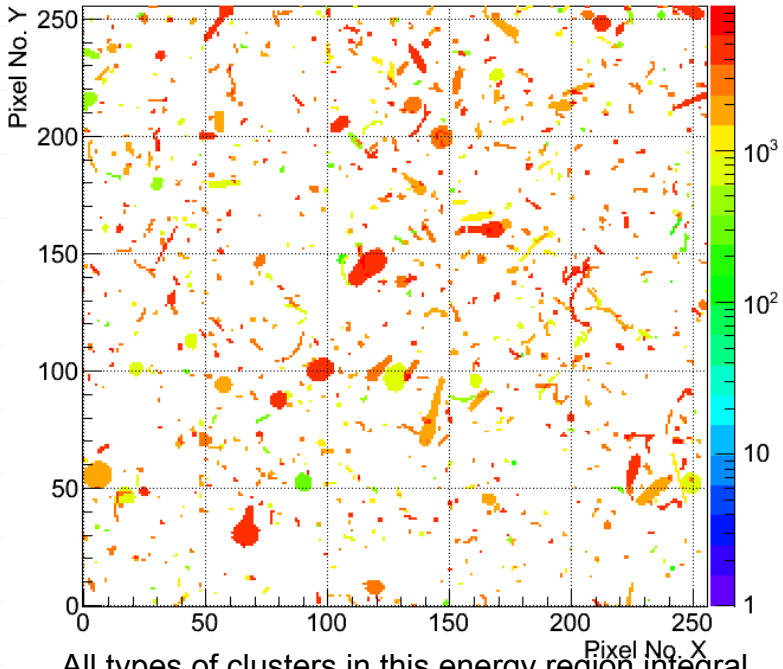
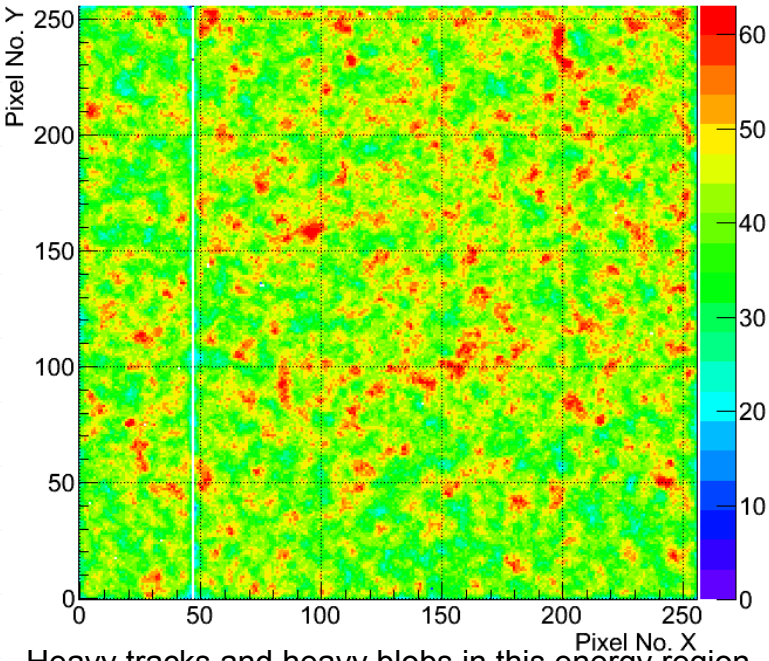
- HETP nearly equally distributed below all regions
- HETP Cluster shapes
  - Are getting bigger and more and more asymmetric
  - Round clusters with outgoing tracks are seen



All types of clusters in this energy region integral picture (1000 events were considered)



Heavy tracks and heavy blobs in this energy region (full statistics - 64755 events were found)

Examples of heavy ionizing events induced by neutrons of different energies selected according their cluster sizes

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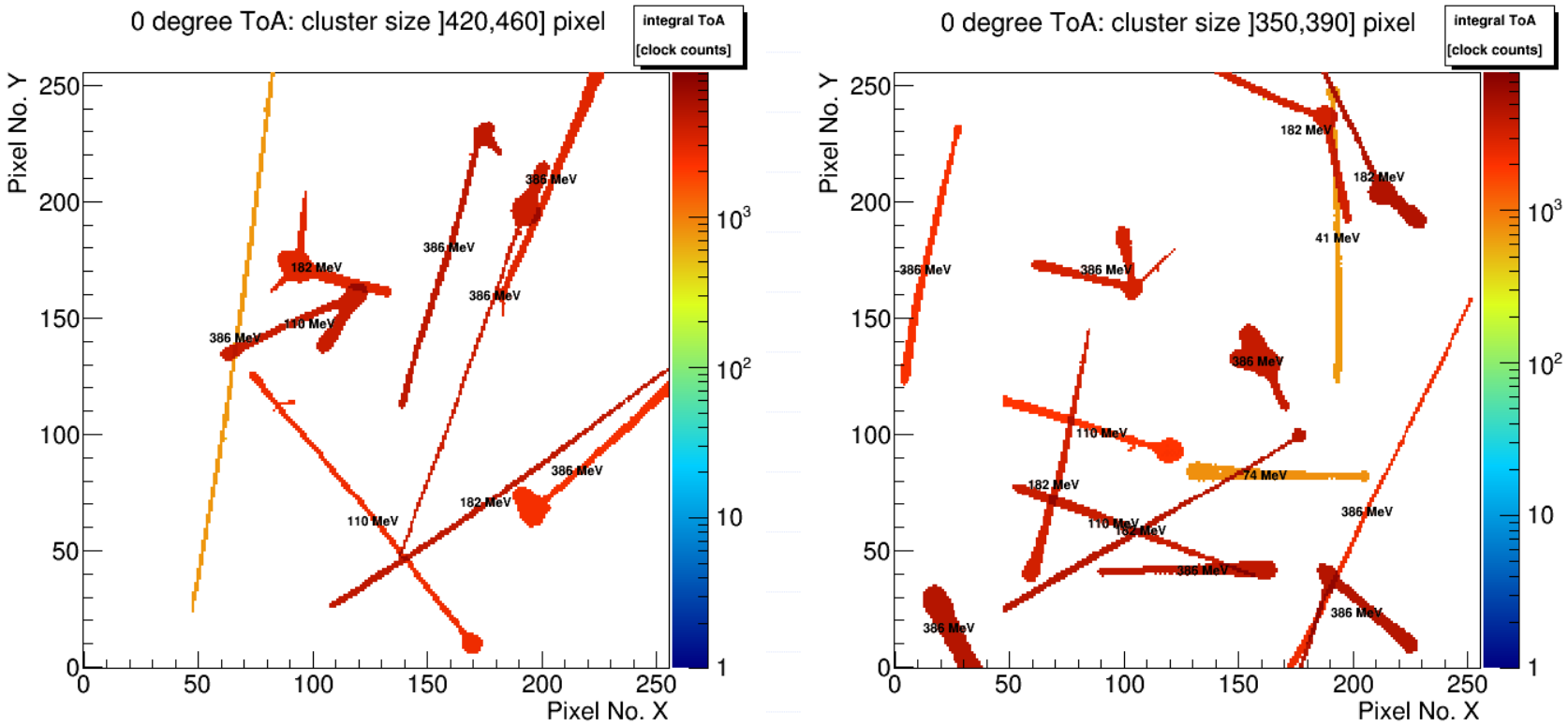

Different colors and black numbers assigned to individual clusters indicate the energy of incoming neutrons as measured by means of the TOF technique

Cluster shapes
Timepix detector responses as a function of neutron kinetic energy

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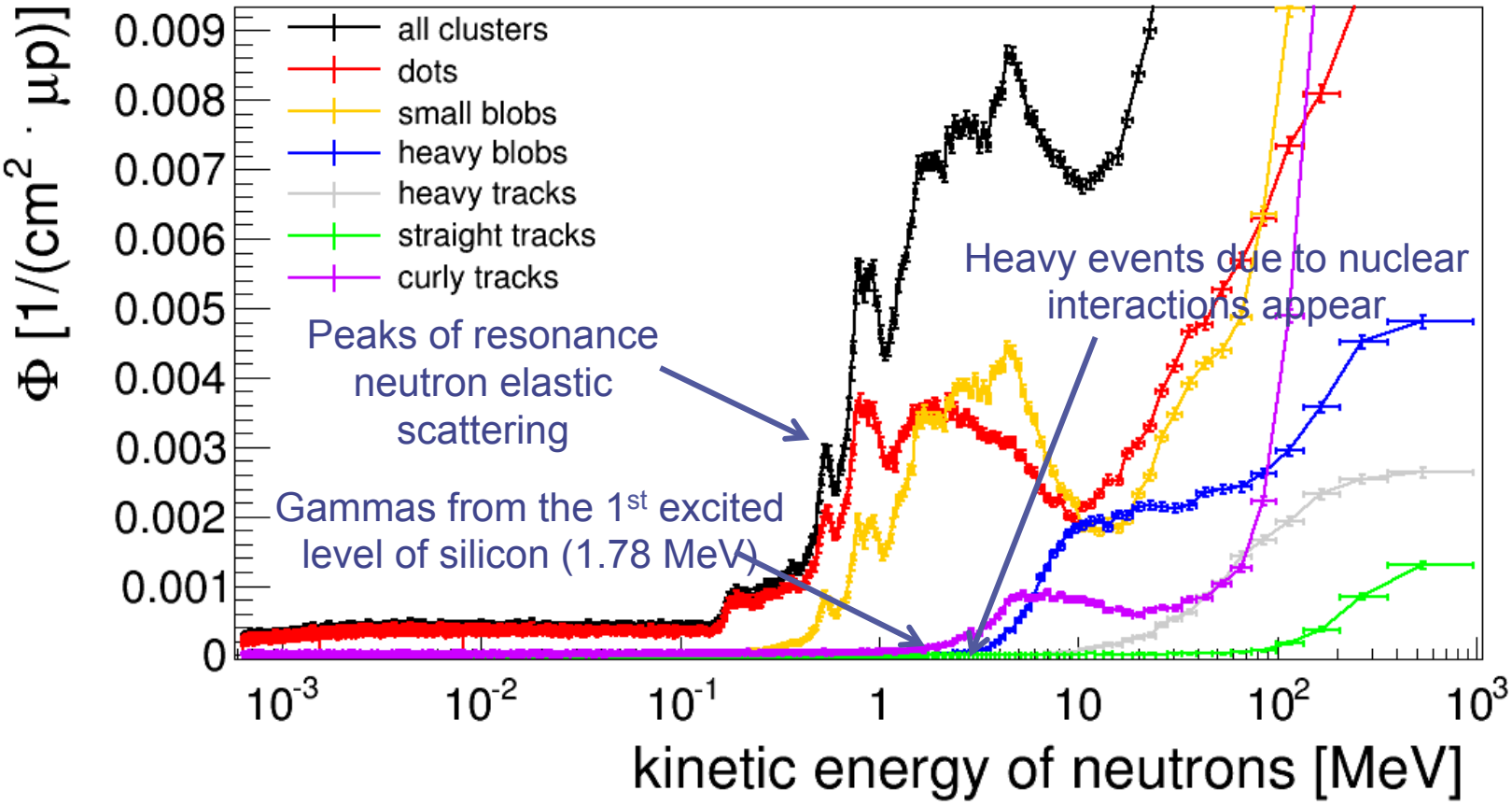
The ToF technique*) was used to assign the detector responses to the corresponding neutron energies (track by track).



*) see: B Bergmann *et al* 2014 *JINST* **9** C05048

Medical application:
Hadron therapy - Experimental setup

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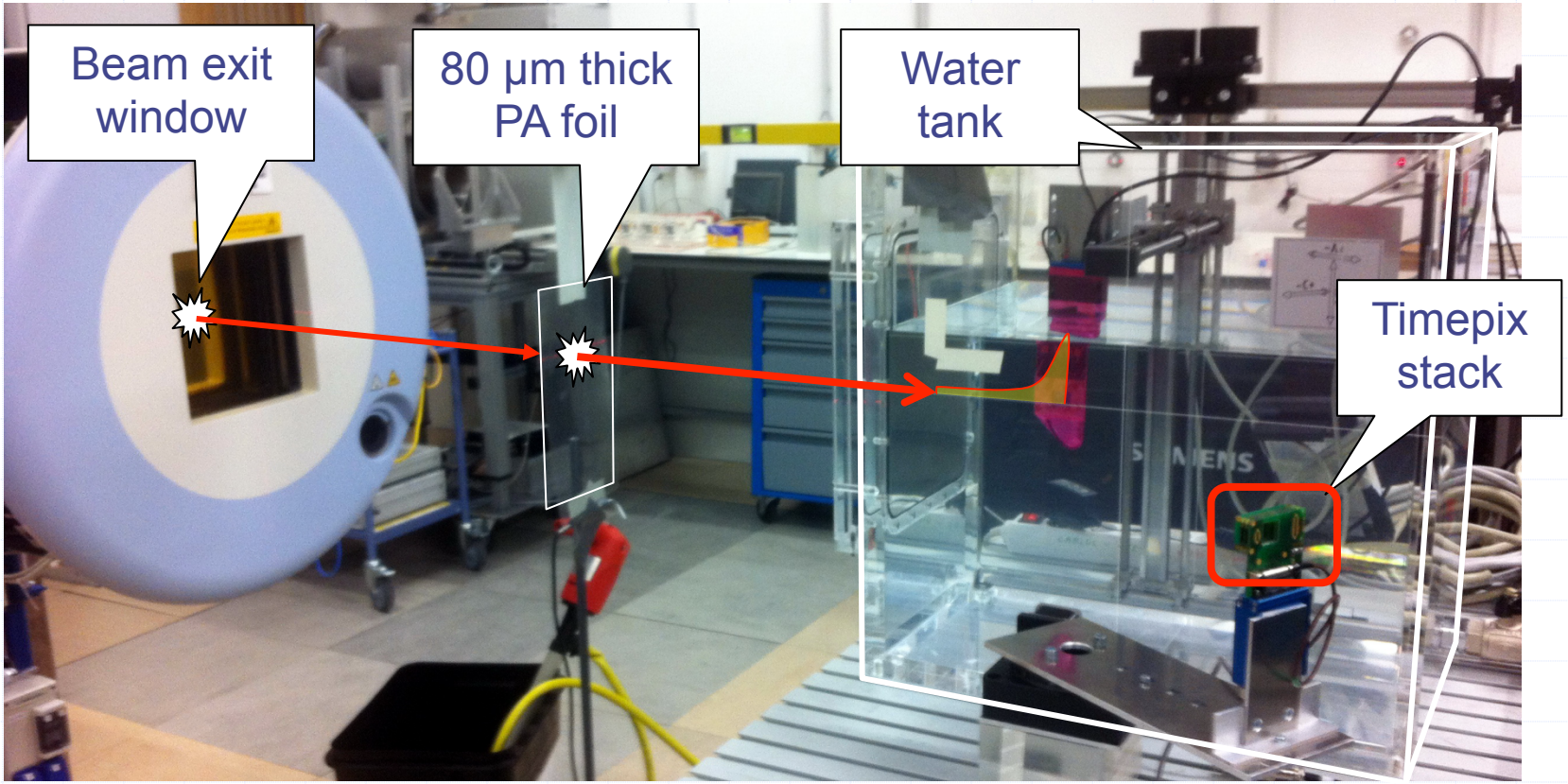
Czech Technical University in Prague



Visualization of secondary particles produced by the beam

in air
and in the phantom

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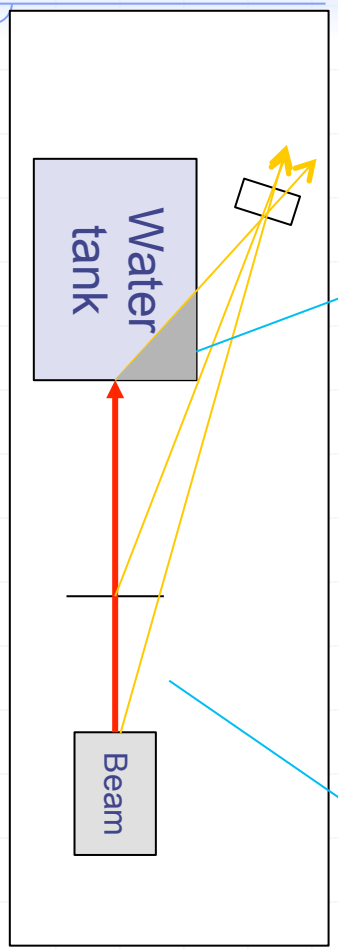
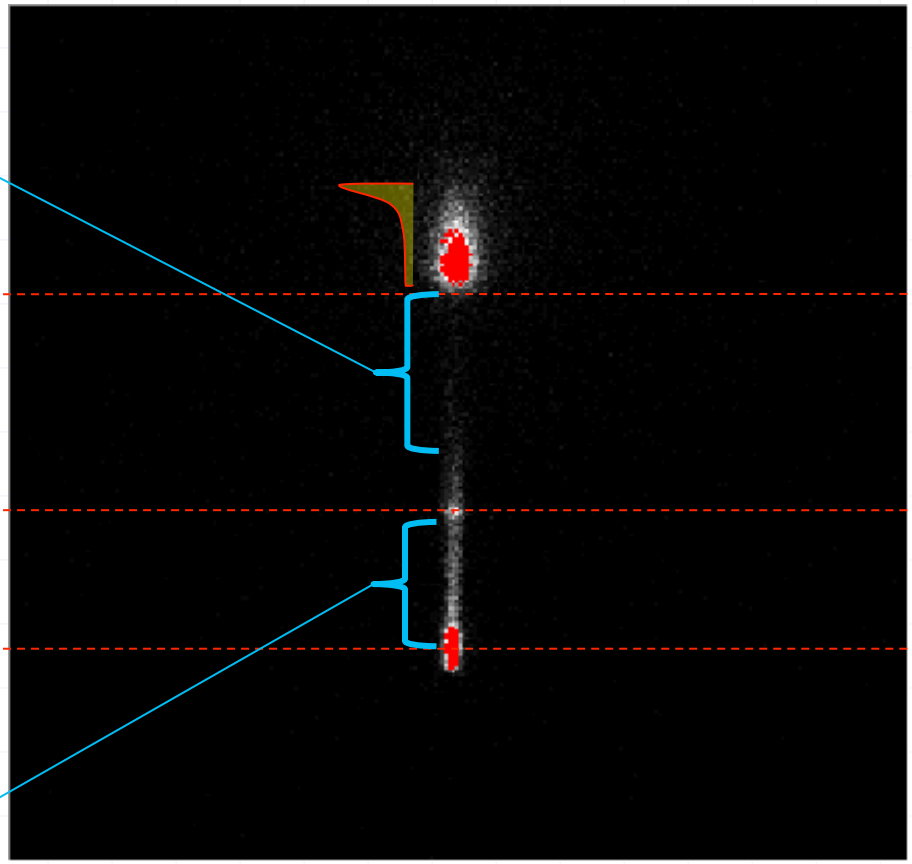


Reconstructed image (all coincident events)



Shielded by tank

Tank impact

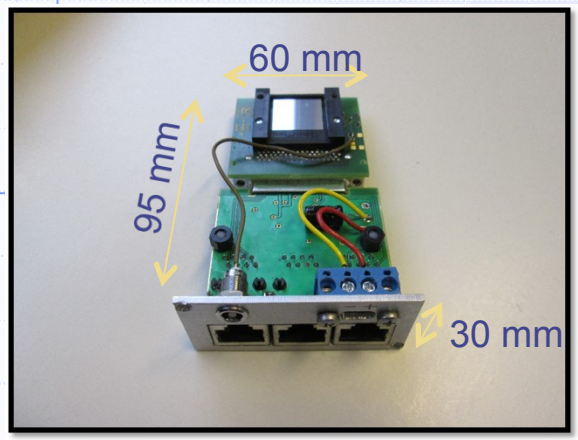
Foil

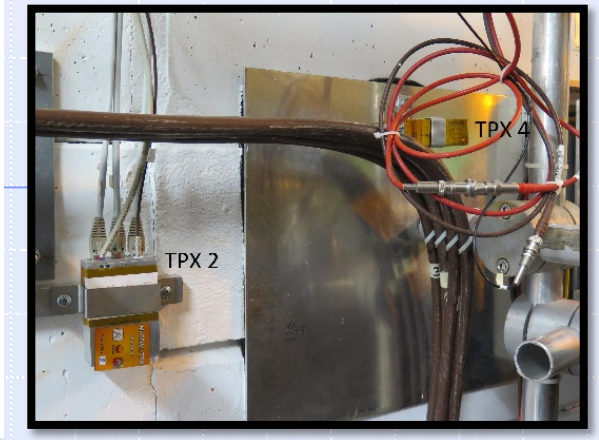
Exit Window

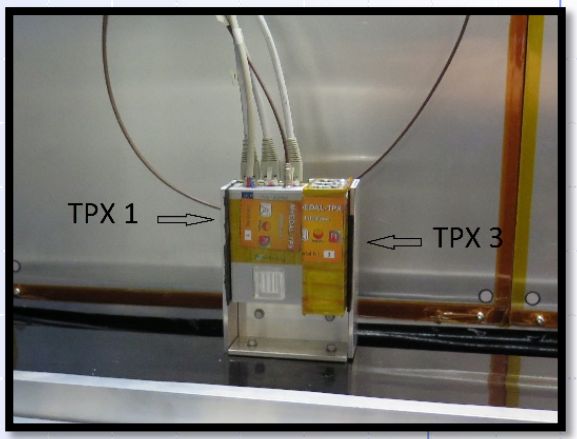
Interactions in air

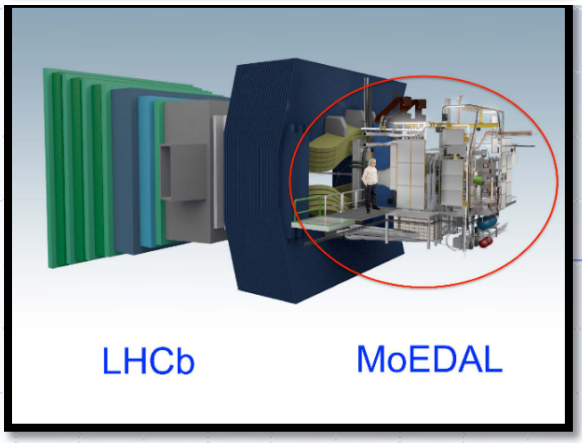
The TPX devices in the MoEDAL network

5 Timepix detectors of different thicknesses (300 μm and 1000 μm, 1 of them equipped with neutron converters) placed in chipboards with radiation tolerant electronics installed in the MoEDAL at LHC





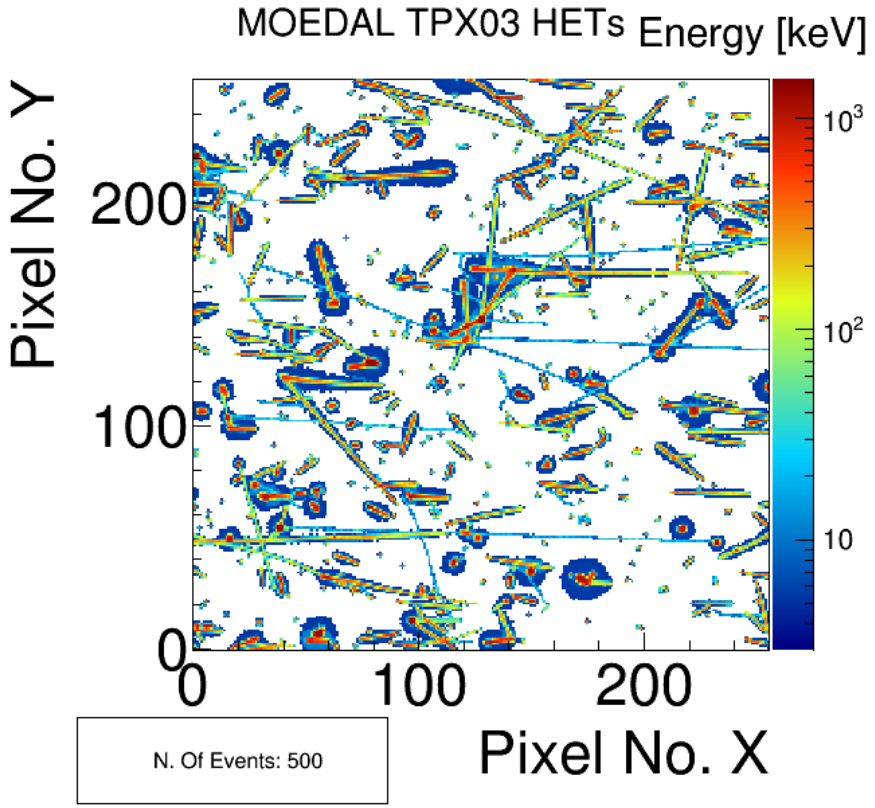




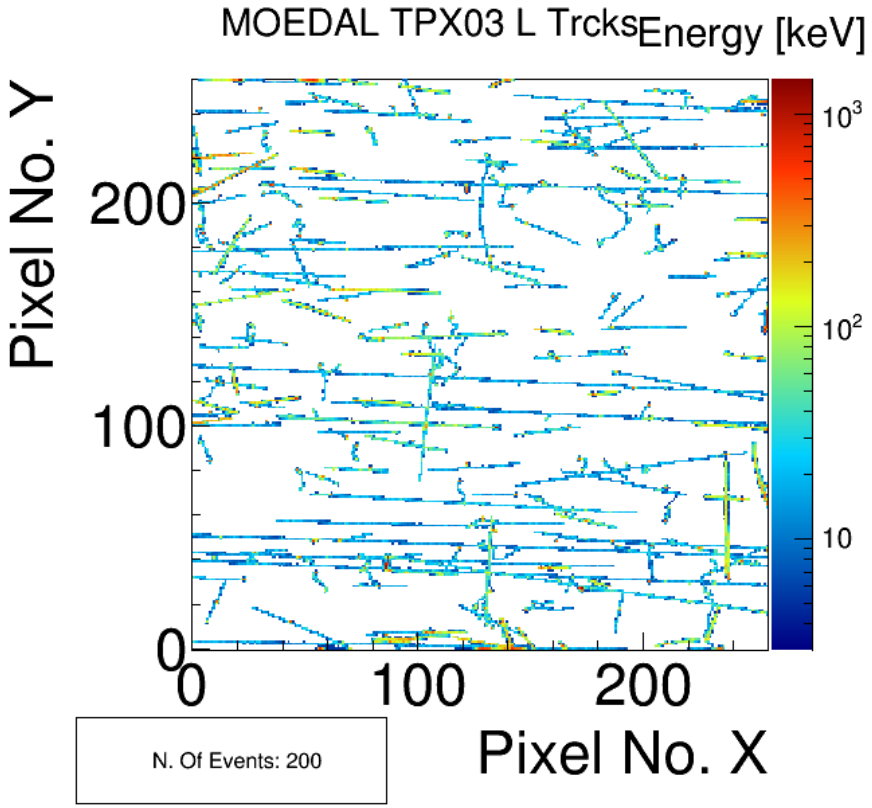
Timepix devices in the MoEDAL experiment

Selected tracks observed with MOEDAL TPX03
12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)

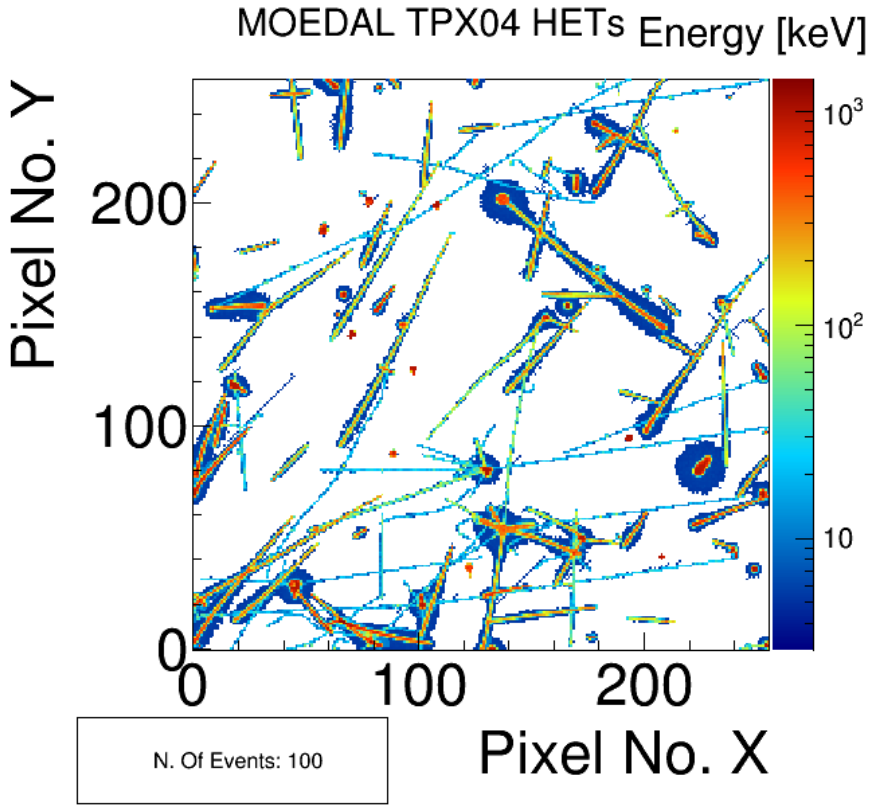


Long Tracks
(Min Clstr Height: 300 keV)

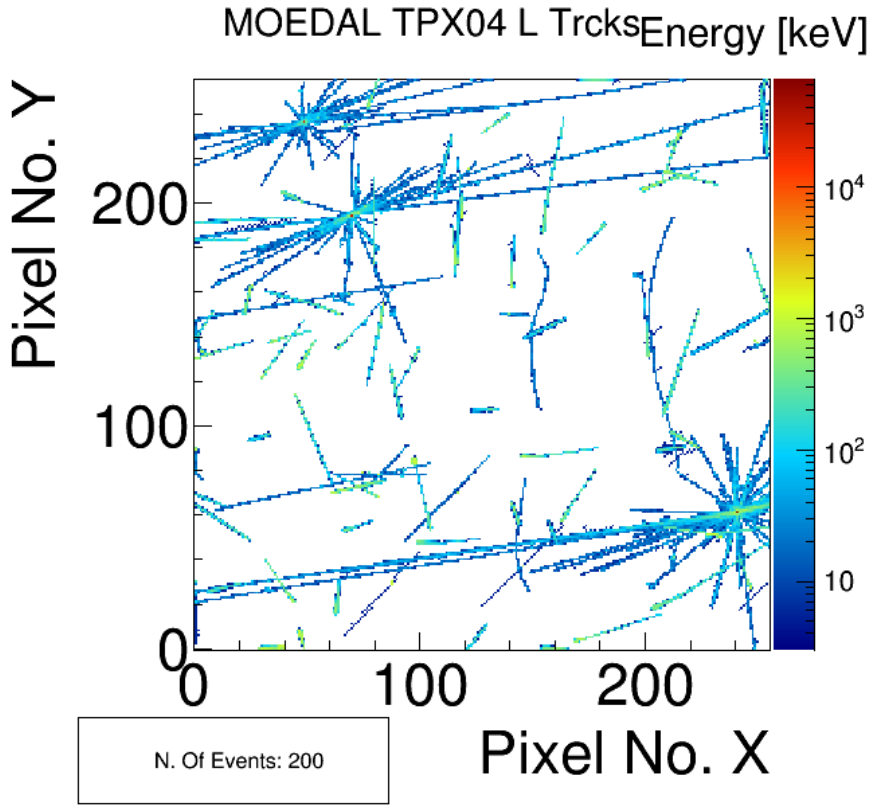


Selected tracks observed with MOEDAL TPX04
12/09/2015

High Energy Transfer Events
(Min Clstr Height: 300 keV)



Long Tracks
(Min Clstr Height: 300 keV)



Timepix3 in ATLAS

synchronized with LHC clock

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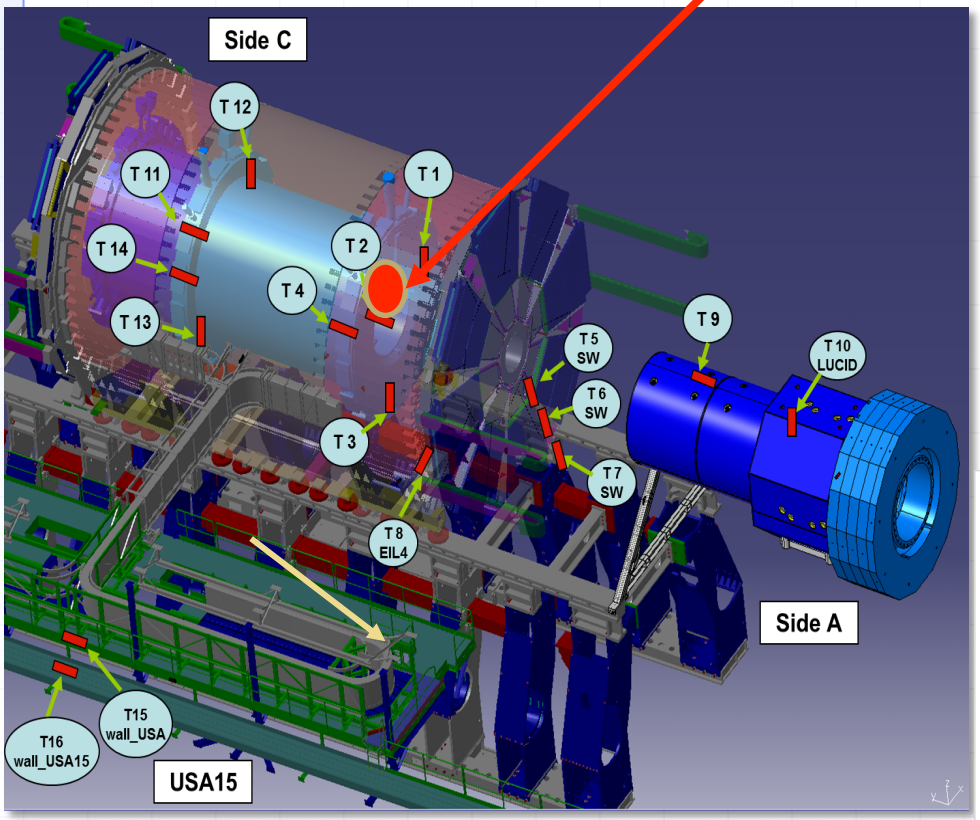
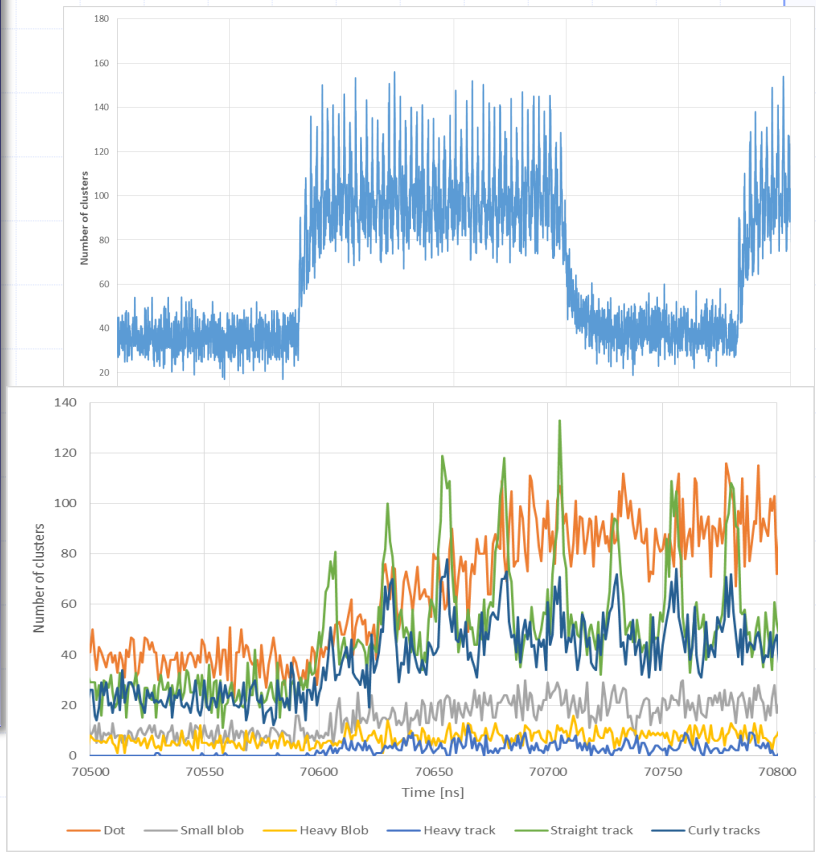
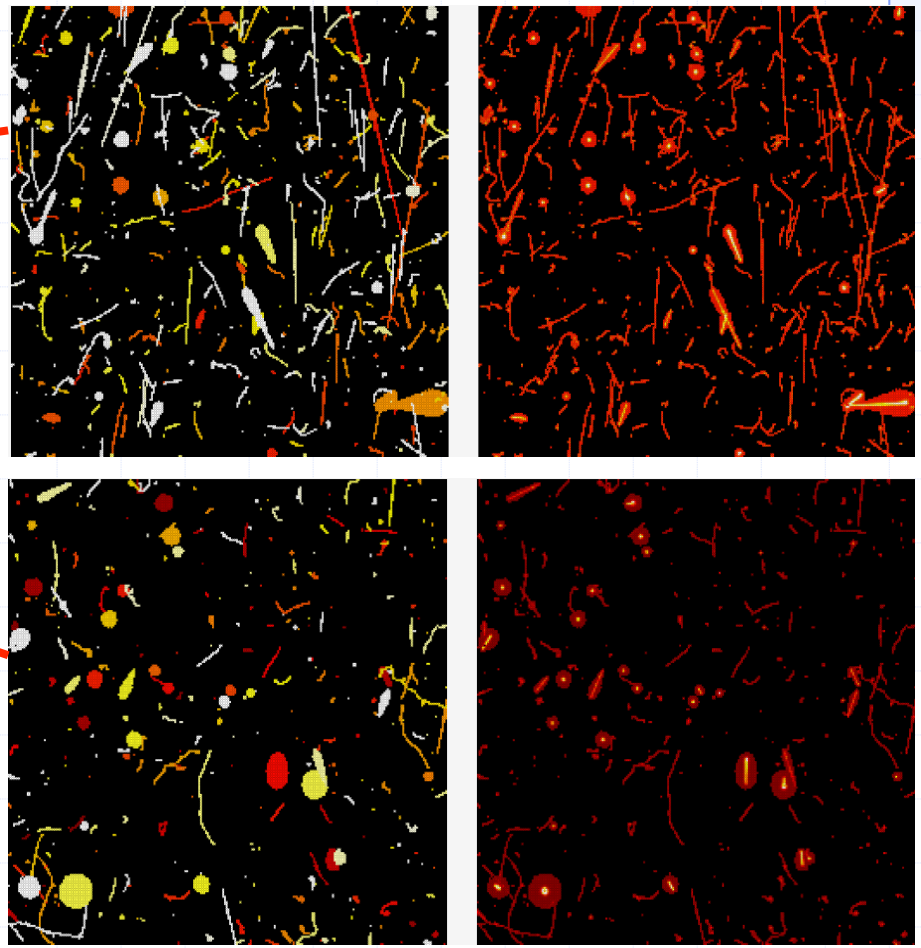


Detail view on bunch-bunch collisions recorded by TPX3



Clusters corresponding to particles generated in the LHC bunch-bunch collisions and recorded according their ToF



3D-visualisation of particle tracks in CZT detector measured at SPS

(z-coordinate determined from the drift time of charge carriers)

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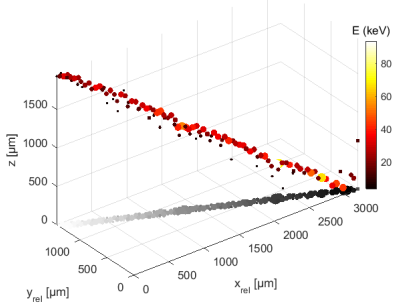
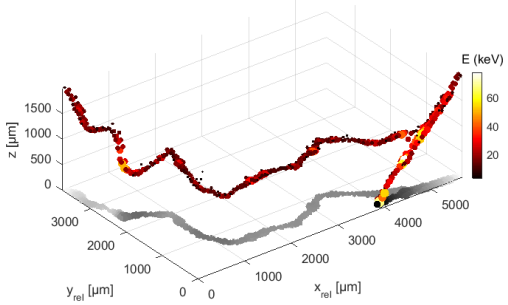
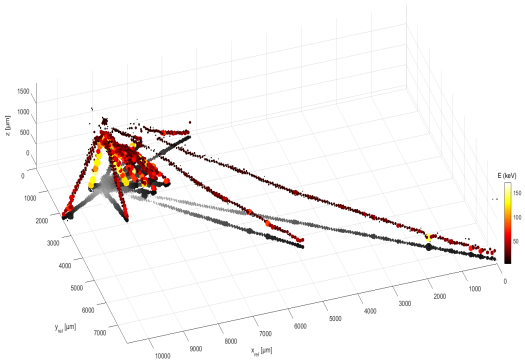
Muon



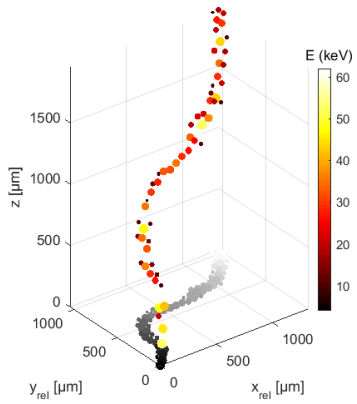
Pion + delta electron



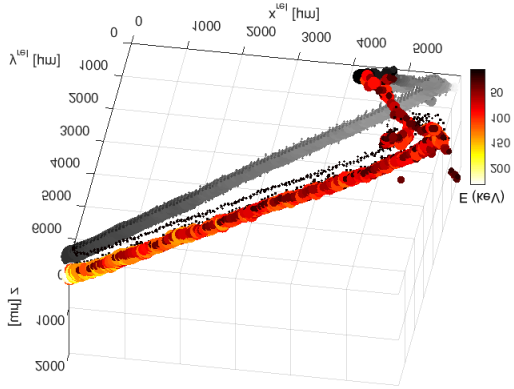
Fragmentation



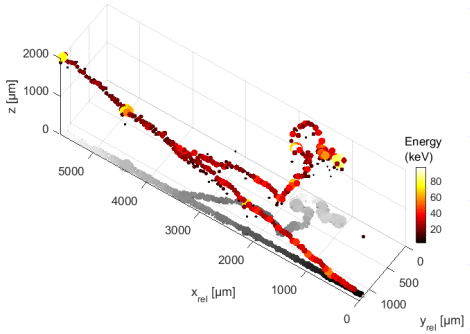
Electron



Heavy track



Pion + delta electron



Space applications

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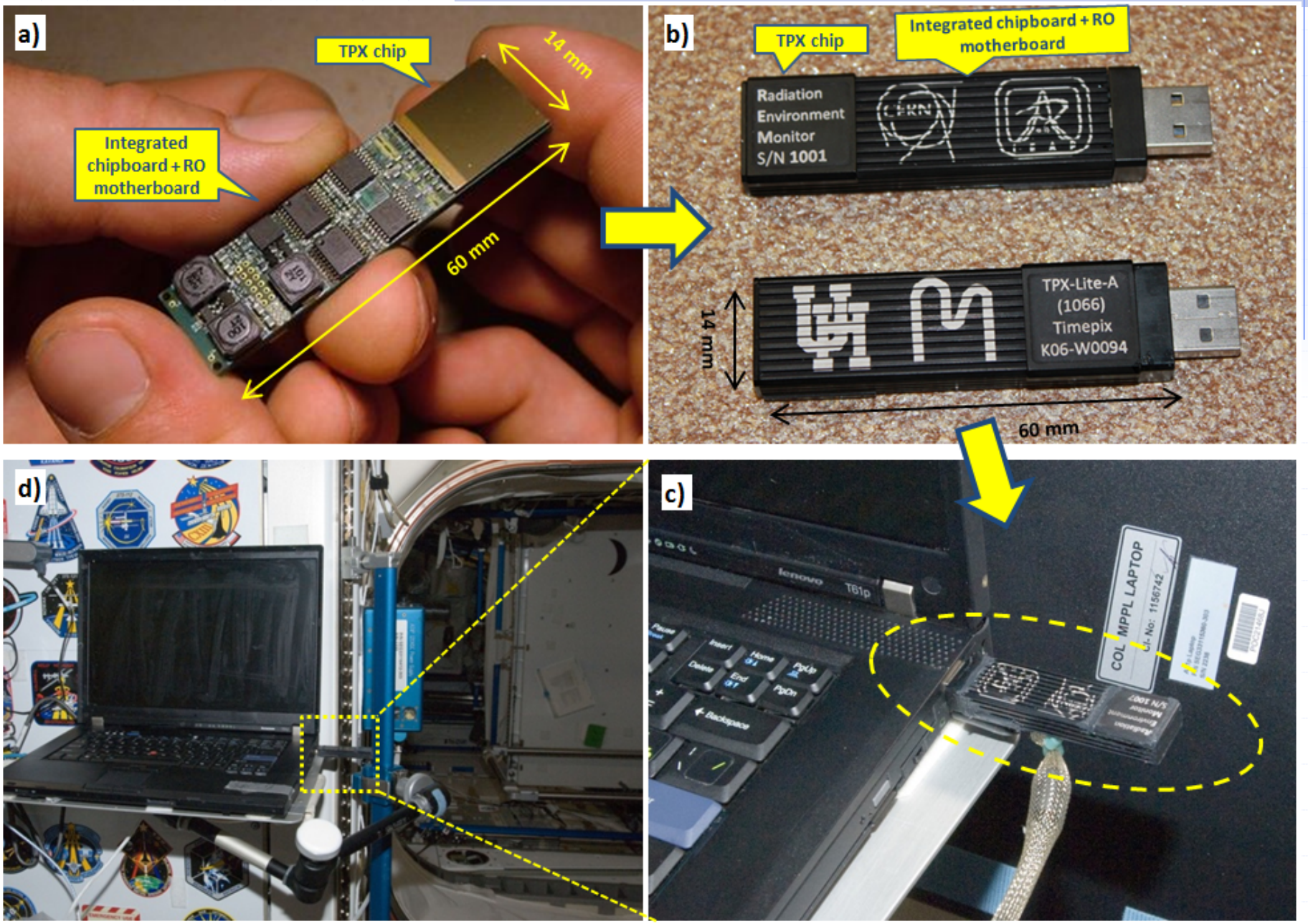

Timepix detector in the highly miniaturized LITE architecture (a) customized for the ISS (b) as deployed with an on-board laptop via USB port (c) in a NASA Module at the ISS (d). Work done in cooperation with NASA and the University of Houston.

The IEAP CTU Timepix based device used by NASA astronauts on ISS (courtesy of L.Pinsky, UoH)

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Dosimetry in space on ISS

- Timepix for the first time in the space on the altitude ~400km
- 5 detectors deployed on ISS fromOctober 2012

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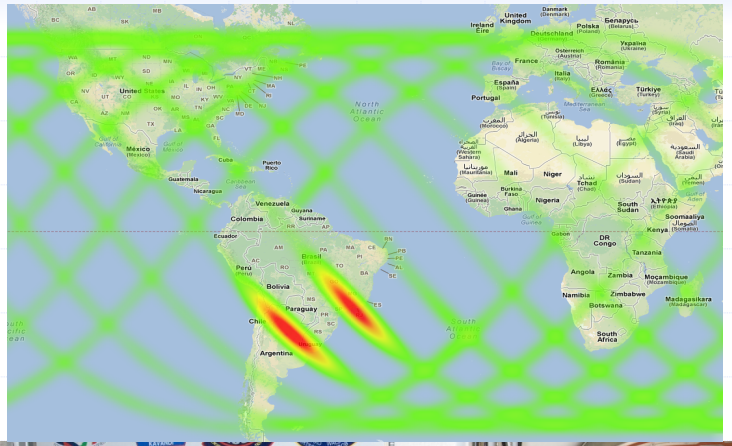

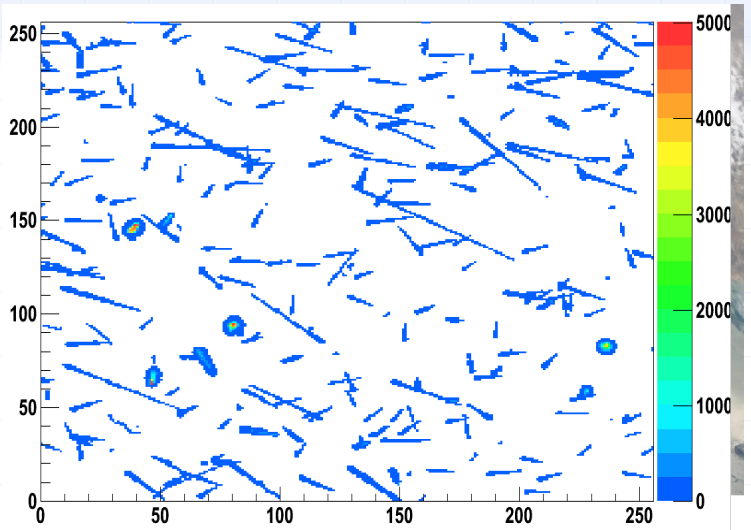

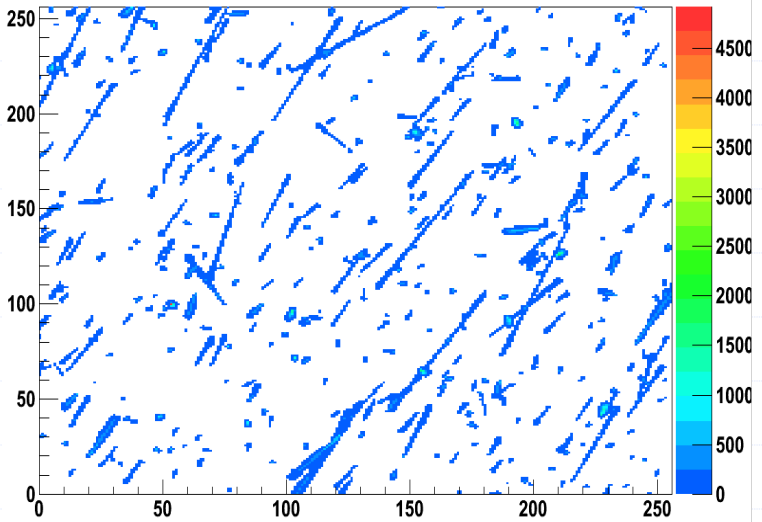

Dosimetry in space: SATRAM – ESA Proba-V satellite

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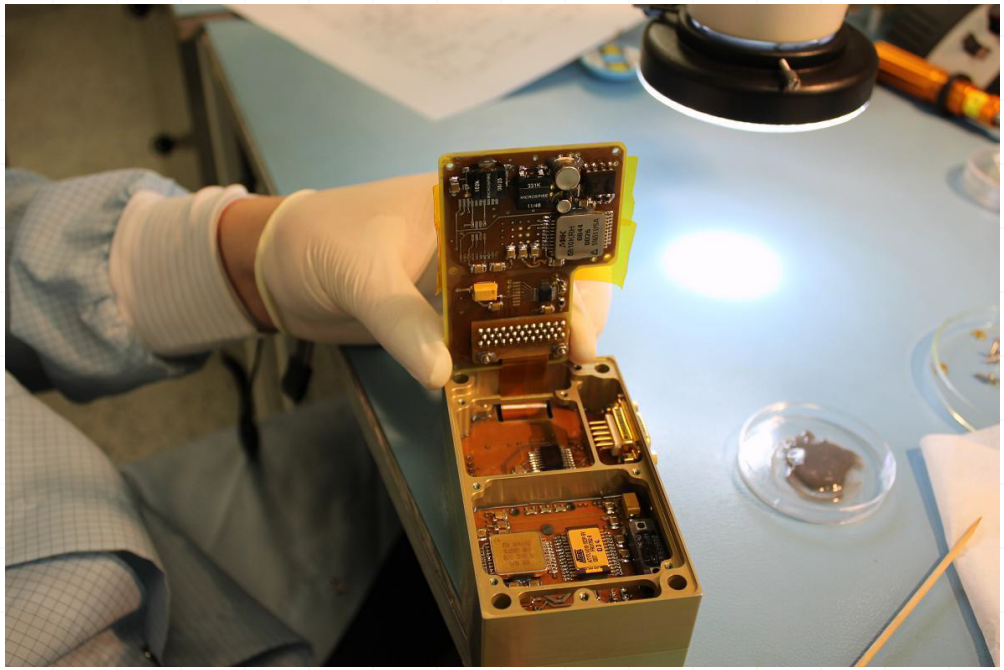
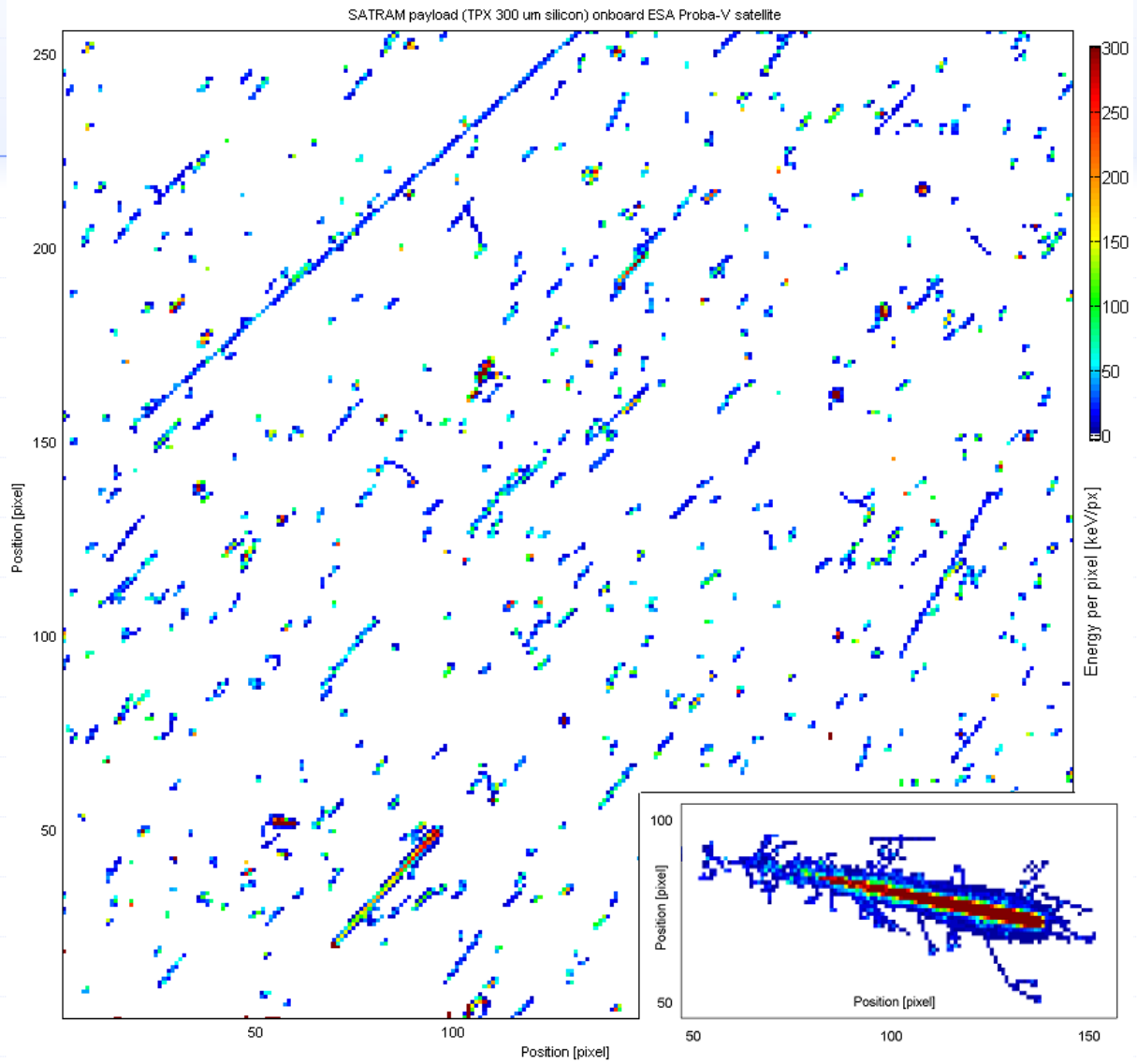
Characterization of mixed radiation field on low orbit of PROBA-V satellite

- Altitude ~ 800 km
- Timepix for the first time outside in the space
- Launched in May 2013



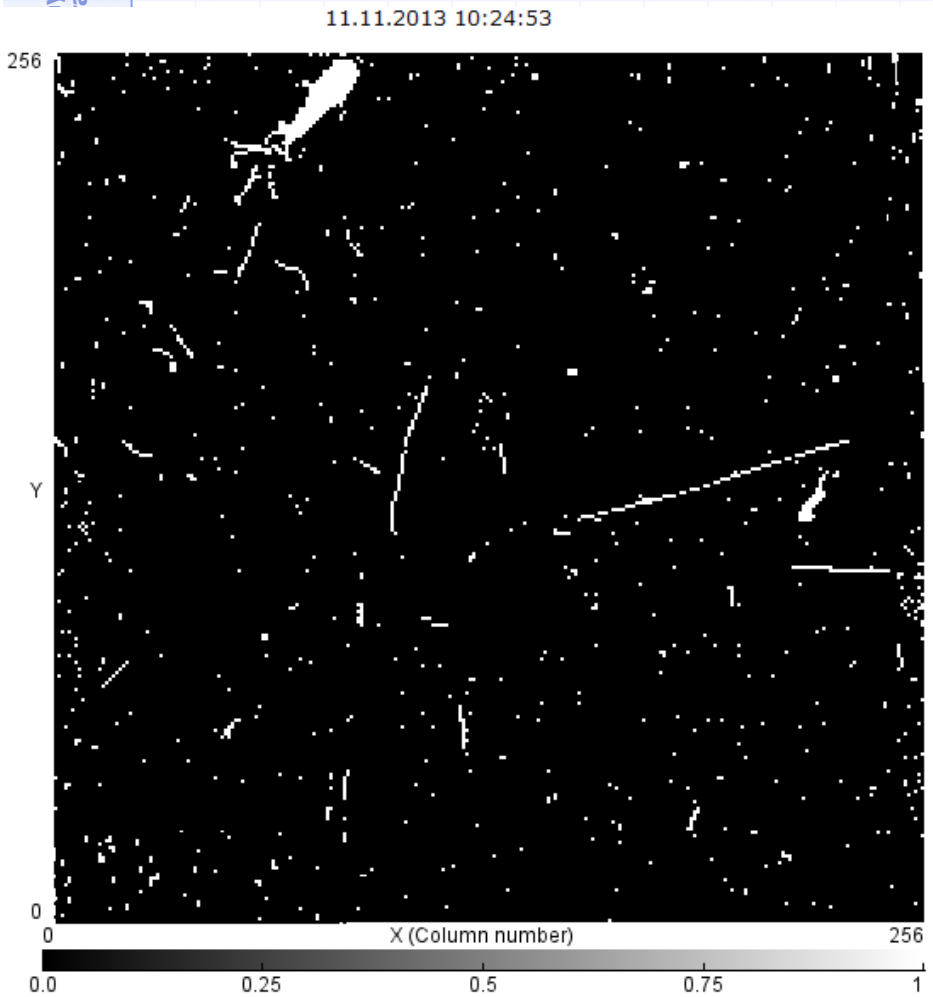
proba VEGETATION

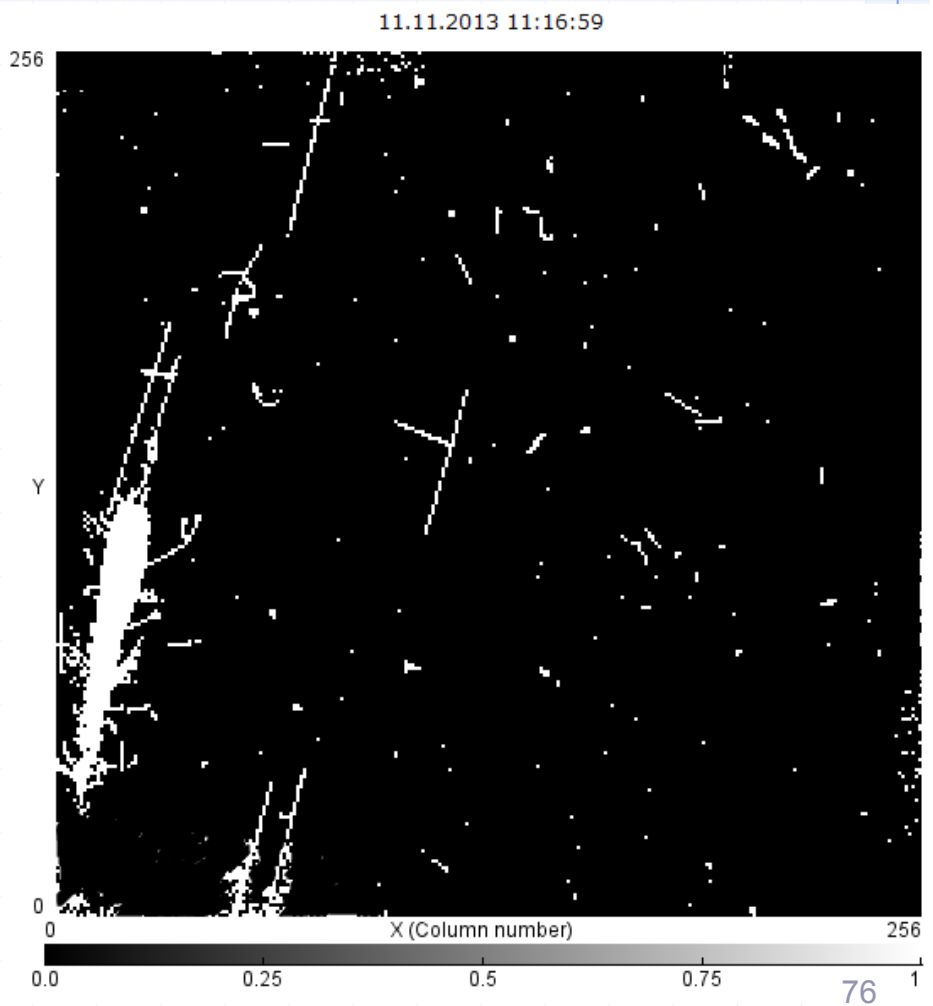
- SATRAM payload (arrow) onboard ESA Proba-V satellite.
- ESA Vega-2 launcher rocket upper stage


SATRAM payload (TPX 300 um silicon) onboard ESA Proba-V satellite
Position [pixel]
Position [pixel]
Energy per pixel [keV/px]
Position [pixel]
Position [pixel]

Timepix/ESA Proba-V: LEO space radiation @ 820 km

Energetic heavy charged particles (ions)





Timepix/ESA Proba-V:

LEO space radiation @ 820 km

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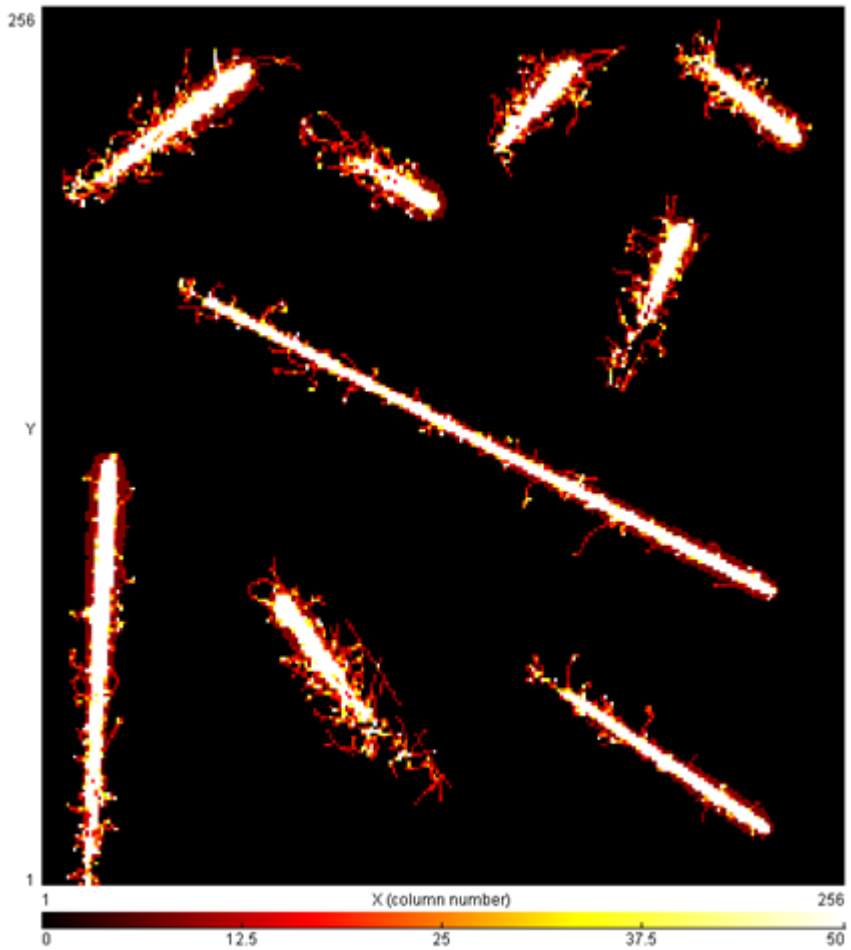
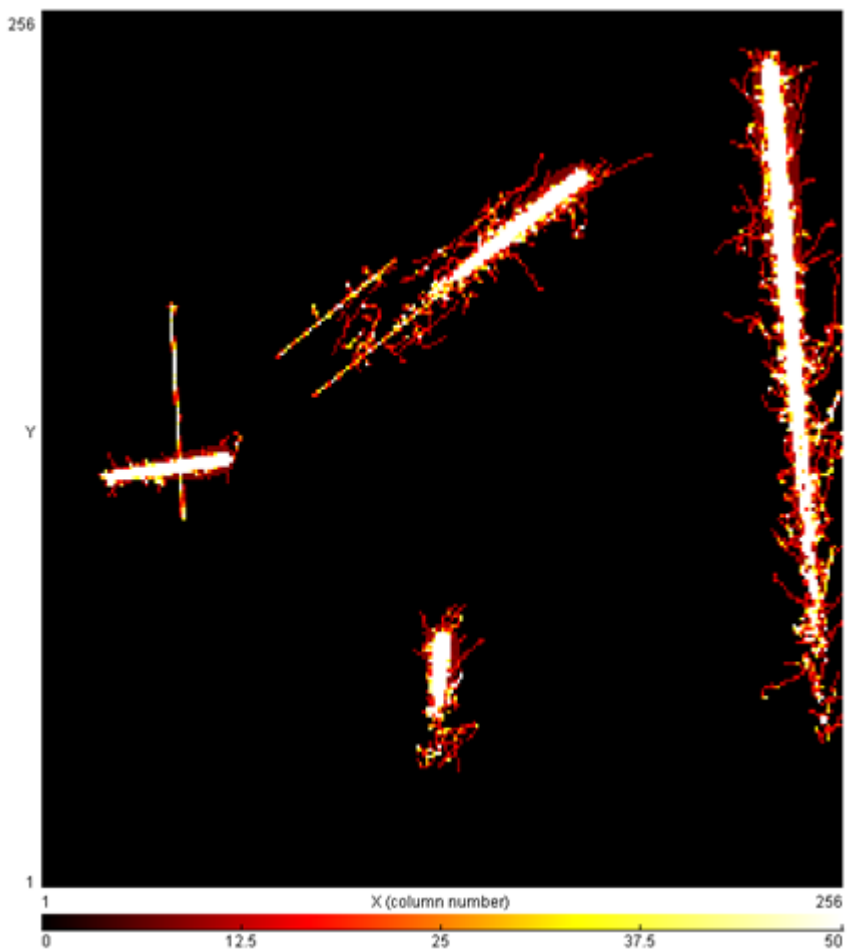
Czech Technical University in Prague

HETPs: Highly energetic heavy charged particles (ions) → HZE's

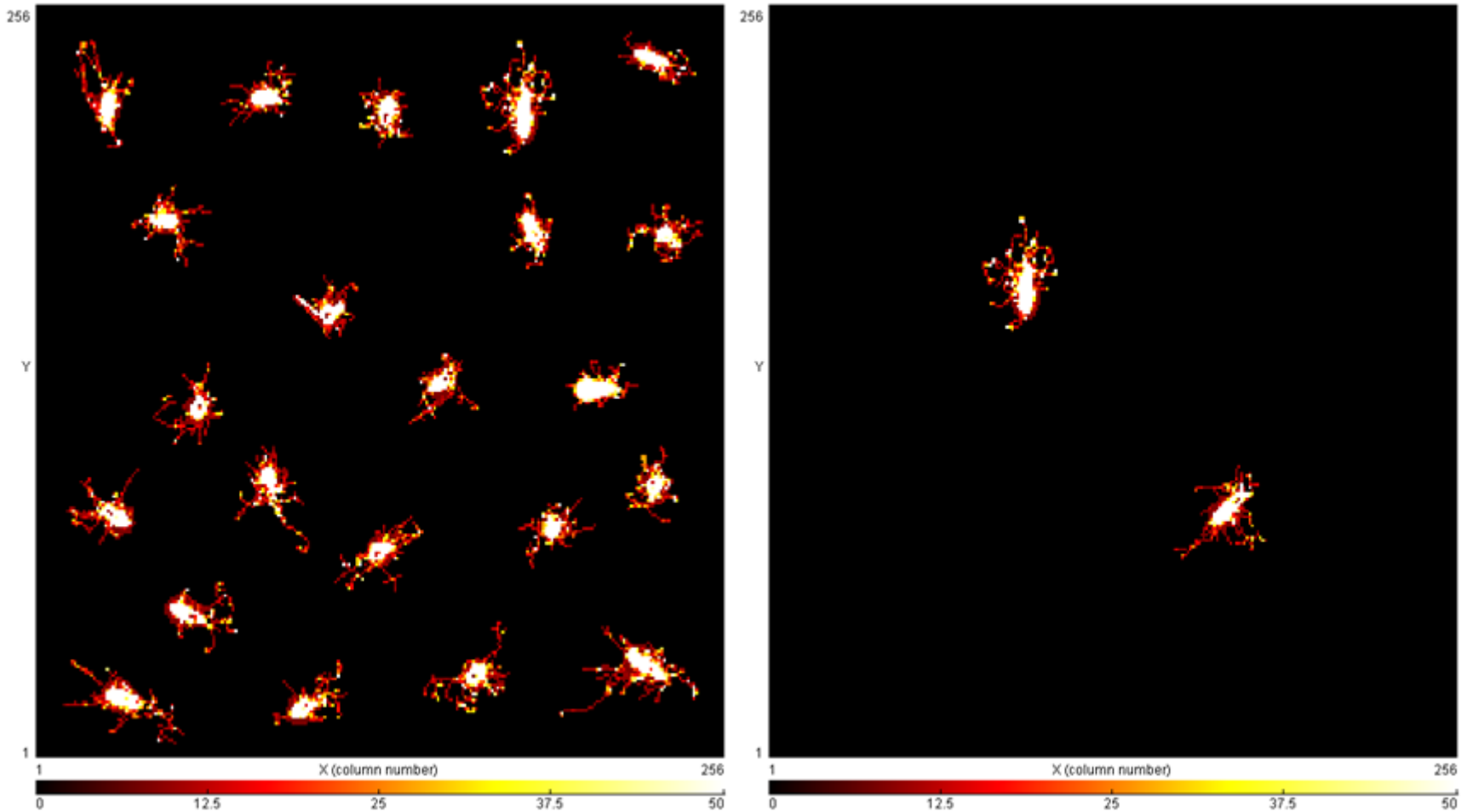




Timepix/ESA Proba-V:
LEO space radiation @ 820 km

Institute of Experimental and Applied Physics
Czech Technical University in Prague

HETPs: Highly energetic heavy charged particles (ions) → HZE's



Timepix/ESA Proba-V:
LEO space radiation @ 820 km

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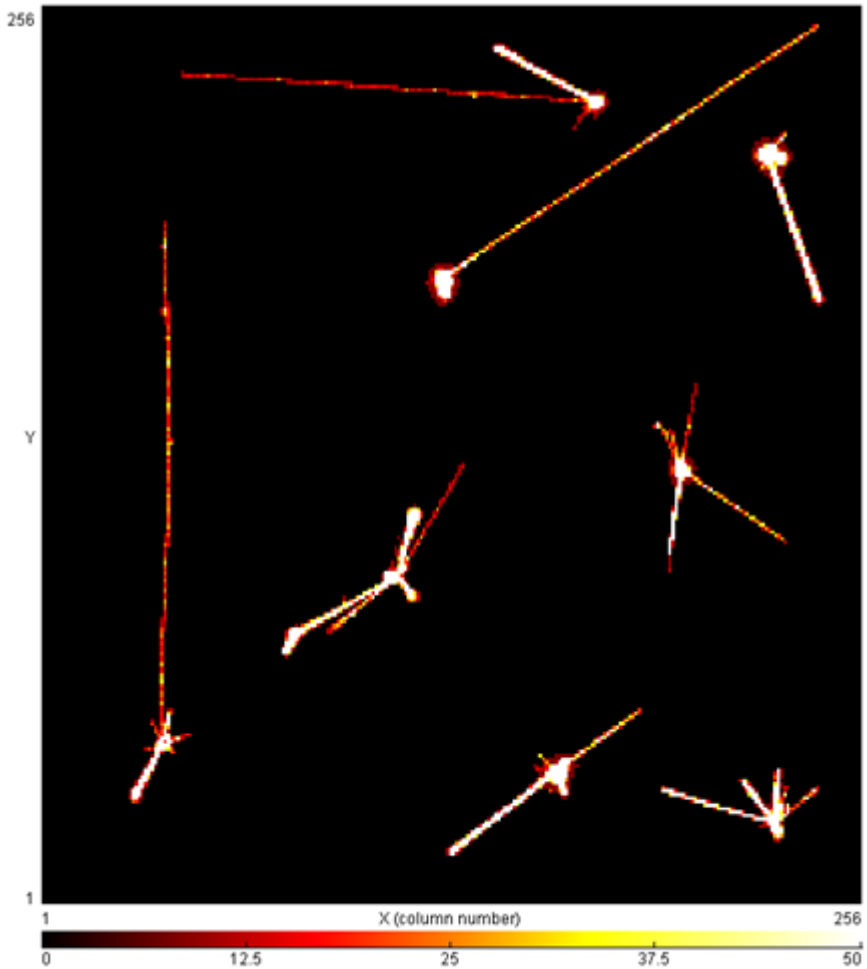
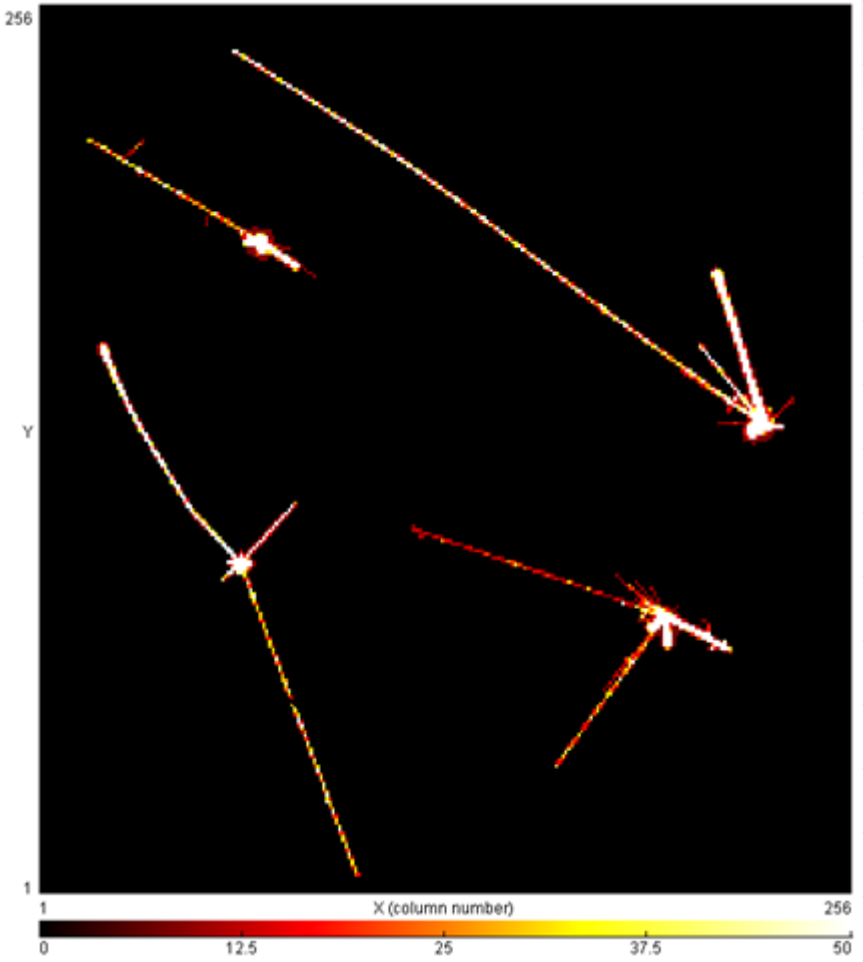
Czech Technical University in Prague

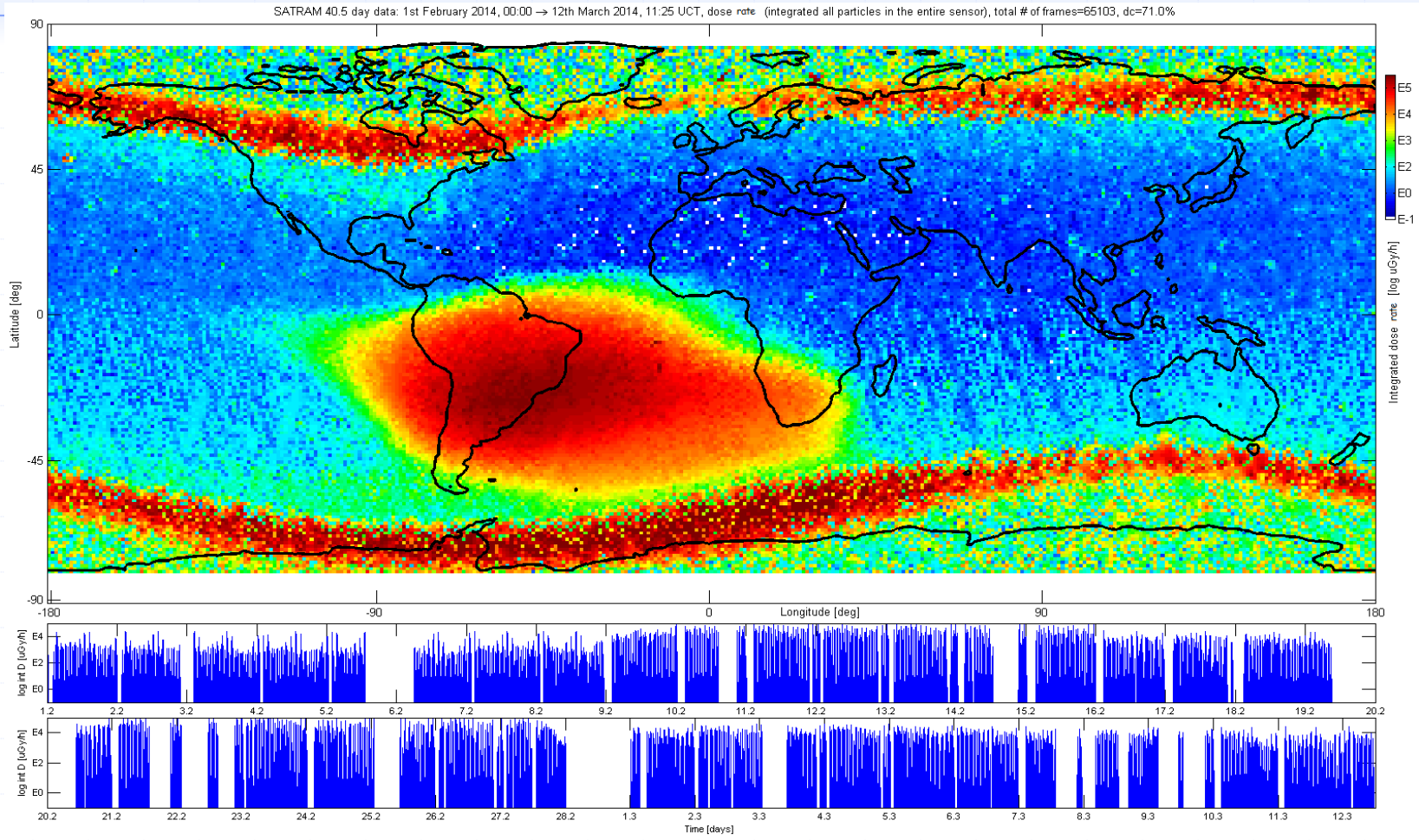
LETPs: Energetic light charged particles (I) + nuclear interactions





Measured radiation map by Satram device in orbit

around the Earth at an altitude of 820 km from the earth's surface obtained within 36 days from January 1, 2014 to February 7, 2014 logarithmic scale in μG/hr.



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Czech Technical University in Prague

RISESAT

(Rapid International Experimental Satellite)
Timepix particle μ-tracker particle telescope – launched on Feb 2019

Institute of Experimental and Applied Physics
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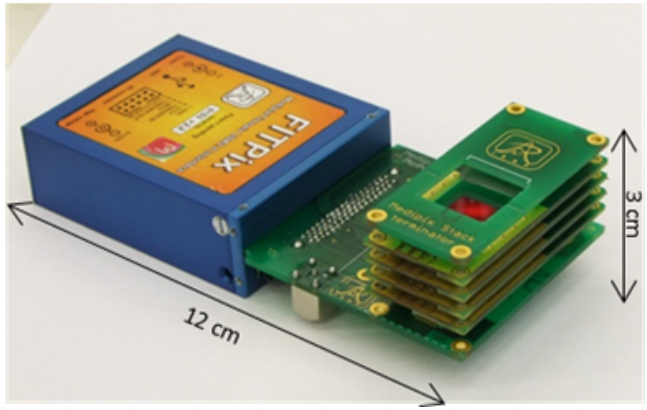
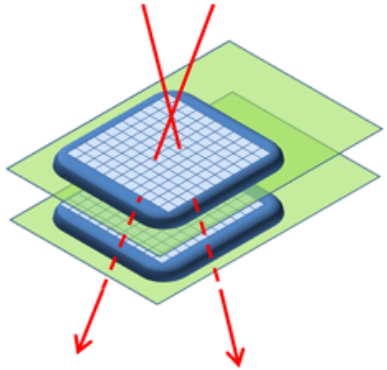
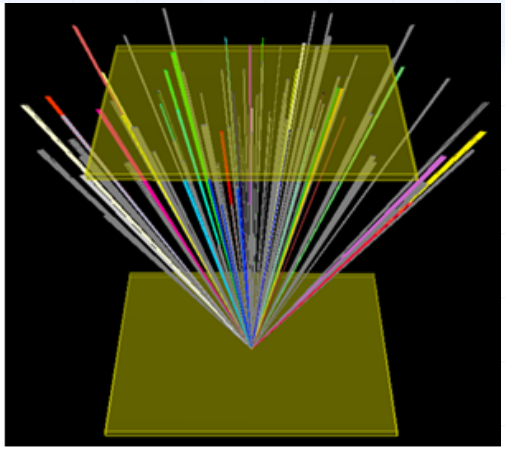
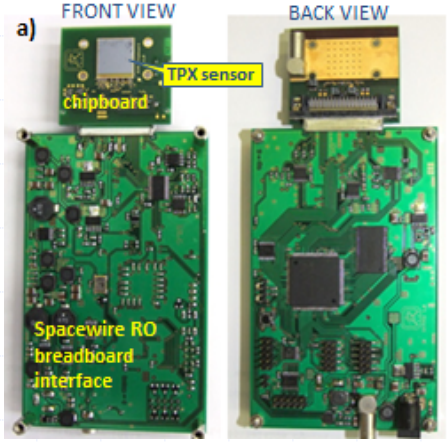
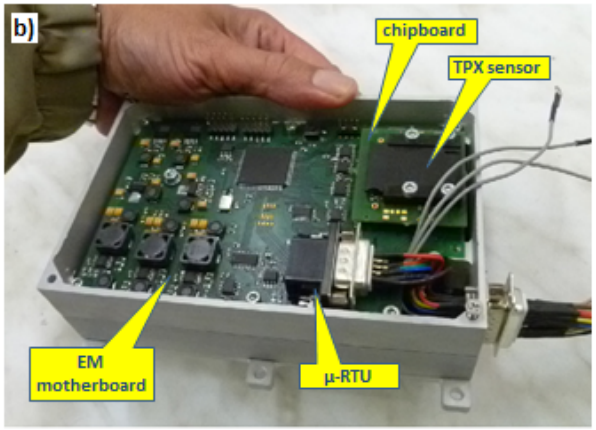


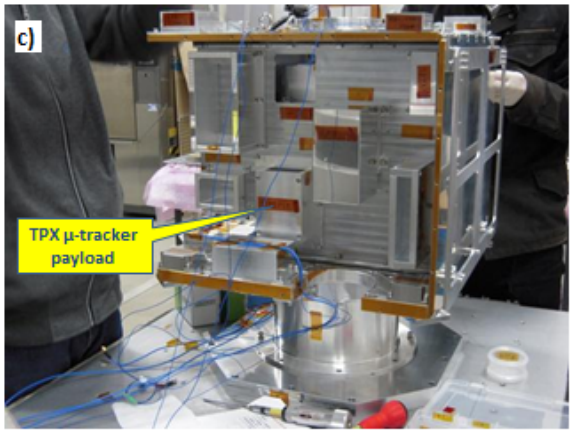




Particle micro-tracker of a stack of Timepix detector chipboards with common motherboard and single integrated R/O interface (left). Illustration of particle telescope on two pixelated sensors determining the direction of particle flight (middle) providing spatial visualization of particle trajectories (right).







Timepix μ-tracker for the RISESAT satellite consisting of two separate devices with synchronized operation. Spacewire interface (a), payload engineering model (b) and its position in the 50 Kg micro-satellite (c).

Timepix3 for coincidence gamma ray spectroscopy
PET – with TPX3 CdTe detectors

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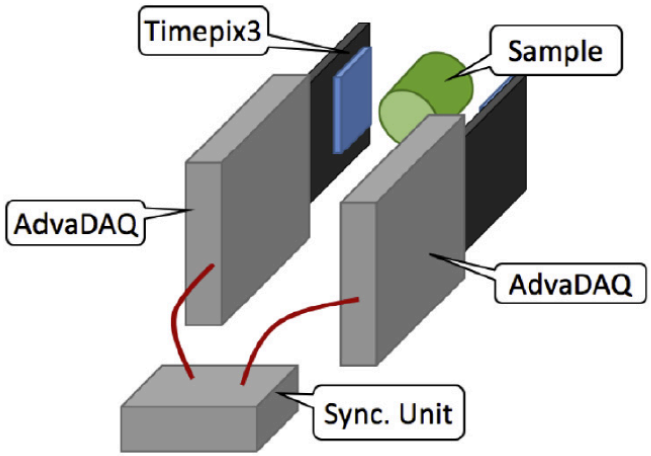

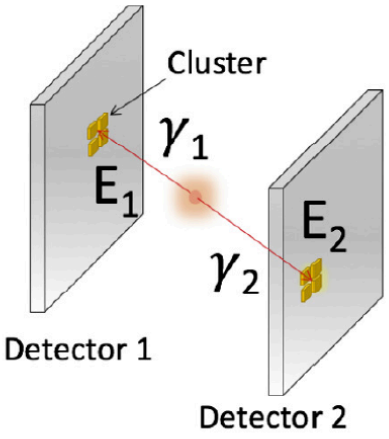

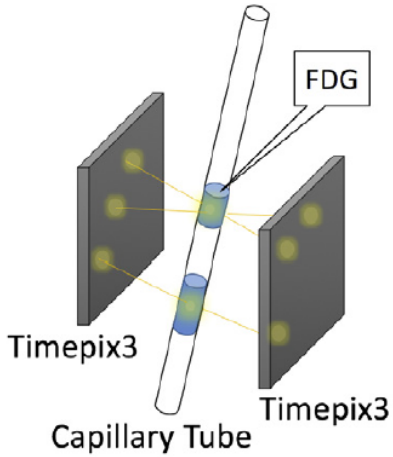

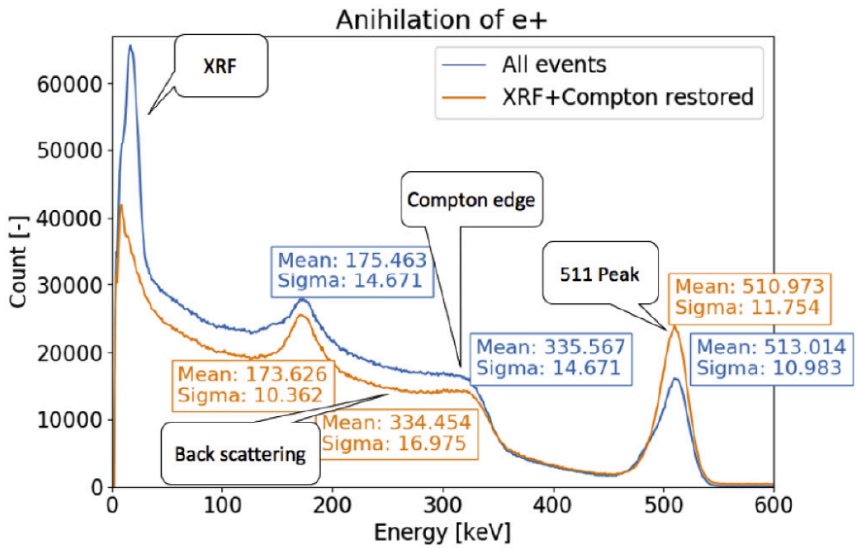

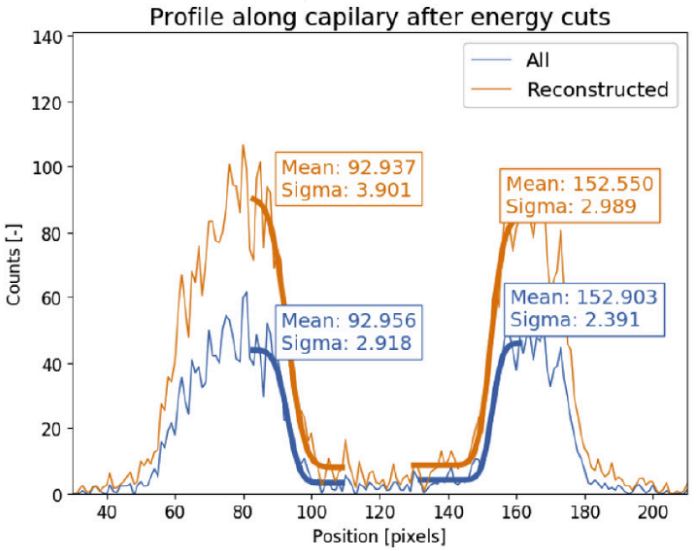

Timepix3 for coincidence gamma ray spectroscopy
Compton camera with CdTe and Si detectors

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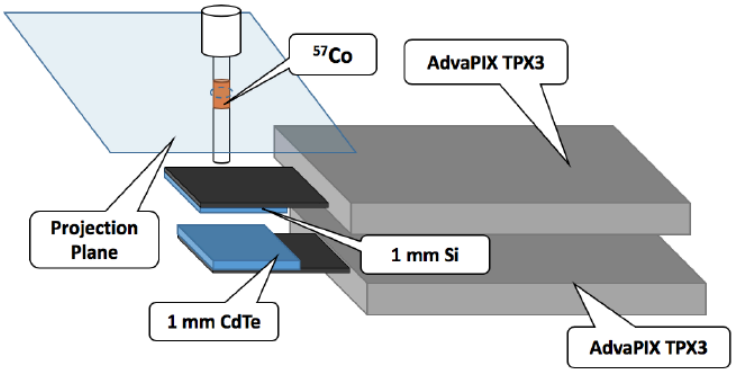

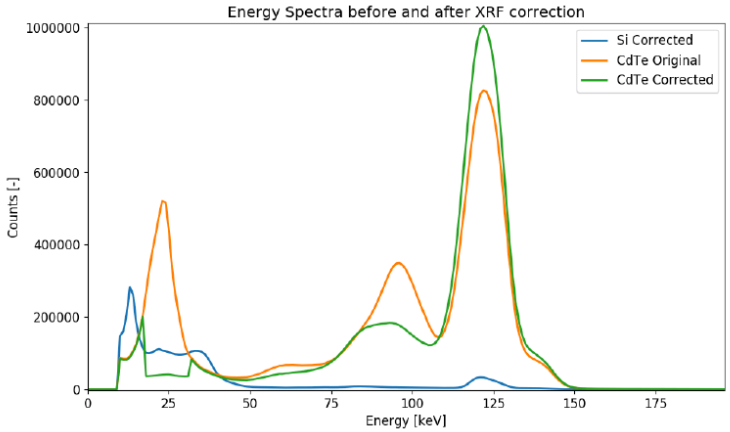

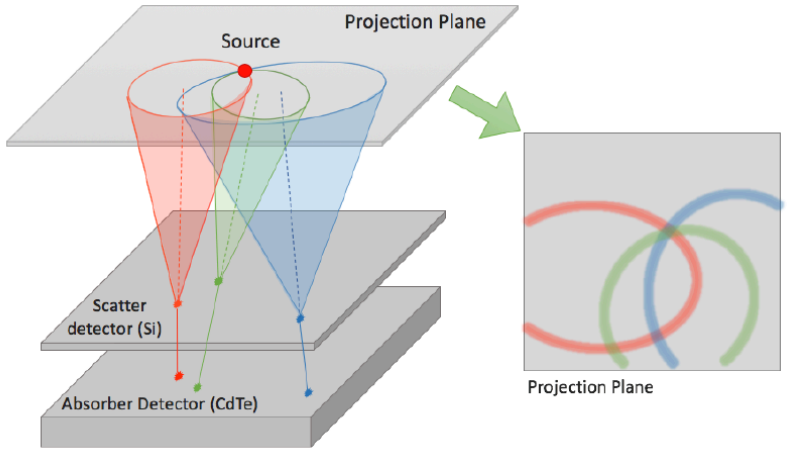

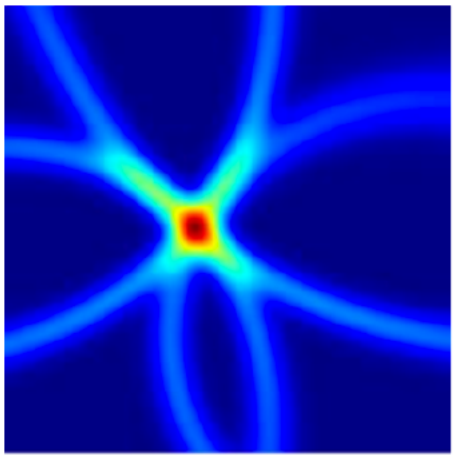

chosen 4 events

Acknowledgement

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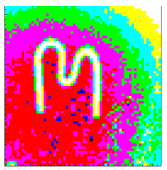
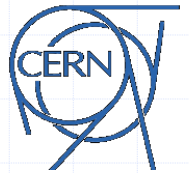
[13] *Glasgow University*





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Thank you for your attention!