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

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Main goals of the lecture

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- To describe family of ***Medipix2 and Timepix 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 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, the latest achievement in high resolution neutron imaging and finally, where to go further.***

Medipix/Timepix hybrid pixel detector device

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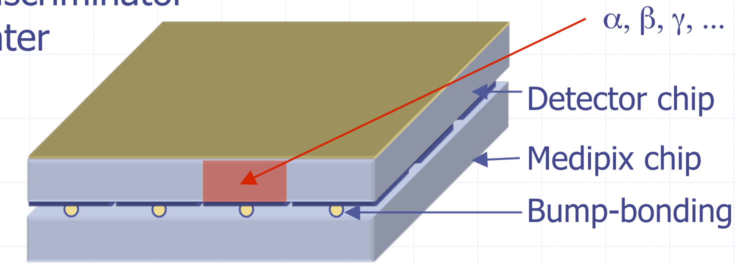
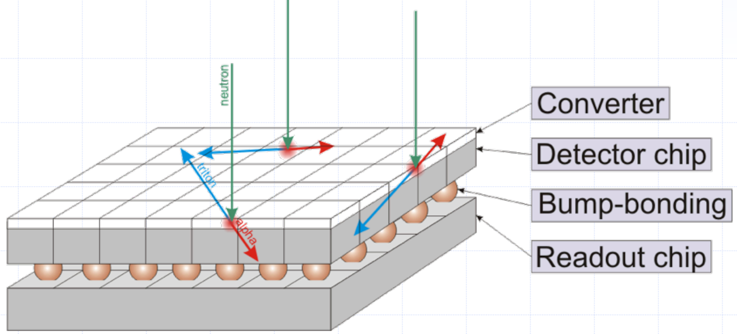
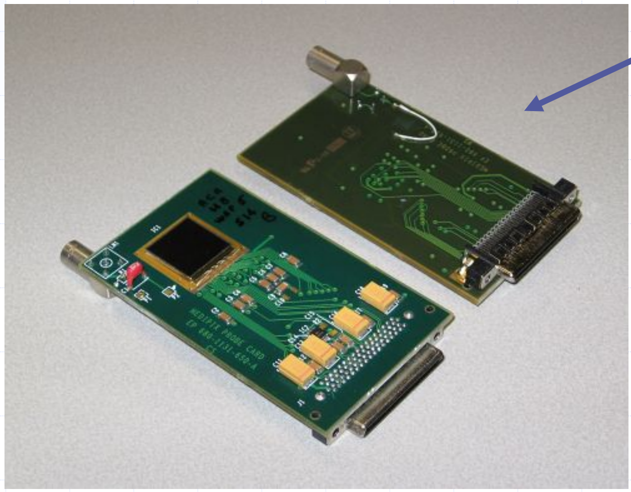
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000μm)
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter

- 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

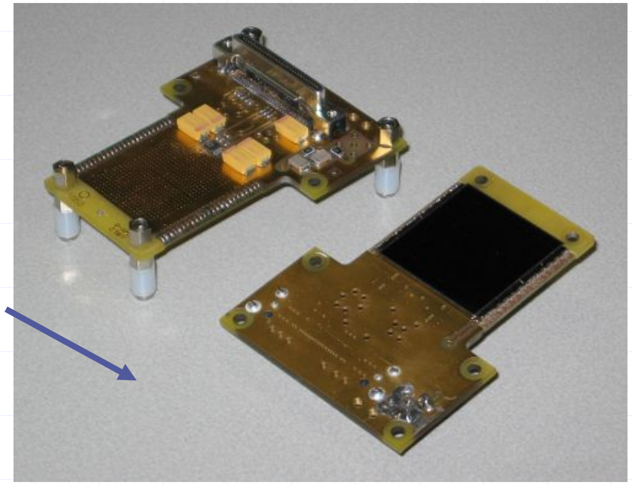




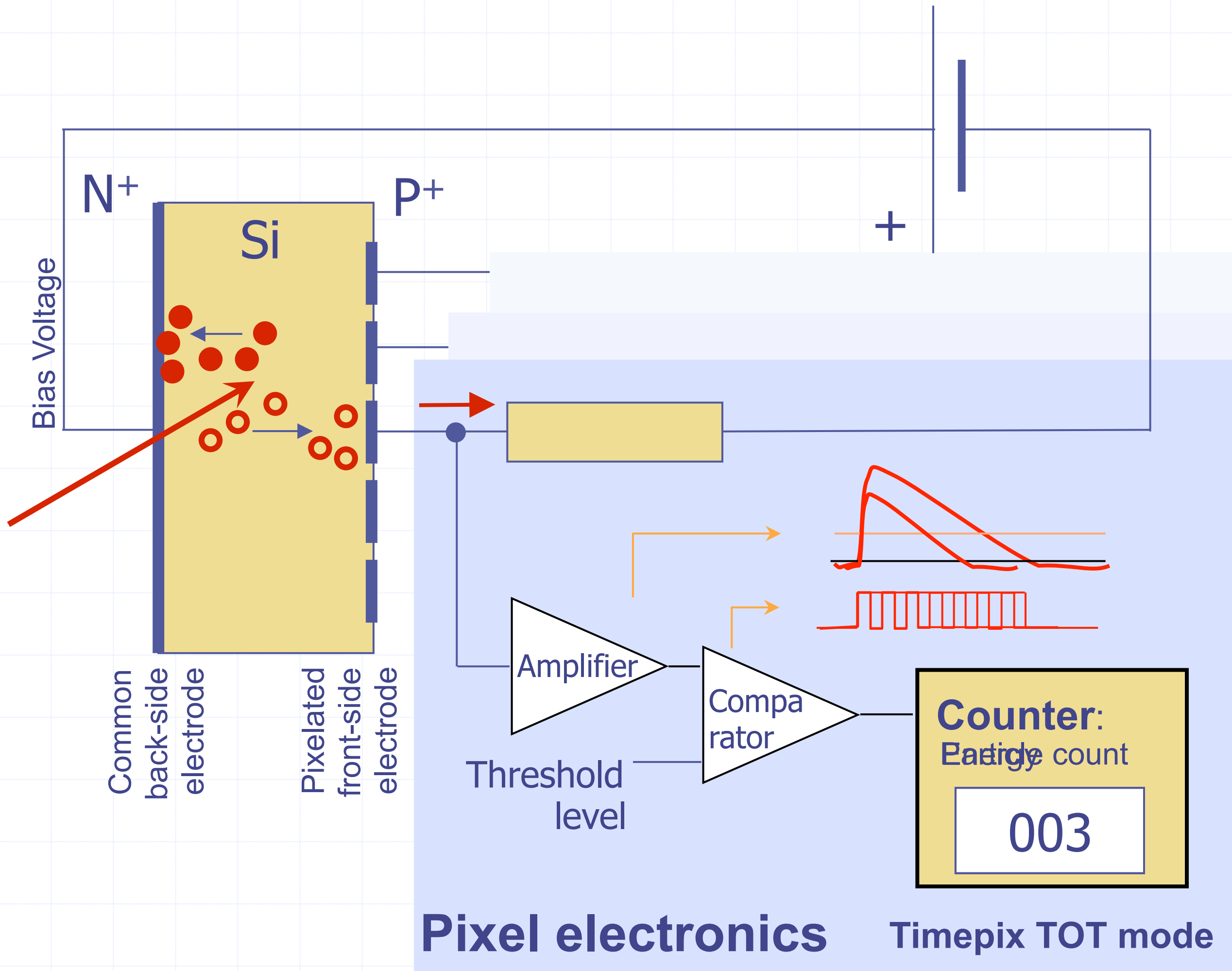


Medipix2/Timepix
Pixels: 256 x 256
Pixel size: 55 x 55 μm^2
Area: 1.5 x 1.5 cm^2

Medipix2/Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2



Medipix – single quantum counting detector
Timepix - spectroscopic pixel detector with ToT and ToA modes of operation



Threshold level above electronic noise
⇒ **No false counting.**

Digital integration (counting)
⇒ **No dark current.**

Unlimited dynamic range and exposure time. Counts obey poissonian distribution.

65k spectroscopic chains:
- SCA in case of Medipix
- MCA in case of Timepix
- MCA+TDC with Timepix3

Energy calibration
(Calibration of 65k MCA! Question: how to deposit defined energy into a volume 55x55x300 μm^3?)

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

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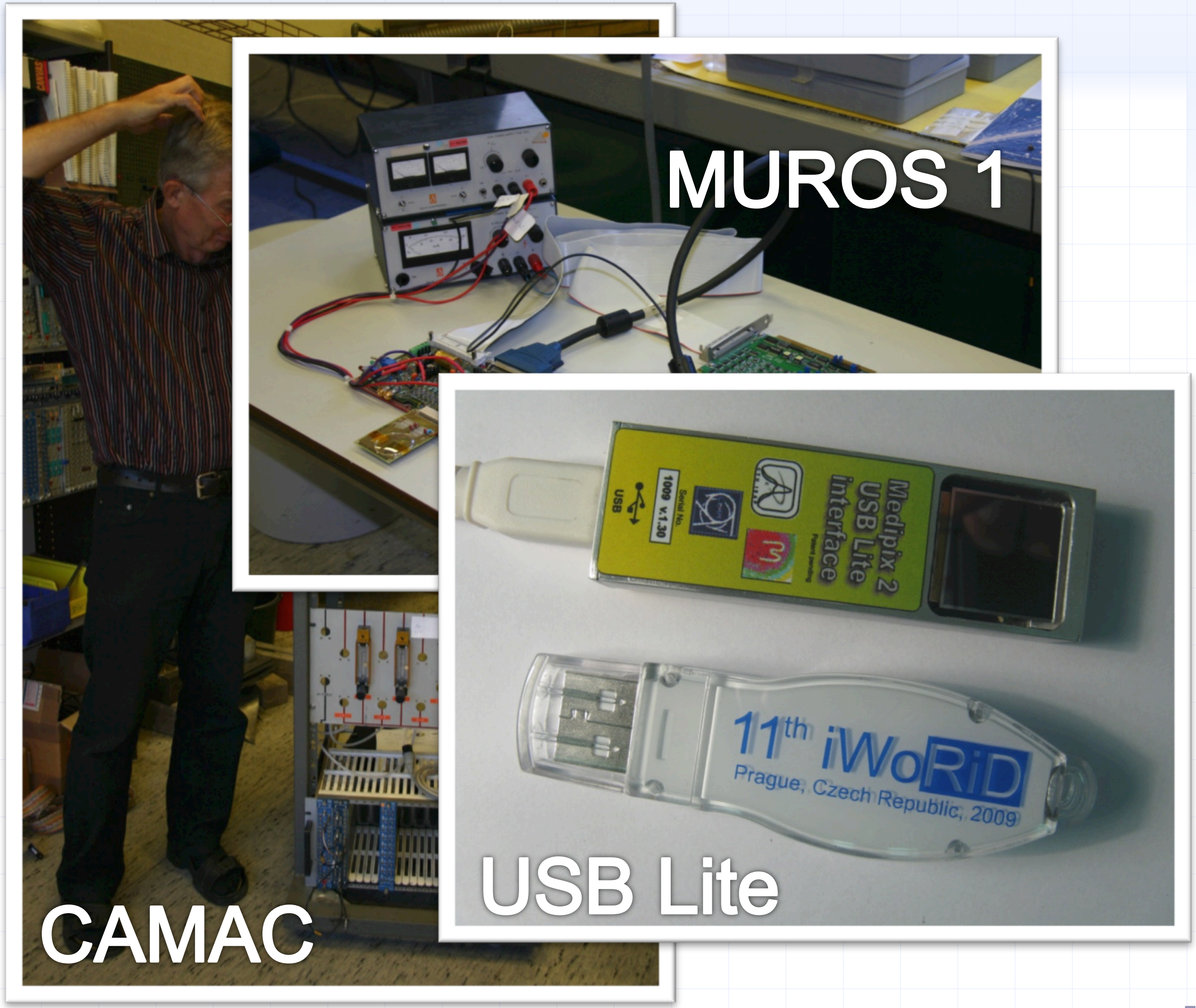
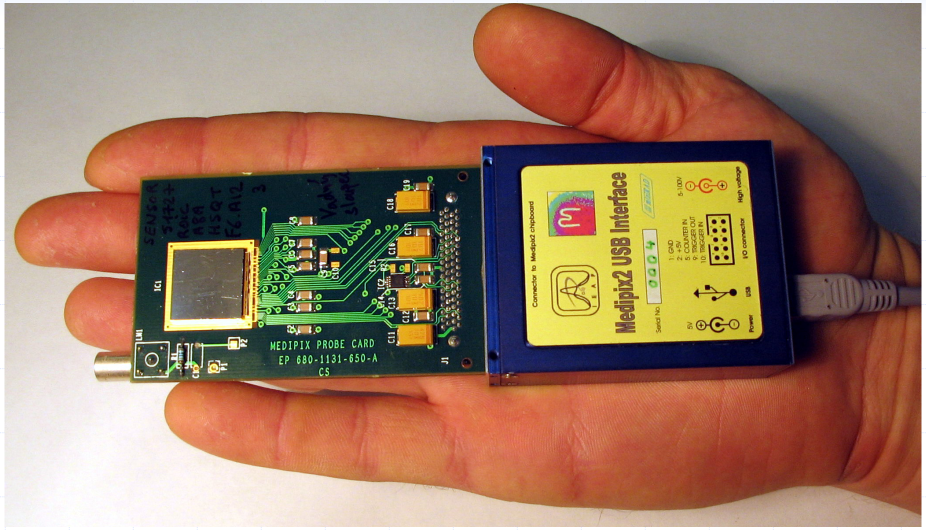
HISTORY 1995-2011:

MAMOGRAPHY

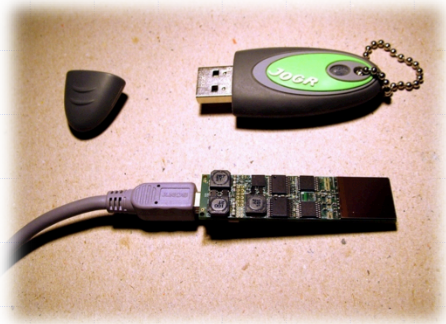
- **CAMAC/VME**
- **MUROS (NIKHEF)**
- **USB1 (IEAP)**
- **USB Lite (IEAP)**
- **RUIN (IEAP)**
- **MARS (NZ)**
- **USB2 (IEAP)**
- **TPX Lite (IEAP)**



Medipix/Timepix – USB2 controlled portable device



- Medipix/Timepix motherboard (R/O chip developed at CERN in frame of Medipix2 collaboration) assembled to USB2 interface board (developed with Pixelman software package at IEAP CTU in Prague), http://www.utef.cvut.cz/MEDIPIX.
- The MEDIPIX/Timepix-USB device connected to the portable PC. Up to 80 frames per second (USB2 serial connection) or 800 f/s (parallel connection). One PC can effectively run up to 50 devices.
- Light version of the Medipix-USB interface (on the right).



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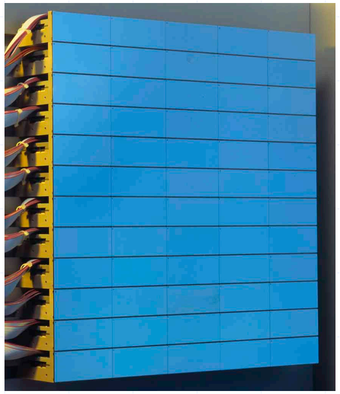
Particle counting pixel detectors

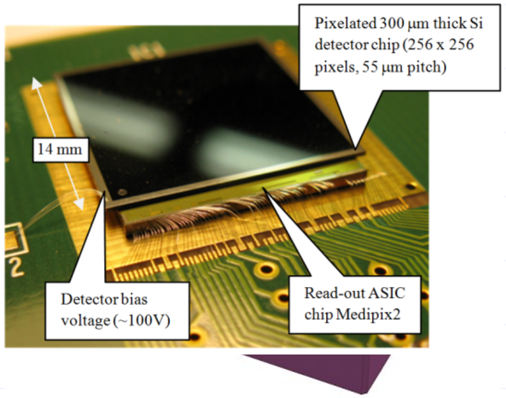
Pilatus - PSI

- 60 x 97 pixels
- Pitch of 172 um
- Counter: 20 bits
- Single threshold
- Module 16 chips
- Large area - tilling



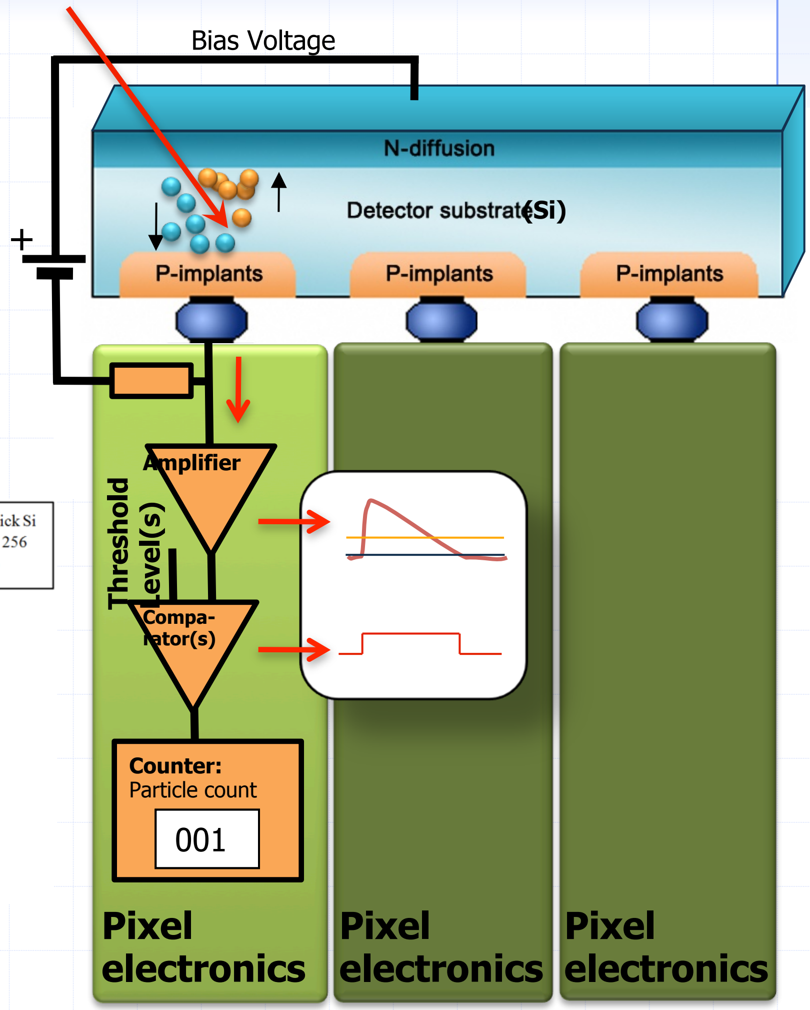
Medipix2 – CERN

- 256 x 256 pixels
- Pitch of 55 um
- Two thresholds
- Module 4 chips
- Large area: under development (RELAXd)



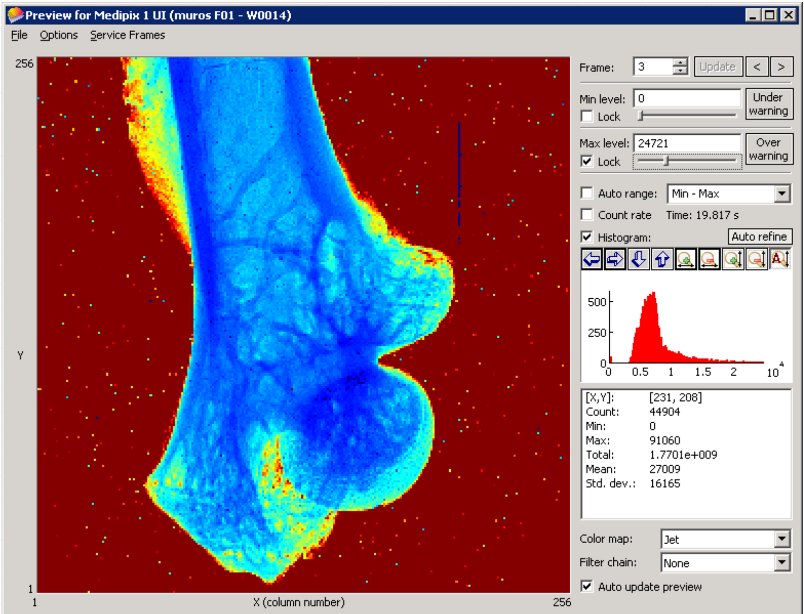
Timepix - CERN

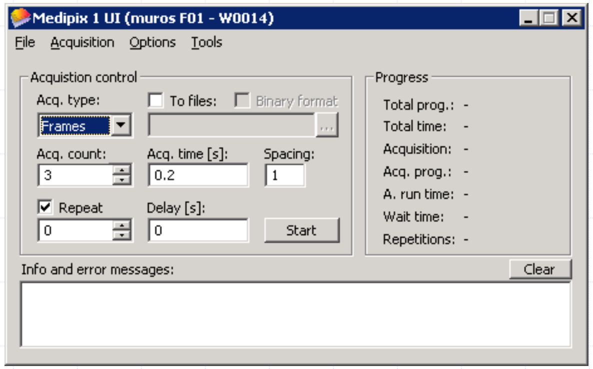
- Time stamp
- ToT or ToA mode
- Timepix3 -ToT and ToA simultaneous



PIXELMAN SW Package
to control, read and evaluate data from pixel devices

- Software package for Medipix/Timepix acquisition control and data evaluation, equalization procedure and energy per pixel calibration
- Supports all available Medipix/Timepix based detectors
- Supports all commonly used readout interfaces
- It is designed for maximum flexibility and interoperability with other devices (like stepper motor control unit) to control complex experiments.
- This is achieved by modular architecture with support of custom made plugins.





Experimental setup

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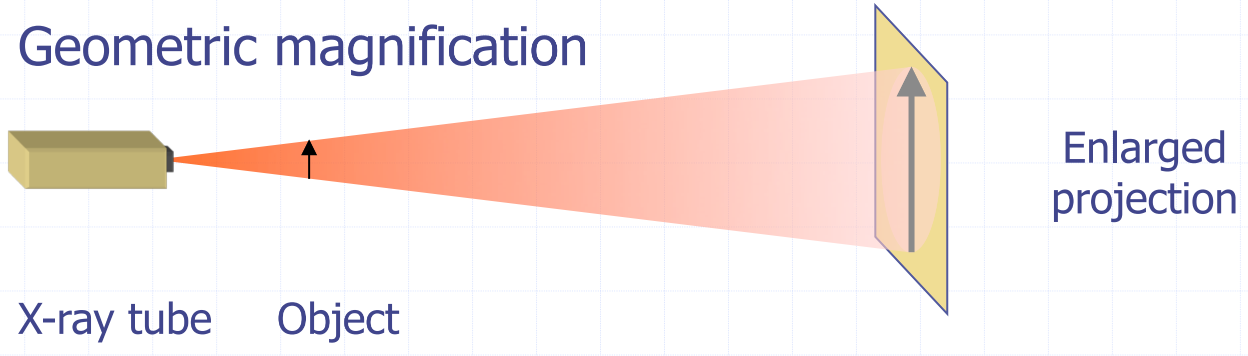
Requirements:

- 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)



Soft tissue X-ray imaging

Mouse Kidney Tomography

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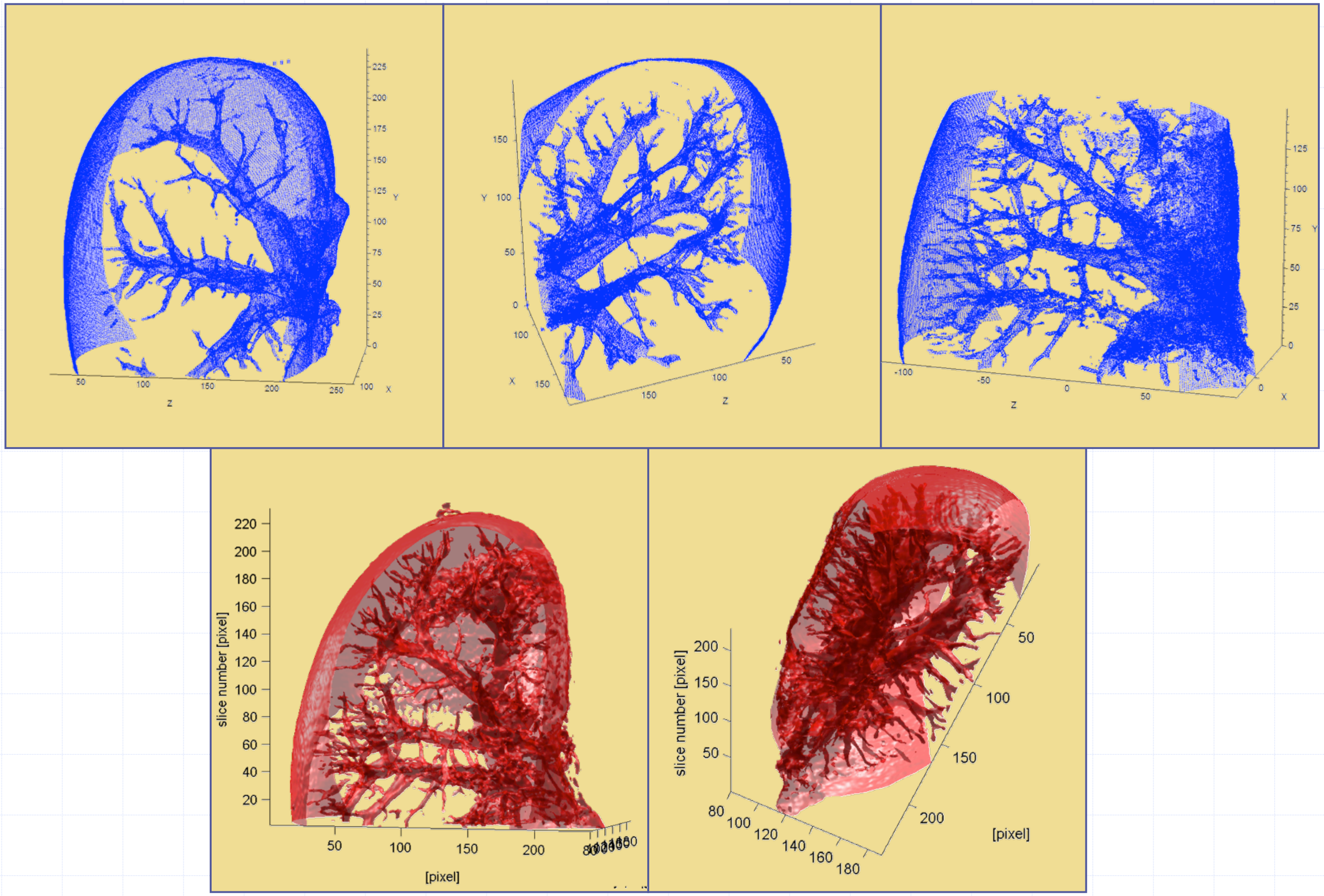
Missing angles => Iterative algorithm instead of Filtered back projection (3 iterations in OSEM 5)



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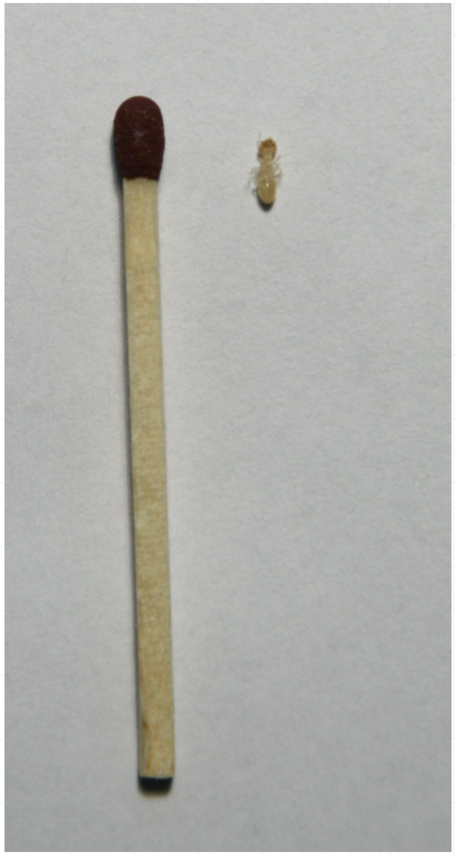
High resolution X-ray radiography:

Imaging of Termites



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.

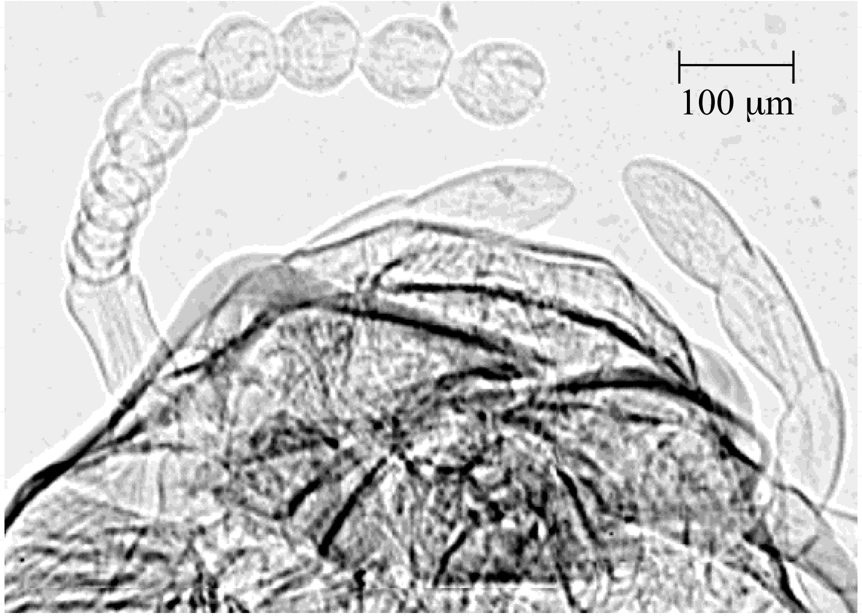
Thus, the termites represent an ideal model to optimize the accuracy and sensitivity of the developed method.

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)



High resolution X-ray radiography:

Imaging of Living Termites

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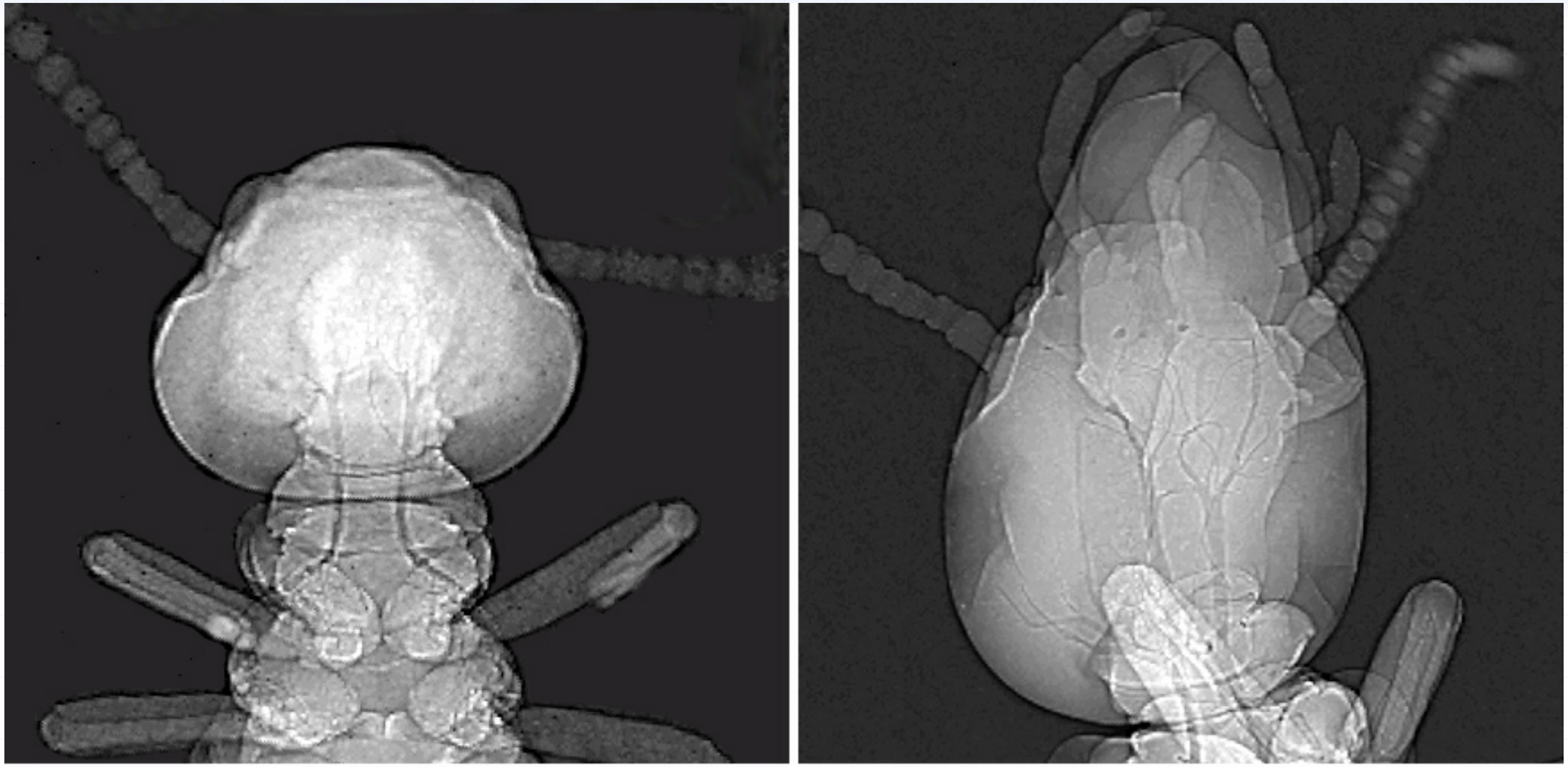


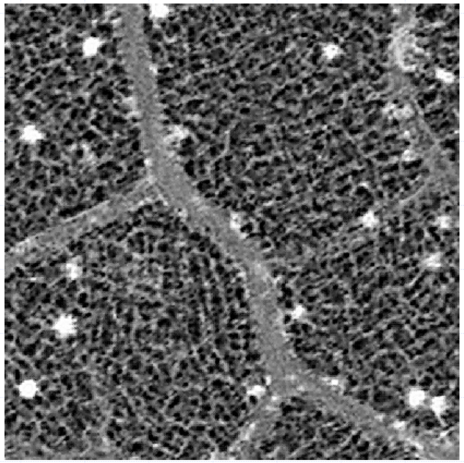
Images of a termite worker before (left) and after (right) its metamorphosis toward the soldier caste (5s exposure ~ 0.7mGy dose)

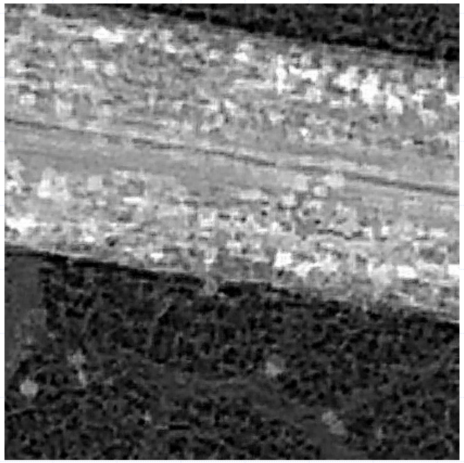
High resolution X-ray radiography:

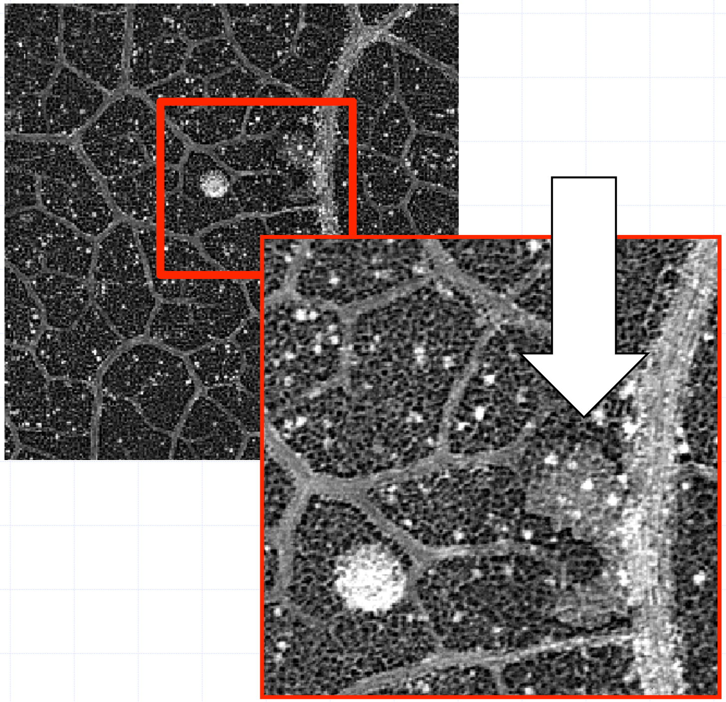
Example: Leaf Miner story

Leaf miner (*Cameraria ohridella*) - small moth. In larvae stadium it lives inside of chestnut tree leafs making "mines" and causing serious problems to the tree. Indication: chestnut leafs get brown, dry and fall down early.

Courtesy of J.Dammer (CTU in Prague), P.M.Frallicciardi (U.of Napoli) and F. Weyda (SBU Ceske Budejovice)







Healthy chestnut tree leaf structure (no parasite) – cellular structure of leaf is nicely observed (resolution below 1 um). The white spots are small drops of resin secreted by the leaf.

High resolution X-ray radiography:

Example: Leaf Miner story

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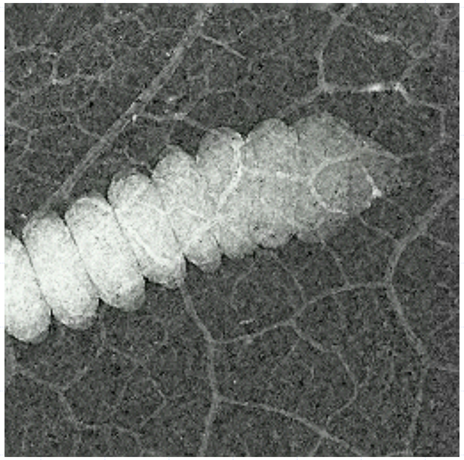
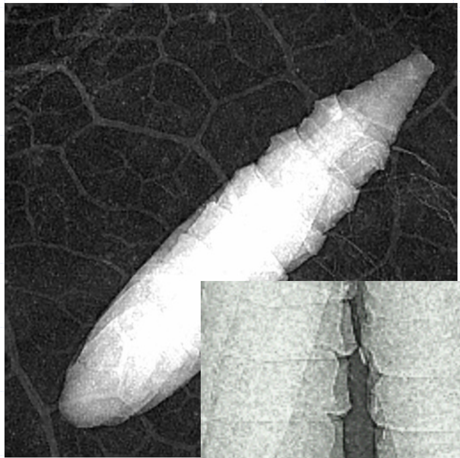
Worms are growing up and after three feeding instars larvae build-up a silken cocoon (pupae)





Several collected pupas

High resolution X-ray radiography:

Example: Leaf Miner story - Cure

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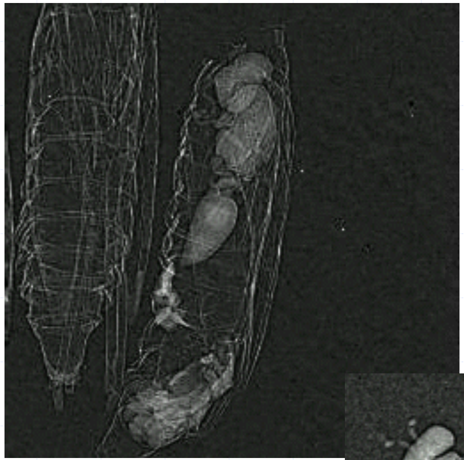
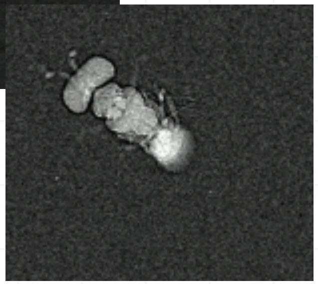
The best cure: natural enemy (parasitic wasp)

Certain small wasps can put eggs into leaf miner pupas

Parasite inside of parasite:





Parasite kills the pupa and leaves it as adult wasp

Imaging of large objects: WidePIX 6.5 Megapixel detector

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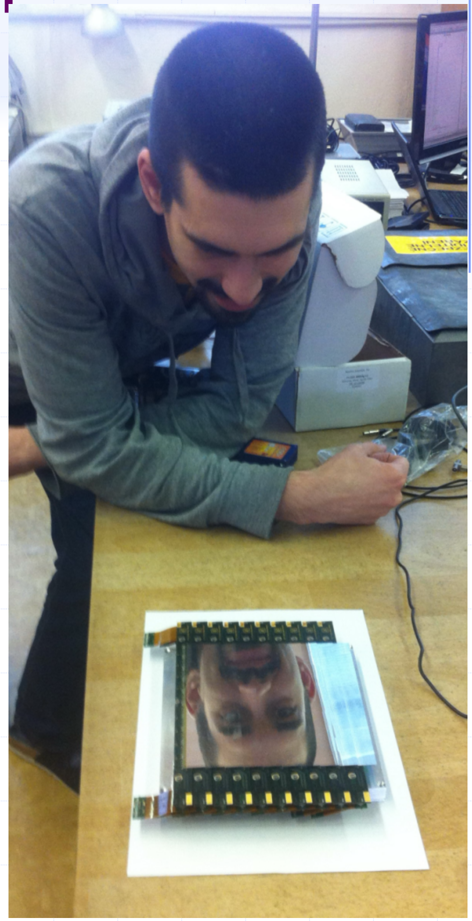
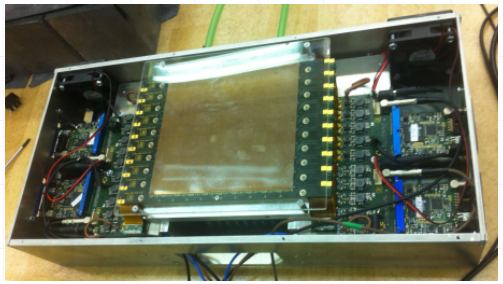
WidePIX camera consists of array of 10x10 of hybrid single quantum counting detector Timepix developed by by Medipix collaboration in CERN. The technology allowing coverage of large area is based on application of edgeless silicon sensors developed in VTT Finland. The whole **WidePIX** device was developed by IEAP CTU in Prague.



Features:

- Superior image quality without instrumental noise
- Large fully sensitive area without any gaps between sensor chips
- Fully digital detection with ultra-high contrast even for light objects (e.g. plastic or soft tissue)
- Energy discrimination allowing "color" radiography
- Compact size and portability
- Support for major operating systems: Windows, Mac OS, Linux

Further details: www.widepix.cz



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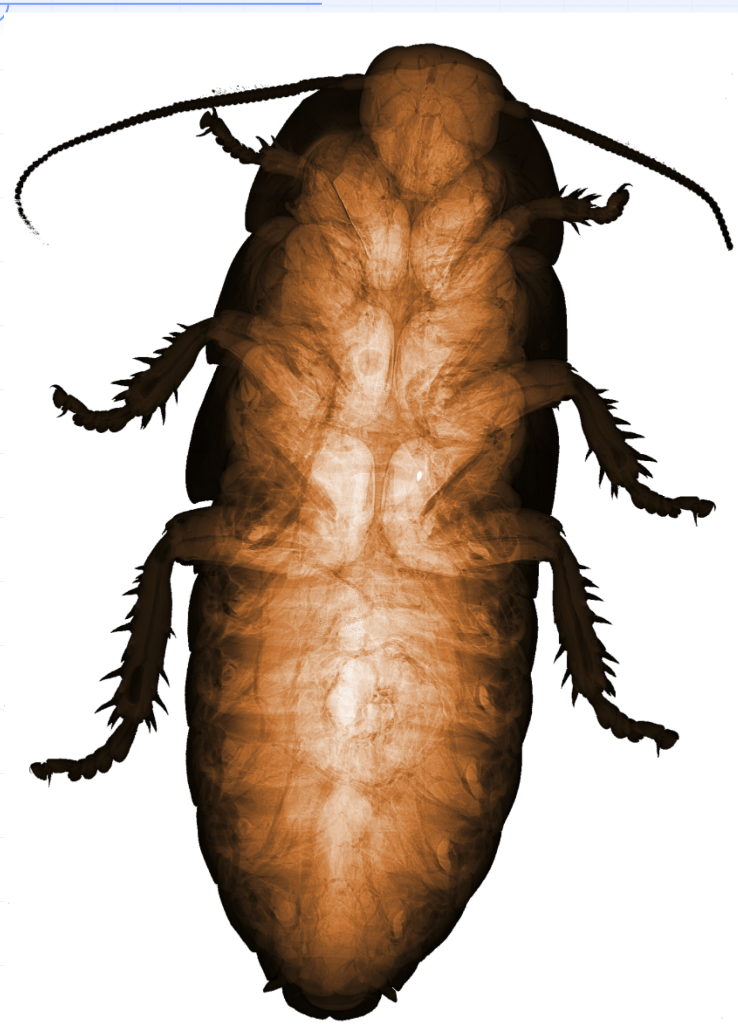
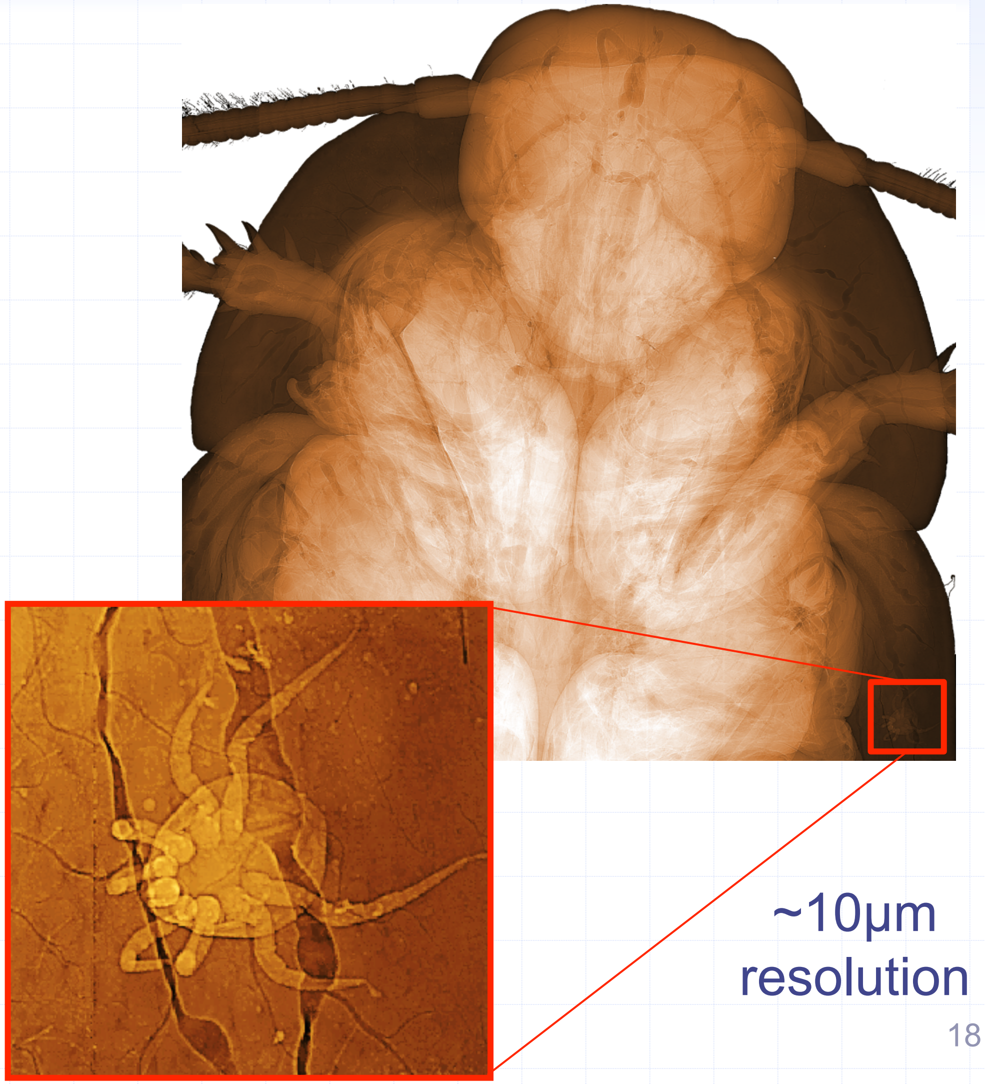
Large size objects:
Cockroach with parasite (magnified)





~10μm resolution

Motivation – neutron radiography

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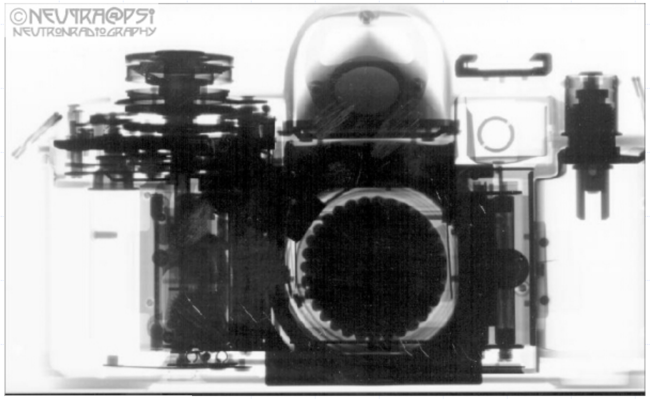
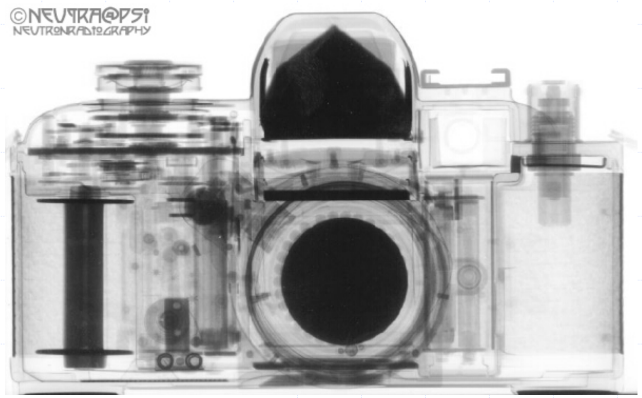
- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



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.

X-rays

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Attenuation coefficients with X-ray [cm?¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

Legend

Attenuation coefficient [cm?¹] = sp.gr. * μ/δ

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

μ/δ: J. H. Hubbell[+] and S. M. Seltzer Ionizing Radiation Division, Physics Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899, http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html.

Thermal neutrons

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Attenuation coefficients with neutrons [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.			

Legend

$$\text{Attenuation coefficient [cm?}^{1}\text{]} = \frac{\sigma\text{-total} * \text{sp.gr.} * 0.6023}{\text{at.wt.}}$$

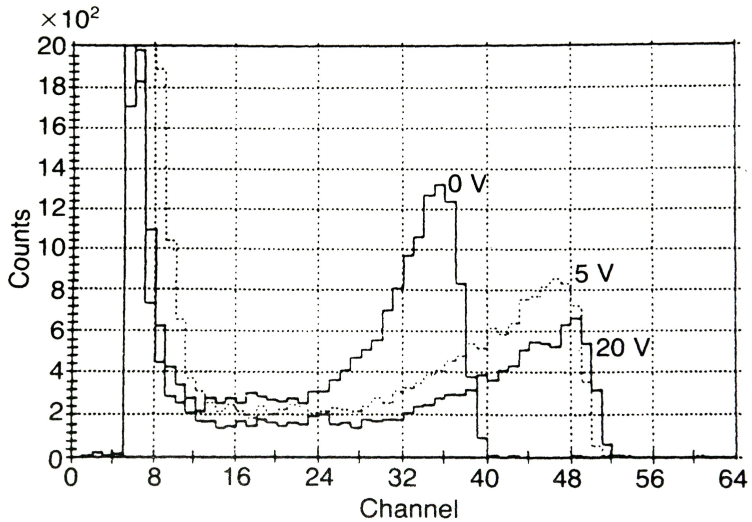
σ-total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.
and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada KOJ 1JO, Neutron News, Vol. 3, 1992, http://www.ncnr.nist.gov/resources/n-lengths/list.html.

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

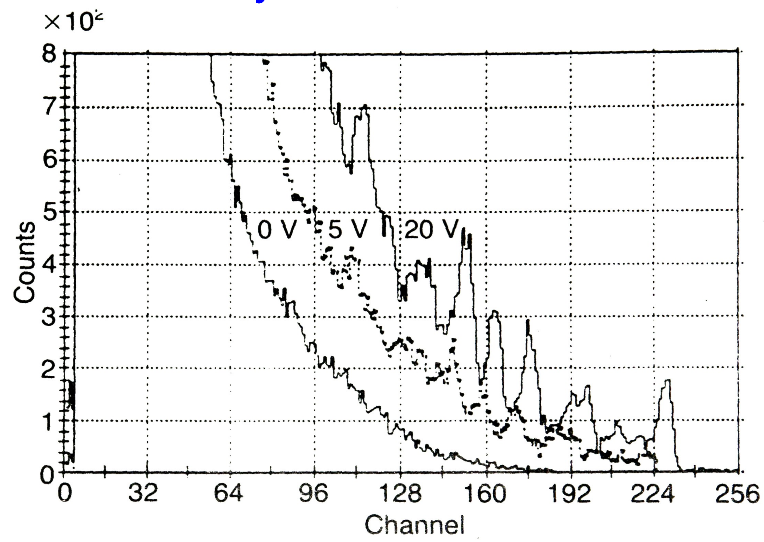
at.wt.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

Responses to neutrons

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



Silicon diode illuminated
by fast neutrons

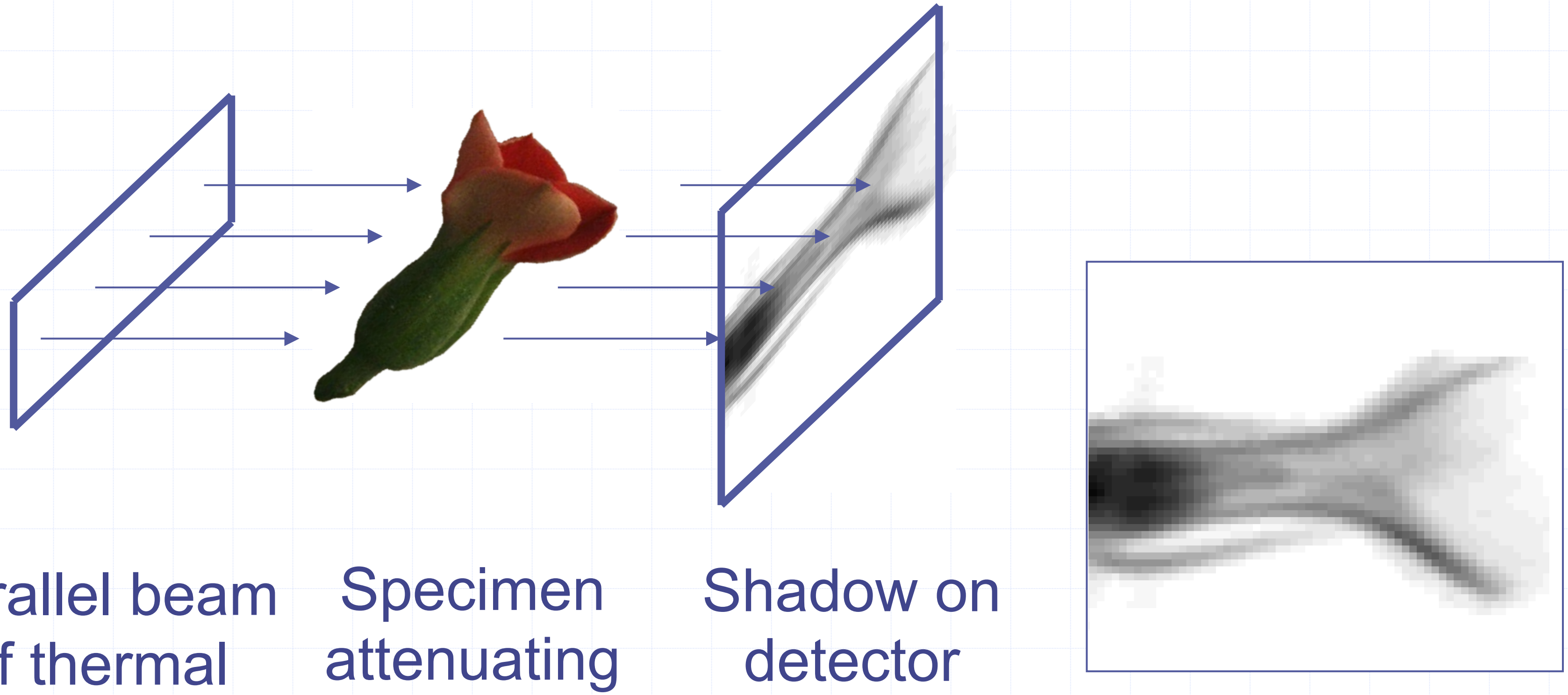


Pulse height distributions of neutron detector on thermal neutrons at different bias (0, 5, 20 V). Detector operates well in the self-biased regime.

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

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)



Parallel beam of thermal neutrons

Specimen attenuating the beam

Shadow on detector plane

Neutronogram

CCD camera with scintillator filled by converter material

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Offers:

- Good efficiency
- Large field of view
- Digital output
  => OK for tomography

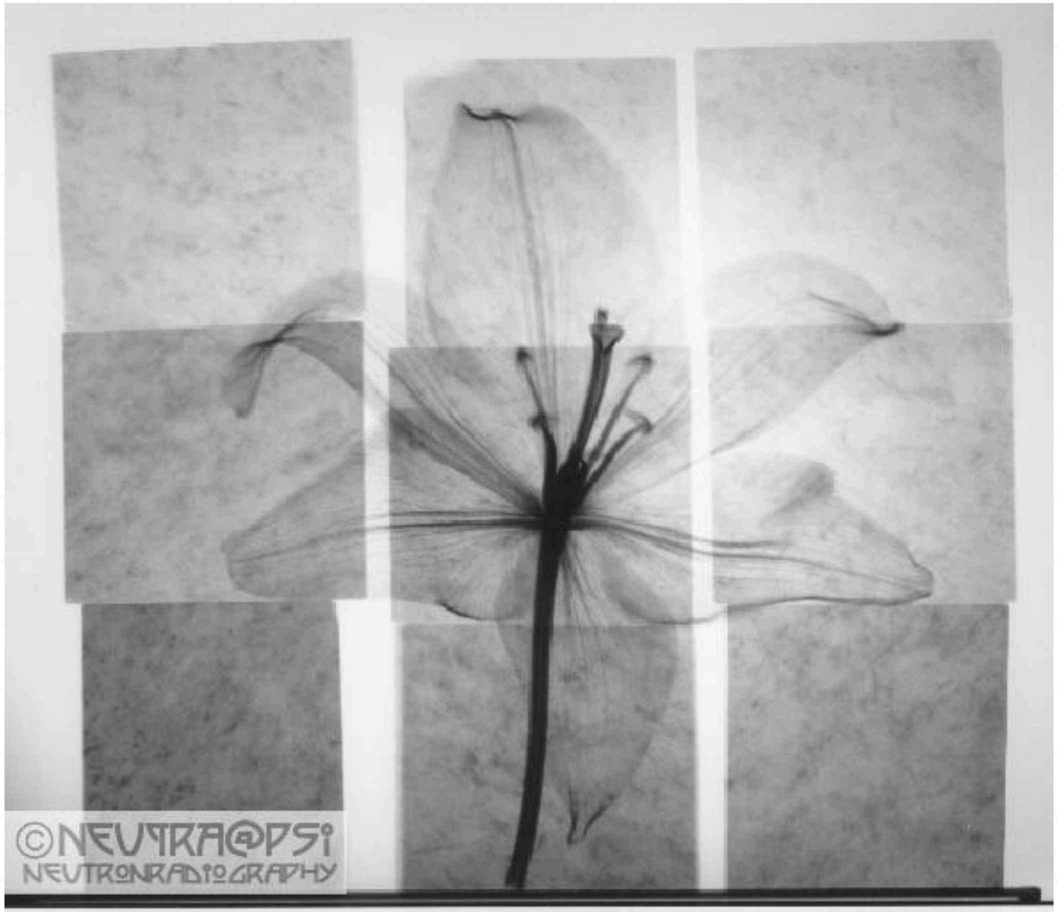
But:

- Low spatial resolution
- Dark current

=> Limited exposure time

=> Limited dynamic range

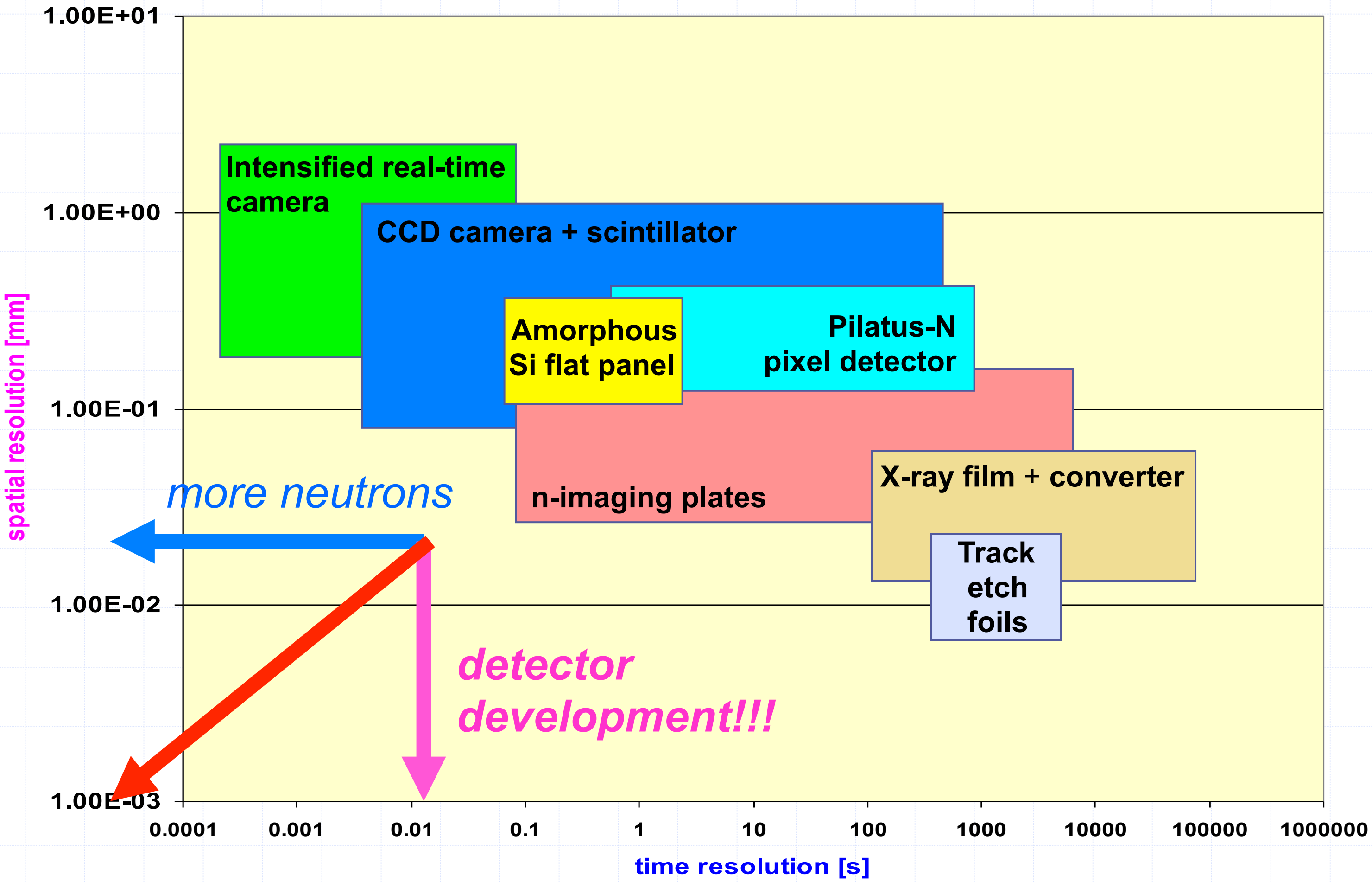
A flower was measured through a "wall of granite bricks" and shows a fascinating high contrast (compared to the stones) because of the strong attenuation of the involved hydrogen.



(courtesy NEUTRA facility at PSI)

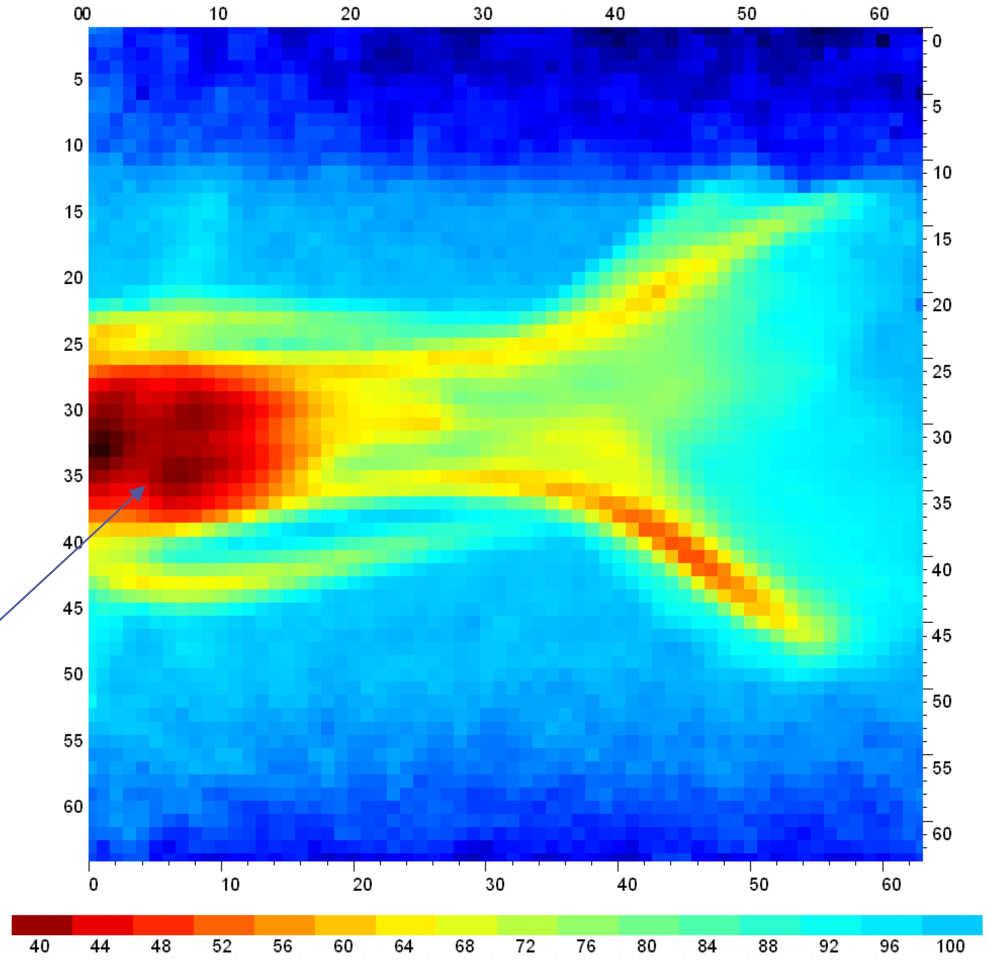
Detectors for neutron imaging

(under the conditions at the NEUTRA facility at PSI)



Flower behind Al plate

Look through metal with thermal neutron beam at NPI Rez



Neutron radiography with Medipix coated by ^{6}LiF: Blank cartridge

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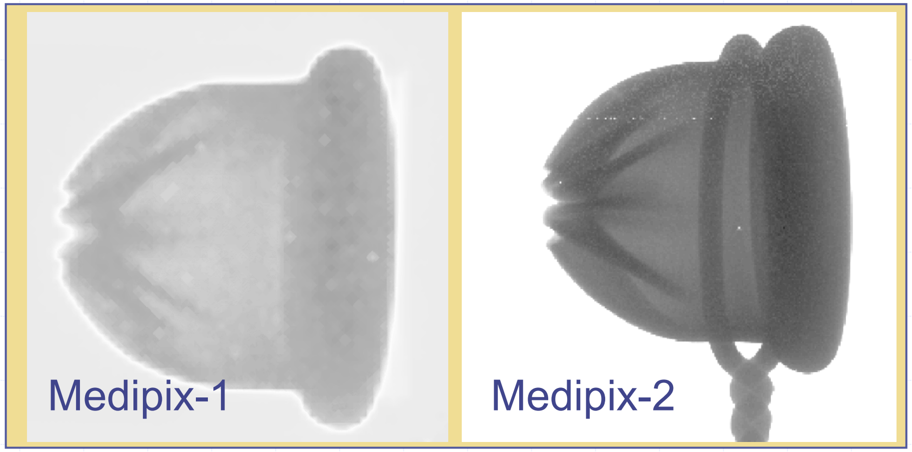
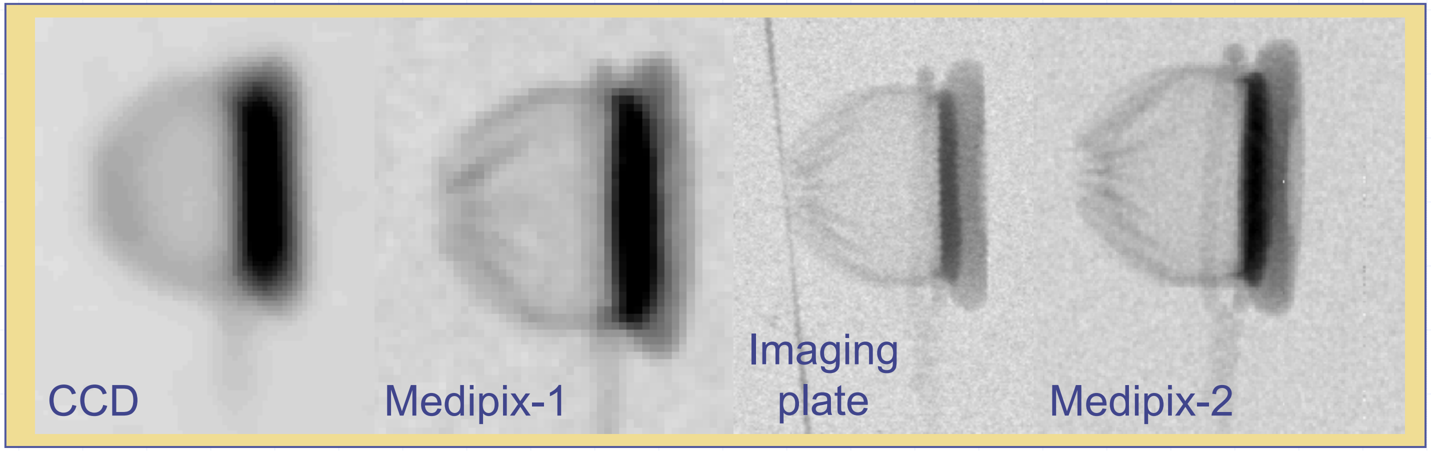
Rentgenography



Neutronography



Glued Al pieces
(measured at NPI Rez)

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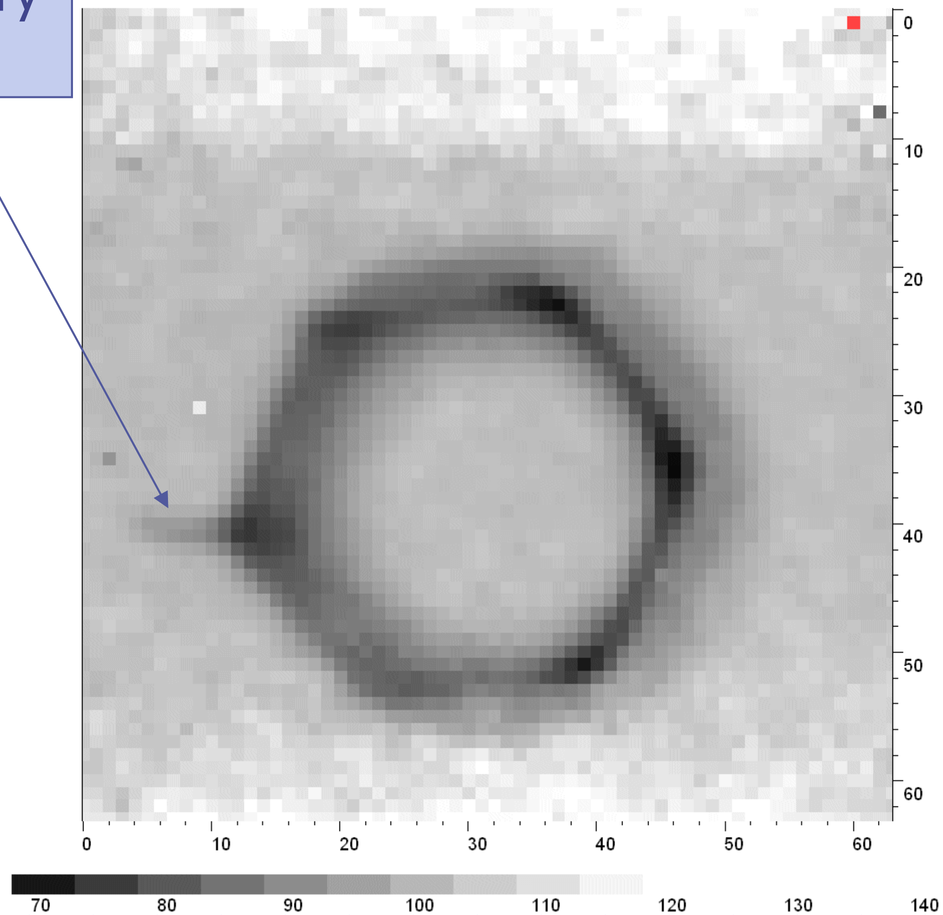
Glue raised through capillary attraction



Cold neutron radiography performed at PSI

Wrist watch

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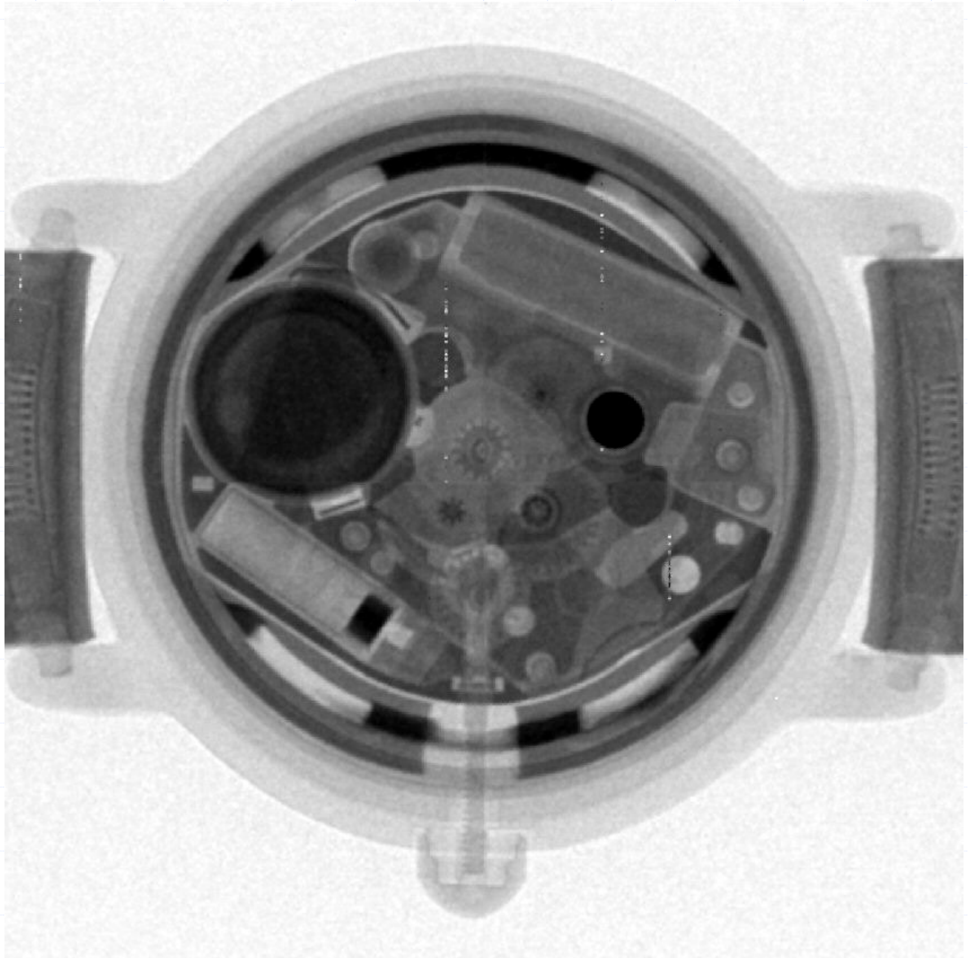

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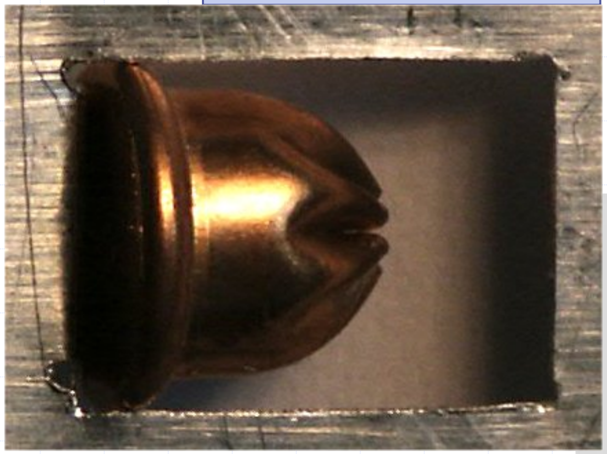
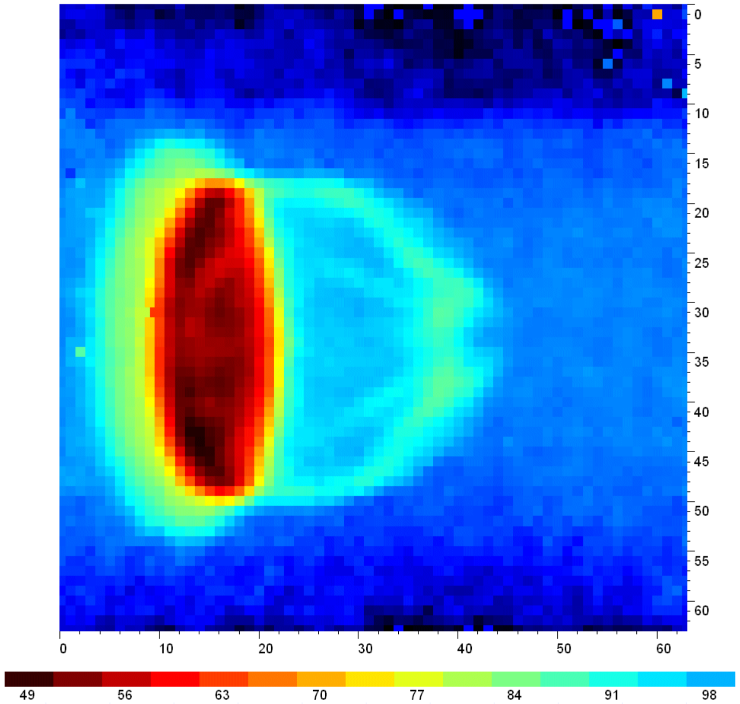
Look through metals!

Photography



Roentgenogram



Blank shell (cartridge)

Explosive filling

3D reconstructions

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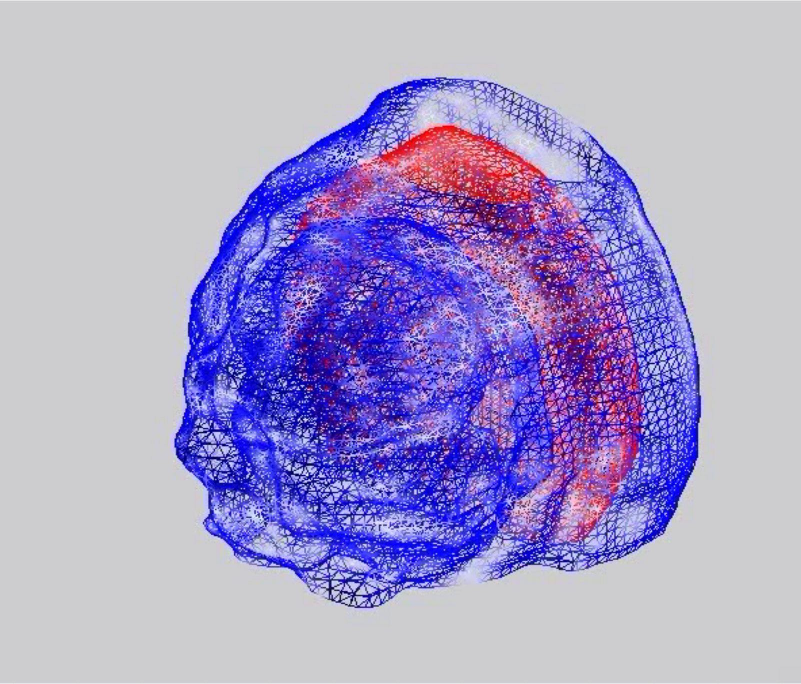
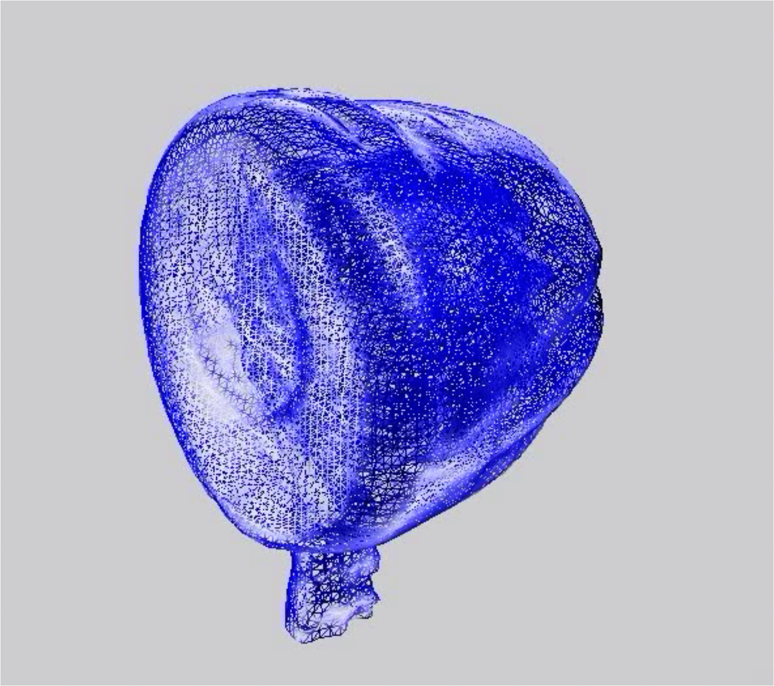
3D reconstruction - neutron	3D reconstruction – X-ray
	

Polystyrene Celtic Cross

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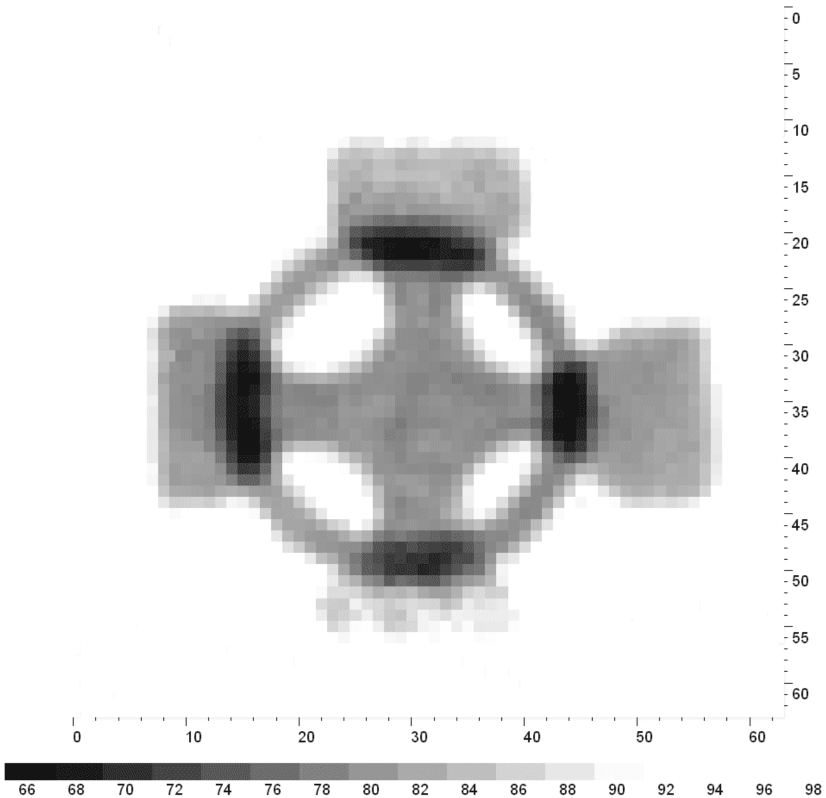

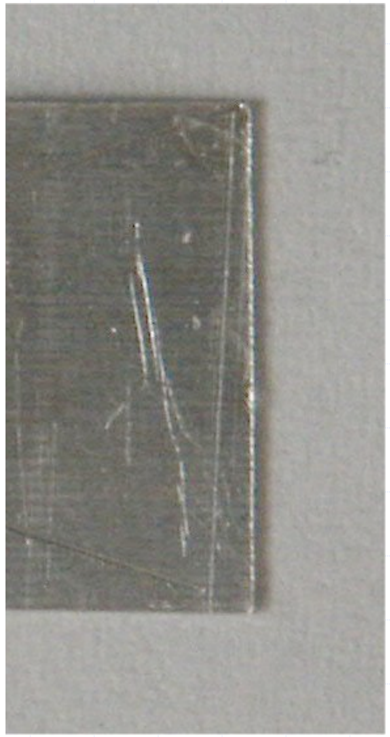

Cold neutron radiography:
Child vertebra

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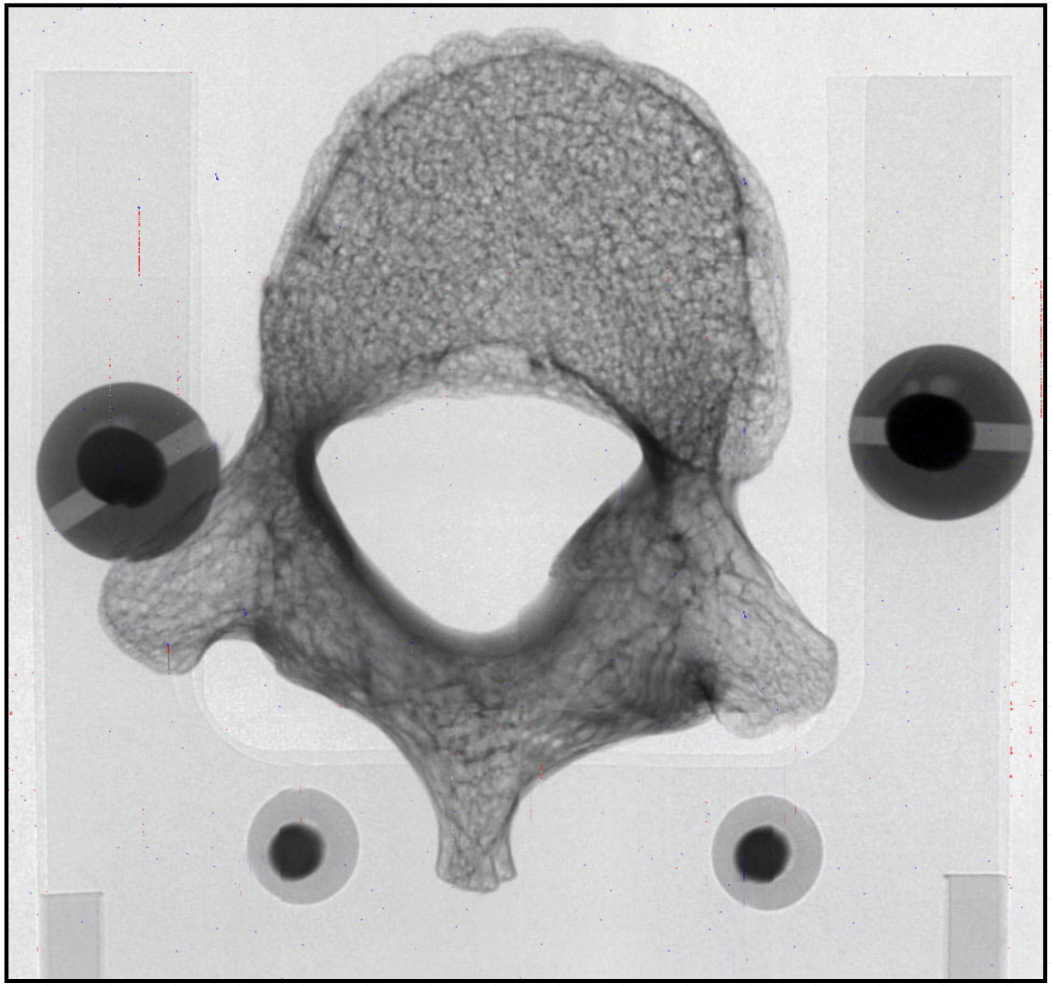

Object is too large
=> Scan performed
(2 x 2 frames)

Neutron microtomography

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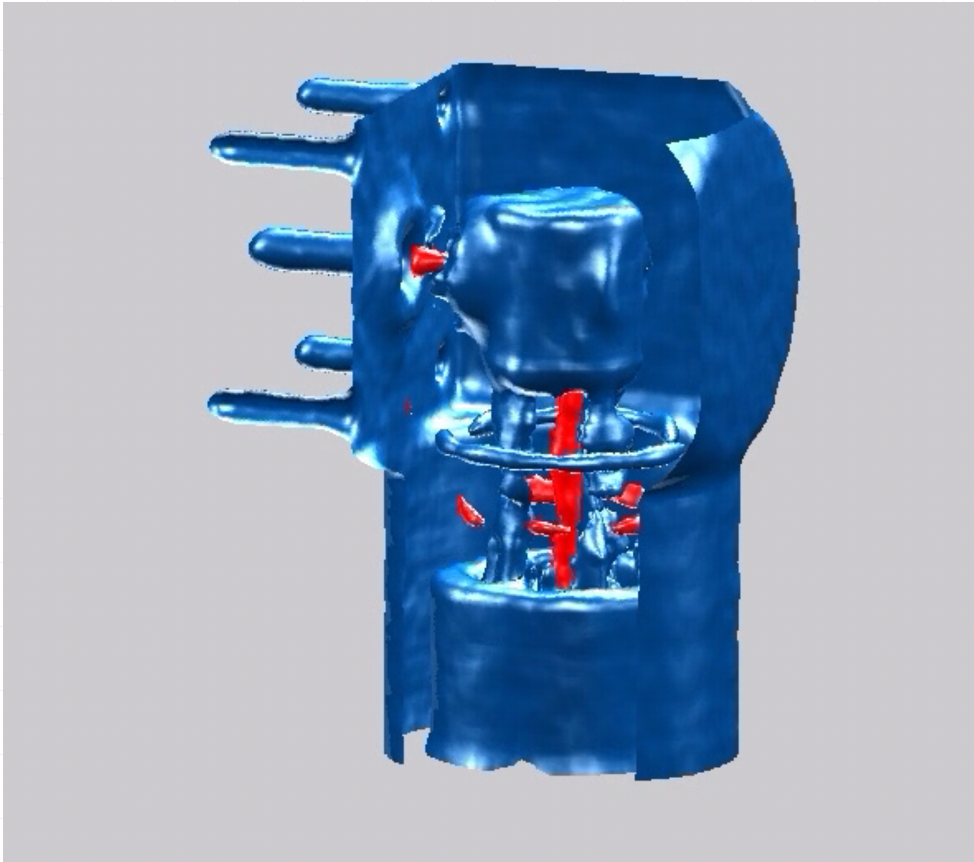
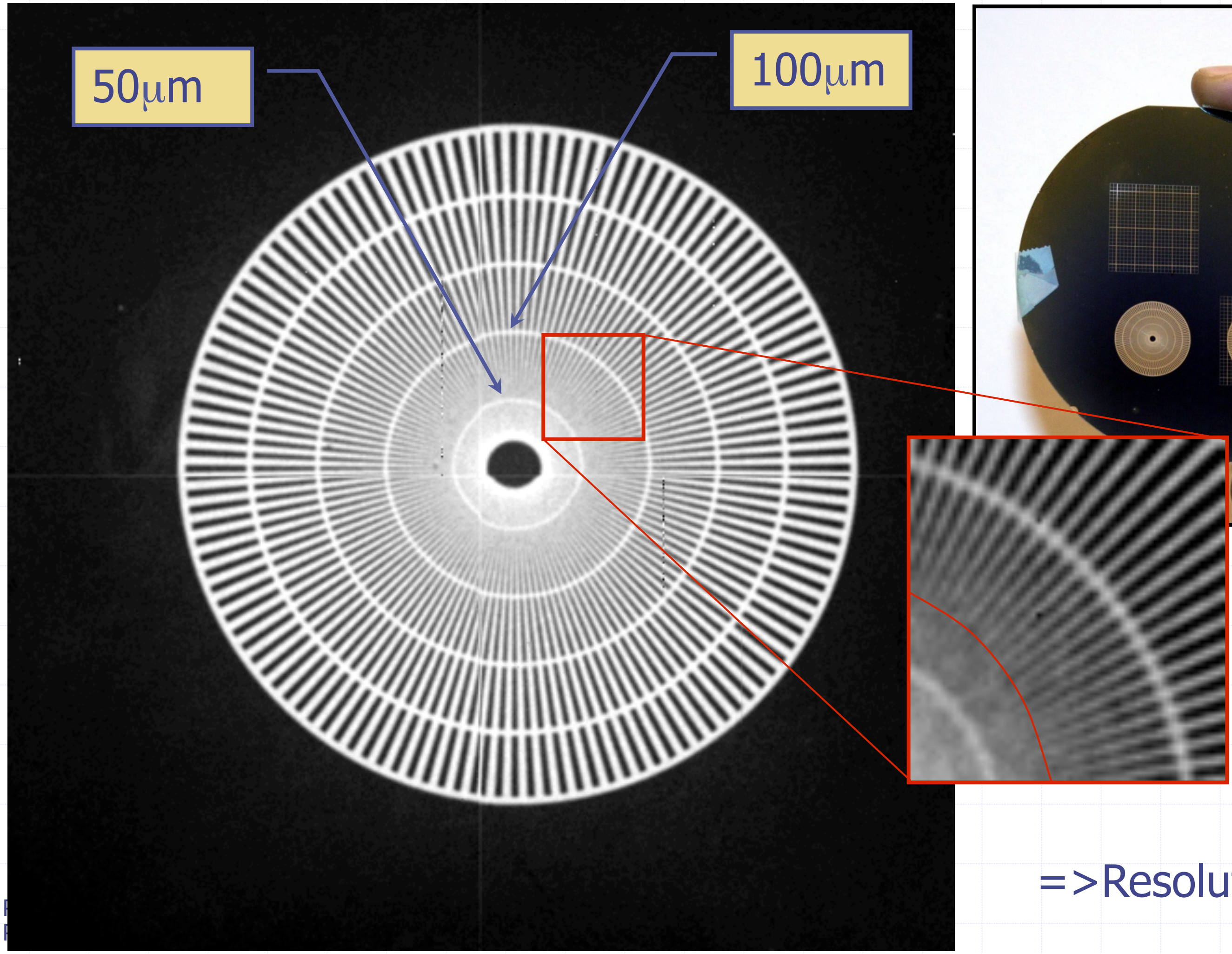
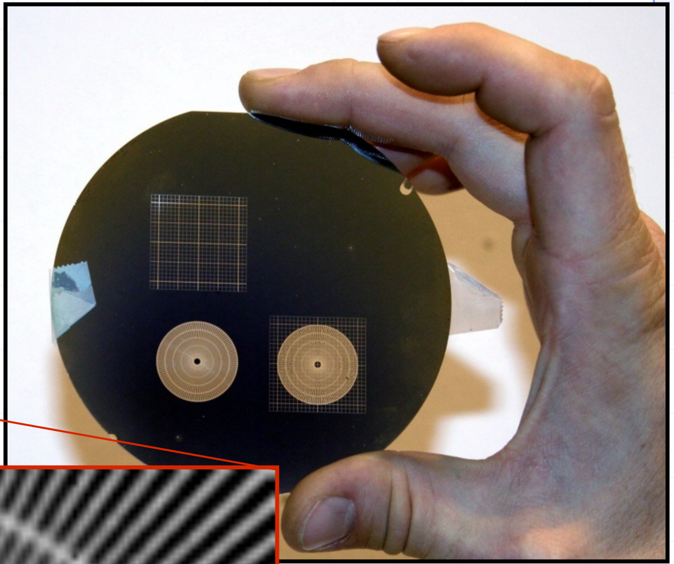
Lemo connector
Golden contacts inside

Taken 100 projections
150 seconds each.
Reconstruction using filtered back-projection algorithm.



Test of Spatial Resolution
(Medipix2 Quad system and cold neutrons)





=>Resolution about 65μm!

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About noiseless single particle detection and track

Tracking mode of pixel detector operation

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

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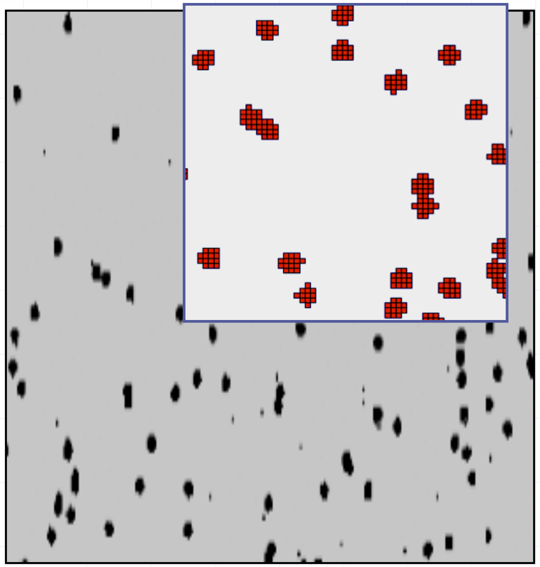

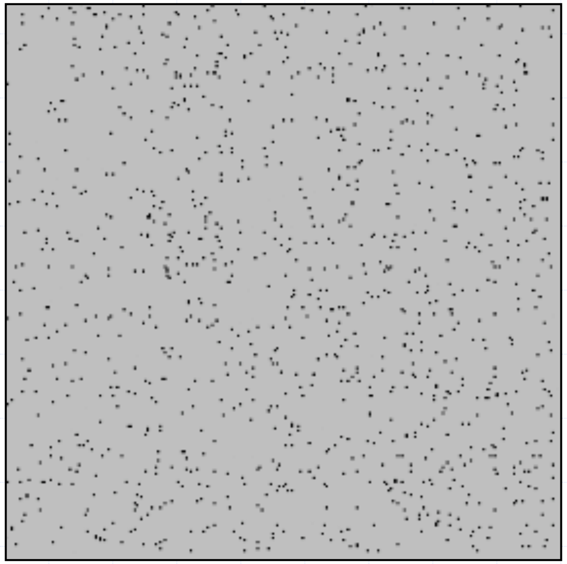

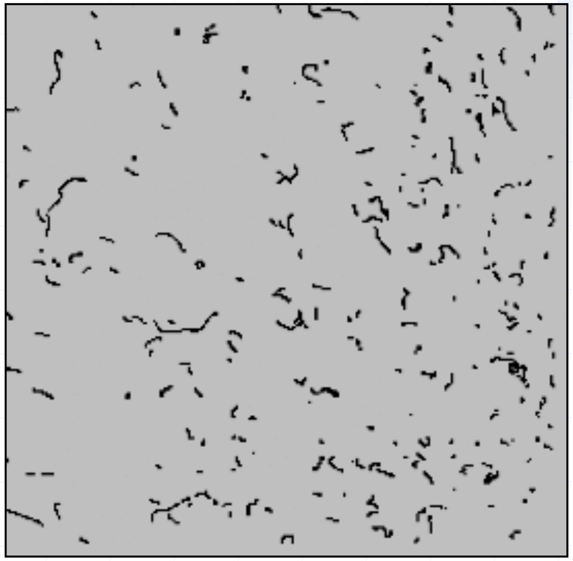

- ^{241}Am alpha source gives clusters of ~5x5 pixels measured with the MEDIPIX-USB device and a 300 μm thick silicon sensor. The clusters are shown in detail in the inlet. The cluster sizes depend on particle energy and threshold setting.
- Signature of X-rays from a ^{55}Fe X-ray source. Photons yield 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.

Response of Medipix2 device to natural background radiation

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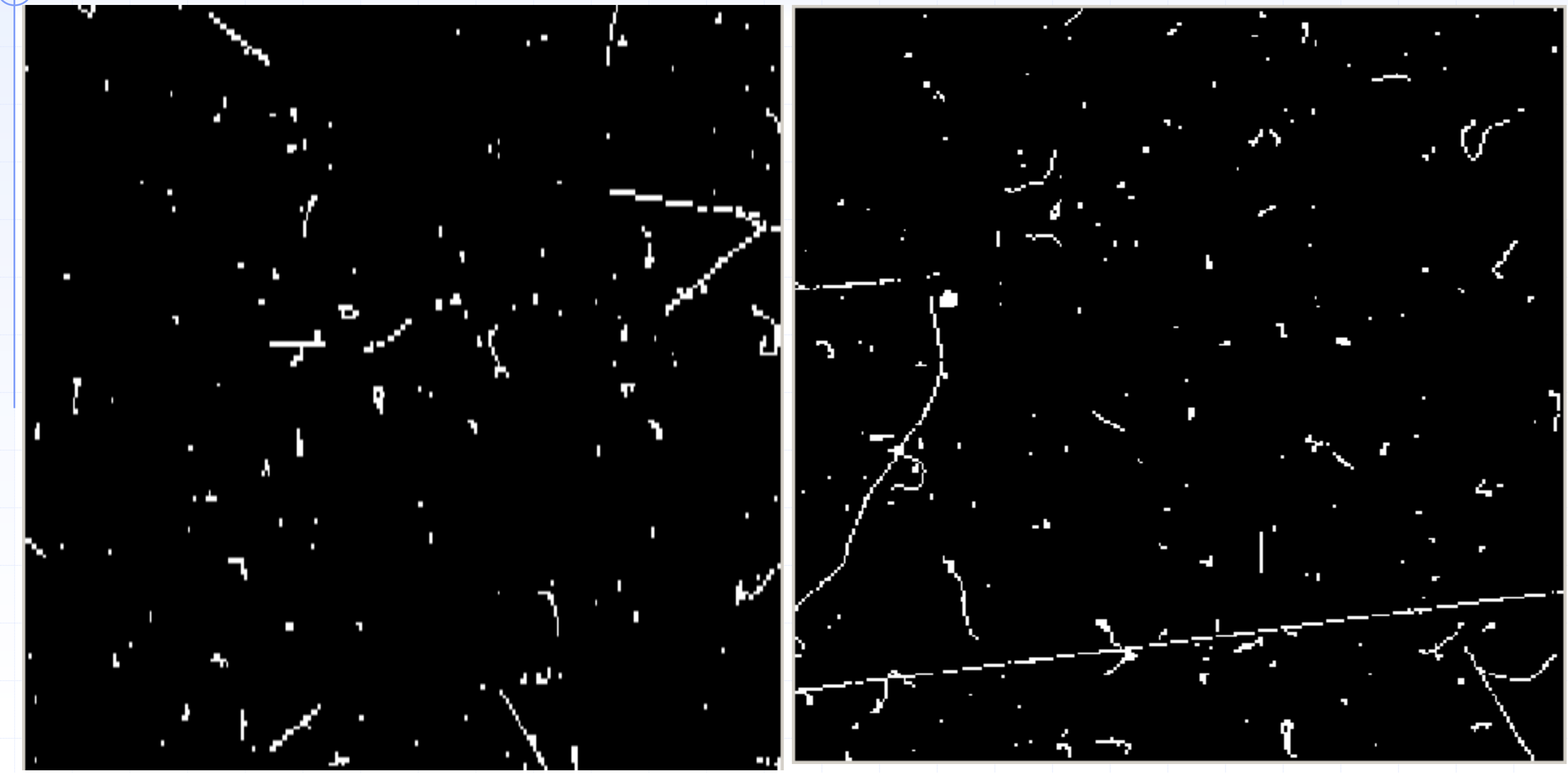

Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, … . Muon tracks can be recognized by submicrometric precision.

Charge sharing effect - clusters

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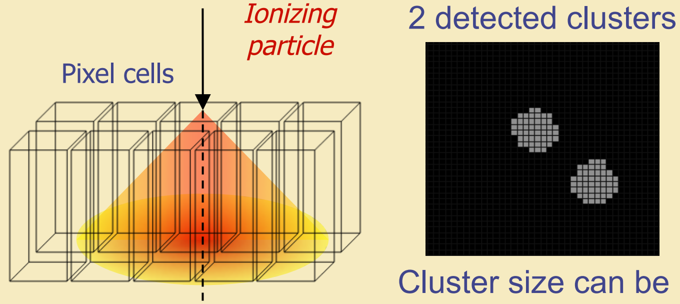
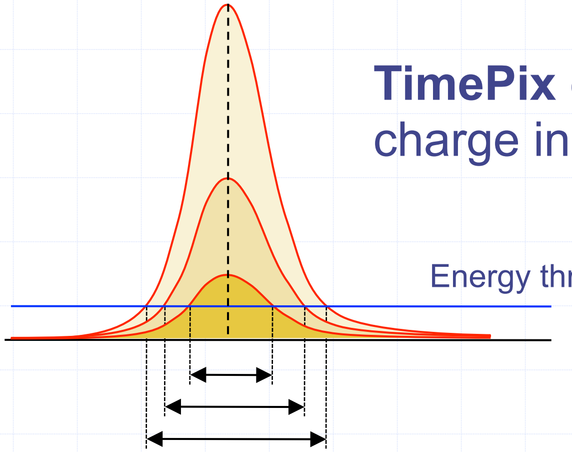
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => **CLUSTER**
- Pixels in a cluster will detect the charge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

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



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)



TimePix can measure charge in each pixel

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

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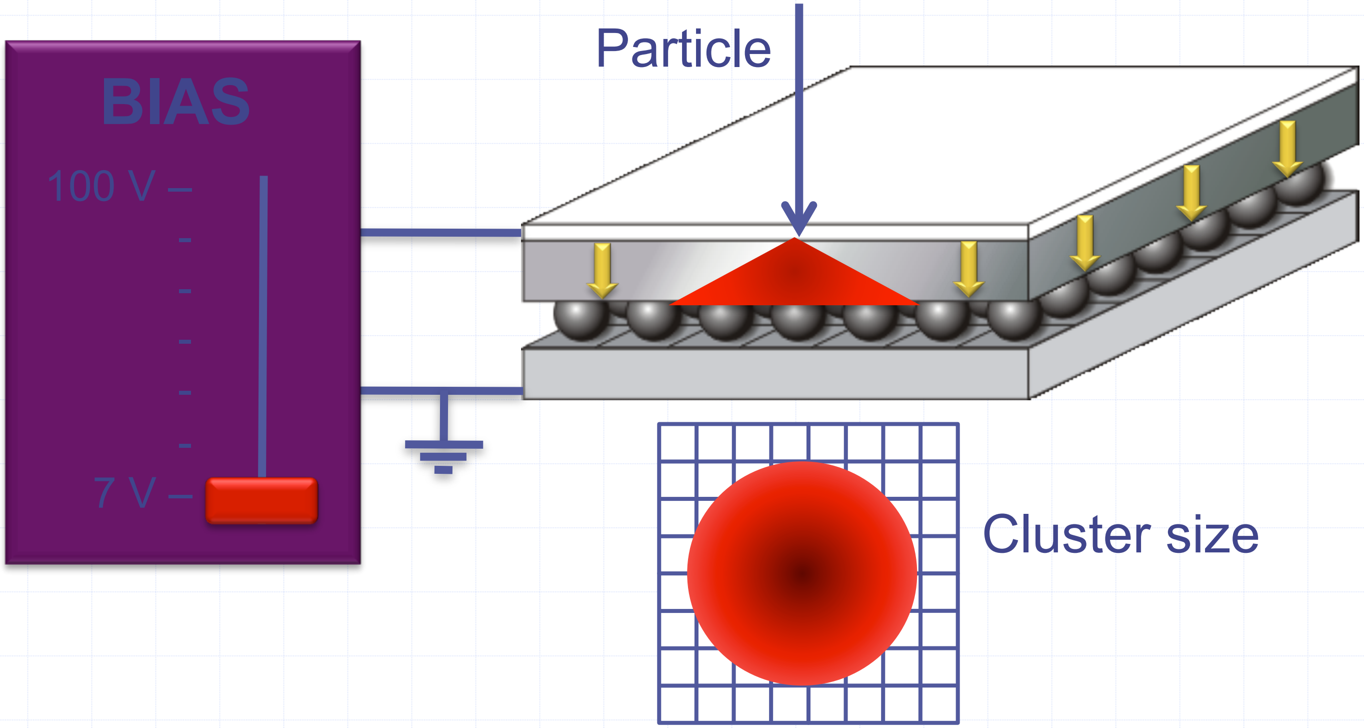
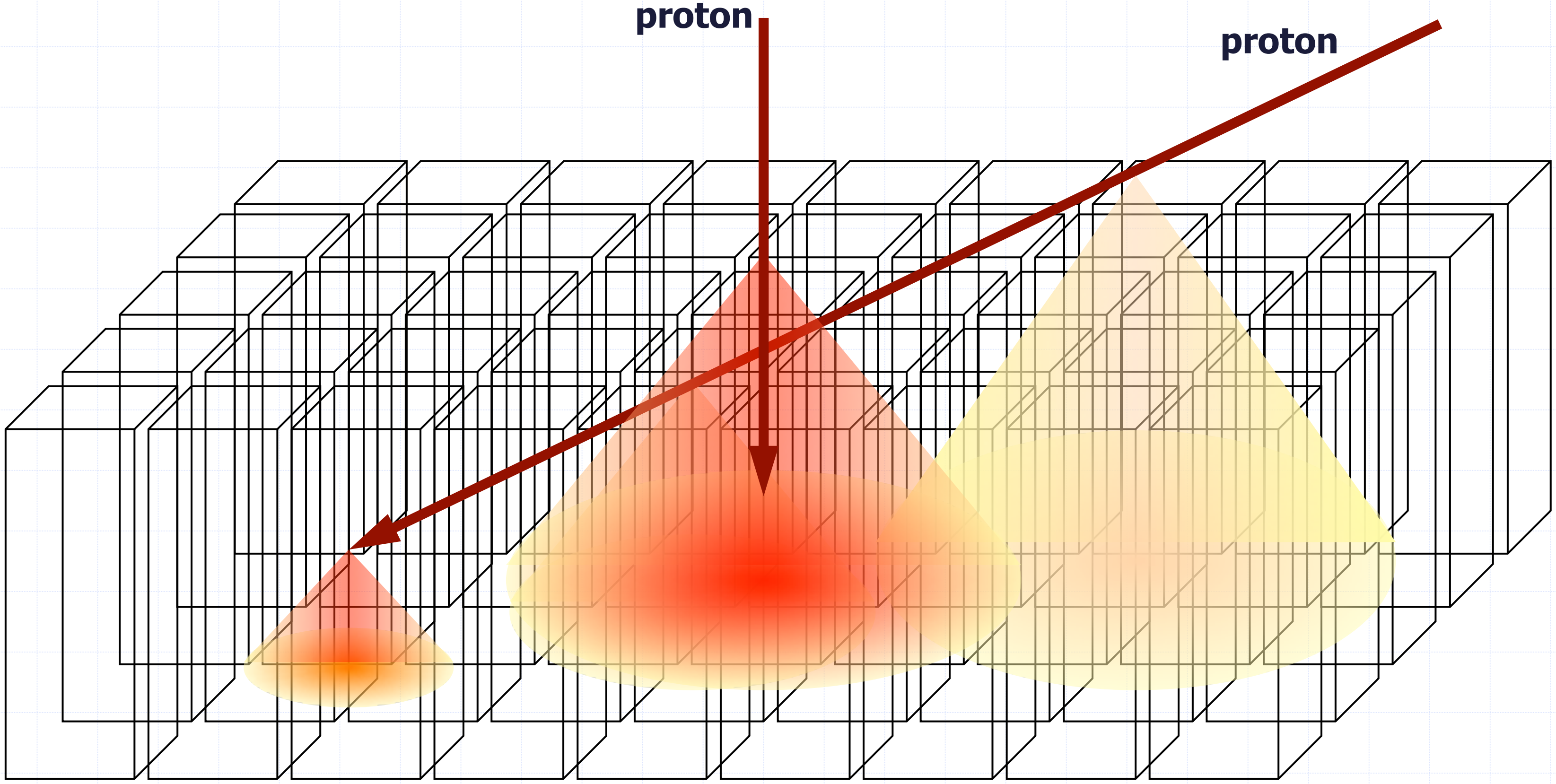


Expected charge sharing in Timepix sensor illuminated by 4.93MeV protons under different angles and different applied bias



Flights of 4.93MeV protons entering back side of Timepix sensor at 0°(perpendicularly) and at 76° (from right to left)

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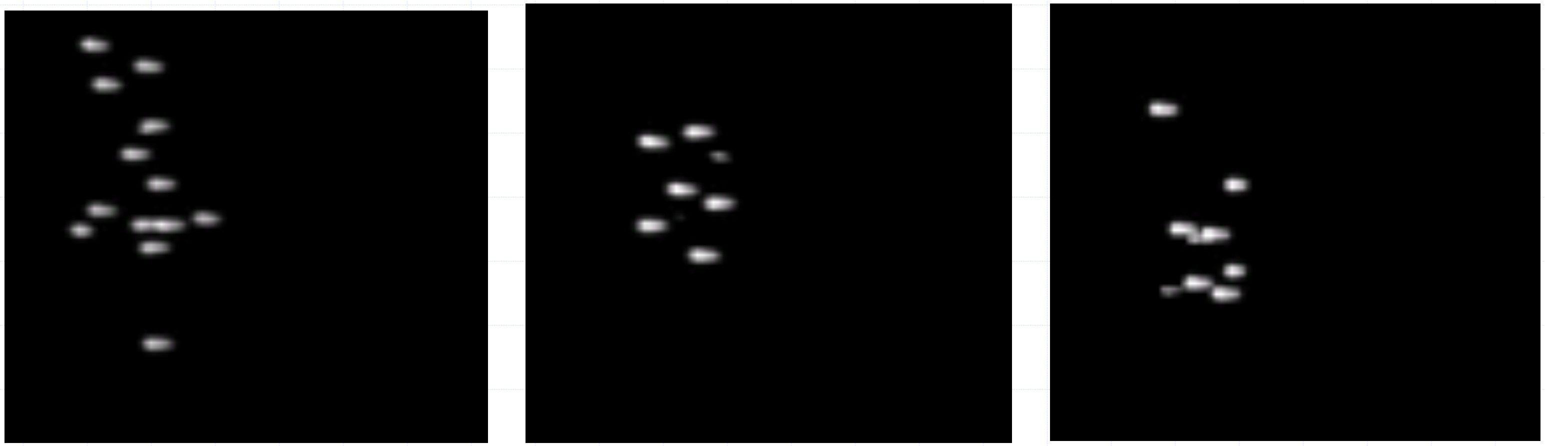
0°

76°



3D-visuallization of proton tracks in silicon pixel detector recorded by Timepix device. Illumination under different angles and different applied detector biases.

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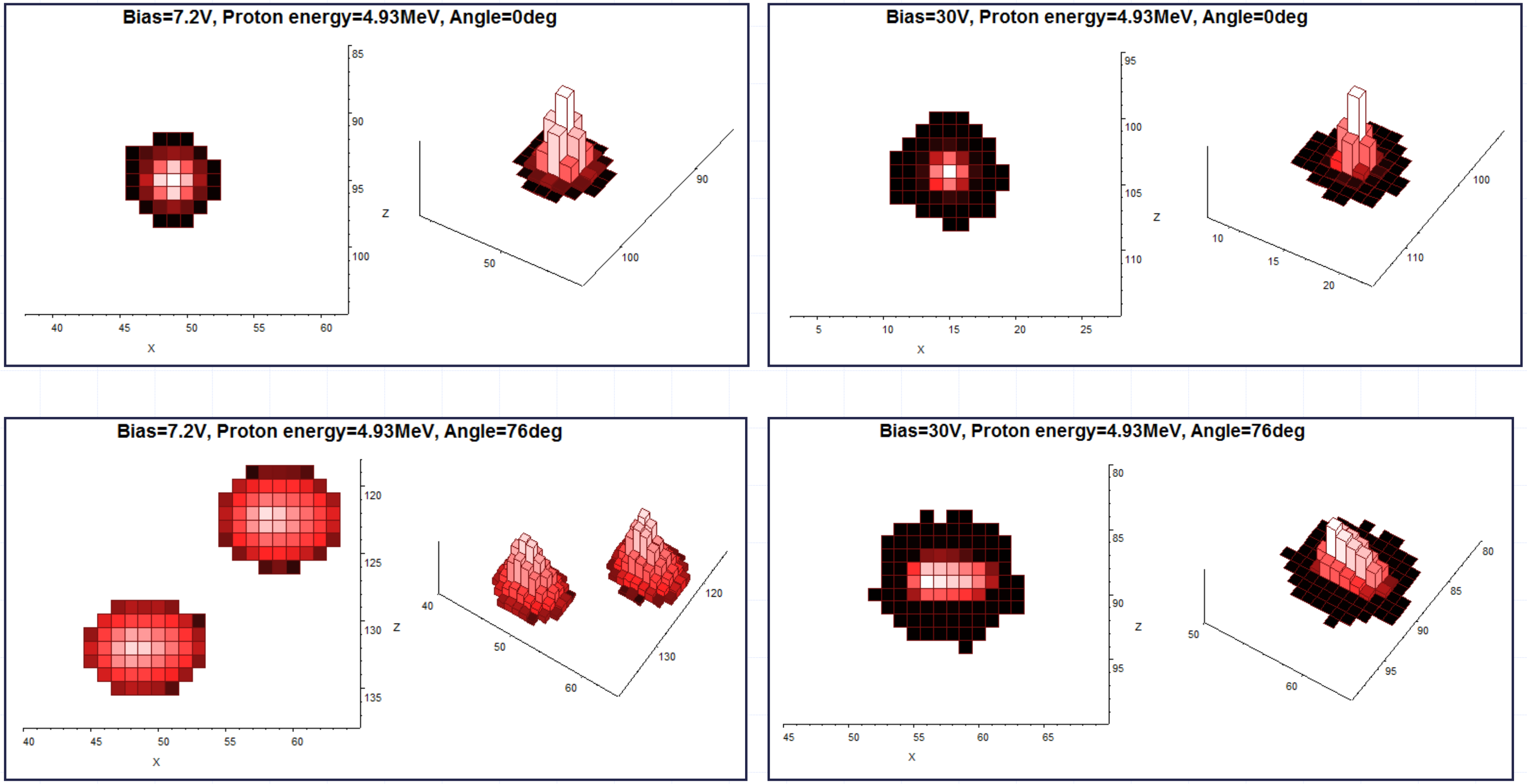
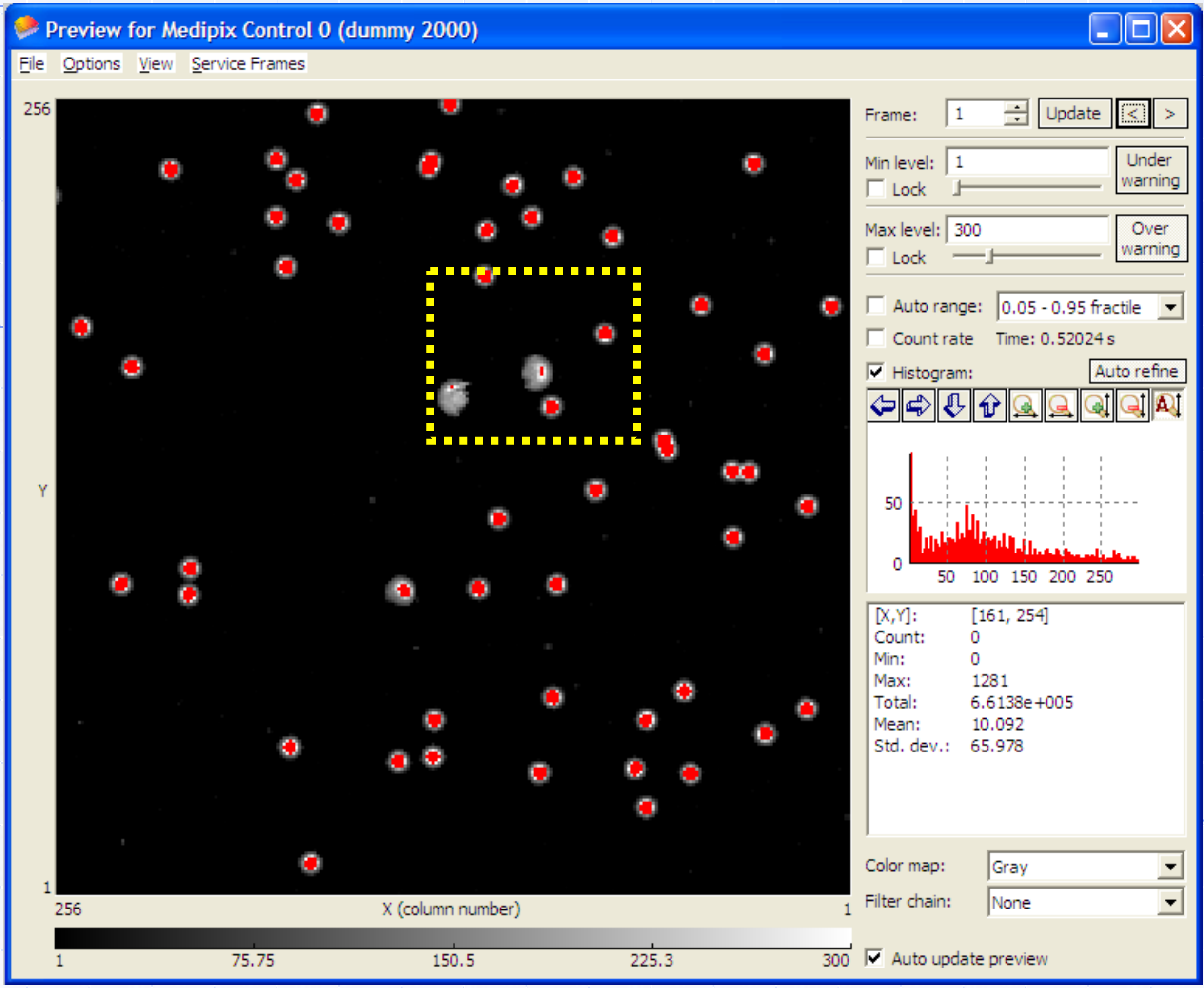


What is the spatial resolution? X- and Y-coordinates are determined with a precision of about 500nm. Determination of angle is with a precision of about 1°. It needs additional experiments.

Response of TimePix damaged regions to 5.9 MeV α's (^{244}Cm)



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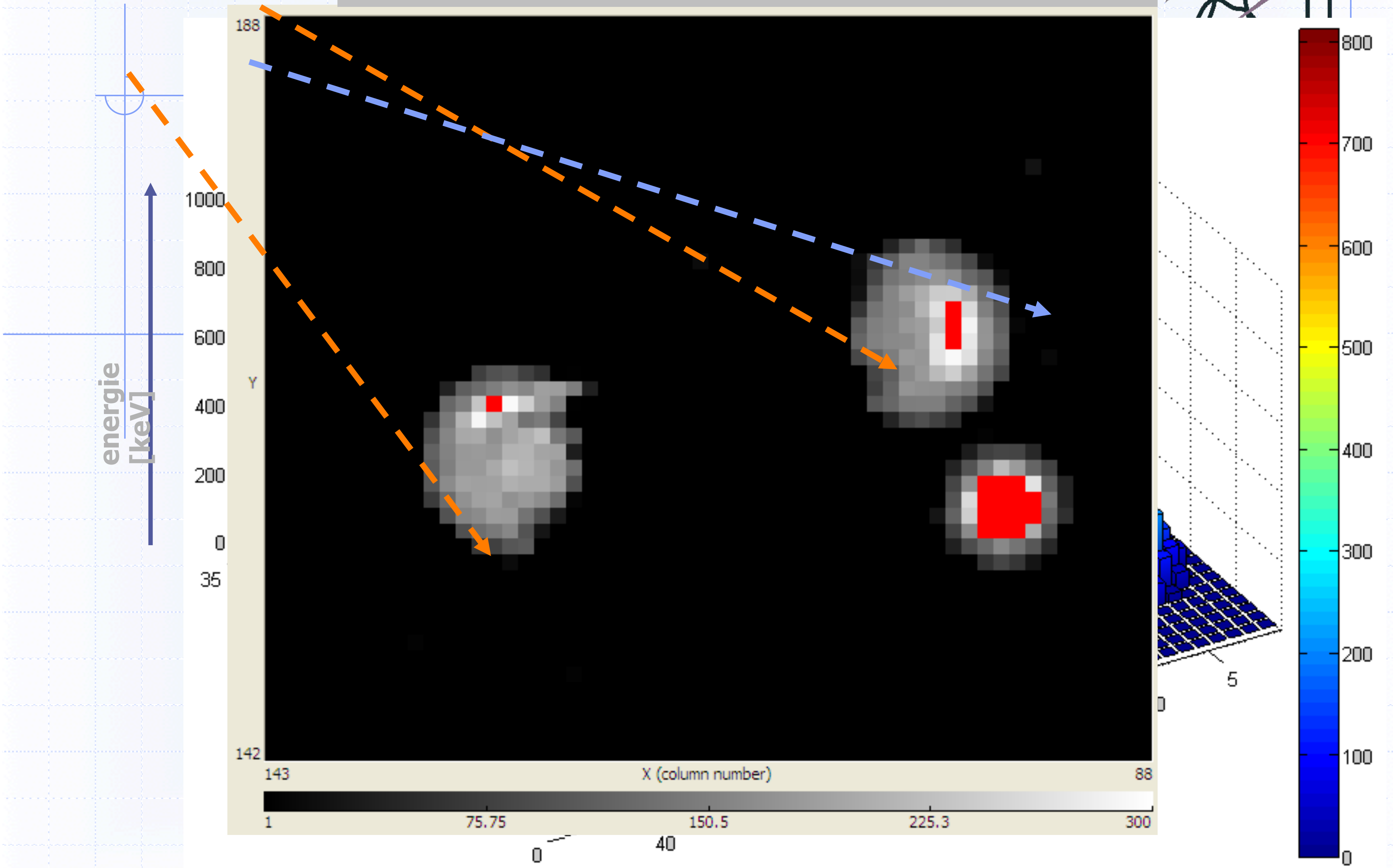
Response of TimePix damaged regions to 5.9 MeV α's (^{244}Cm)



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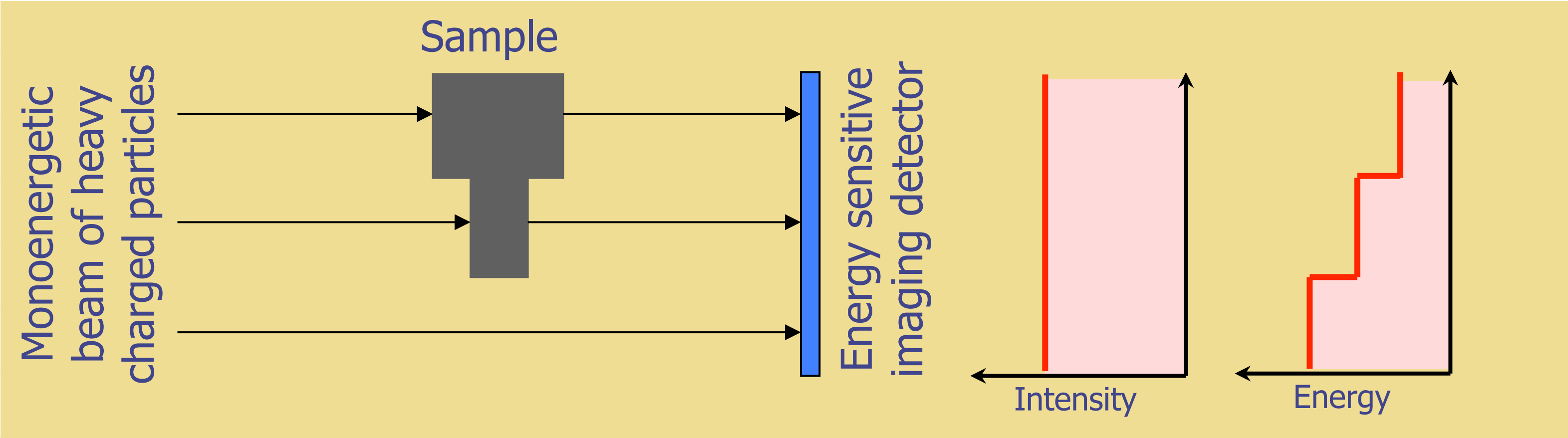
Application:

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:

Simple example 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)

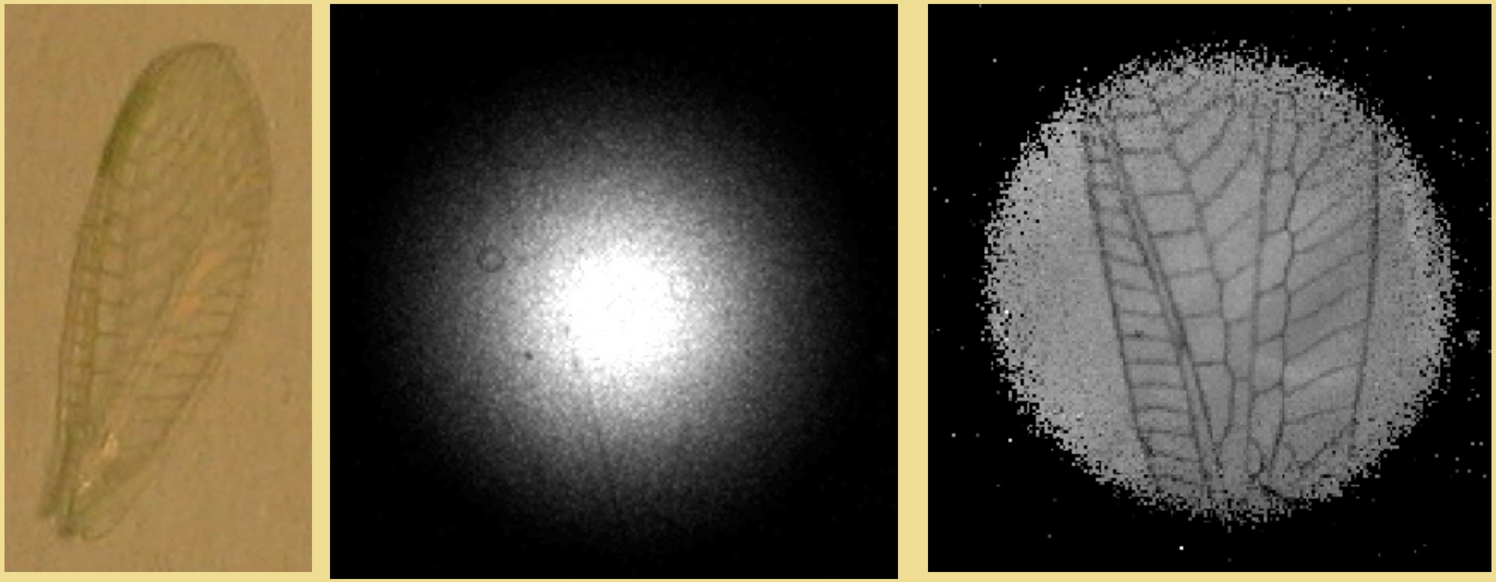

Photo Intensity Energy

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

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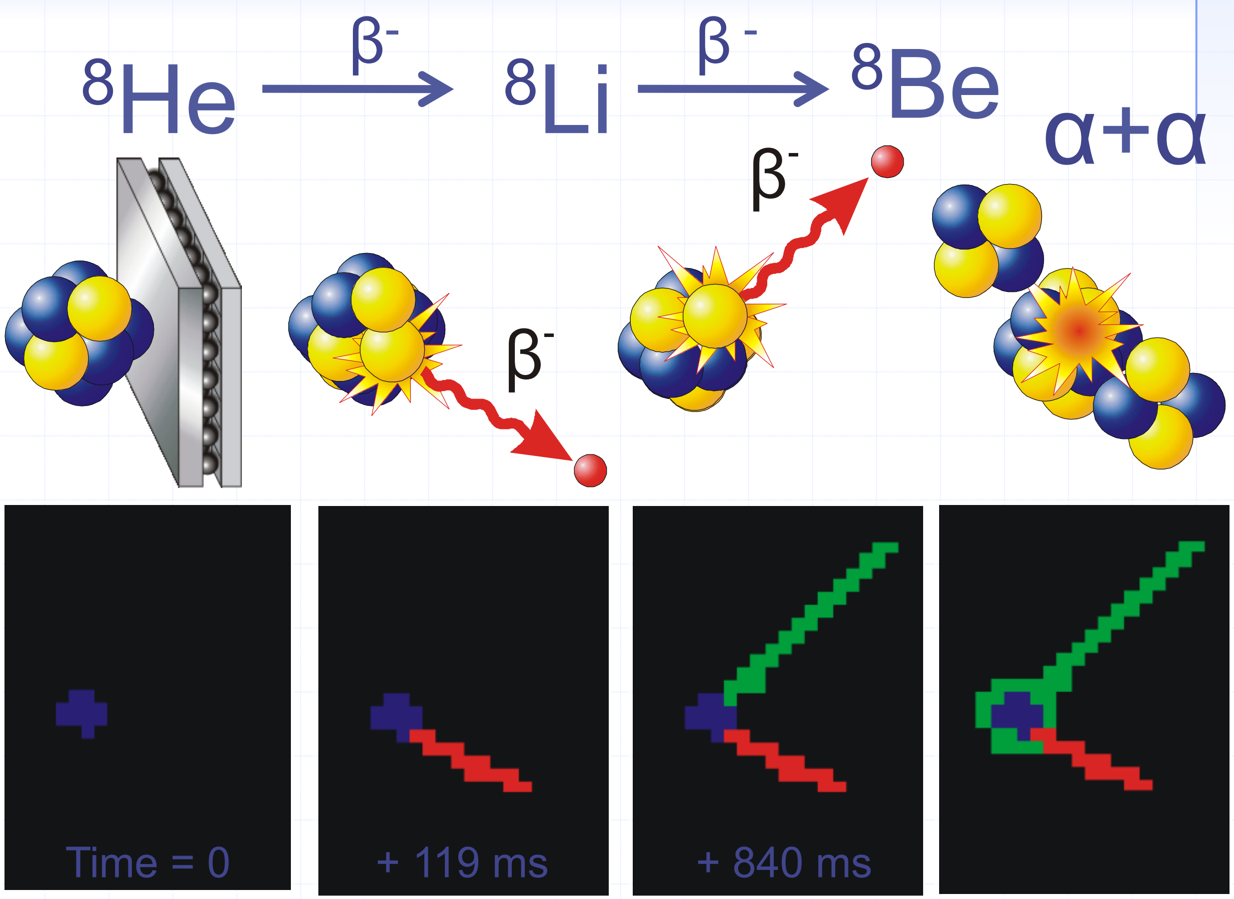
^{8}He ion hits the Timepix sensor where undergoes β-decay

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



Observation of decays of individual atomic nuclei in short times (≤ milisecond)

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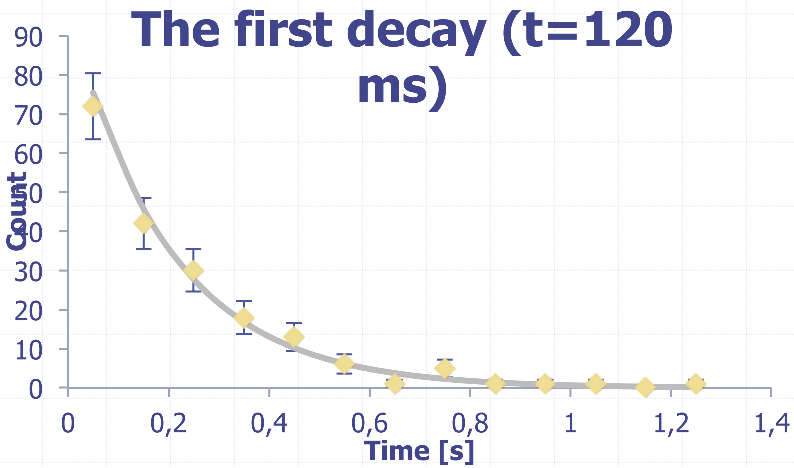

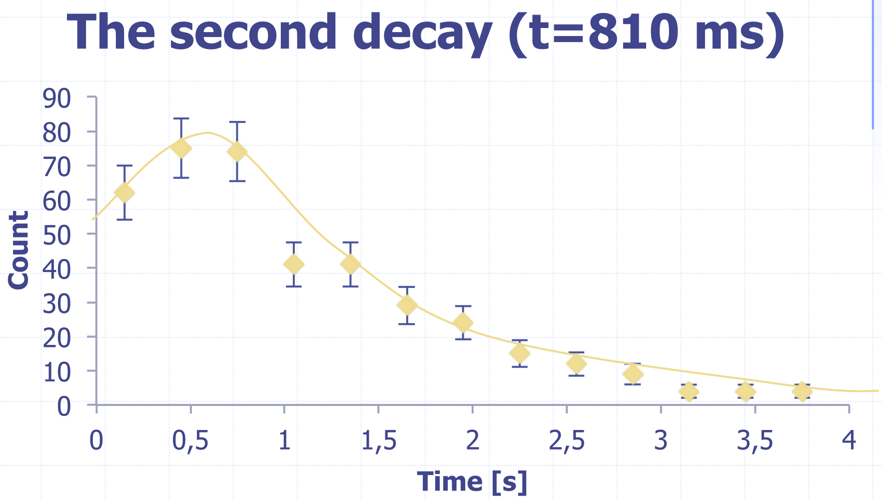

Time and spatial coincidence technique permits:
- observation and measurement of decay of individual nucleus
- in range from microseconds to seconds (and longer).

One can exactly observe what has happened in well known position of semiconductor and when. What about SEE studies?

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

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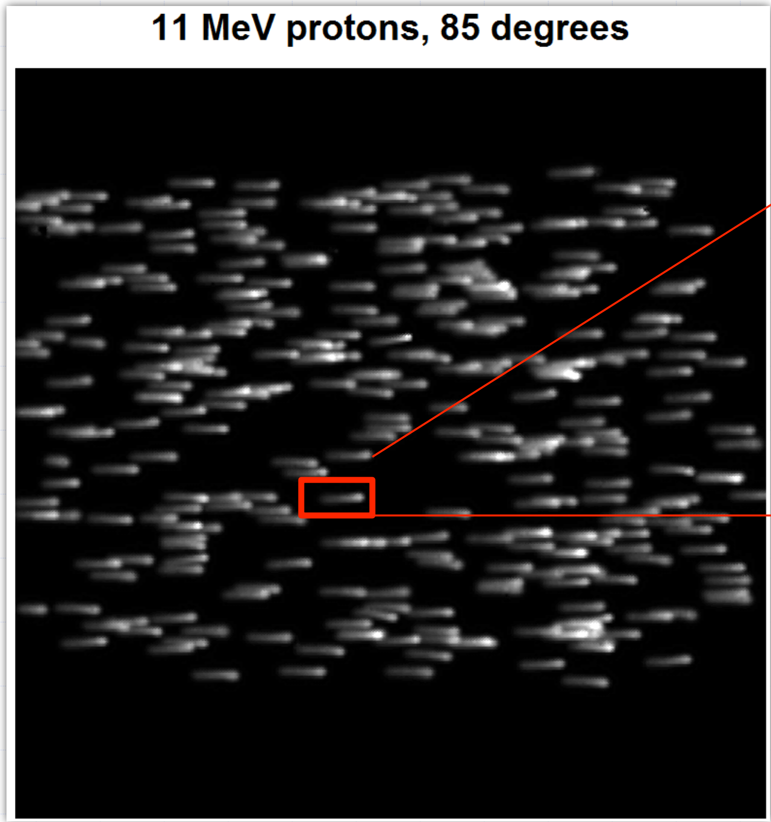
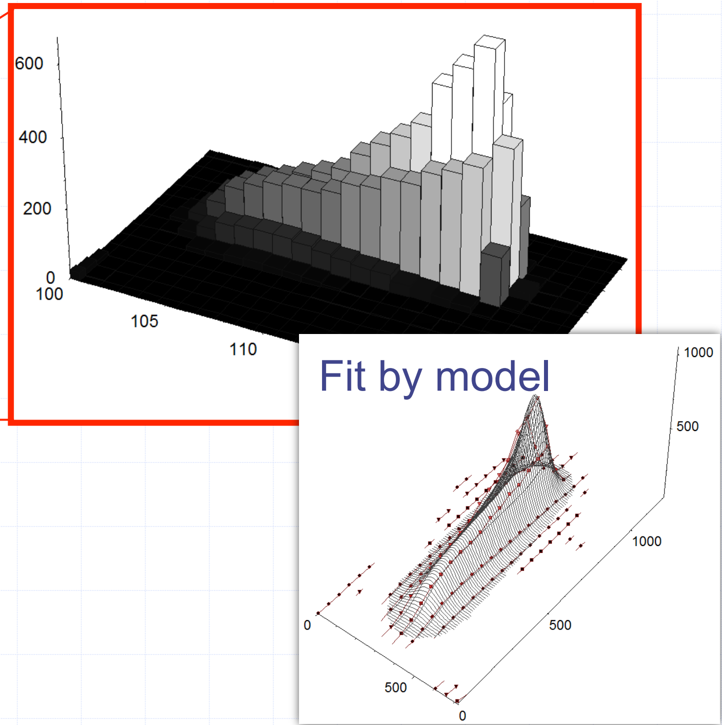


ΔE/Δx Bragg profile nicely pronounced, proton range about 960 μm



Typical observed tracks of particles used for hadron therapy beam

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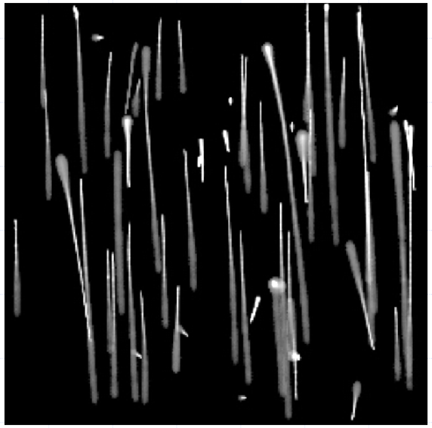
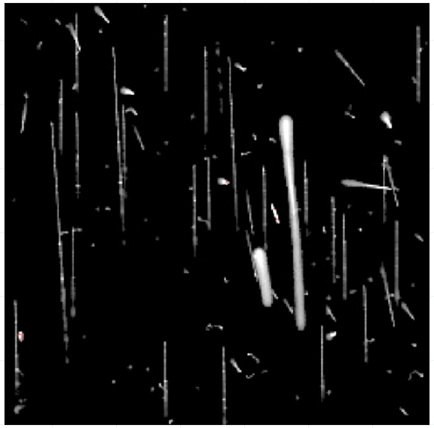
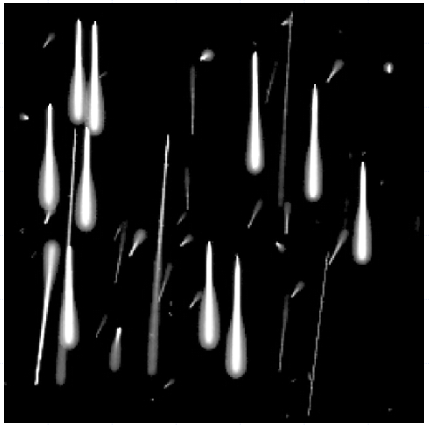
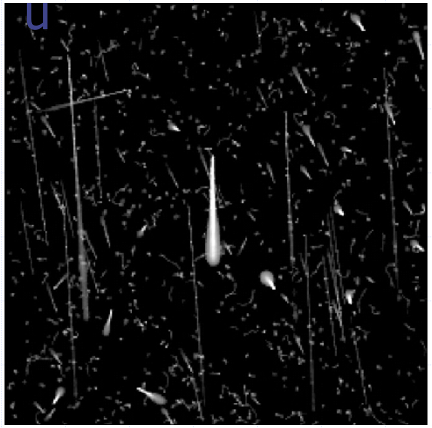
Protons 48 MeV	Protons 221 MeV	Carbons 89 MeV/u	Carbons 430 MeV/u
			
Only protons and their scattering, no secondaries.	Many secondaries, (delta electrons fragments).	Carbons and protons and their scattering, no secondaries.	Carbons and many secondaries.

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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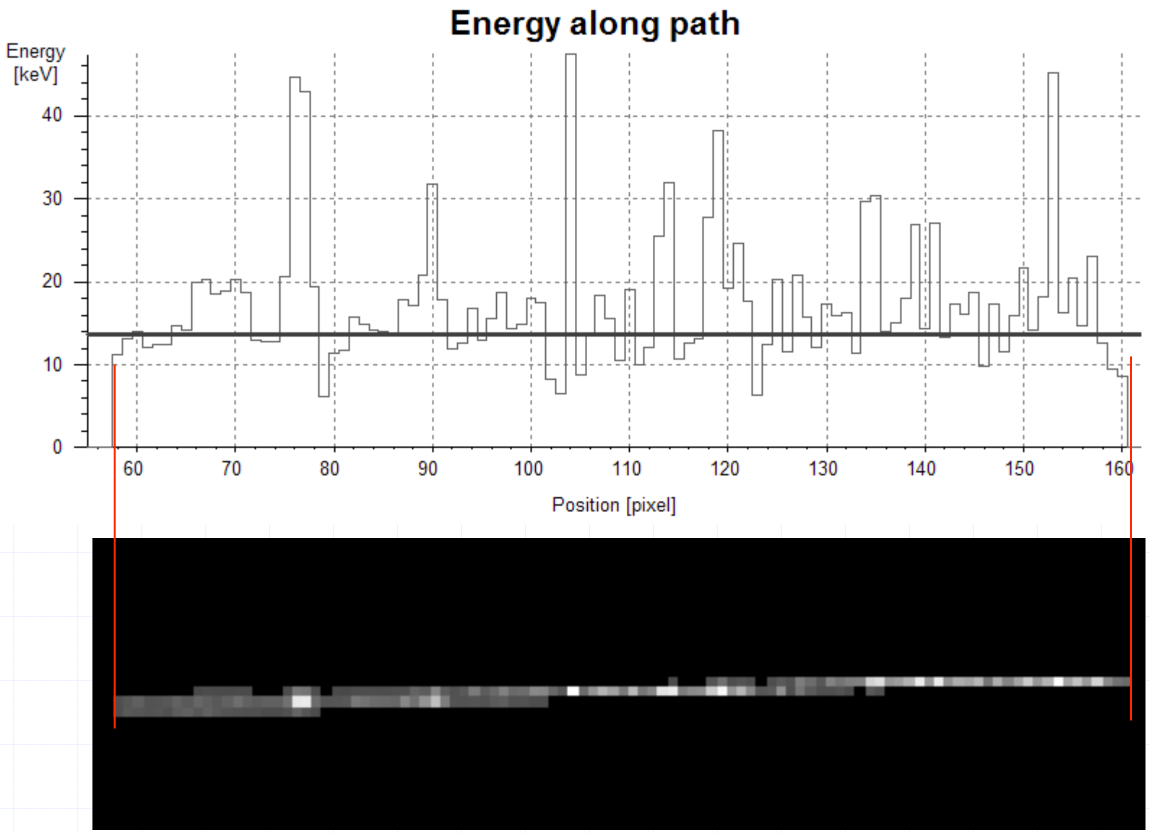
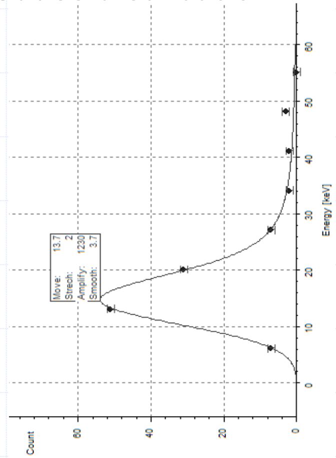
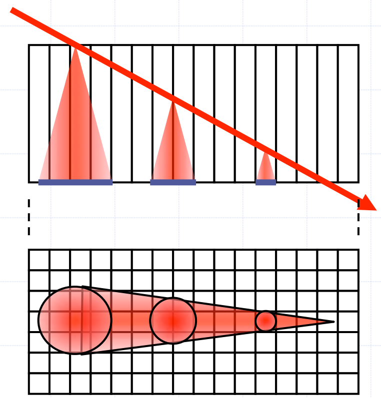


Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





Detailed visualization of interactions in the Silicon sensor

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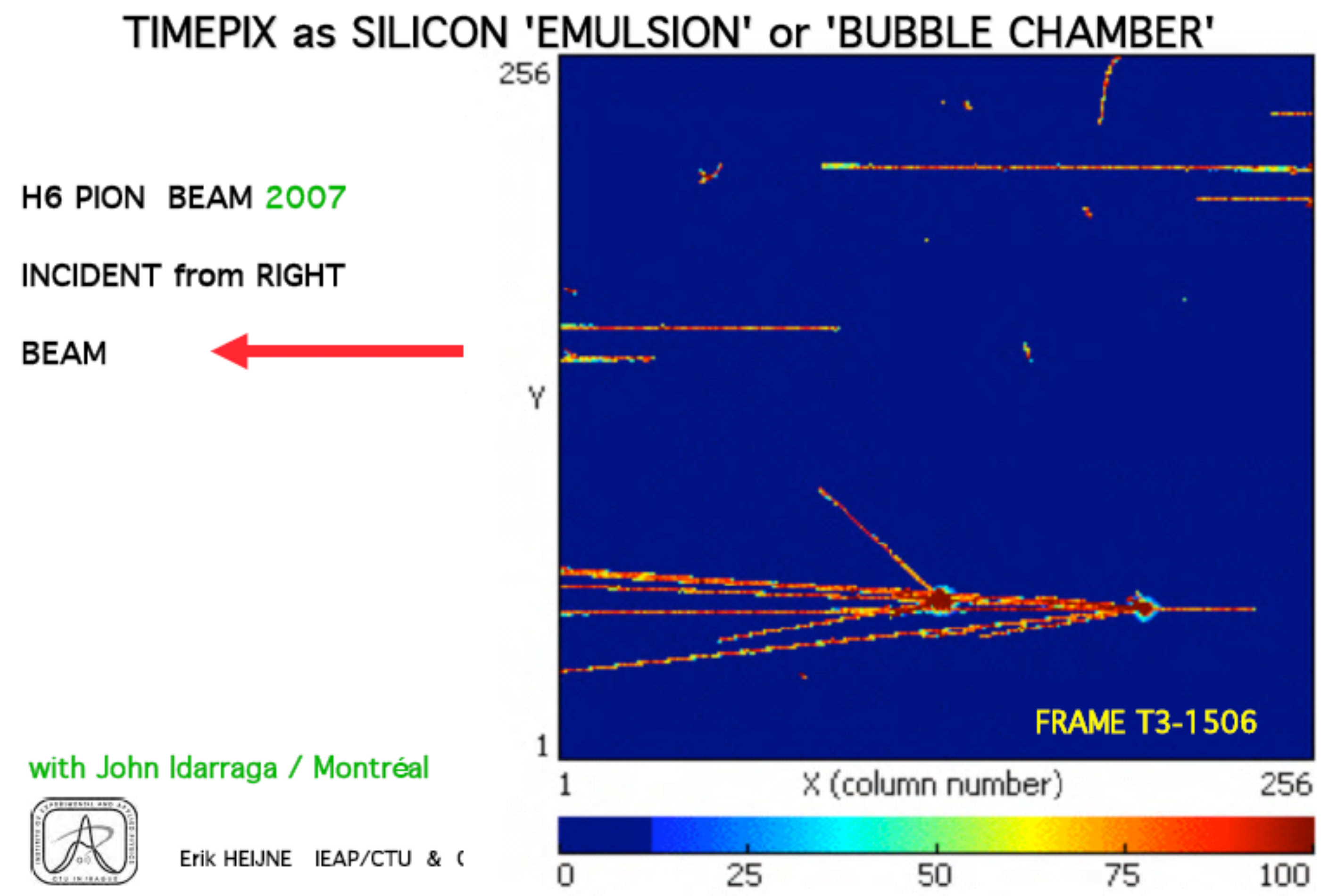

Relativistic Ions @ small (grazing) angles

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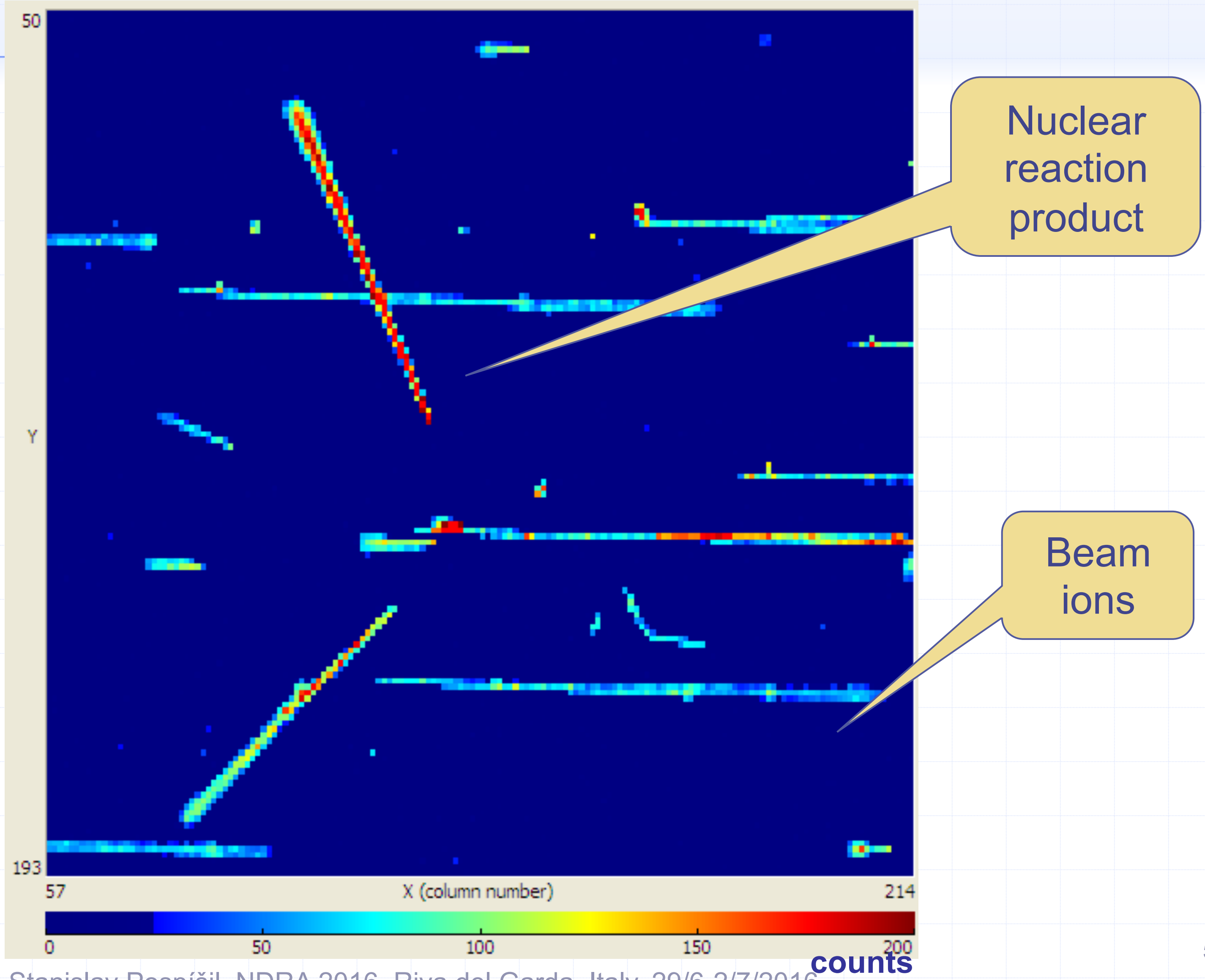
^{2}H

angle = 3°



Timepix exposed in flight over Atlantic (Santiago-Madrid)

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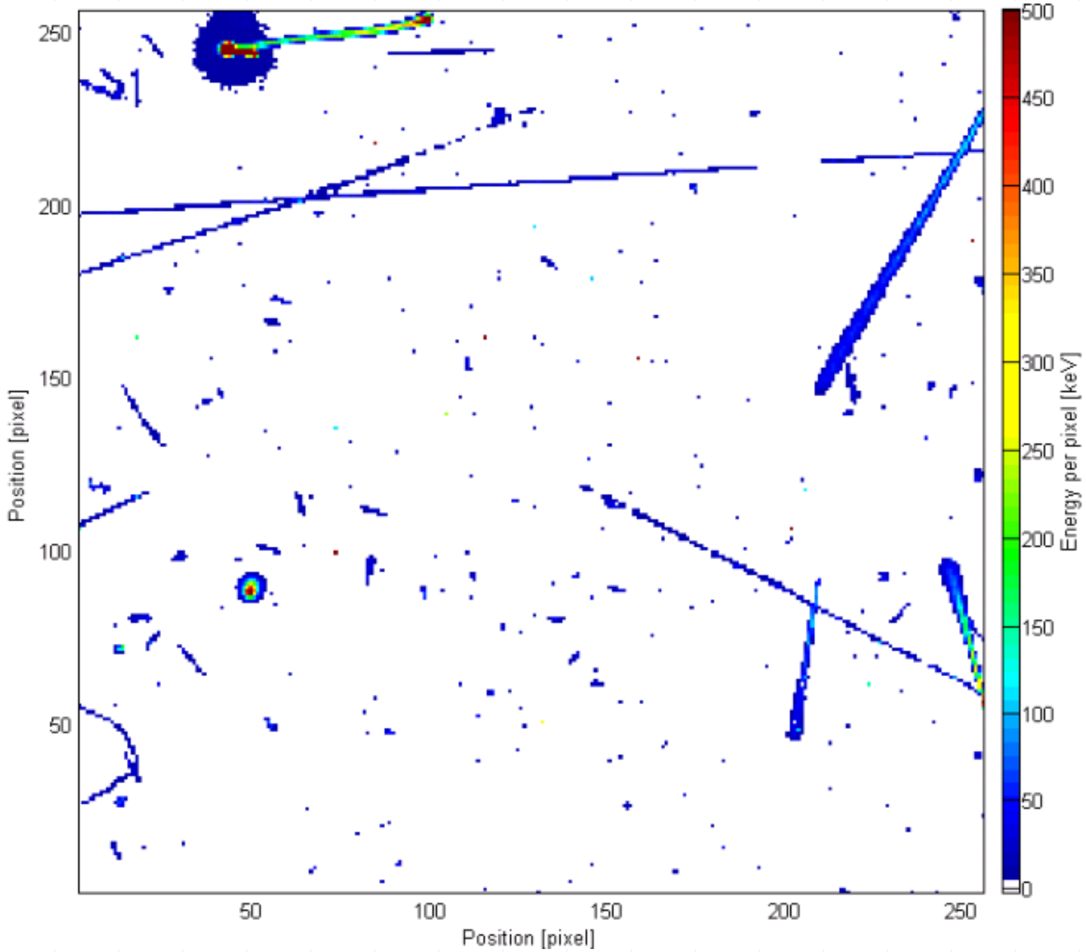

Response of Silicon diode with CH_2 converter to 4.2 MeV neutrons

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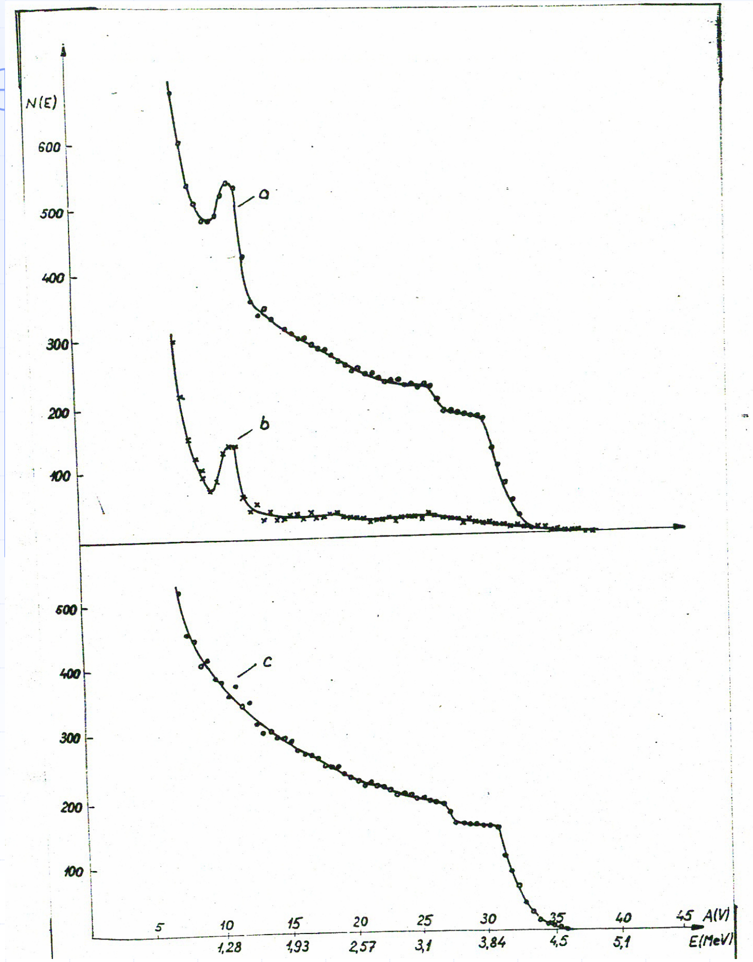
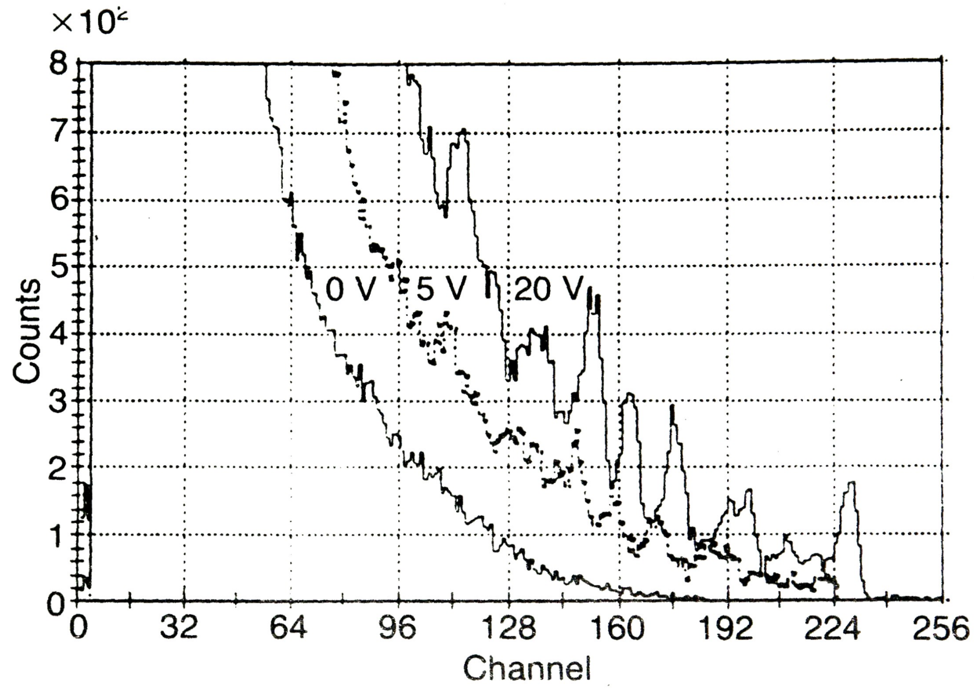


a) Silicon diode with CH2 converter
b) Silicon diode without CH2 (background)
c) Pure spectrum of recoiled protons



Pulse height spectrum of Silicon diode 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 MEDIPIX-USB device with polyethylene converter (on the right hand side) to fast monochromatic neutrons (17MeV)

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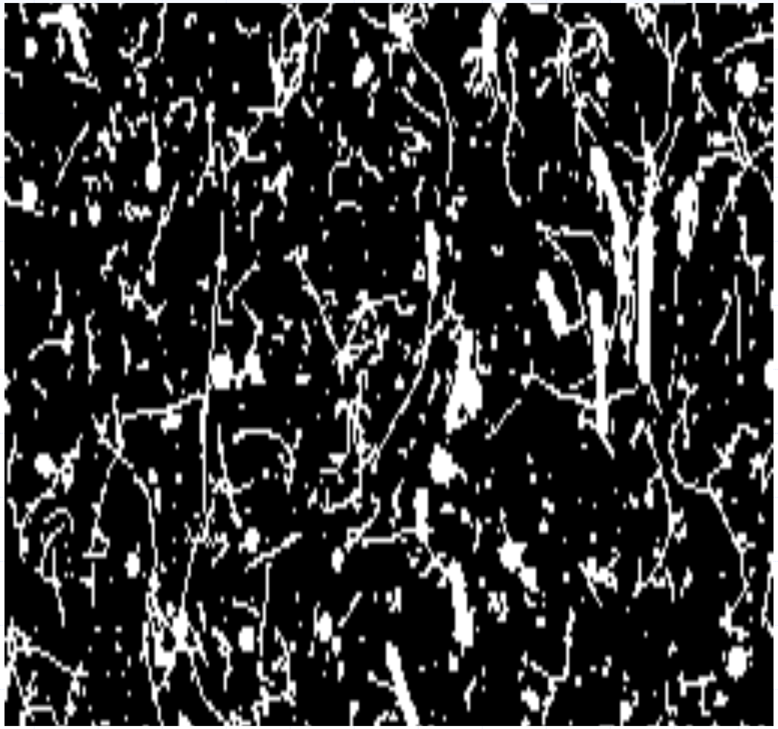

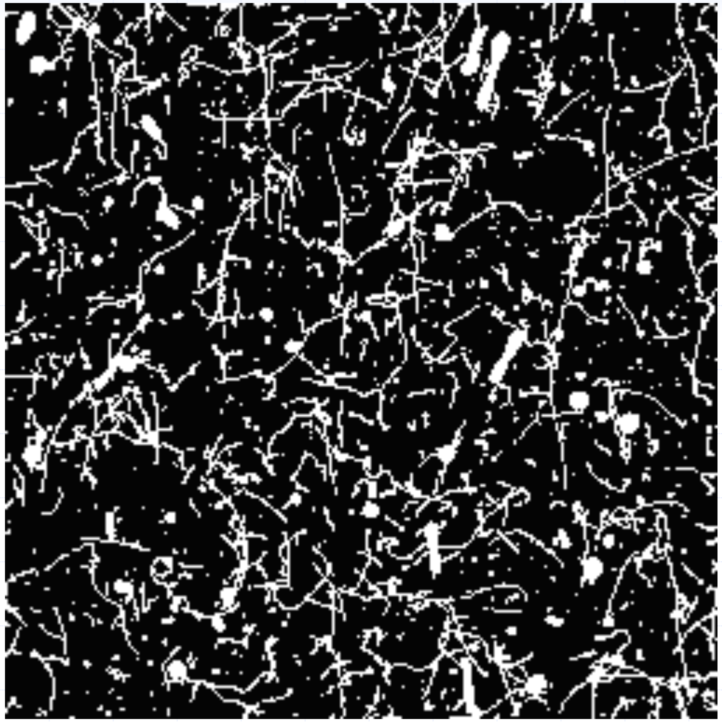

- The direction of the neutrons with respect to the image was upstream (from bottom to top). The huge background is due to gamma rays which accompany neutrons. Half of the sensor (the right-hand side) was covered with a CH2 foil about 1.3 mm thickness.
- One can clearly recognize long and rather thick 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.

Review of the characteristic patterns
Event by event processing

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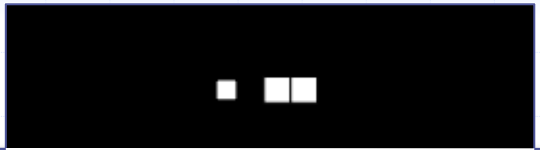
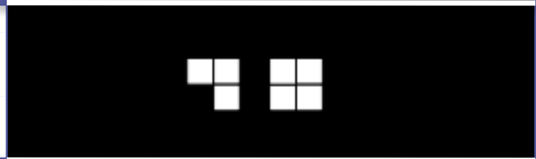
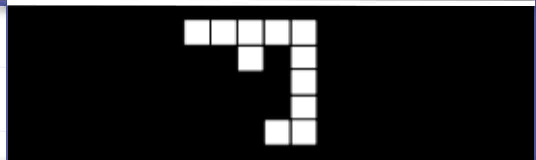
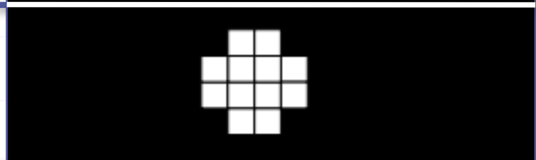
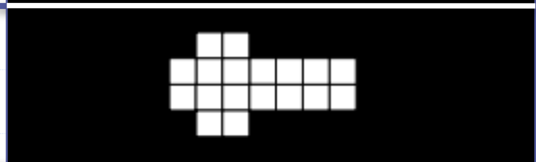
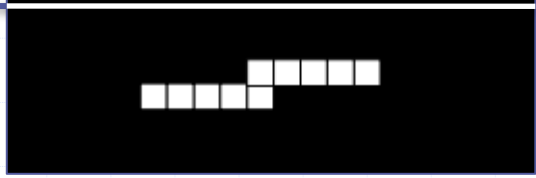
1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with low range (alpha particles,…)
5) Heavy track		Heavy ionizing particles (protons,…)
6) Straight track		Energetic light charged particles (MIP, Muons,…)

Track visualization – pattern recognition of interacting quanta and its energy

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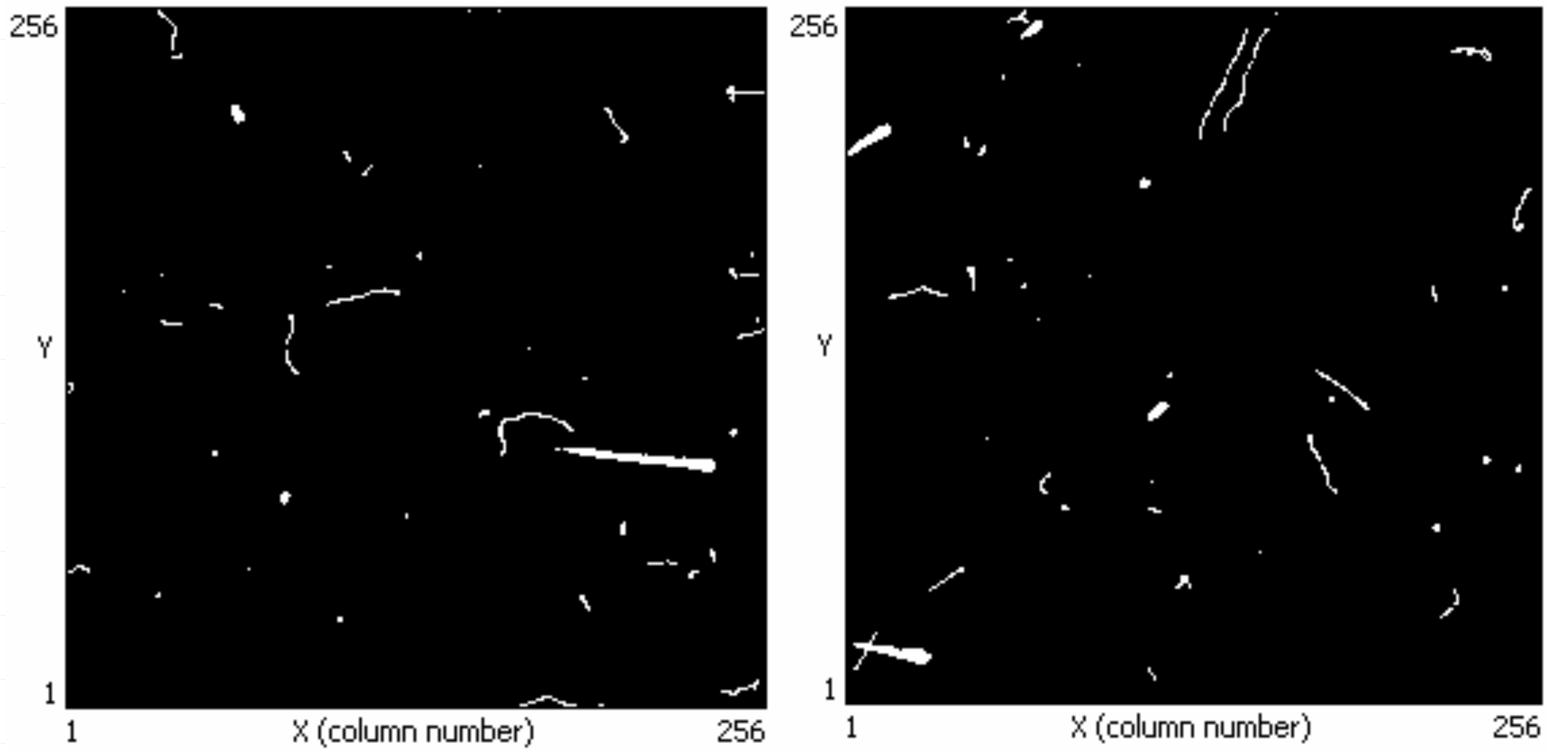

Medipix2 device with 700 μm thick silicon sensor
illuminated by fast neutrons (up to 30 MeV)

Track pattern recognition of interacting particle and its energy

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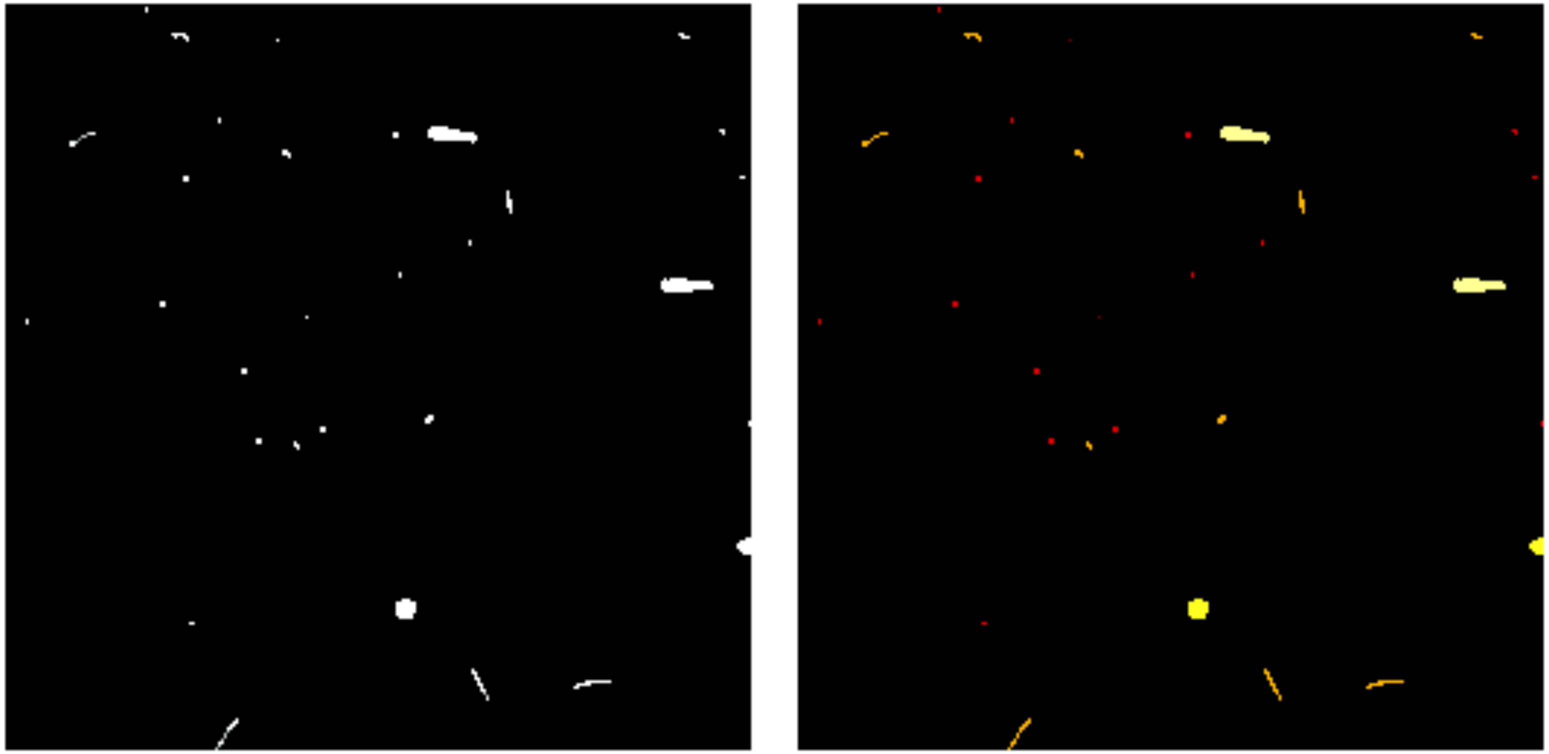

200 frames recognized in 1 sec on standard PC (courtesy of Tomas Holy)

Detail view on conversion layers

added for a neutron detection in mixed radiation fields

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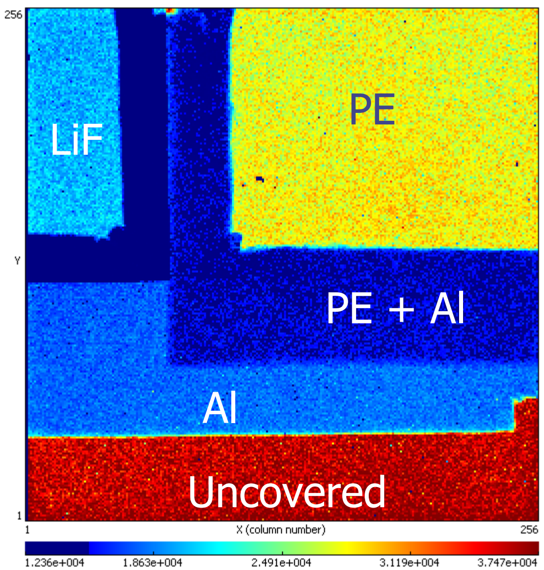
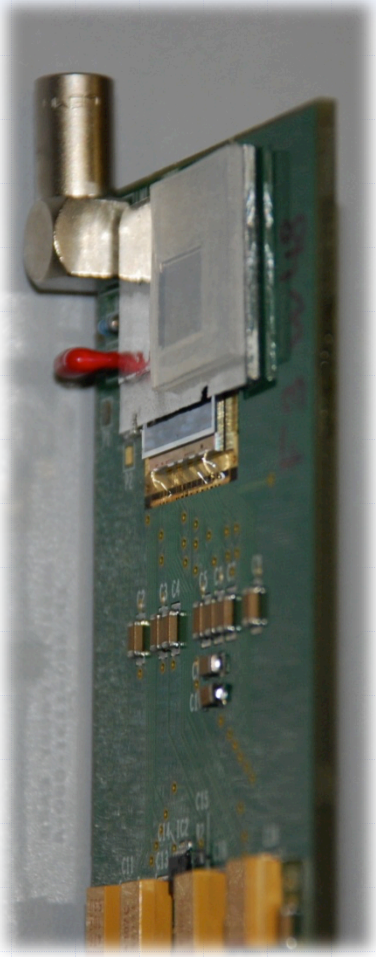
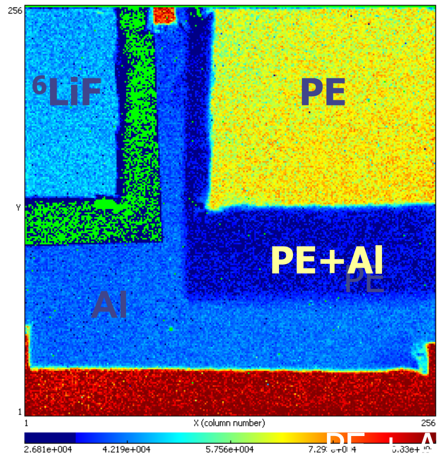
Several different regions:

- 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



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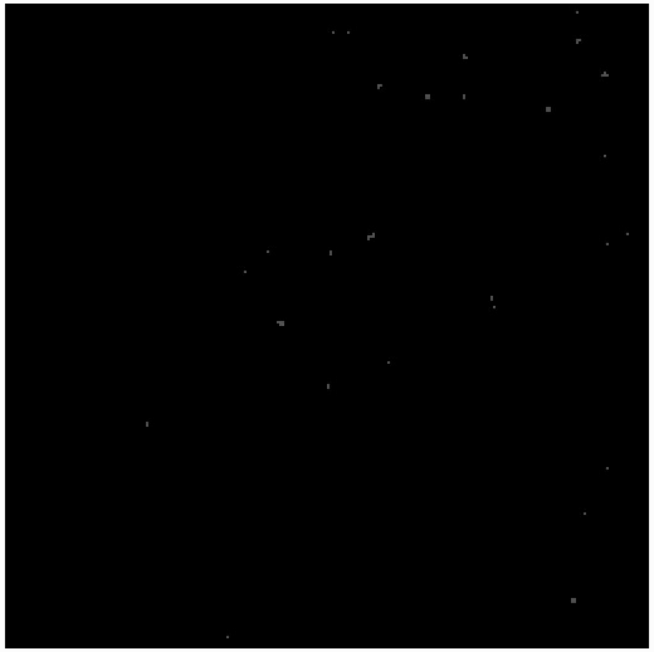
252Cf, low threshold (8 keV)

252Cf, high threshold (300 keV)



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

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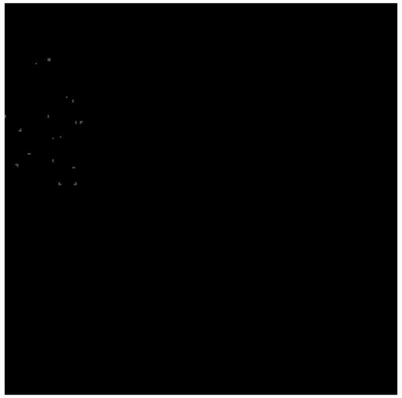
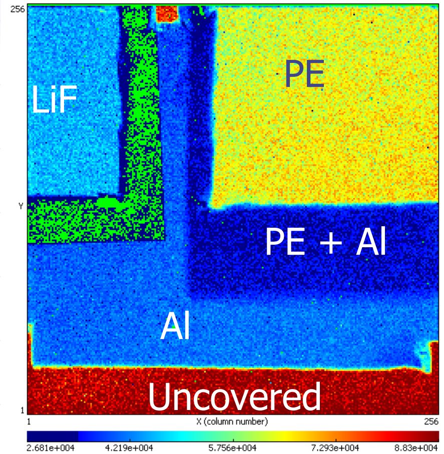
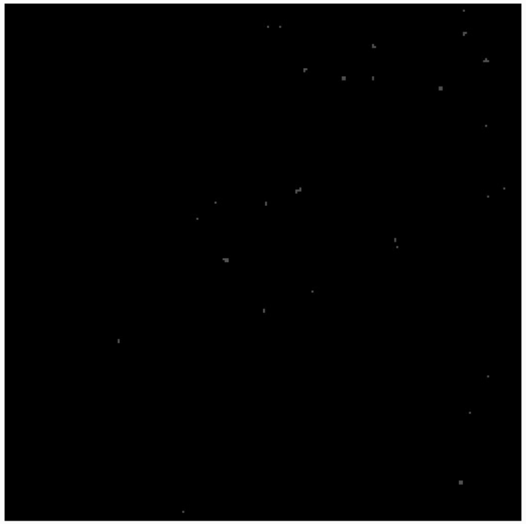
Identification of spectral composition of incoming neutron radiation can be done by comparing responses of different sensitive regions.

Thermal neutrons – 500s



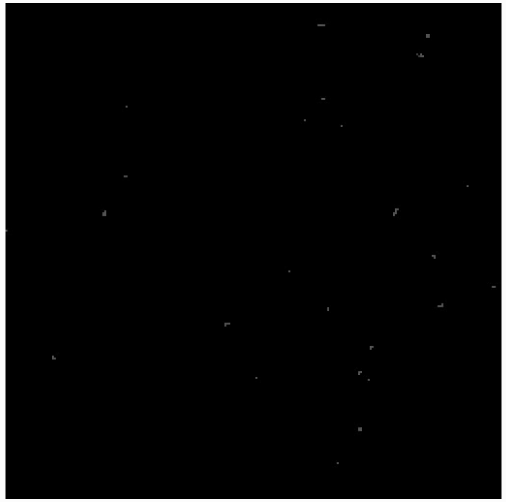


252Cf – 2000s



AmBe – 2000s

17 MeV neutrons at 0^{o}



On-line radiation monitoring in ATLAS experiment at LHC (16 devices installed within ATLAS)

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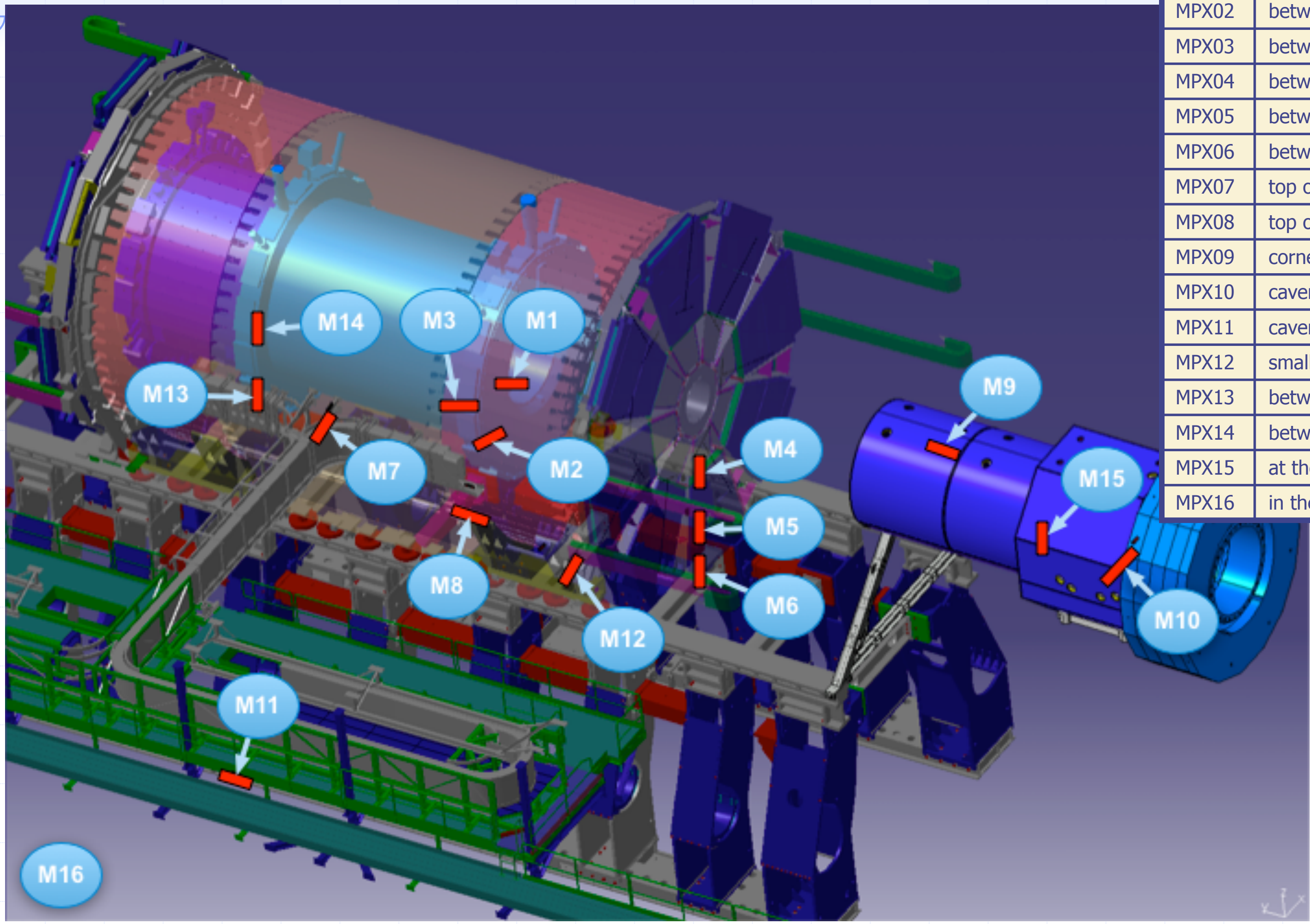

MPX01	between ID and JM plug
MPX02	between ID, LARG and JM
MPX03	between LARG and LARG EC
MPX04	between FCAL and JT
MPX05	between LARG and JT wheel
MPX06	between LARG and JT wheel
MPX07	top of TILECAL barrel
MPX08	top of TILECAL EXT. barrel
MPX09	corner between JF cyl. and hexagon
MPX10	cavern wall A or C side
MPX11	cavern wall USA side
MPX12	small wheel
MPX13	between ID and JM plug
MPX14	between ID, LARG and JM
MPX15	at the back of Lucid detector
MPX16	in the USA15 cavern

ATLAS-MPX device no. 15
(position R=200mm; Z=18.74m)

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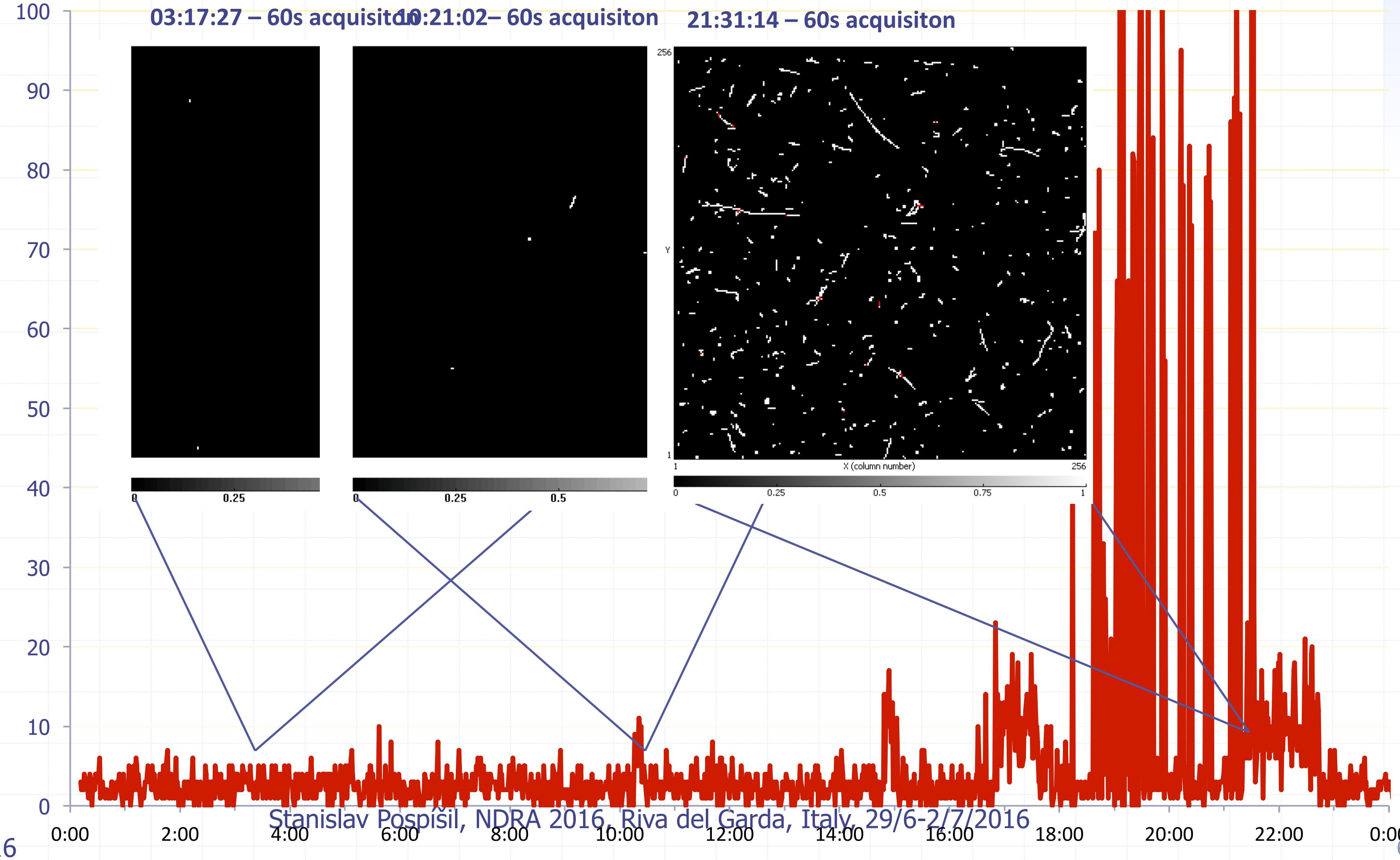
Recognized number of individual tracks vs time – LHC beam test 10.9.2008



Correlation between the responses of the ATLAS-MPX detectors and the LHC luminosity

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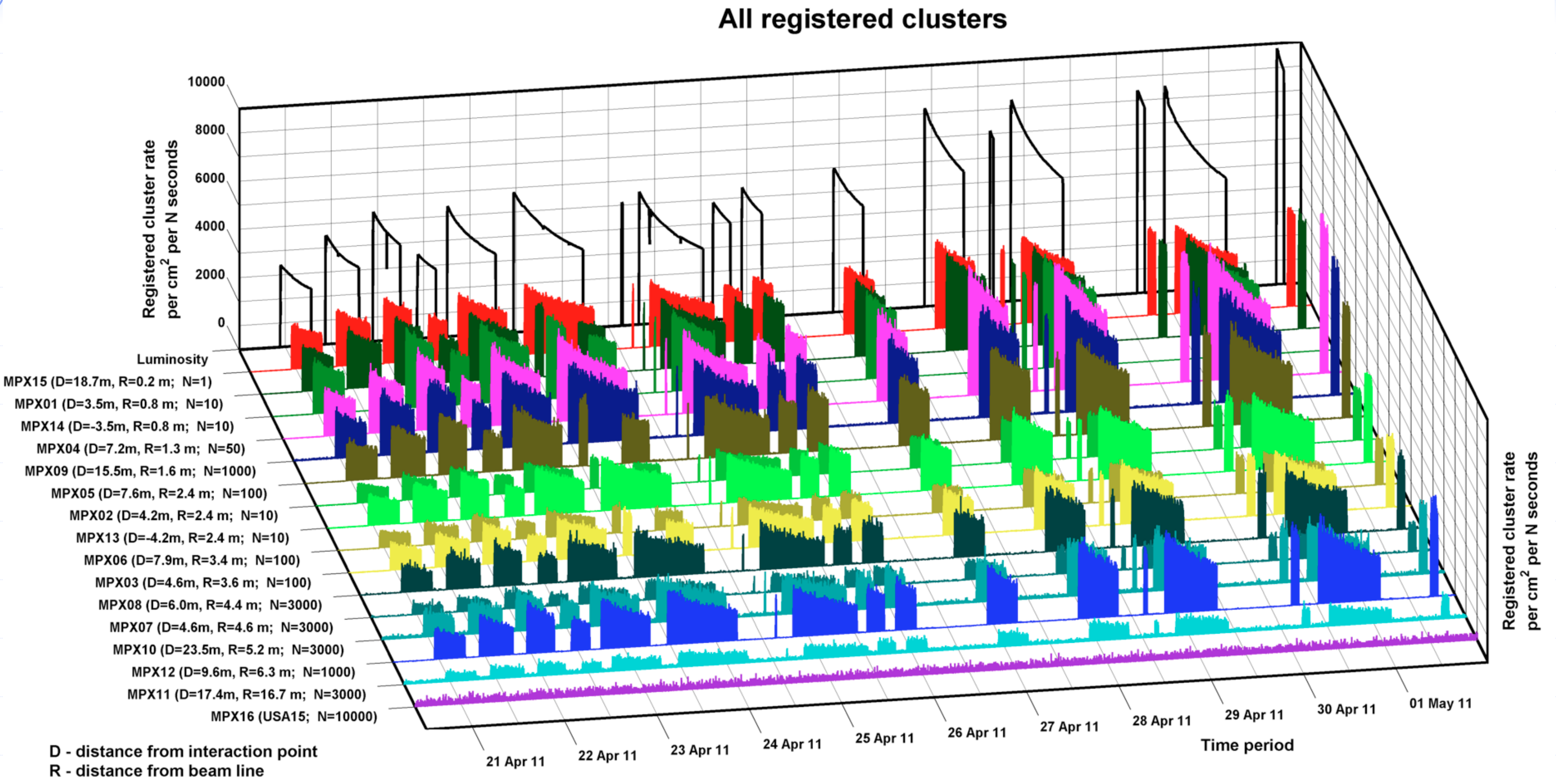

Period 21 April 2011 – 01 May 2011

Van der Meer scans (2 horizontal followed by 2 vertical) as observed with the detector MPX15 during p-p Fill 1089 on 9.05.2010.

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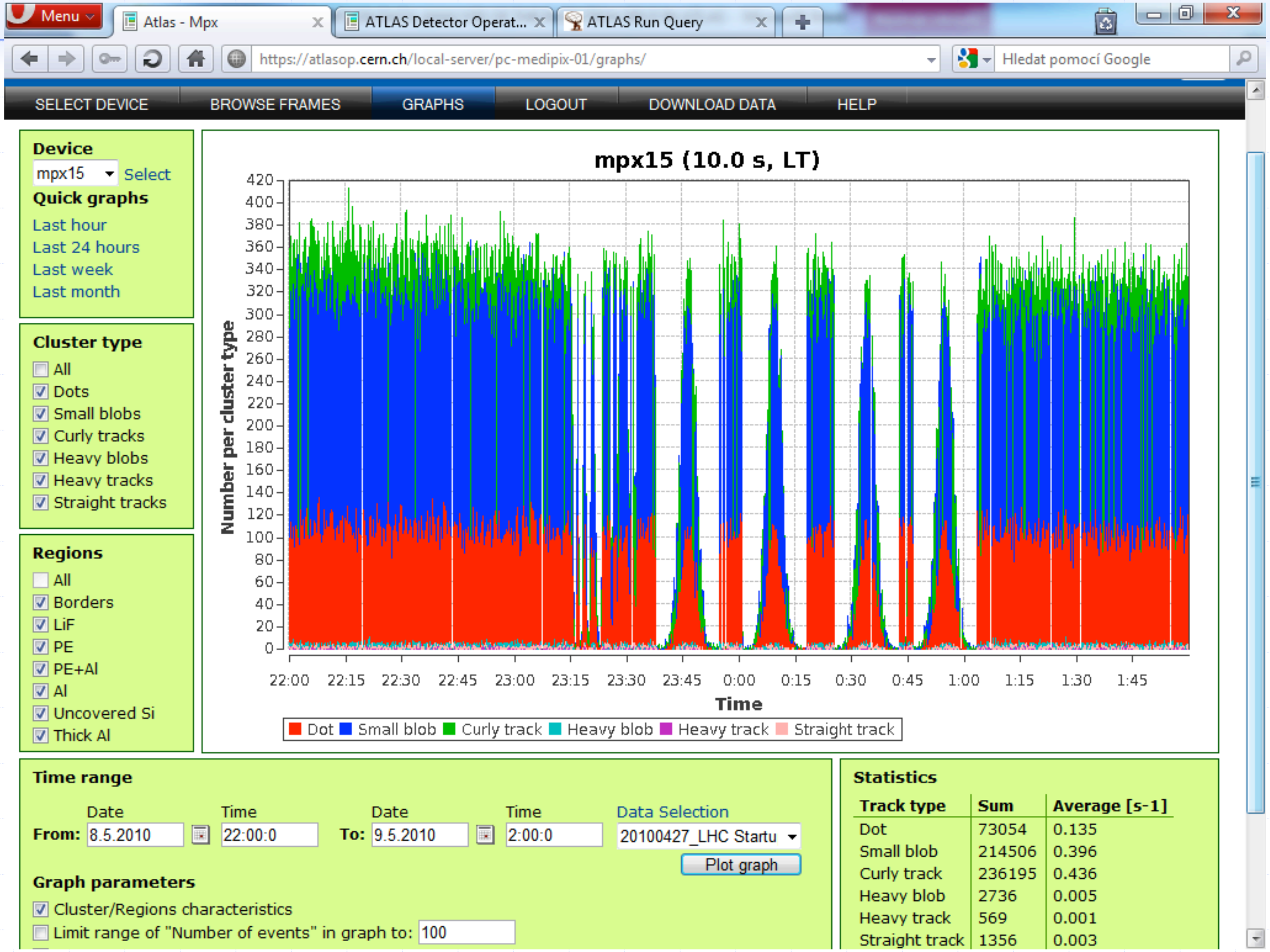

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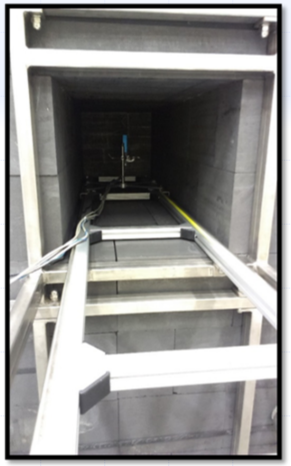
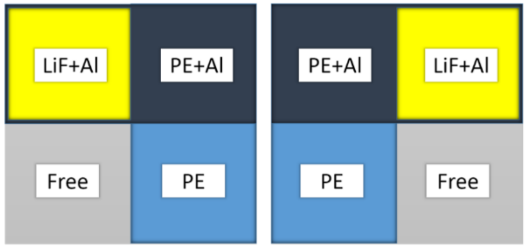
ATLAS-TPX network
Neutron Efficiency Calibrations

All ATLAS-TPX devices were irradiated with thermal (25 meV) and fast (Cf, AmBe) neutrons from well characterized sources in the Czech Metrological Institute.

The reference device was also irradiated with fast 16.7 MeV neutrons from D+T reactions in the IEAP VdG accelerator.

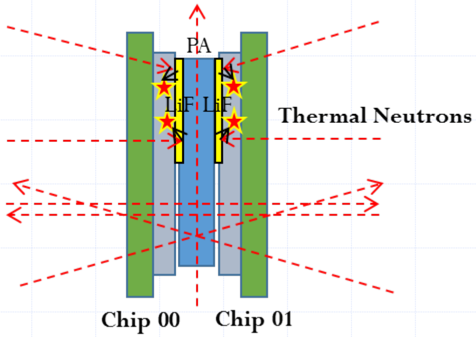


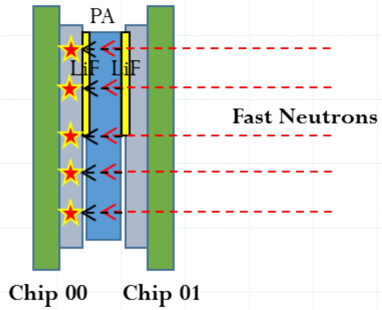
Layout of neutron converters



View for the 300 um sensor

View for the 500 um sensor



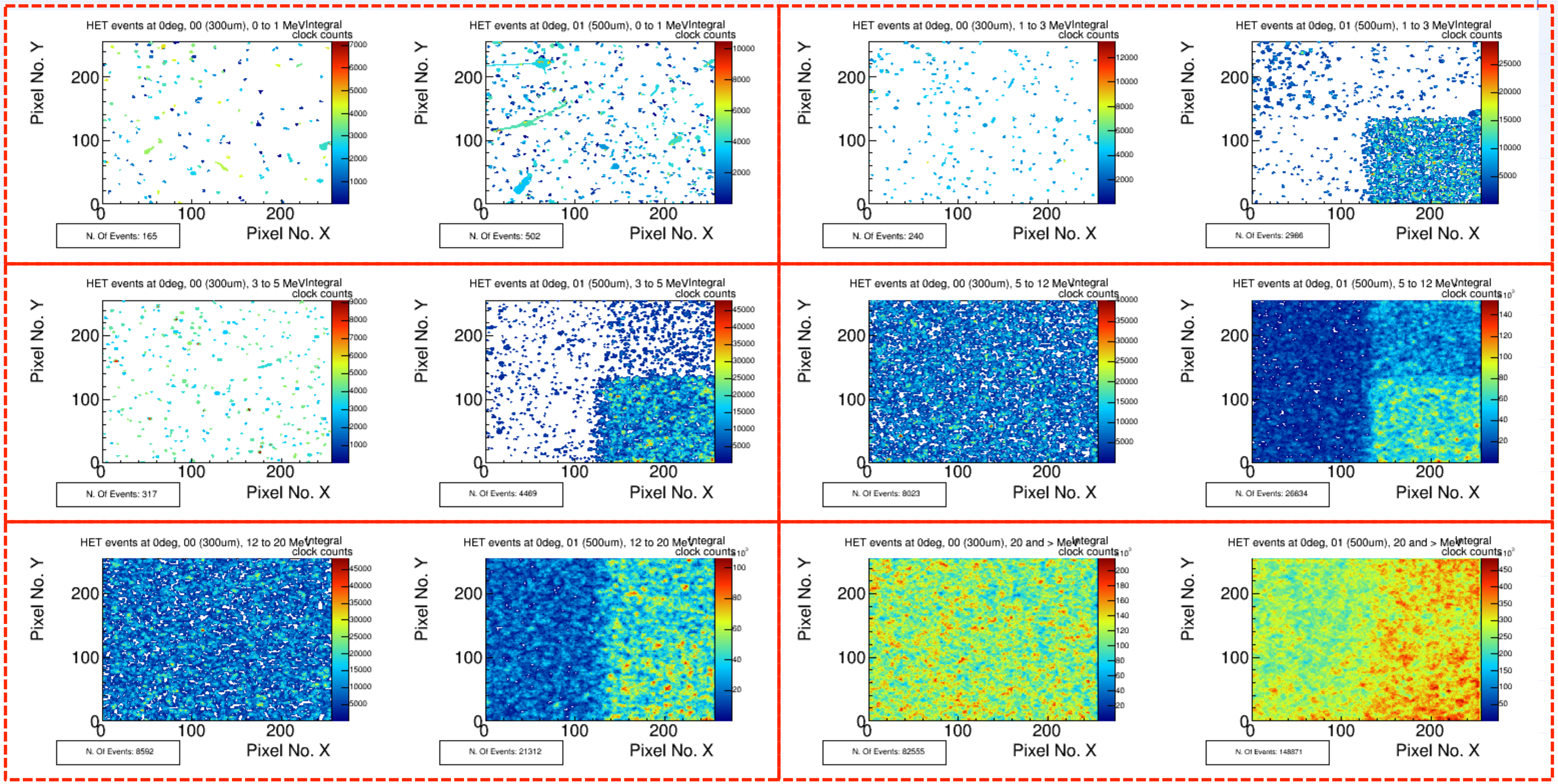


To calculate every converter efficiency:

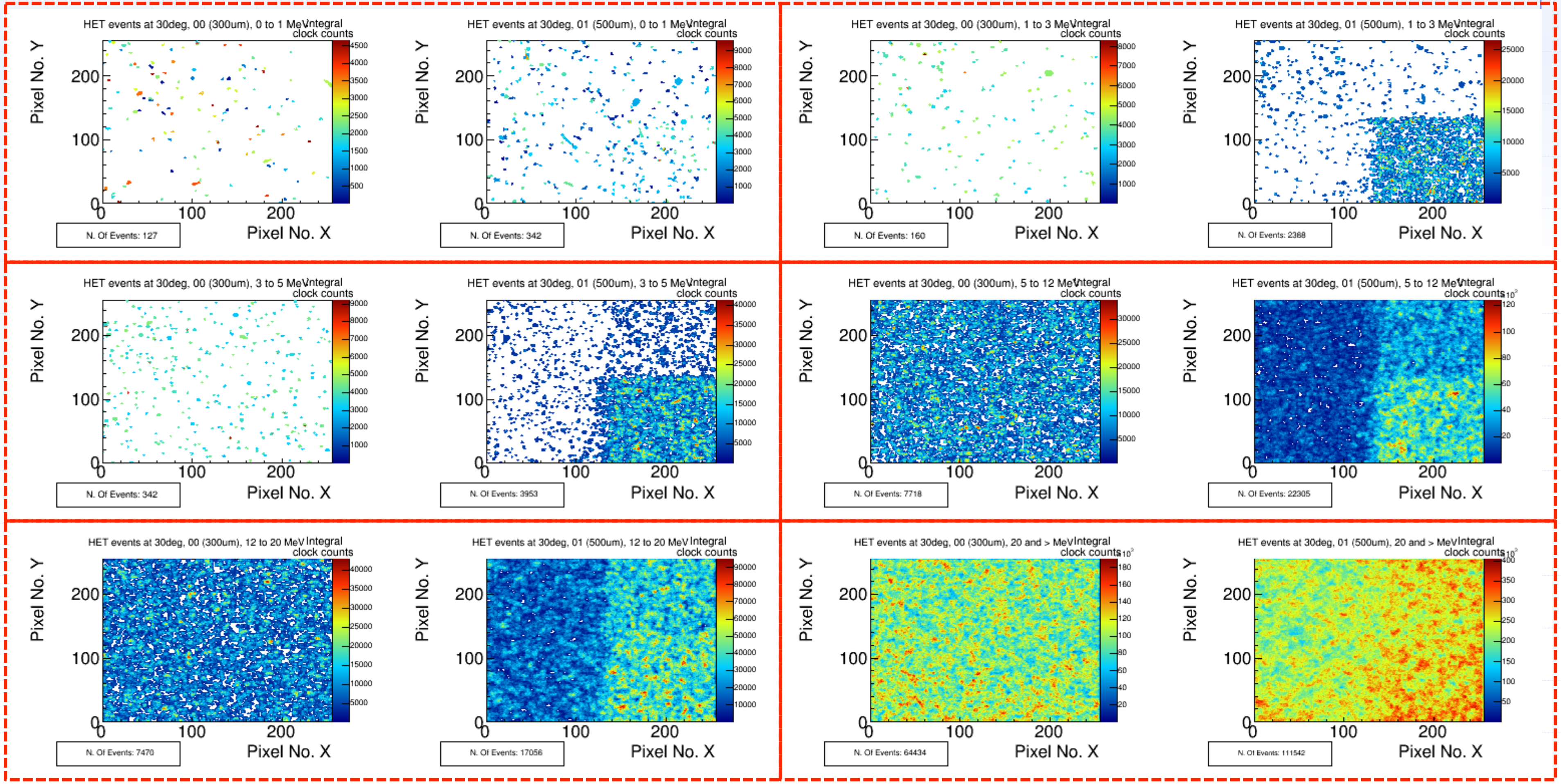
$$\varepsilon_{C-Si} = \frac{\frac{N_C}{S_C} - \frac{N_{Si}}{S_{Si}}}{\Phi . t}$$

Where N_C and S_C are the number of selected events and area of a given converter "C", respectively; N_{Si} and S_{Si} correspond to those characteristics in the Silicon (Free) area only; Φ is the total flux of neutrons expected in the converter area and t the live time of the detector while measuring.

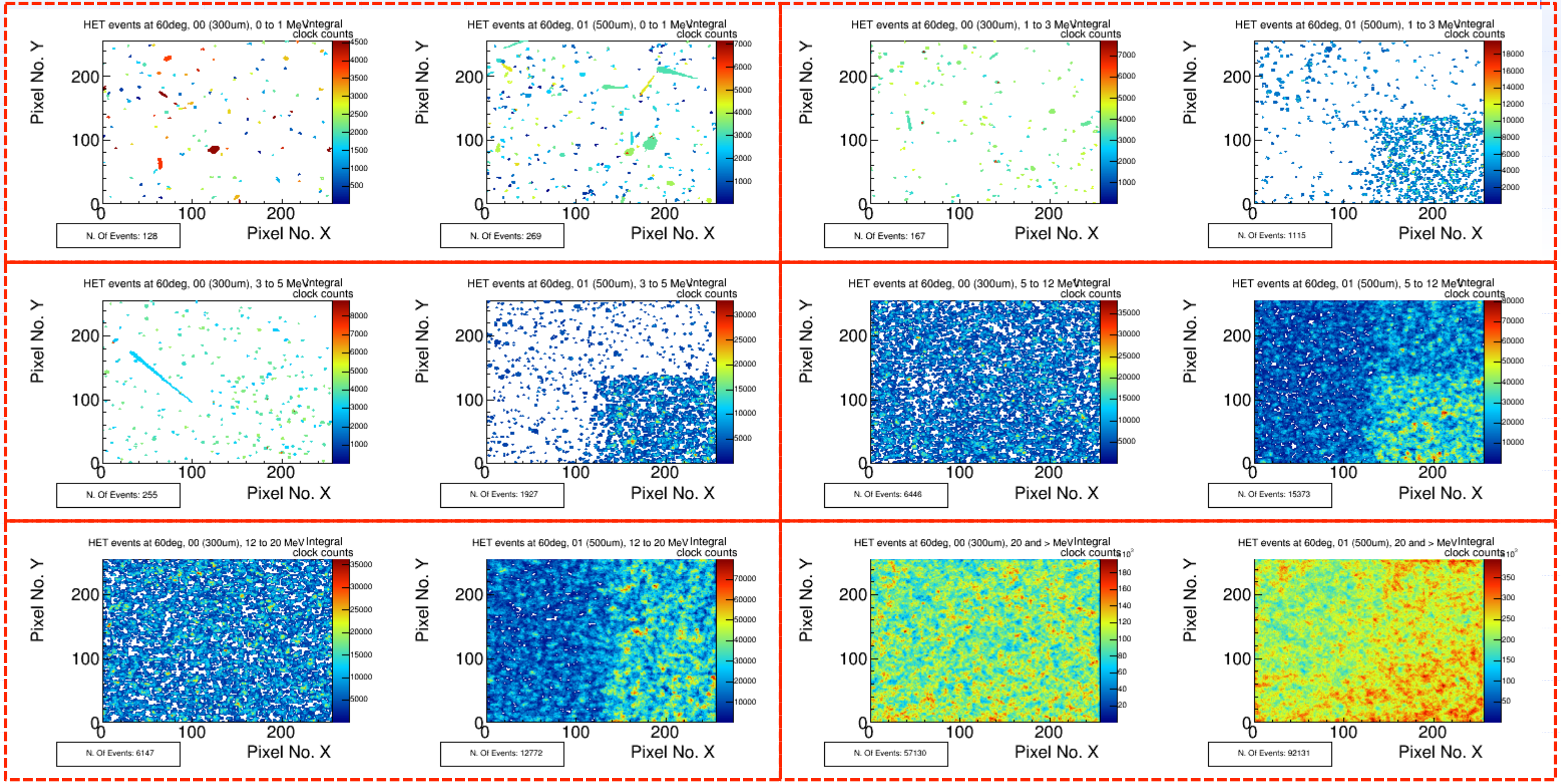
Neutron efficiency calibration from ToA (Los Alamos)
Heavy Tracks and Blobs from 0 to 180 degrees
(0 degrees)



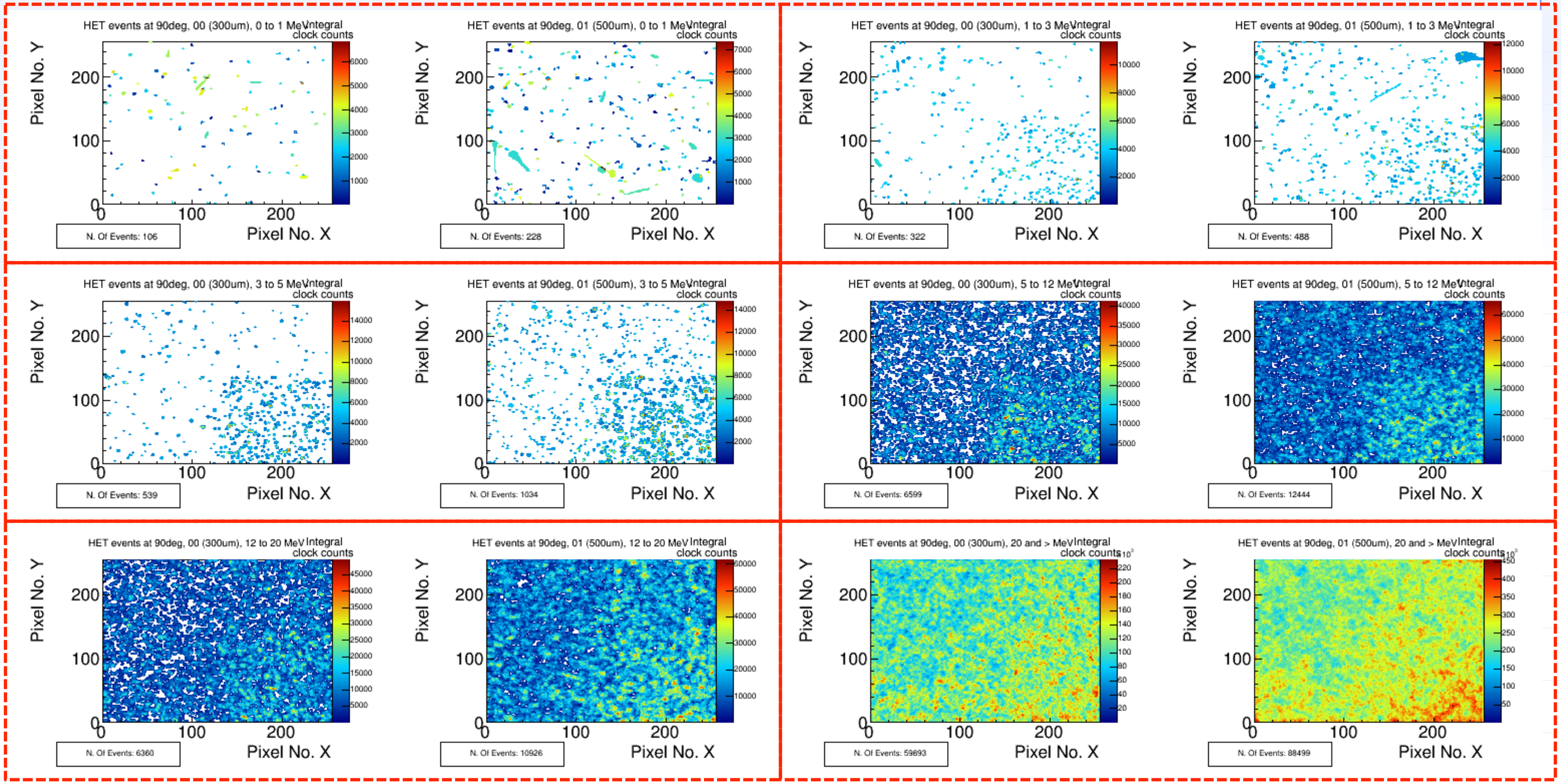
Neutron efficiency calibration from ToA (Los Alamos) Heavy Tracks and Blobs from 0 to 180 degrees (30 degrees)



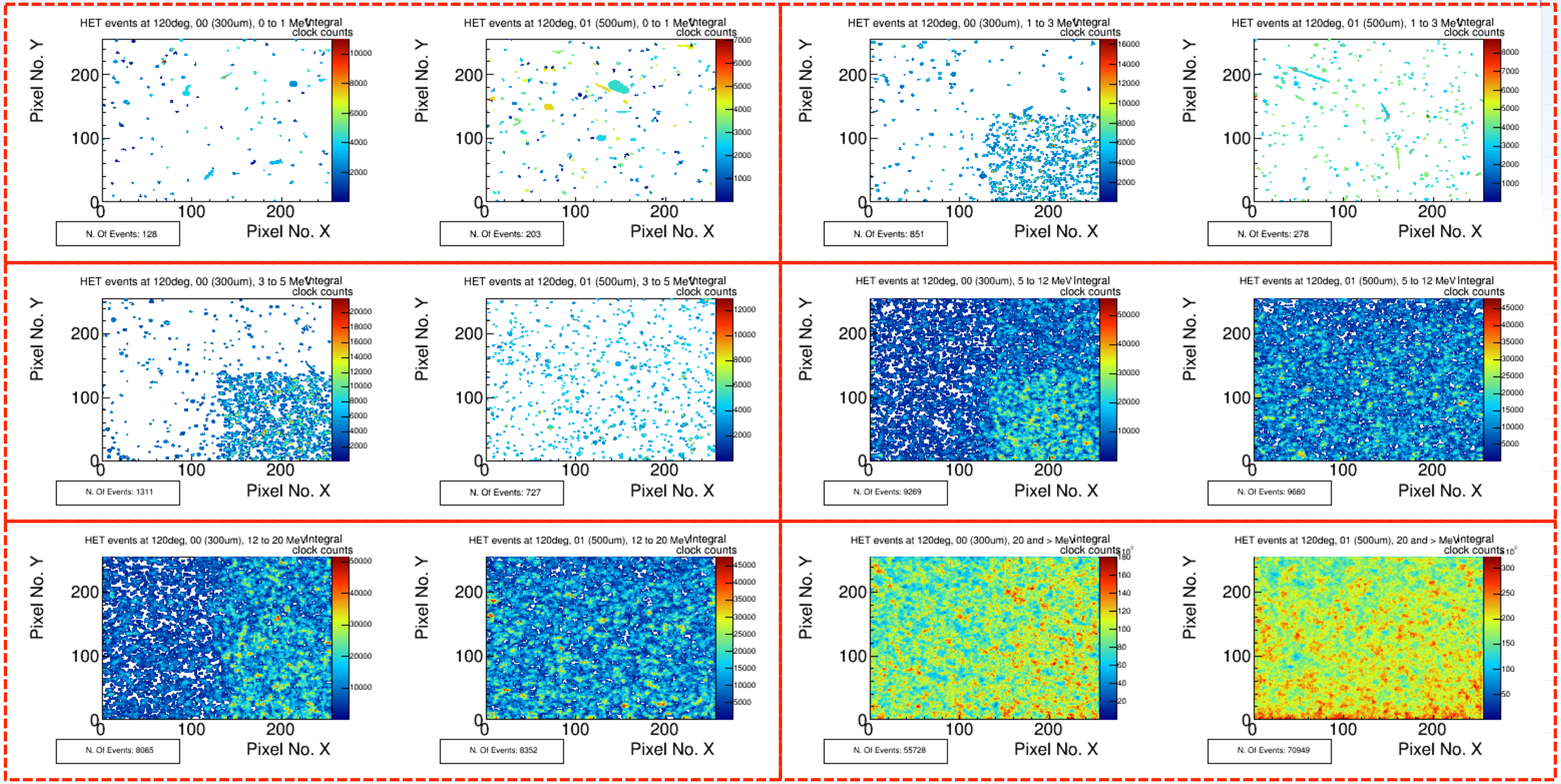
Neutron efficiency calibration from ToA (Los Alamos)
Heavy Tracks and Blobs from 0 to 180 degrees
(60 degrees)



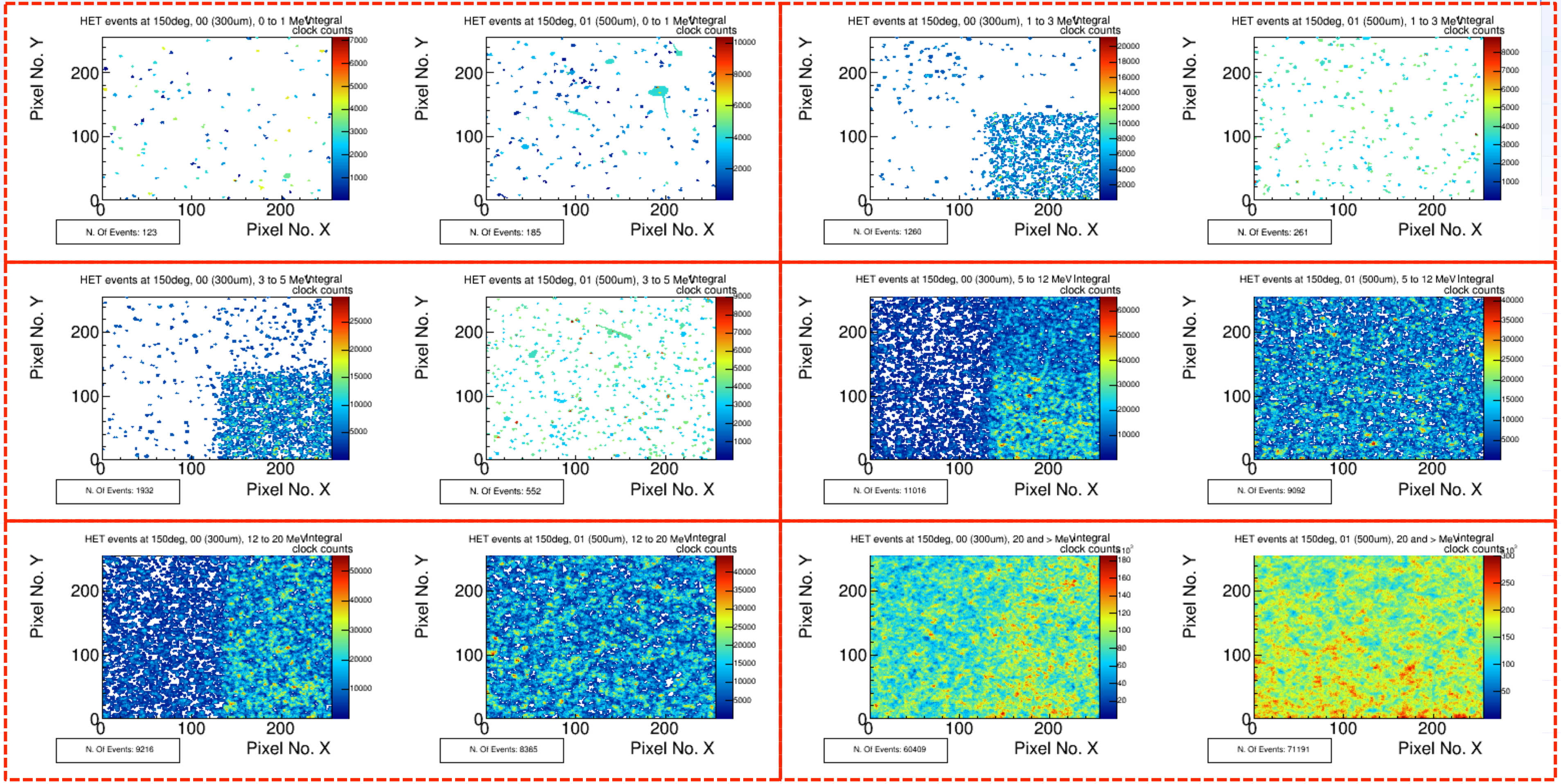
Neutron efficiency calibration from ToA (Los Alamos)
Heavy Tracks and Blobs from 0 to 180 degrees
(90 degrees)



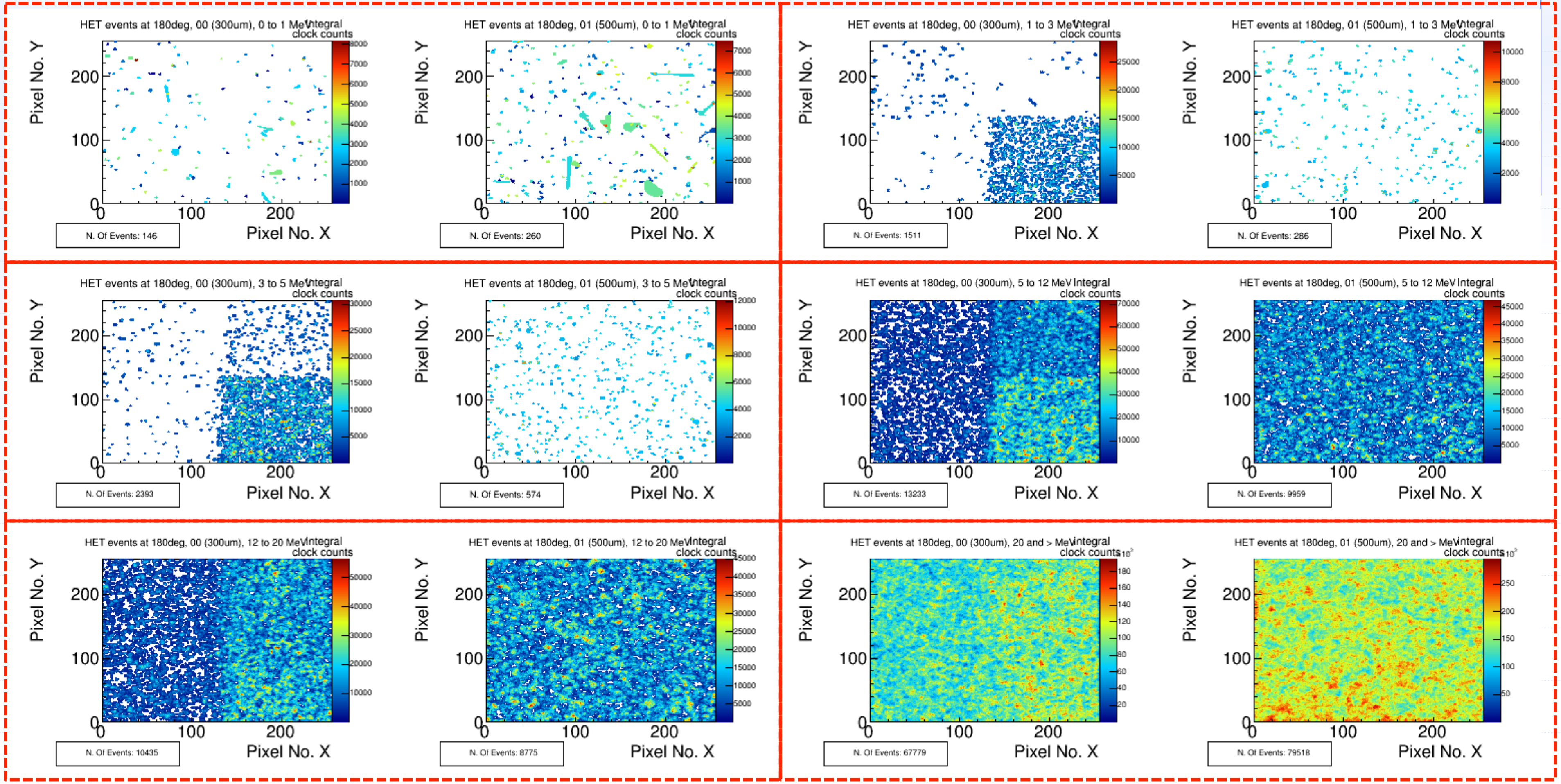
Neutron efficiency calibration from ToA (Los Alamos)
Heavy Tracks and Blobs from 0 to 180 degrees
(120 degrees)



Neutron efficiency calibration from ToA (Los Alamos) Heavy Tracks and Blobs from 0 to 180 degrees (150 degrees)



Neutron efficiency calibration from ToA (Los Alamos)
Heavy Tracks and Blobs from 0 to 180 degrees
(180 degrees)



Fast neutron ToF measurement with TIMEPIX

LANSCE neutron sources and nuclear science flight paths

(combined ToA and ToT modes)

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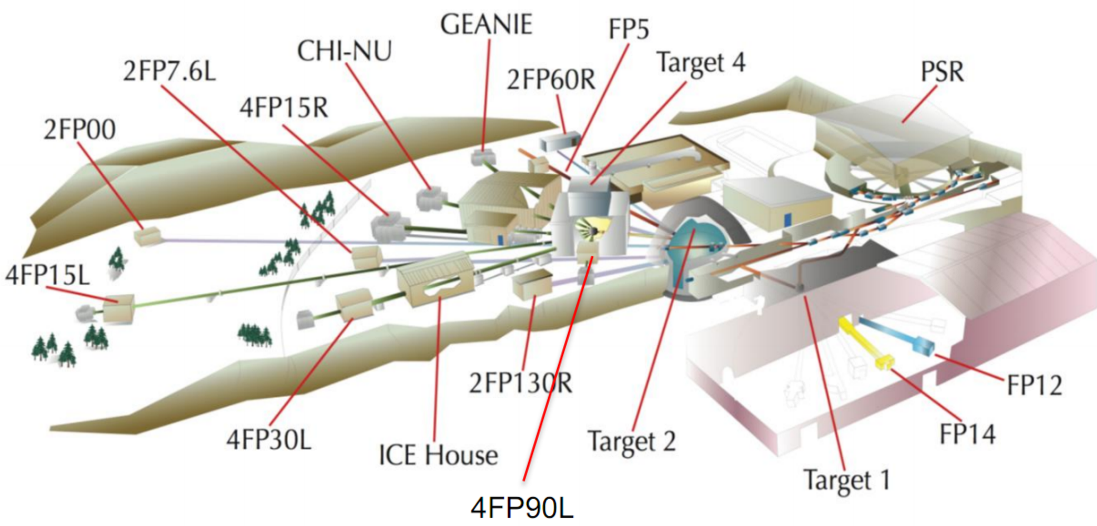
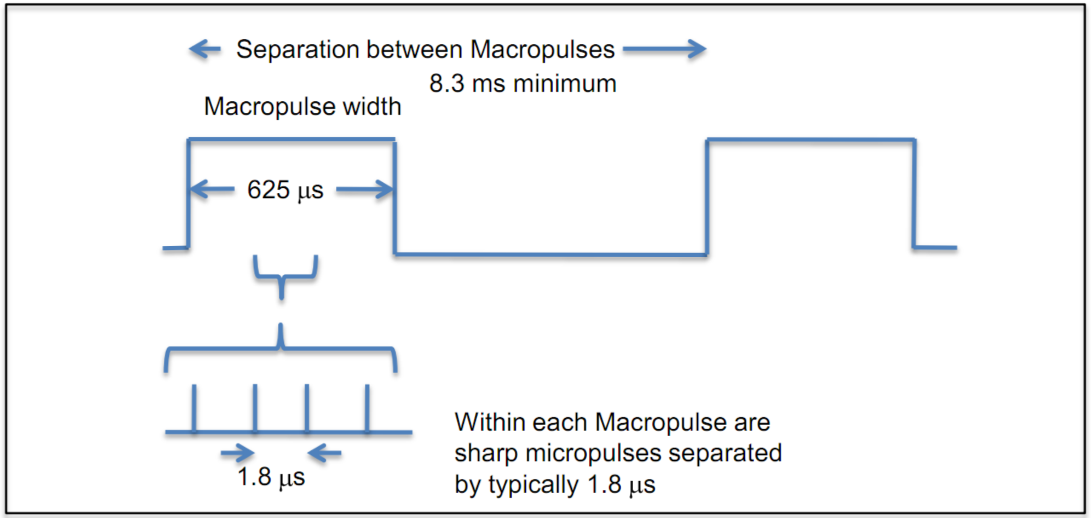
- The layout of the LANSCE neutron sources and Nuclear Science flight paths



- Time structure of the proton beam for typical Target-4 operation



Fluences of different cluster types over energy

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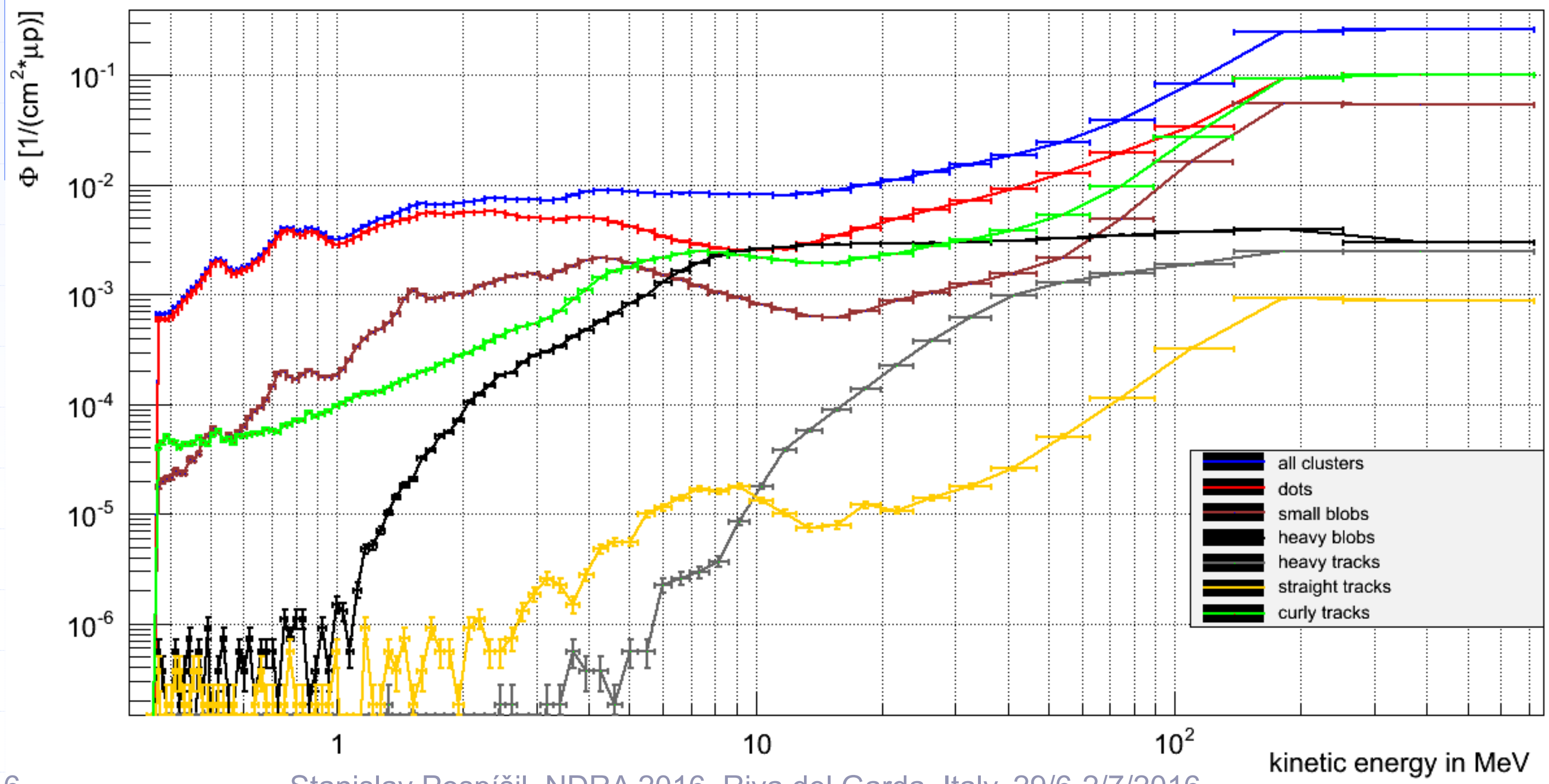
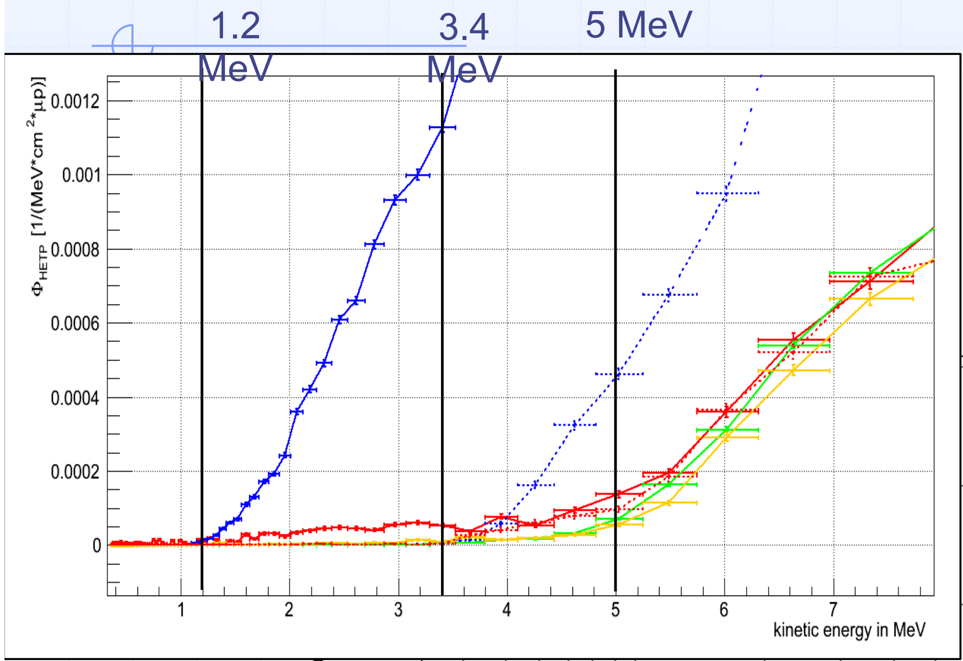
- Curly tracks, dots and small blobs dominate nearly over the whole energy range
- Asymmetric errorbars in x-direction due to binning of the measurement
- Three humps are present at lower fast neutron energies (<1 MeV) -> dots

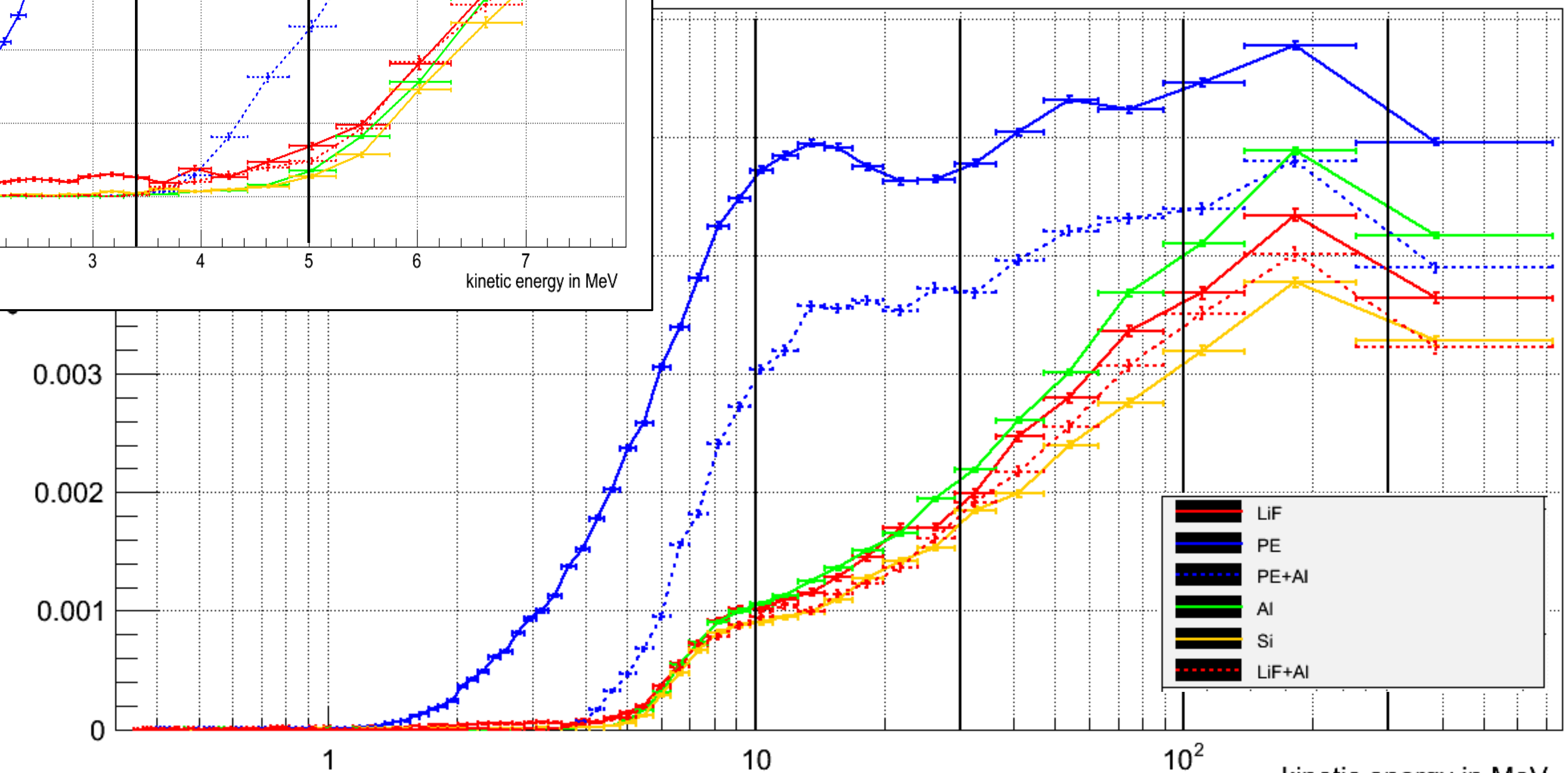


Fluences below different conversion layers

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

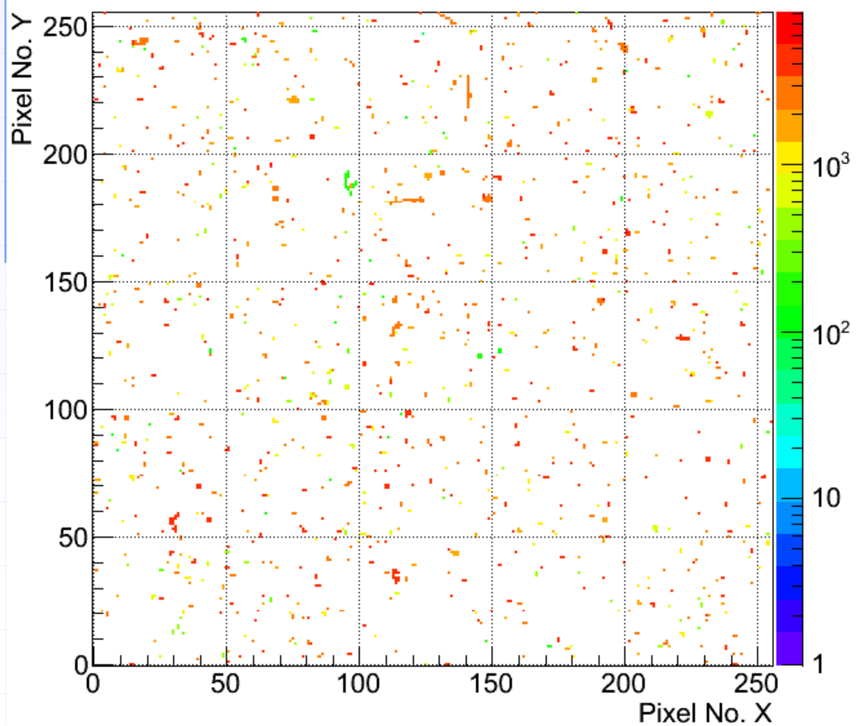
- Threshold for PE+Al at ~ 3.4 MeV
- Enhanced signal below LiF up to 4 MeV
- Recoiled protons visible above 1.2 MeV



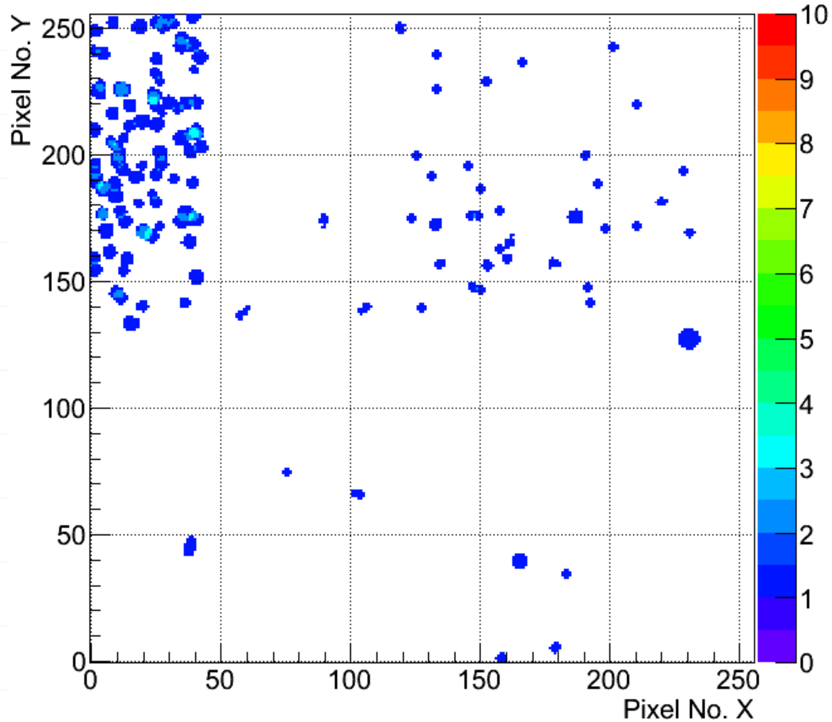


Response of Timepix: Energy region 0.4 – 1.2 MeV

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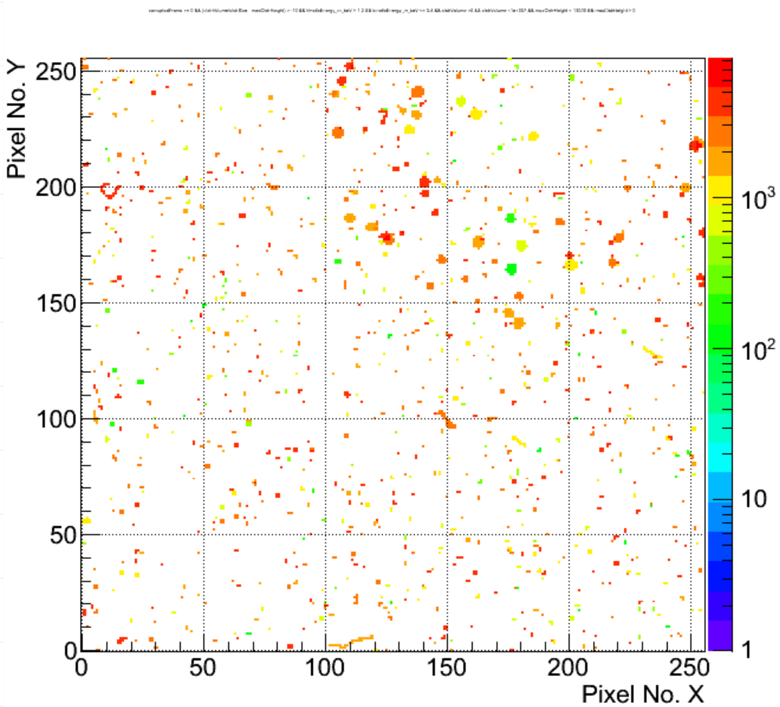
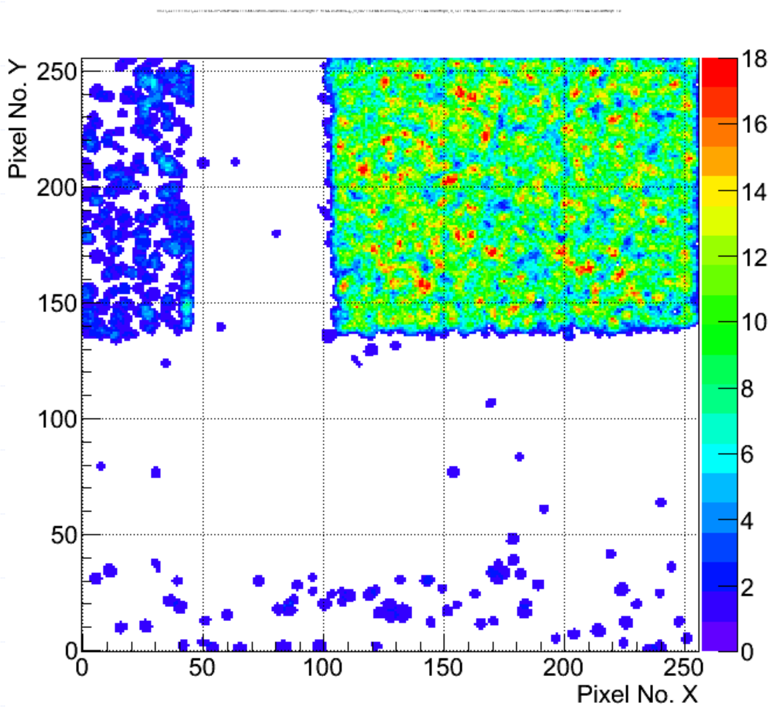
- Heavy blobs below LiF indicate presence of slow/thermal neutrons
- Clear signal of High Energy Transfer Particles (HETP) below PE
- uncovered area shows also a few events



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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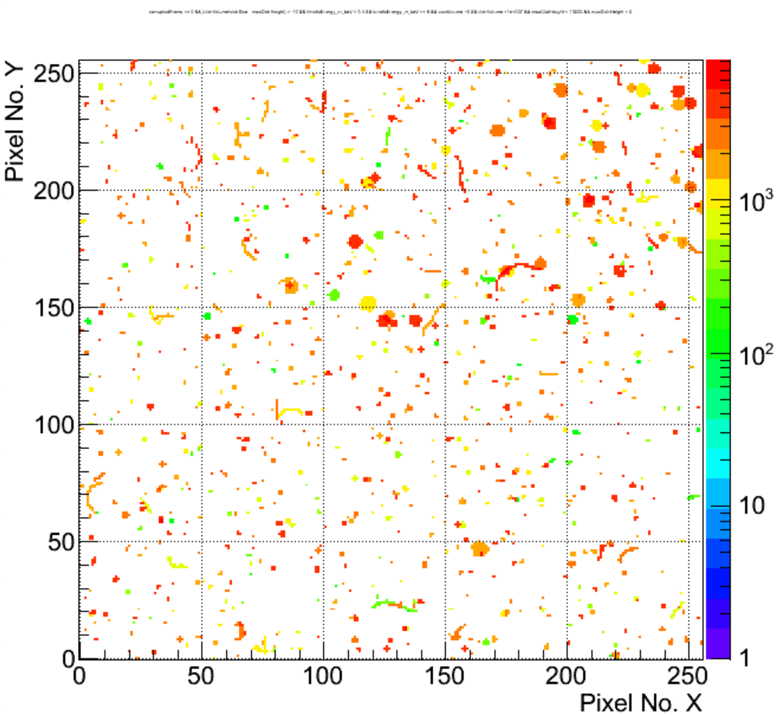
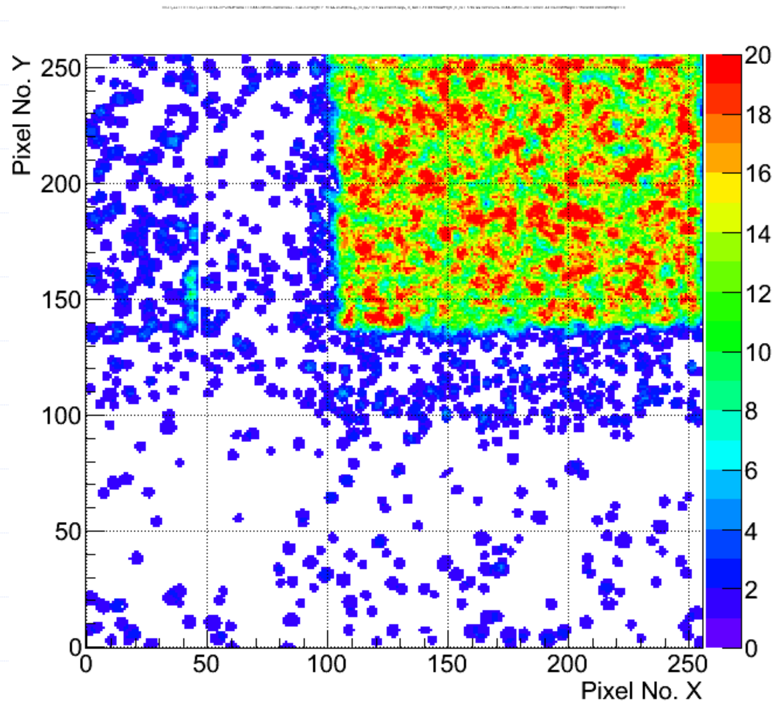
- Clear signal of HETP below PE
- Also in PE+Al region HETP are becoming visible



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 5.0 – 10 MeV

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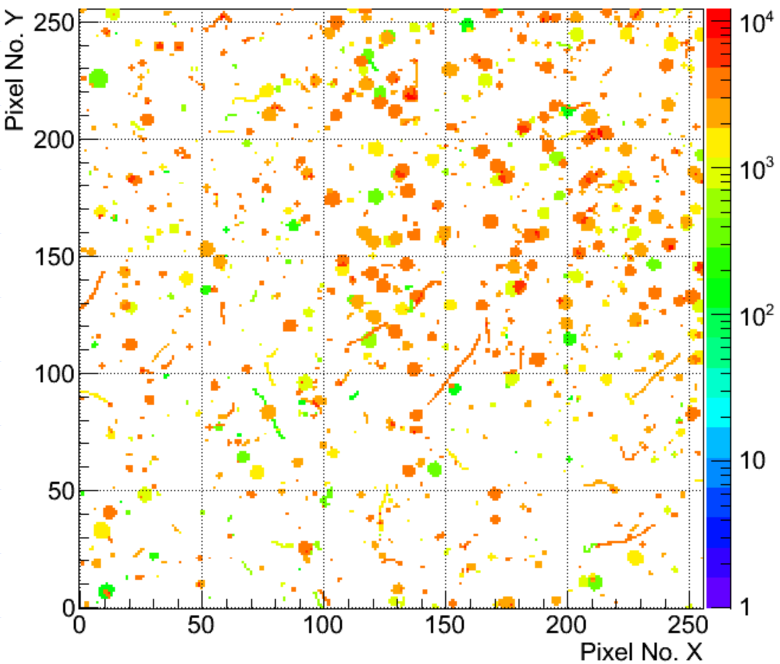
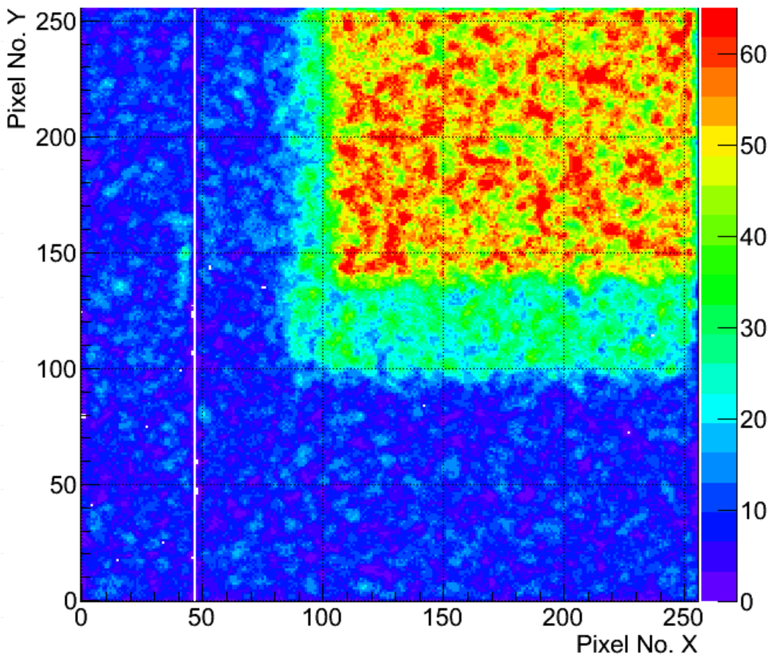
- Higher HETP count rate below PE and PE+Al
- HETP: cluster still look roundly shaped
- Almost no enhancement below LiF



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 - 61712 events were found)

Response of Timepix:
Energy region 10 – 30 MeV

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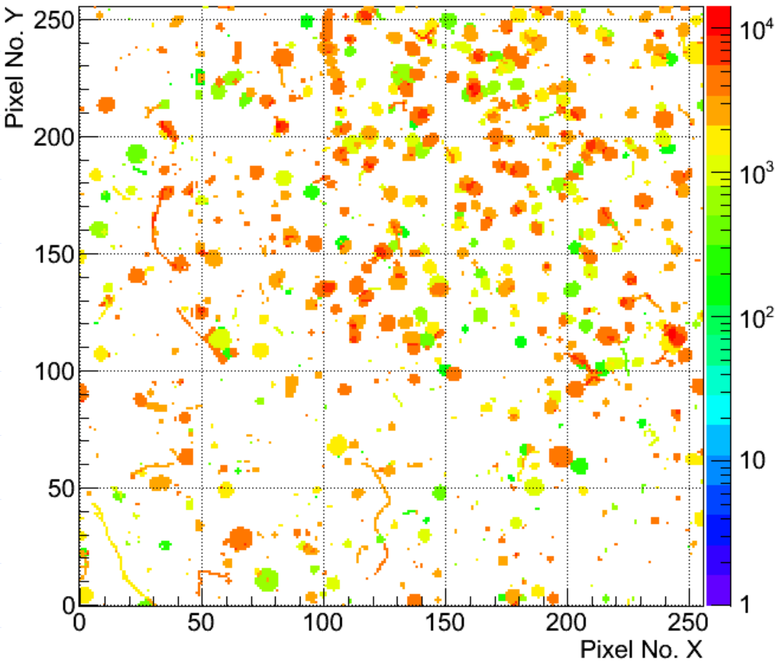
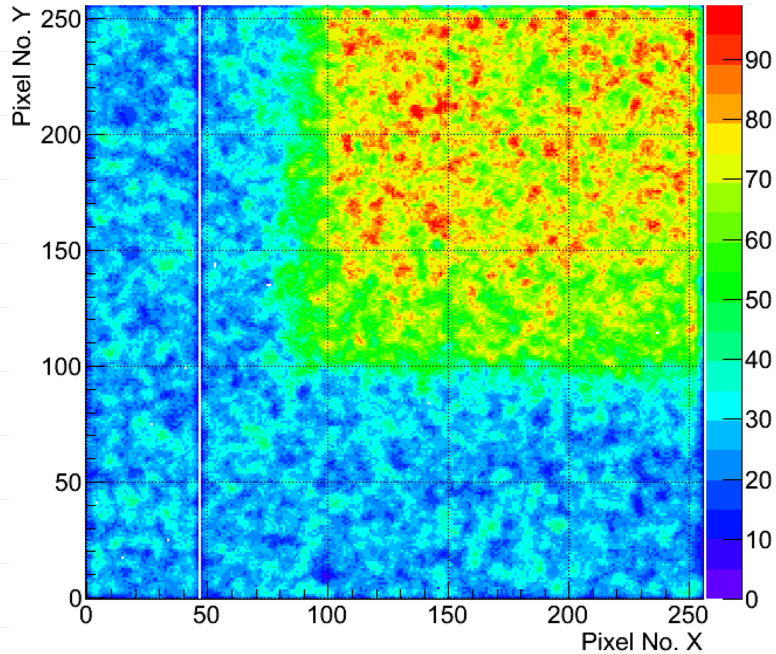
- Higher HETP count rate below PE and PE+Al (contrast to other regions begins to decrease)
- HETP equally distributed below all other regions
- HETP: Clusters become bigger and asymmetric



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 - 111901 events were found)

Response of Timepix: Energy region 30 – 100 MeV

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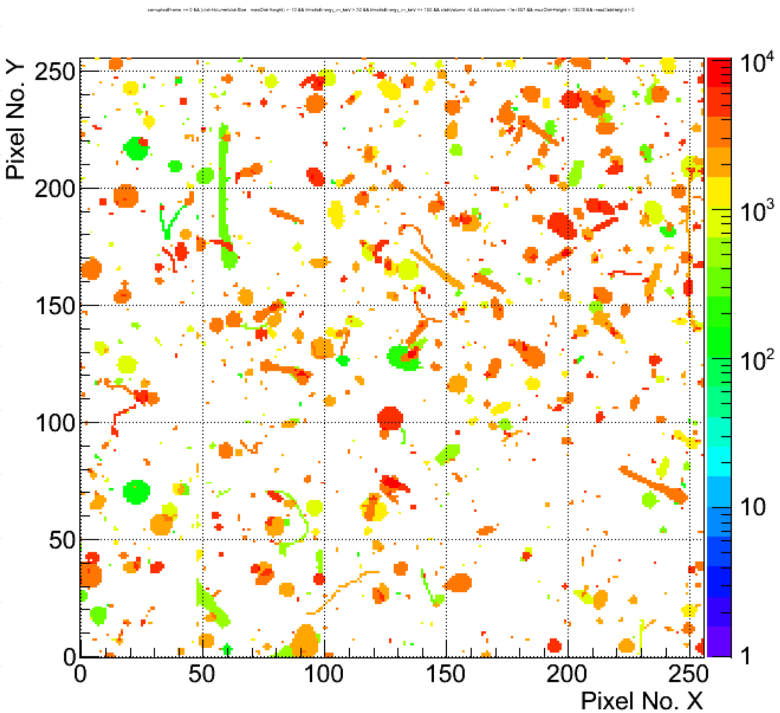
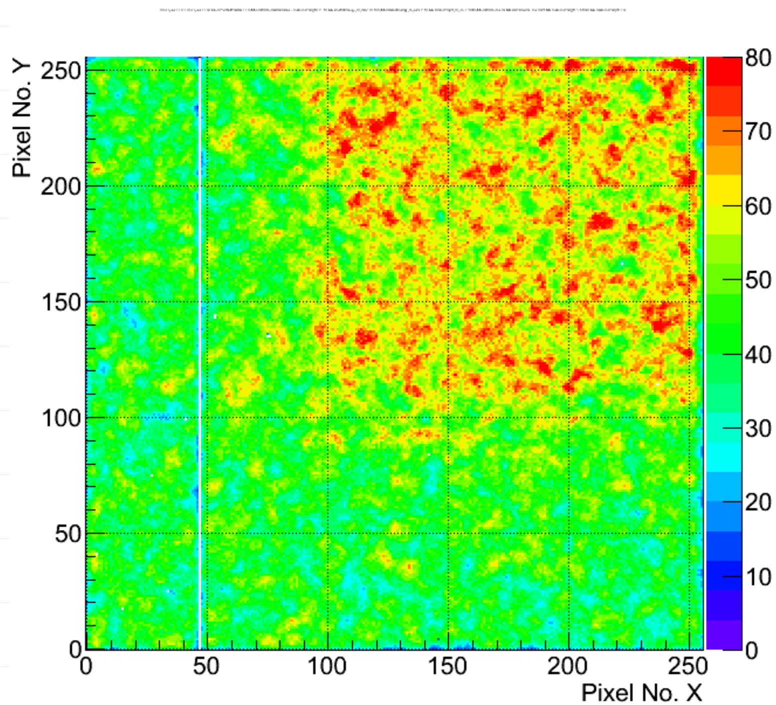
- Still enhanced response below PE and PE+Al
- Contrast to all other region is decreasing
- Cluster are getting bigger and more and more asymmetric



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 - 93227 events were found)

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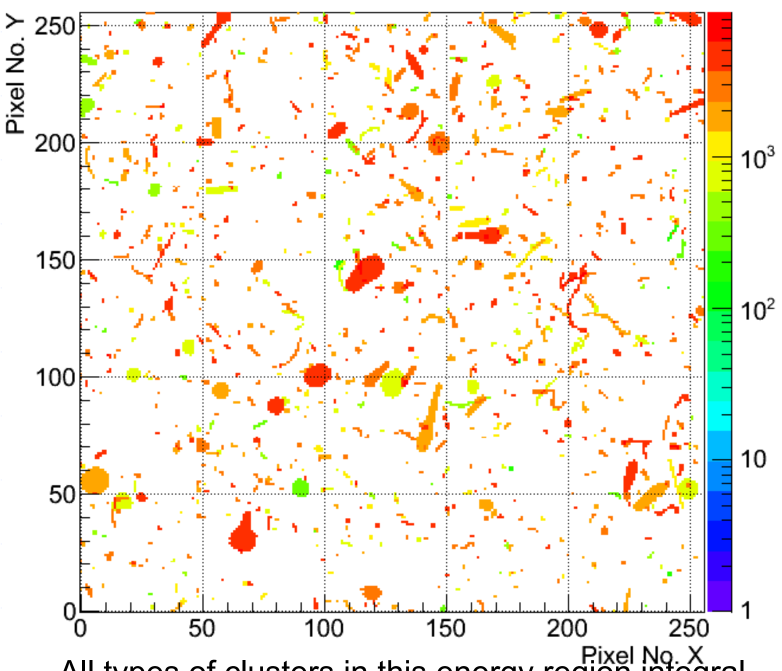
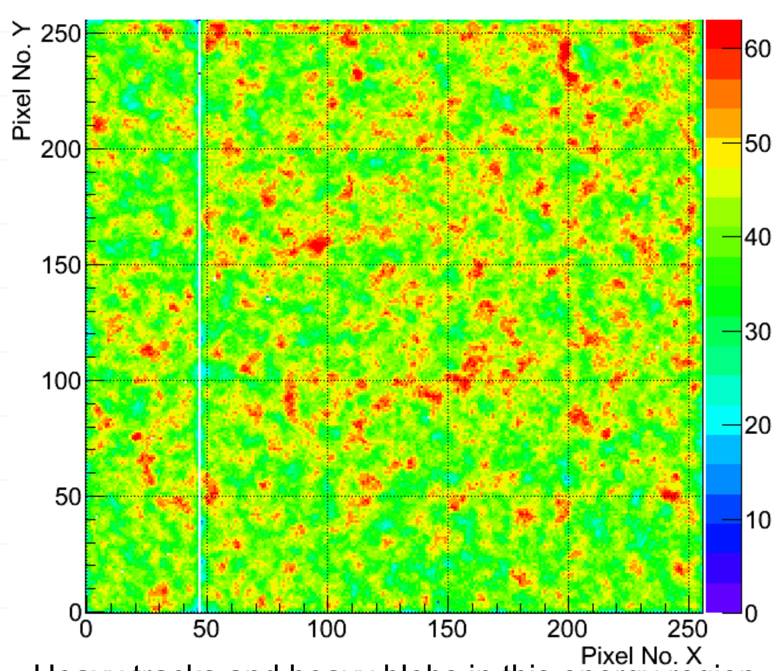
Response of Timepix: Energy region 100 – 300 MeV

- 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)

Response of Timepix: Energy region 300 MeV +

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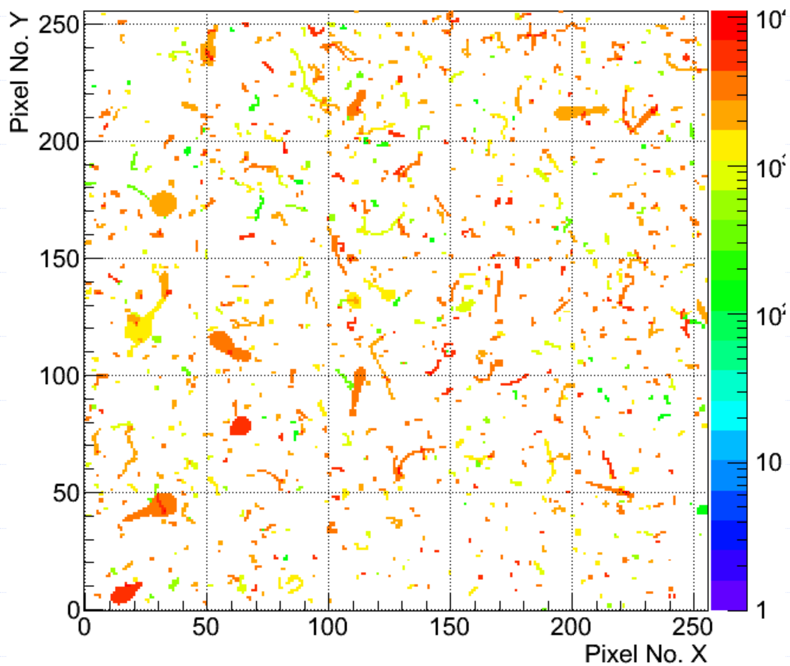
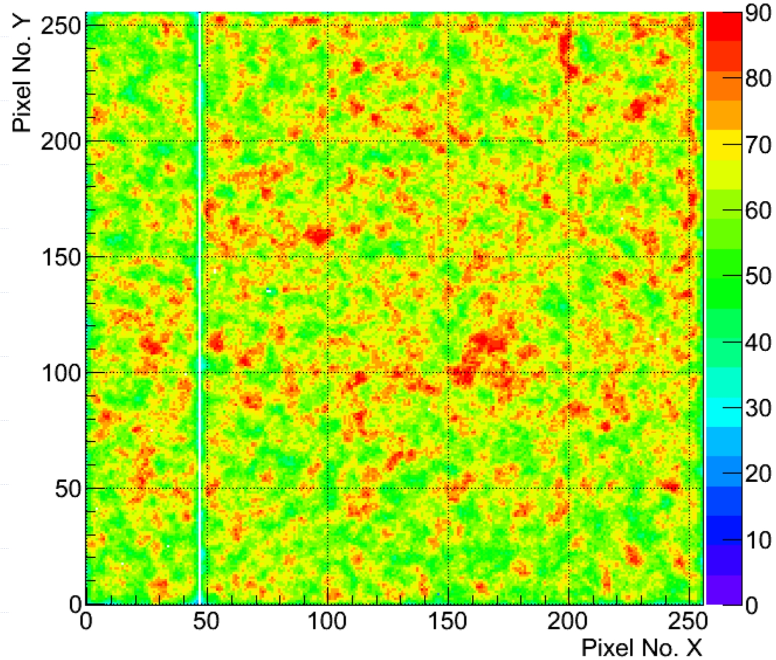
- HETP nearly equally distributed below all regions



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 - 29634 events were found)

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

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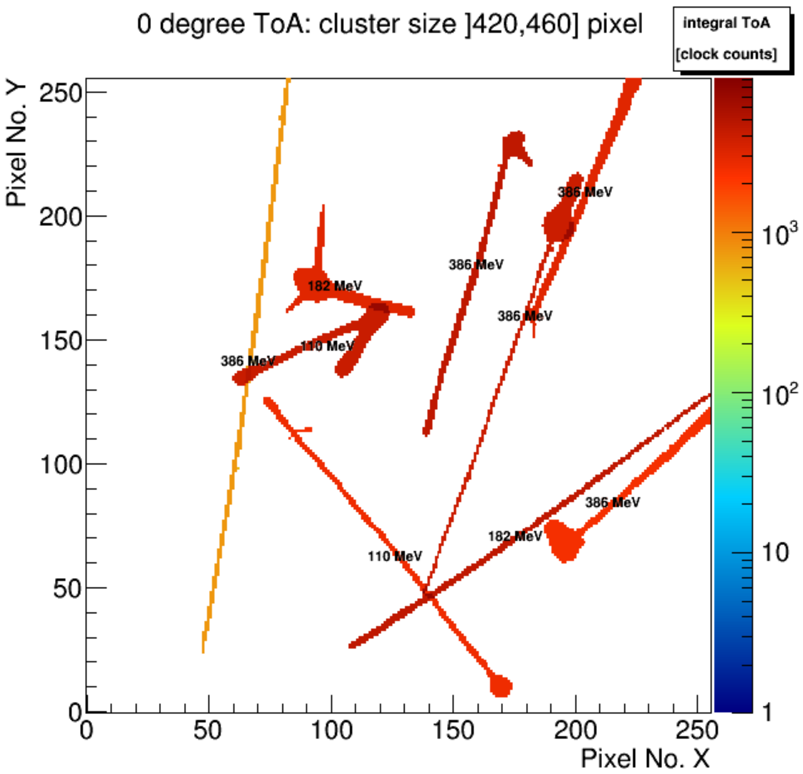

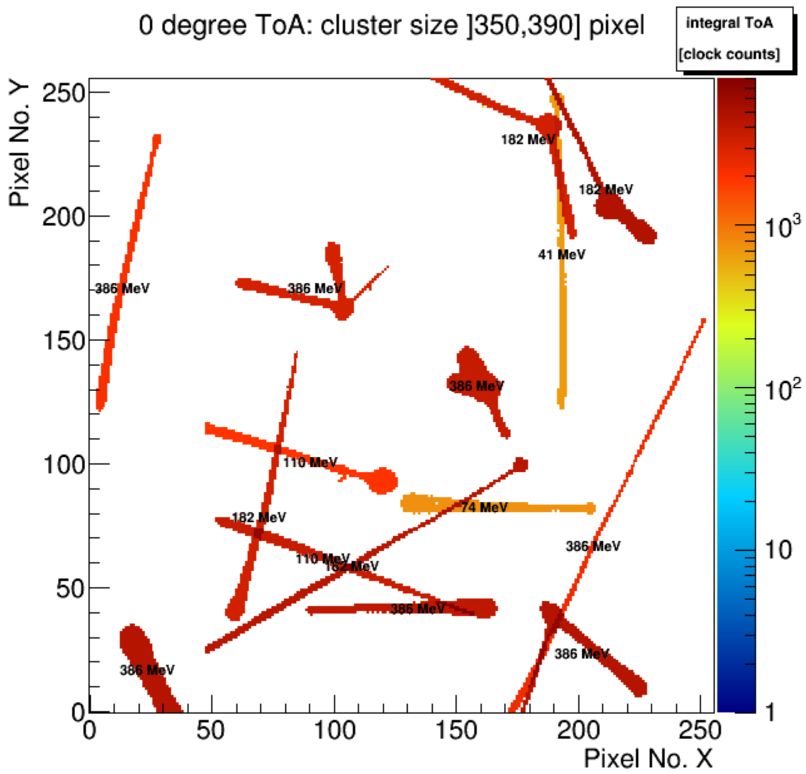

Different colors and black numbers assigned to individual clusters indicate the energy of incoming neutrons as measured by means of the TOF technique

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

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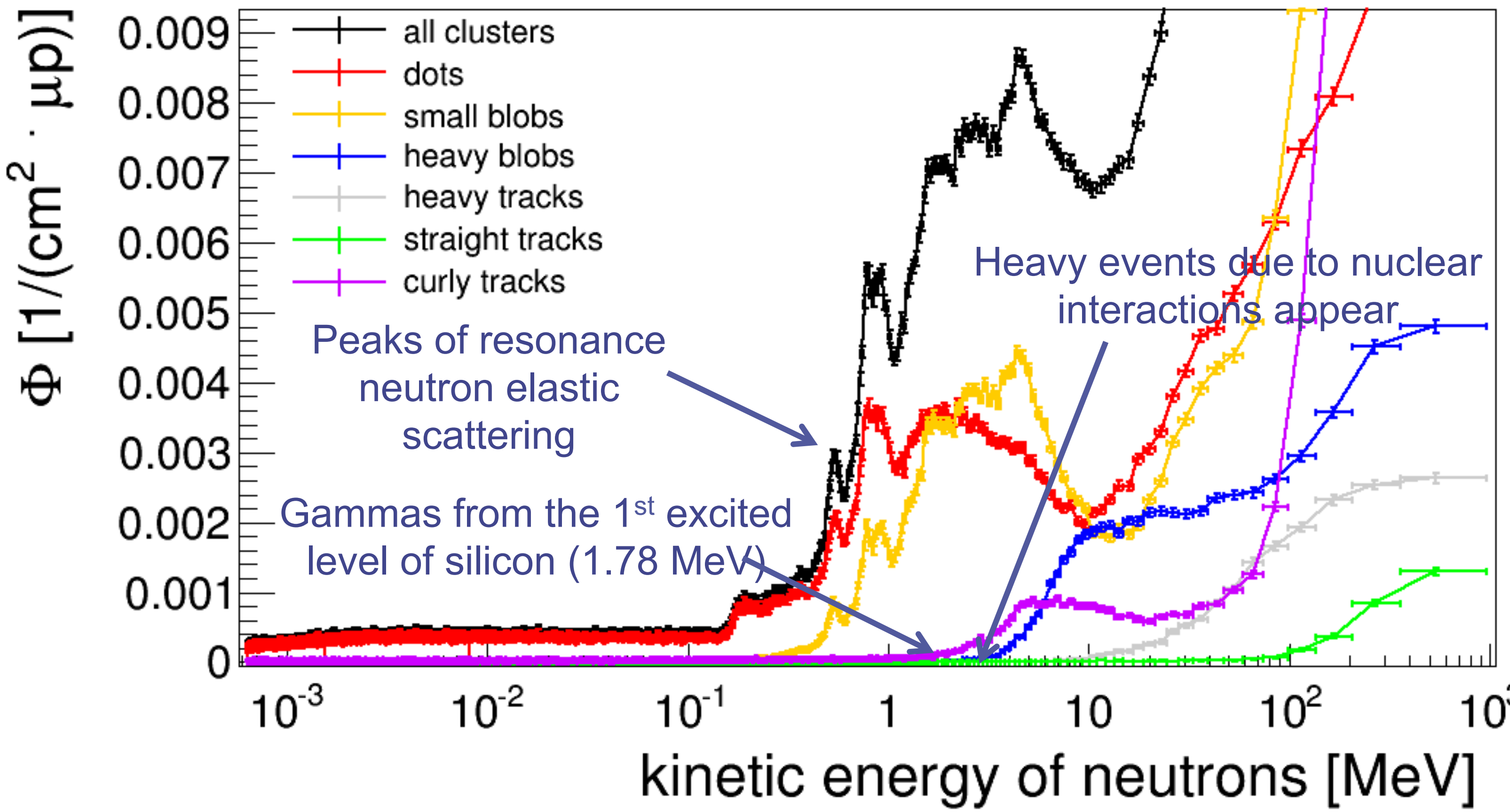
- The ToF technique*) was used to assign the detector responses to the corresponding neutron energies (track by track).



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

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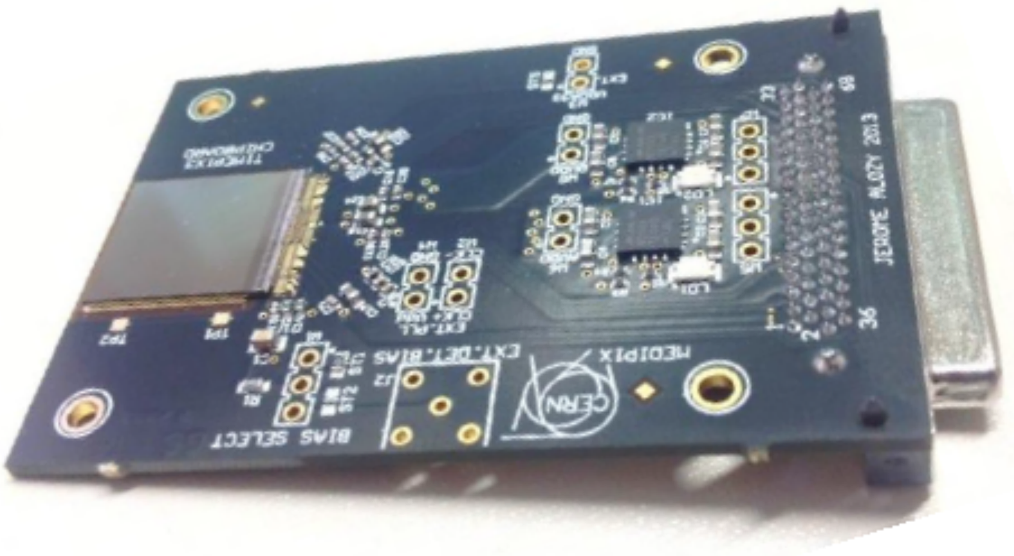
TIMEPIX3

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



Timepix3 CERN chip board

TIMEPIX3: Cluster shapes (detector responses) as a function of neutron kinetic energies

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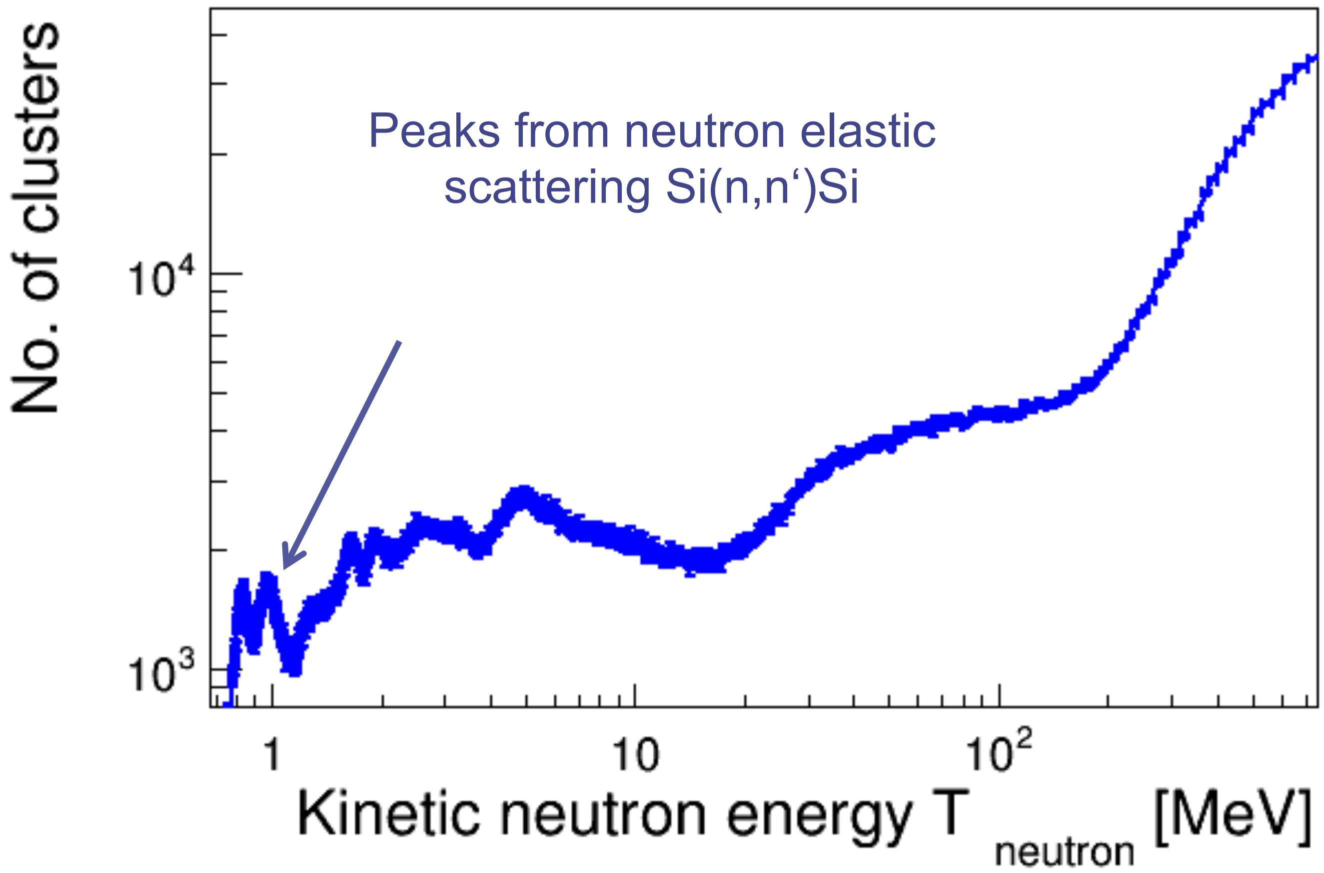

TIMEPIX3: Examples of energy spectra for selected neutron energy intervals

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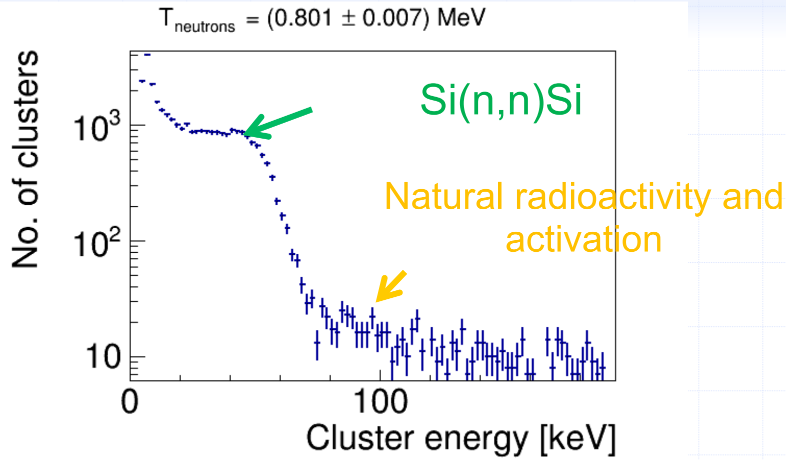

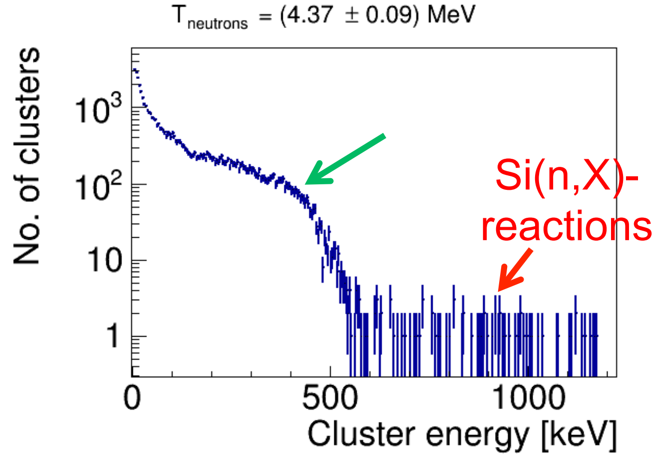

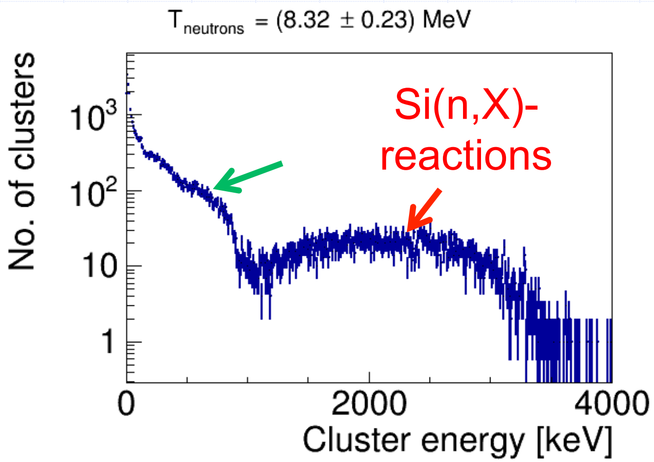

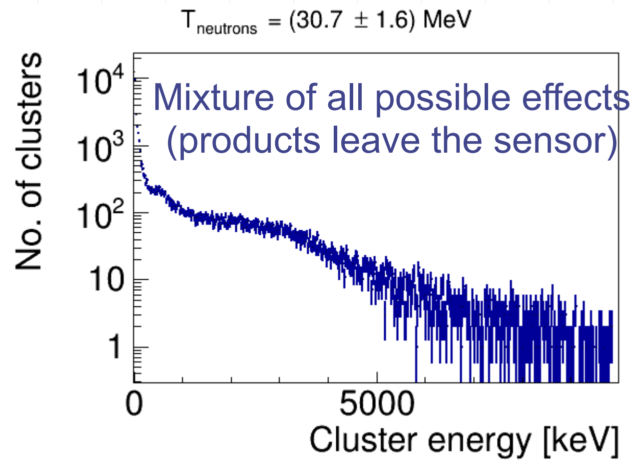

Edges identification by spectrum analysis and interpretation

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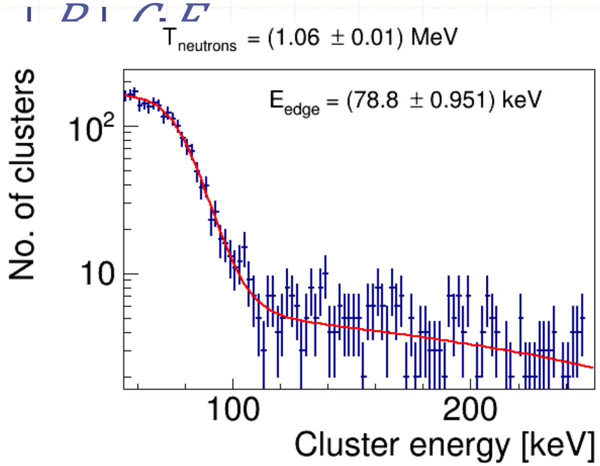
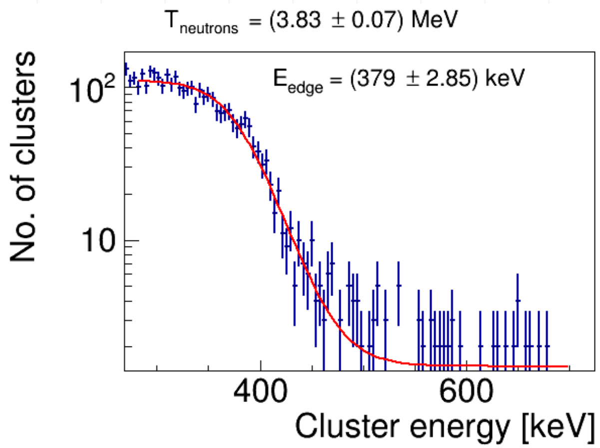
- Fit Fermi-function with background: $f(E)=\frac{A}{e^{(E-E_{edge})}+1}+B+C\cdot E$





Energy transfer to the silicon nucleus:

$$T_{Si,max}=\frac{4M_{Si}\,m_n}{(M_{Si}+m_n)^2}\,T_n=0.133\cdot T_n$$

→ Energy goes partly into displacement E_{NIEL} (NIEL) and ionization E_{ion}.

Energy measured: $E_{edge}=E_{ion}$.

→ Fraction of ionizing energy losses: $f_{meas,\,ion}=E_{edge}/T_{Si,\max}=E_{edge}/0.133\cdot T_n$

Neutron scattering: Losses by ionization vs losses due to displacement

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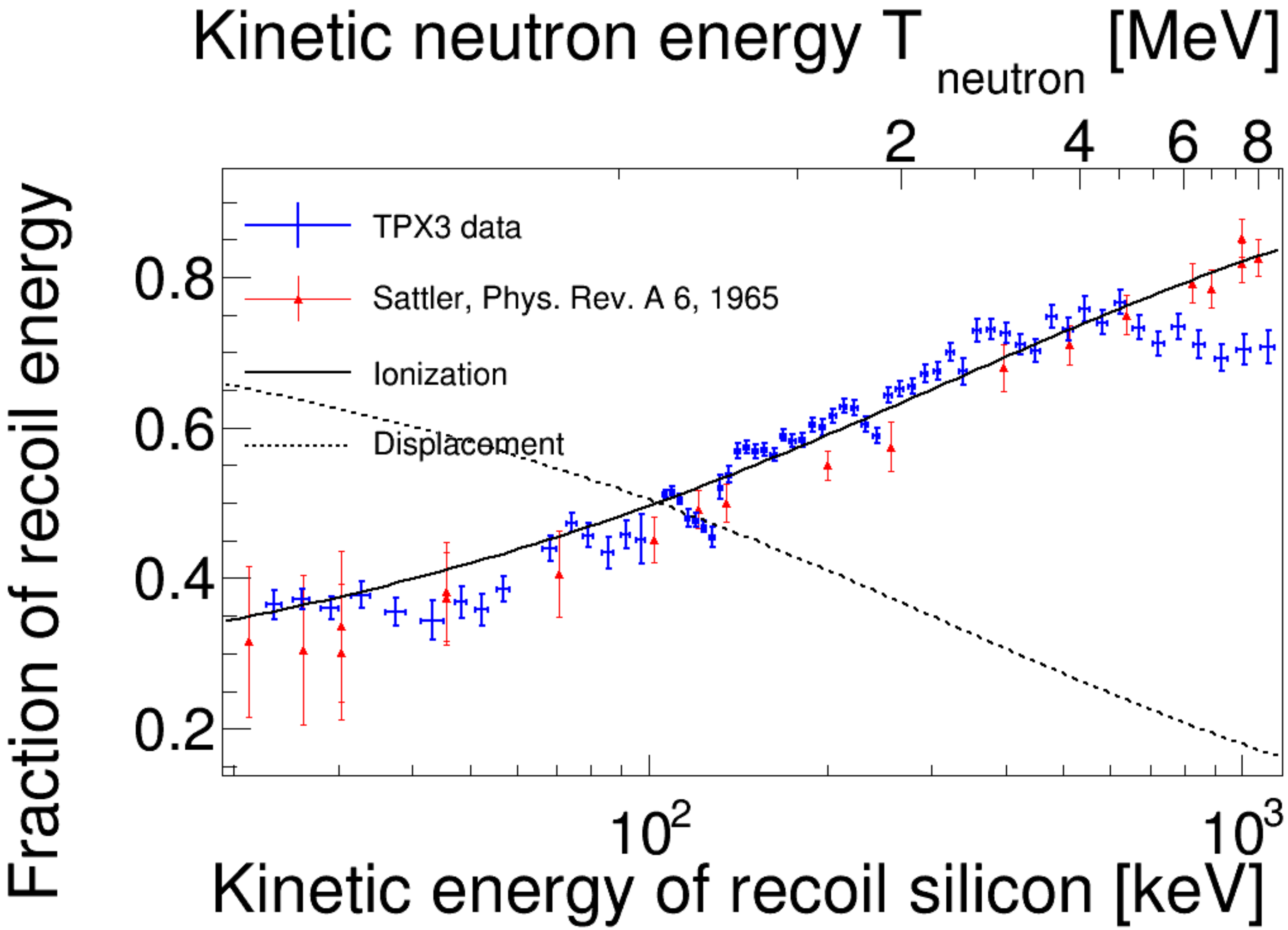

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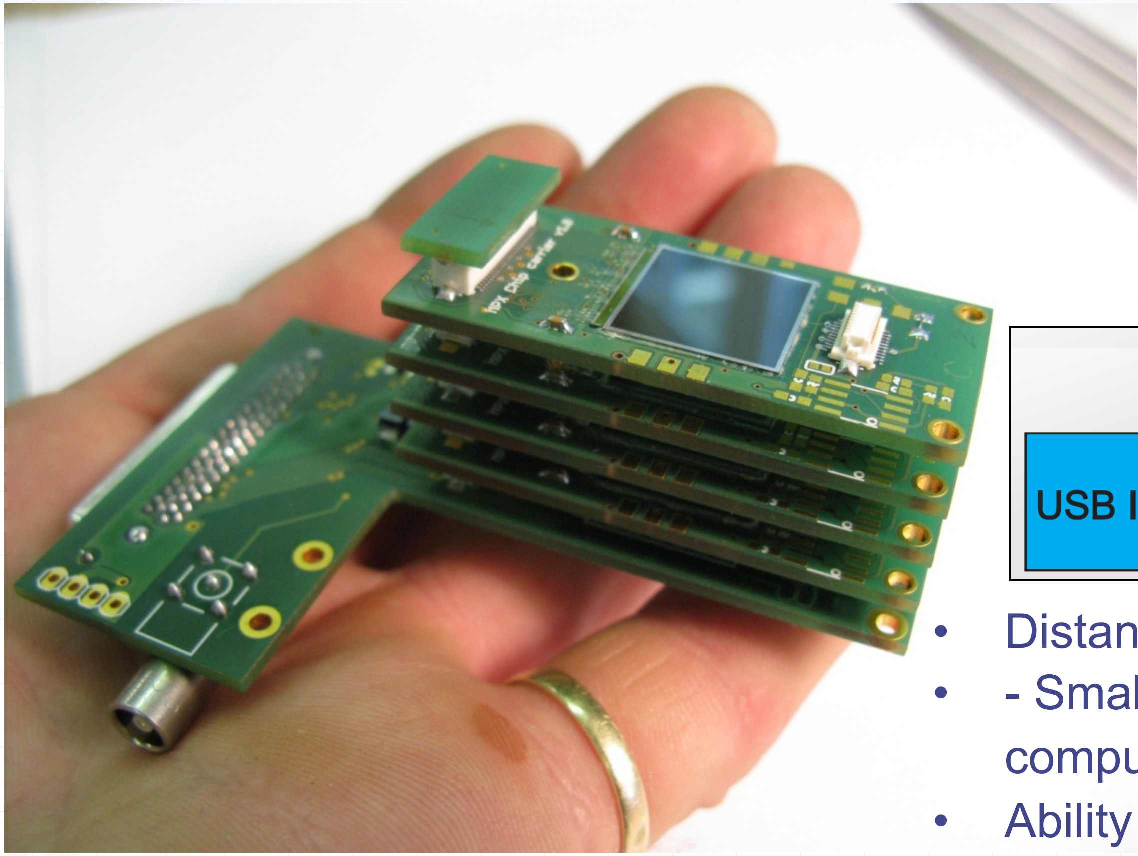
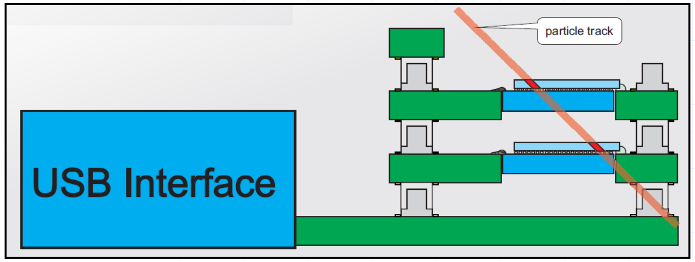
Palm-top particle telescope concept

Variable setup - number of detectors can be stacked





- Distance of layers down to 1.6 mm
- - Small USB interface and laptop computer used for readout
- Ability to distinguish charged and neutral particles by means of coincidence between layers

Medical application:
Hadron therapy - Experimental setup

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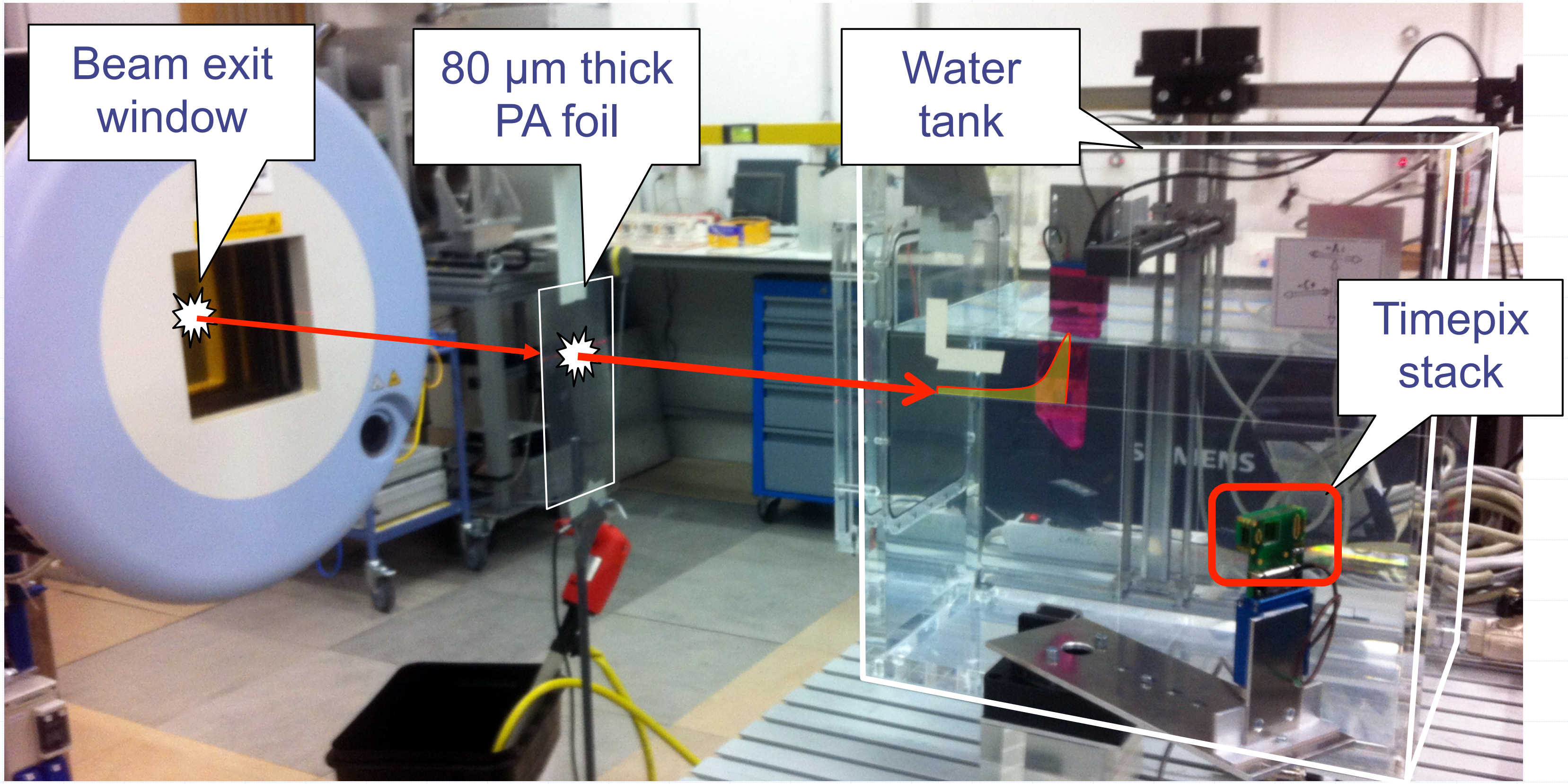

Visualization of secondary particles produced by the beam

Particle beam vizualization in air and in the phantom

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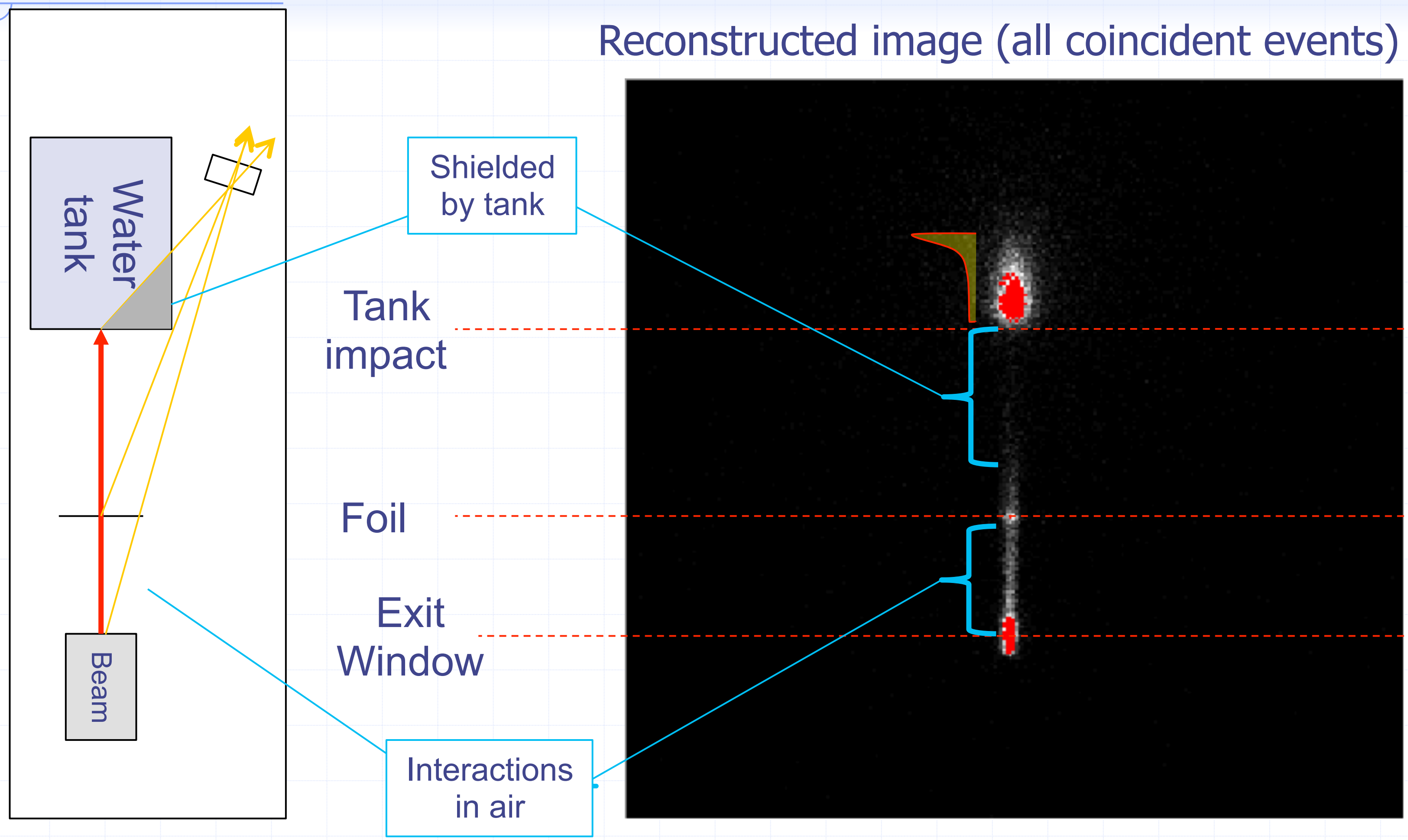

Imaging of secondary radiation produced by Medical Ion beam

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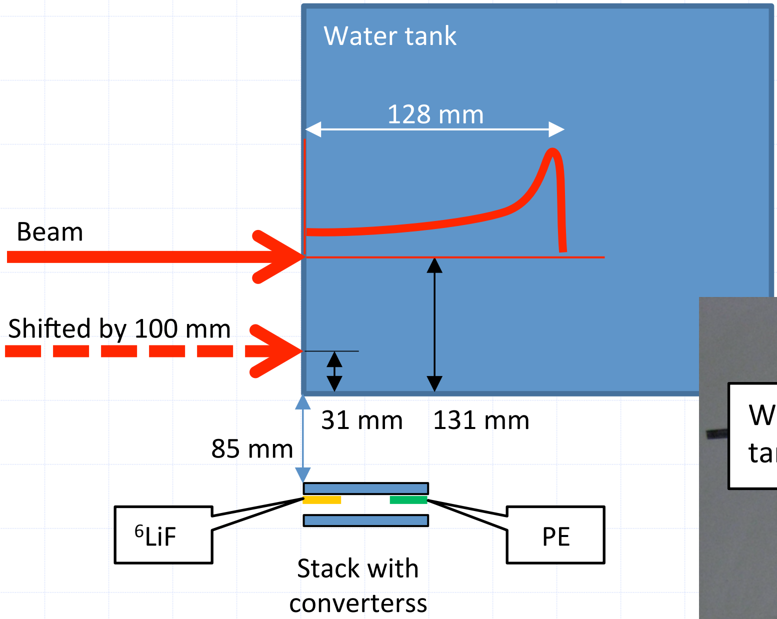
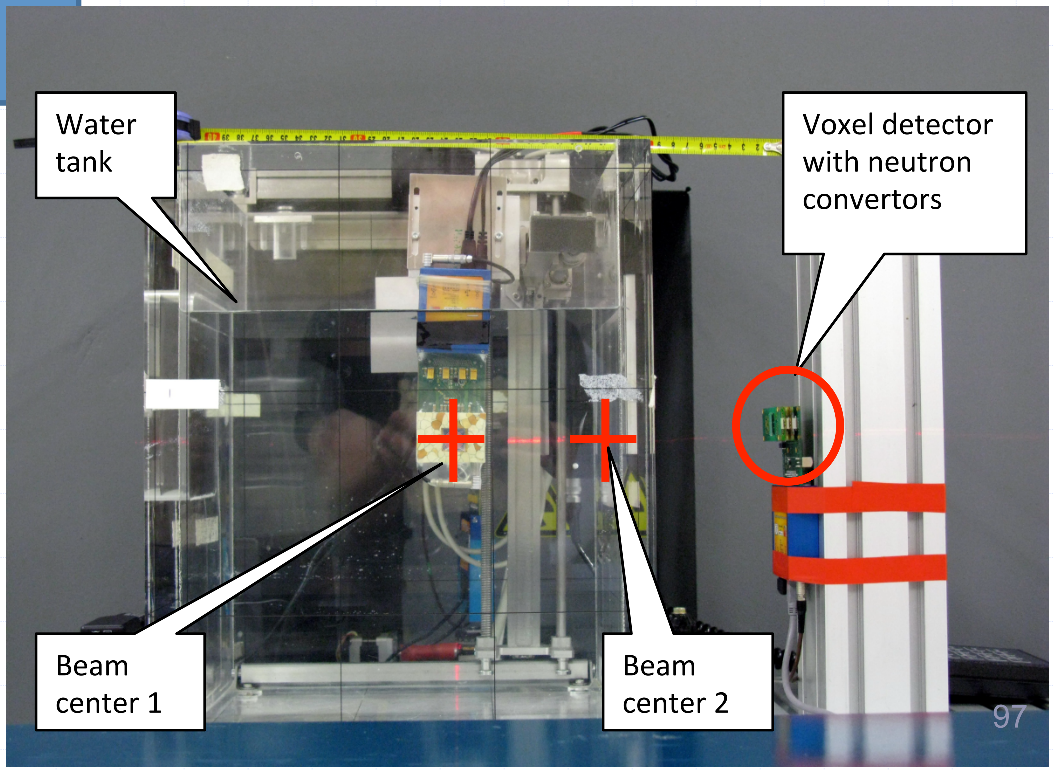


Beam: Carbon 250 MeV/u



Data processing: Sample frame (^{12}C at 250 MeV/u)

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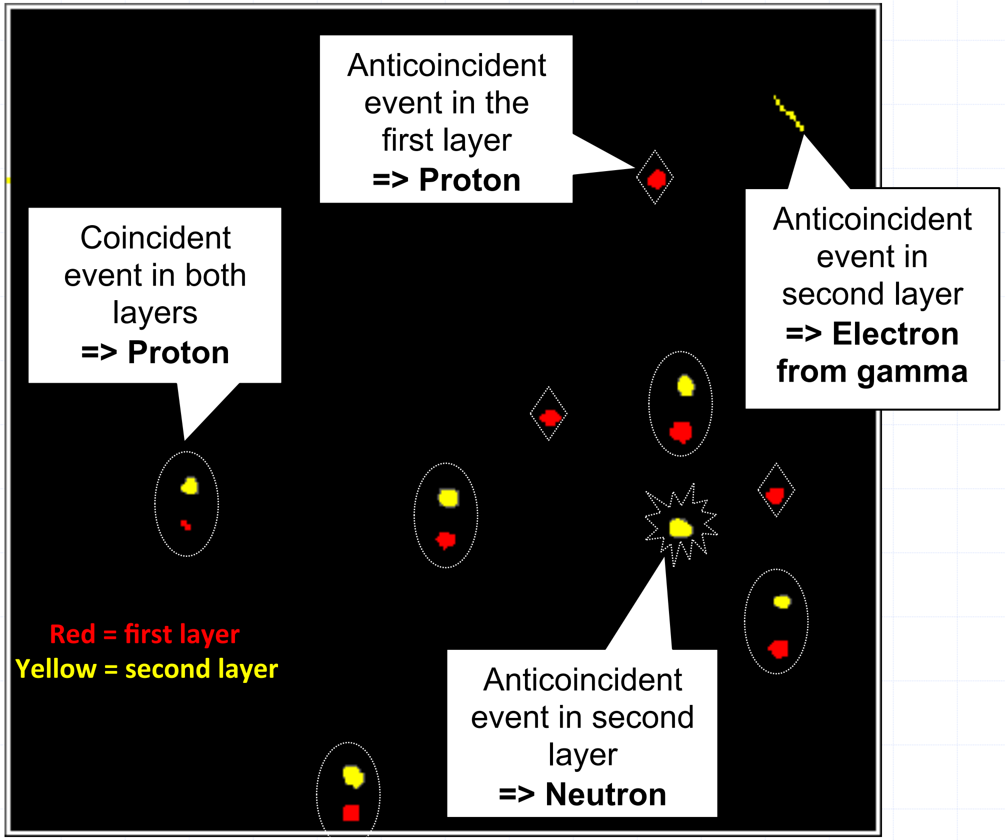
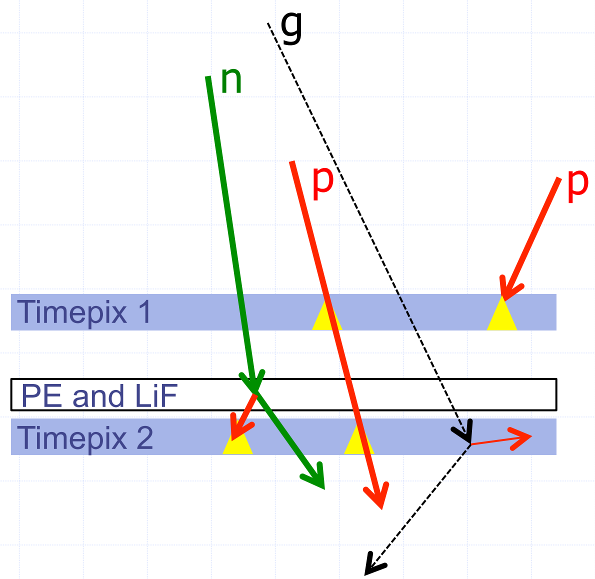


Coincidences = ions

Anticoincidences in 2nd = neutrons



Water tank results:

(^{12}C at 250 MeV/u)

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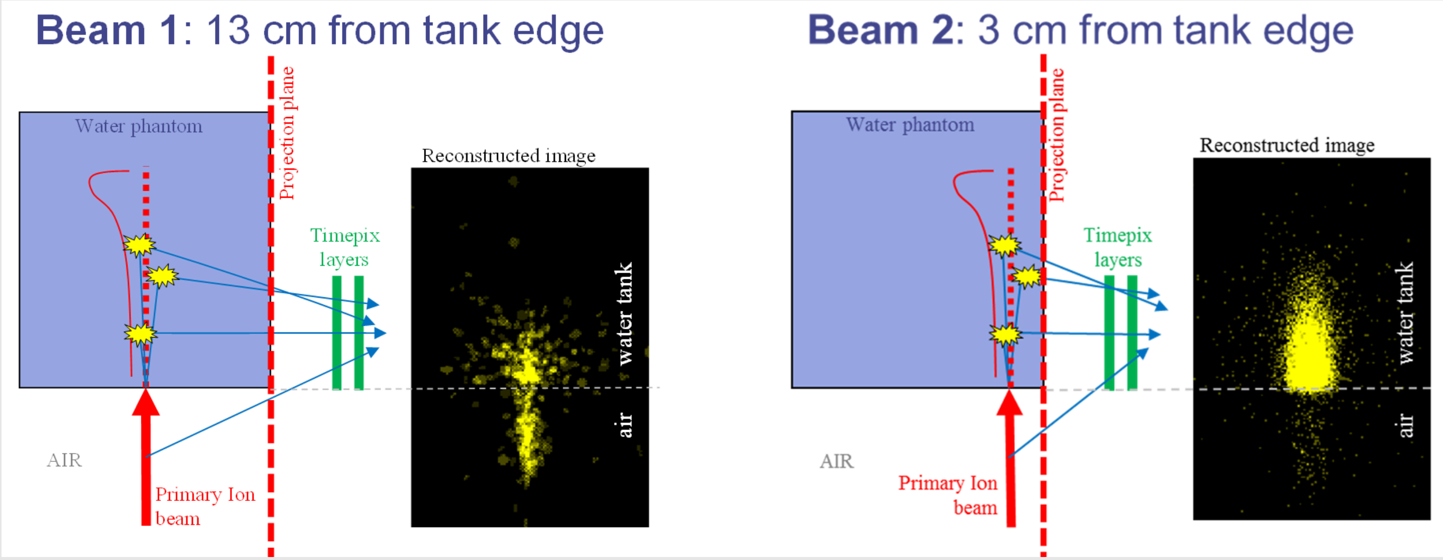
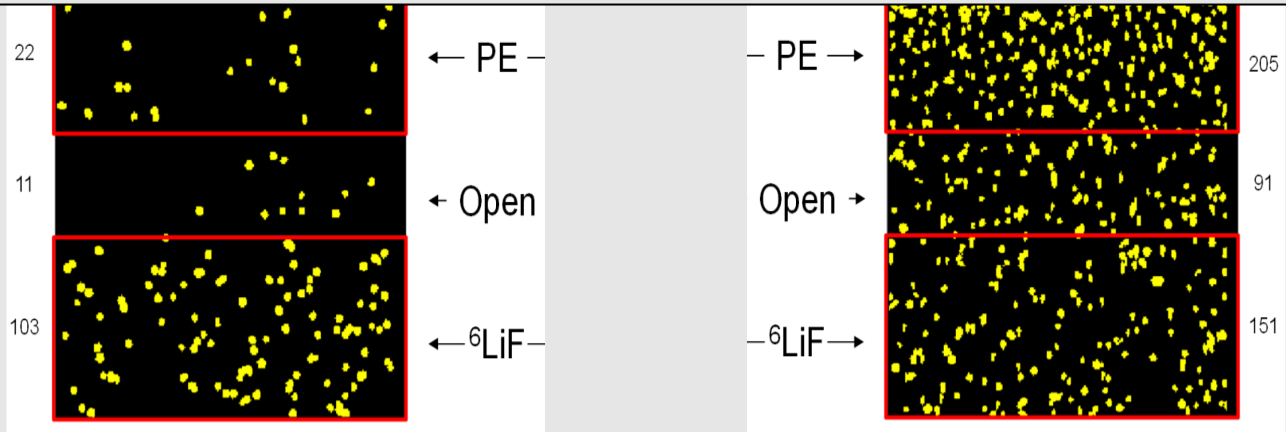
Coincidences



Anticoincidences



Fast/Slow = **0.45**

Fast/Slow = **6.70**

Protons with different energies: 90 degree

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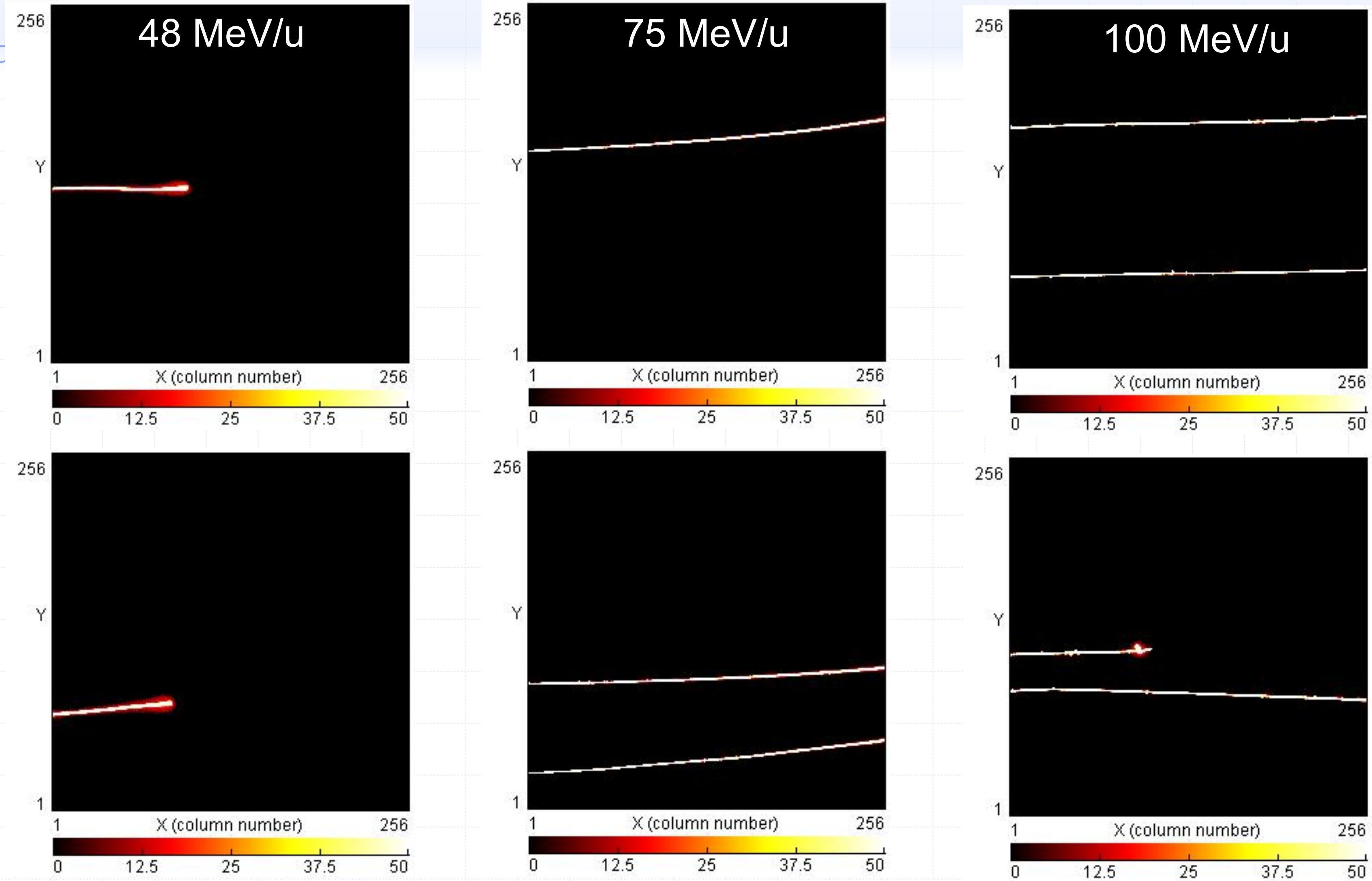

Carbon ions with different energies: 90 degrees

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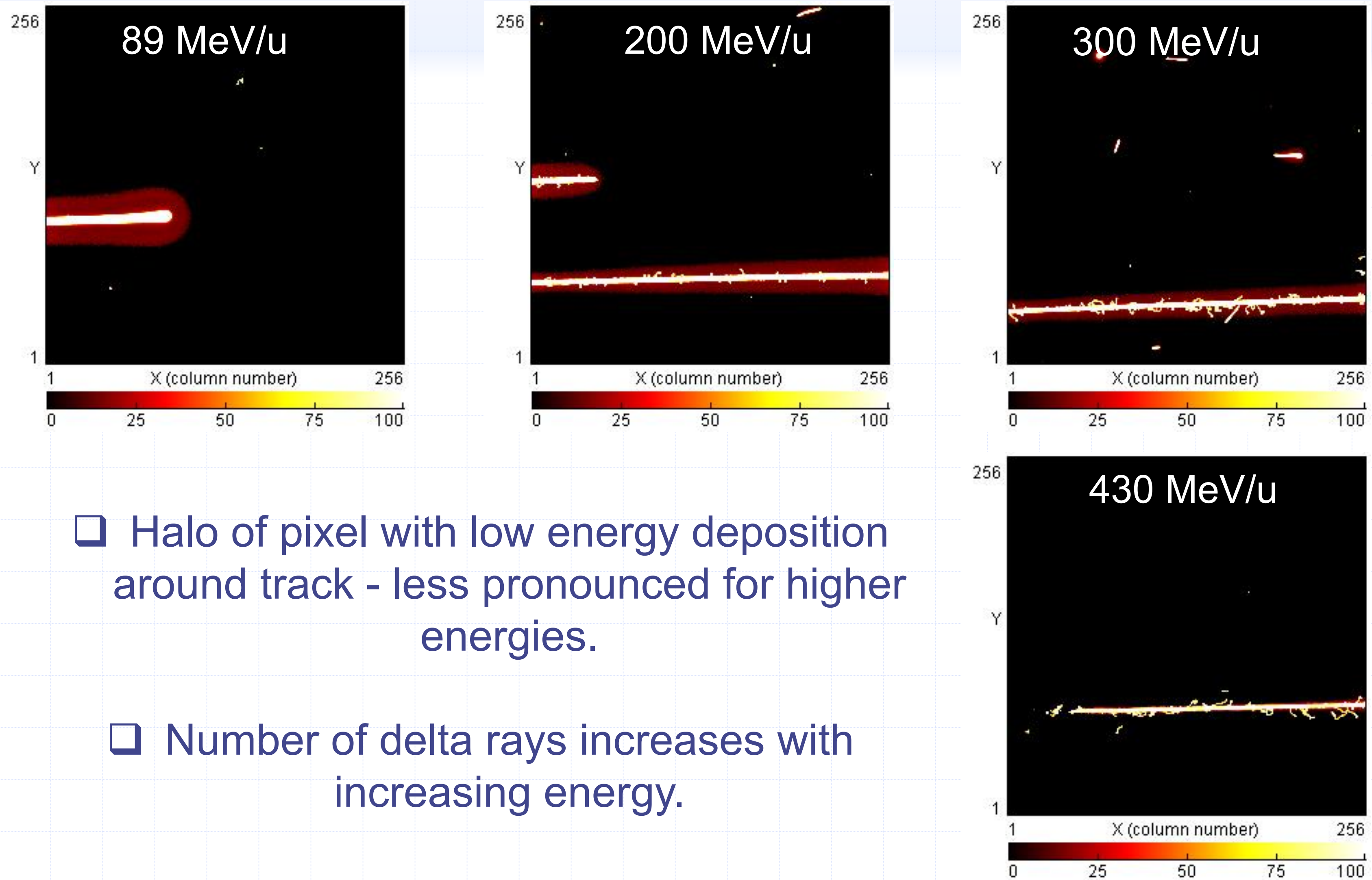

- Halo of pixel with low energy deposition around track - less pronounced for higher energies.
- Number of delta rays increases with increasing energy.

Oxygen ions with different energies: 90 degrees

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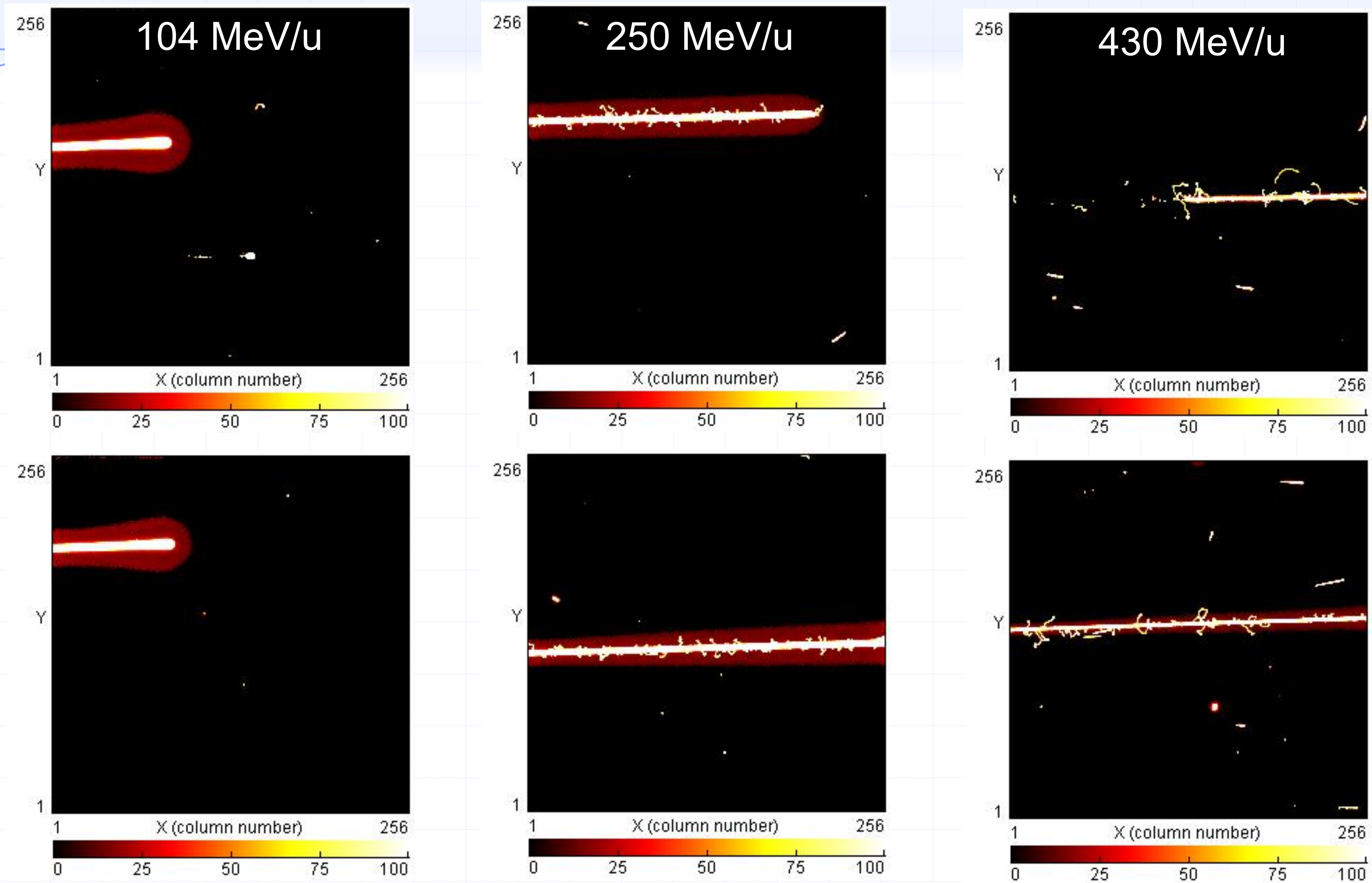

Alphas with different energies: 90 degrees

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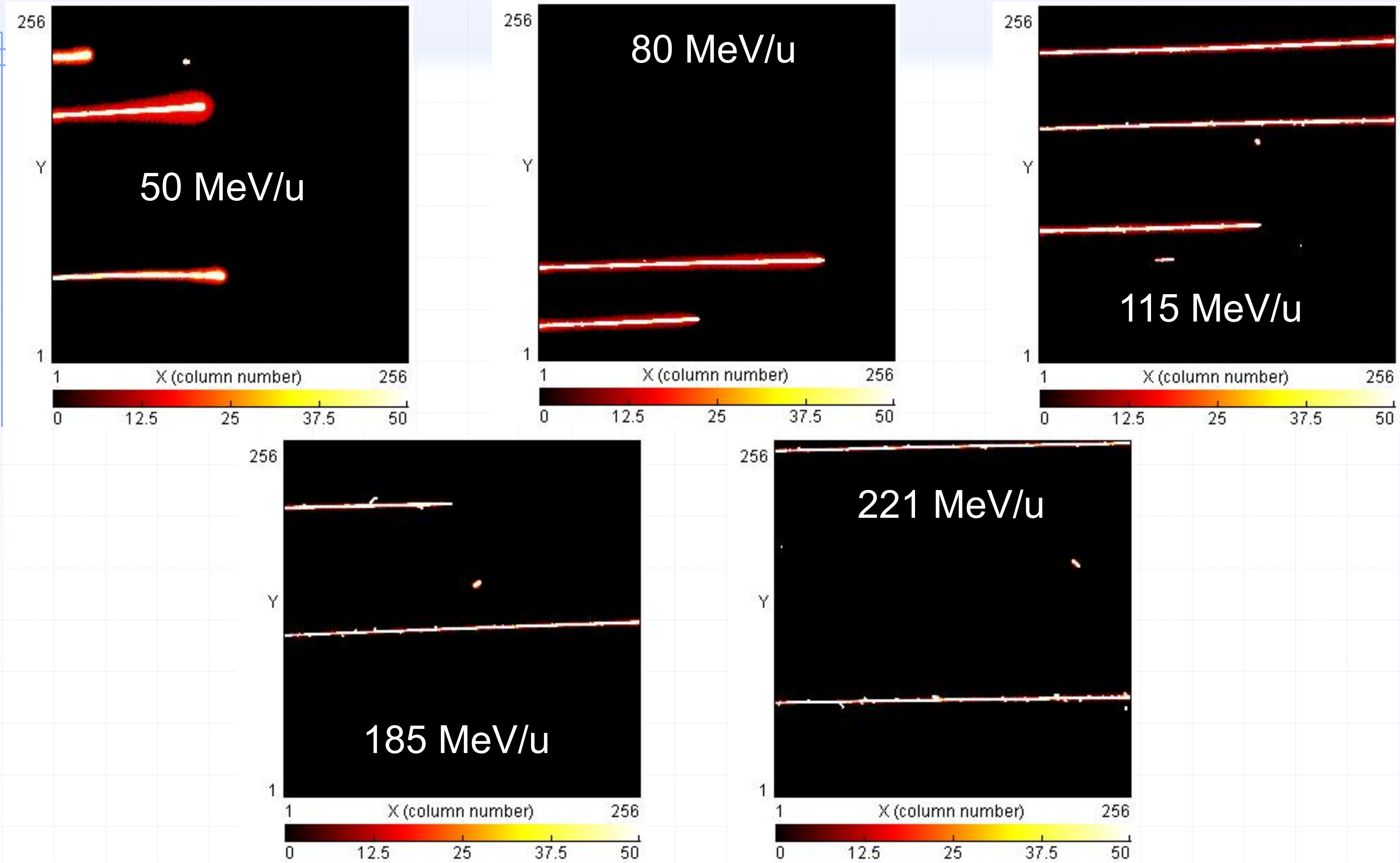

Tracks of Pb ions as measured on SPS beam at CERN (rear-side glancing angular incidence about 4.1 degree)

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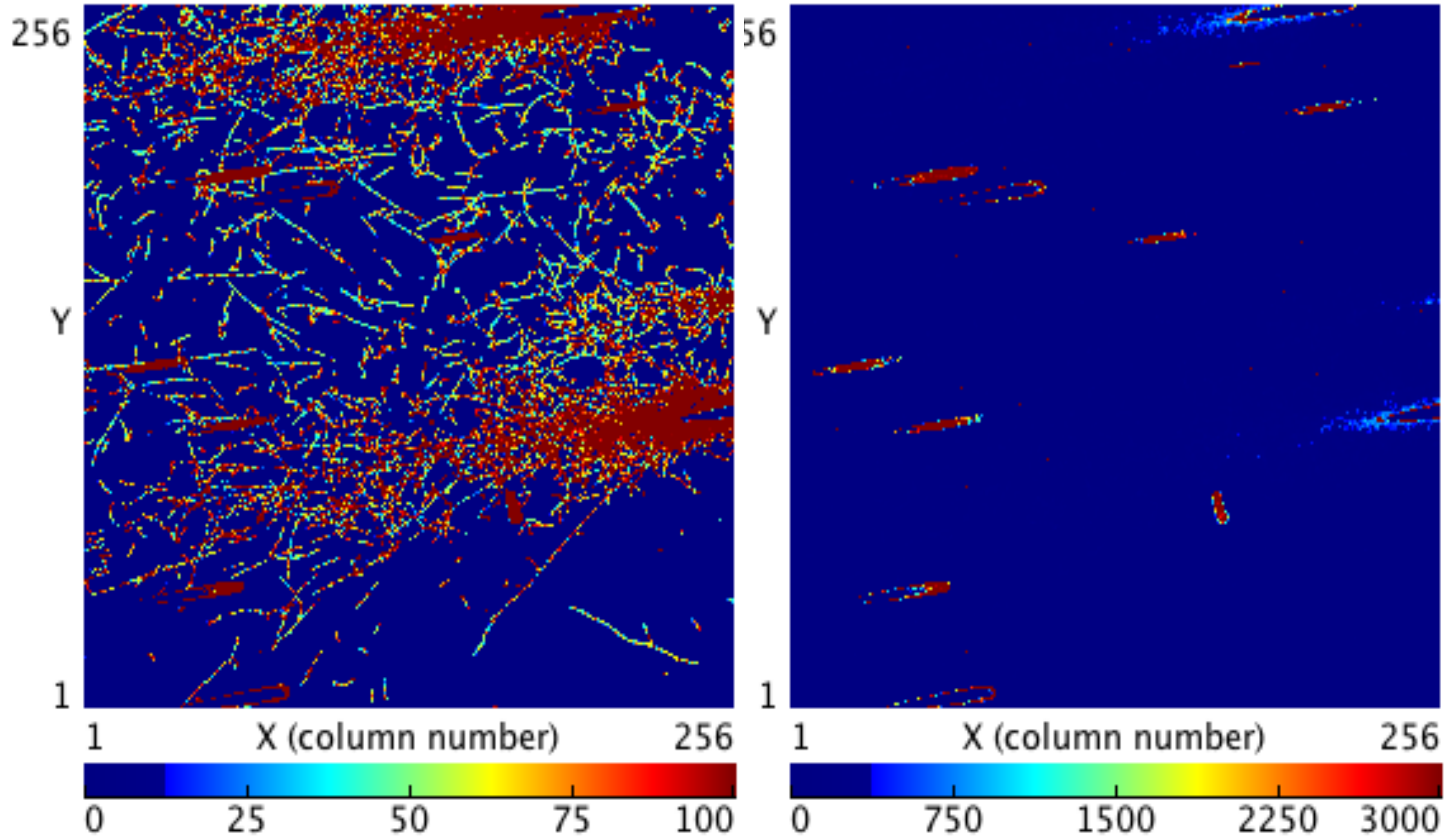

scale 100

scale 3000

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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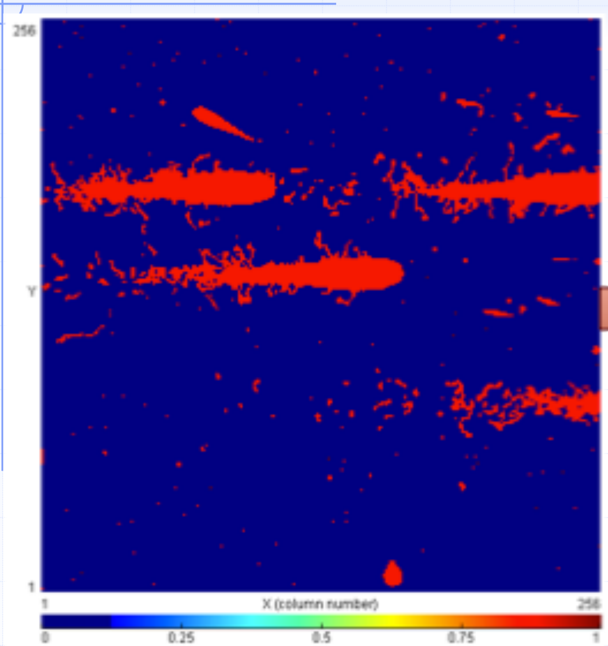
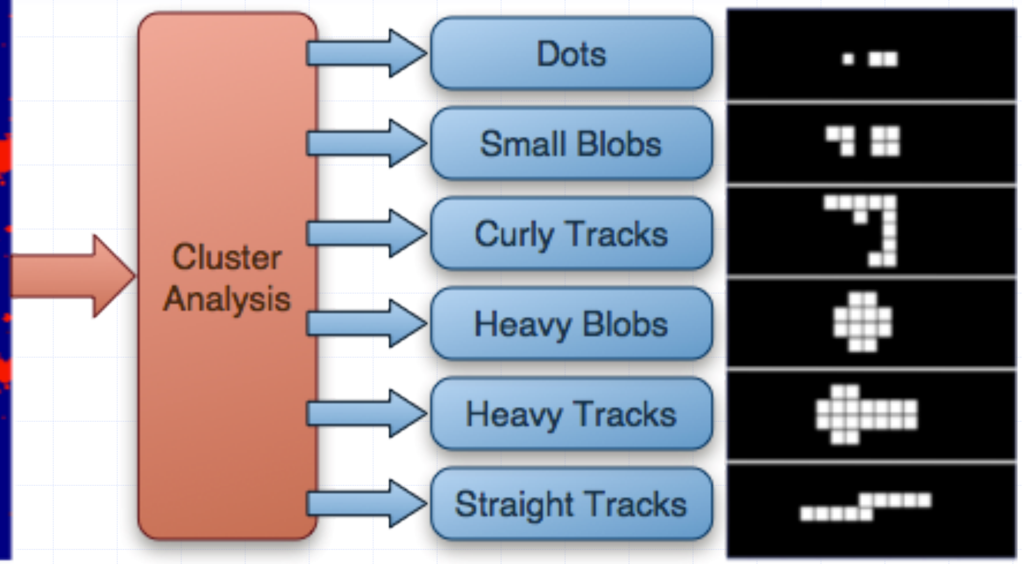
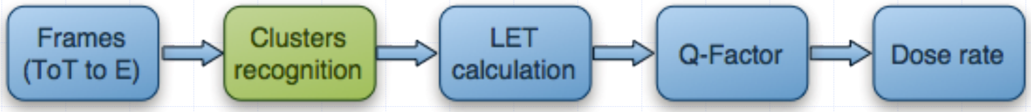


Frame containing 400 MeV 56Fe, 85°, measured at HIMAC, Japan



Cluster analysis algorithm is successfully working in ATLAS-MPX network



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The global network of Timepix detectors for radiation monitoring is under development

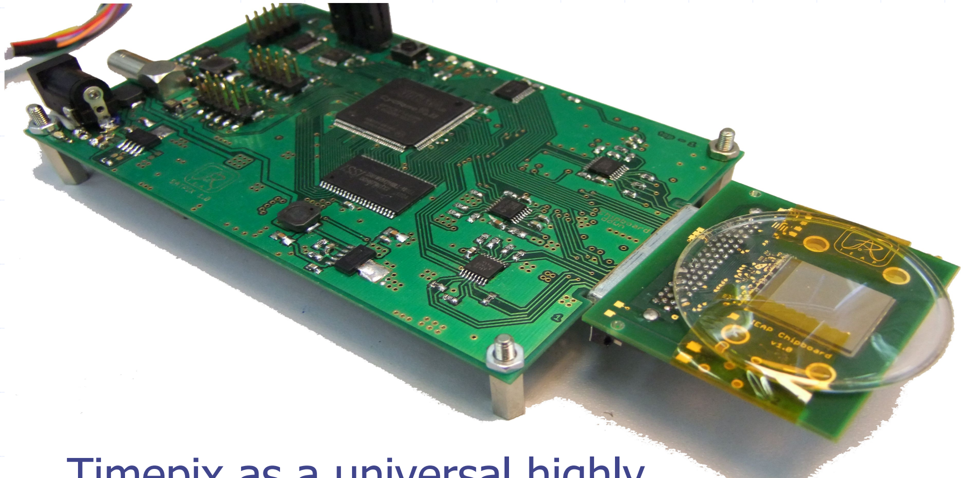
- Medipix radiation monitors are placed on different places (accelerators, space, laboratories, companies, …) to measure composition and spectral characteristics of mixed radiation fields including neutrons.

- Various pixel detector types (with Si, CdTe, GaAs sensors) are controlled by Pixelman software through local machines or by micro PCs either via Ethernet or wirelessly.

- Measured data are continually uploaded to server machine in the IEAP CTU in Prague.

- Data are accessible on web server dedicated to their visualization and evaluation.

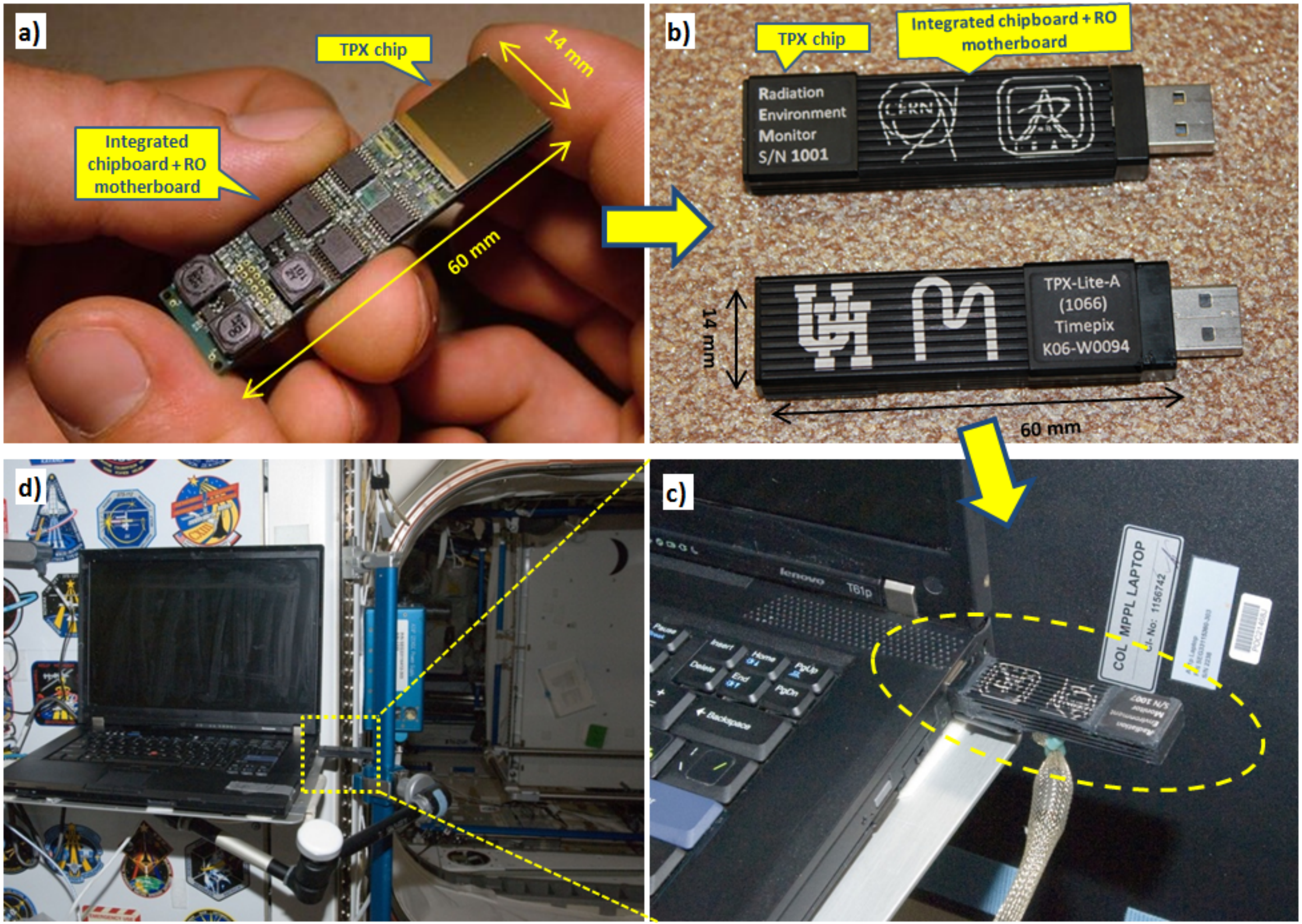
Timepix devices for space applications
NASA, ESA



Timepix as a universal highly miniaturised radiation Monitor for use on ESA spacecraft.

The proposed device is called SATRAM and it is scheduled to fly on PROBA-V in late 2014. Motherboard of control unit for Timepix detector as developed for ESA project at IEAP CTU in Prague.

Miniaturized USB unit with detector Timepix as prepared (in cooperation with University of Houston) and delivered to NASA (10 pcs). Will be used for dosimetric measurements at ISS.



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.

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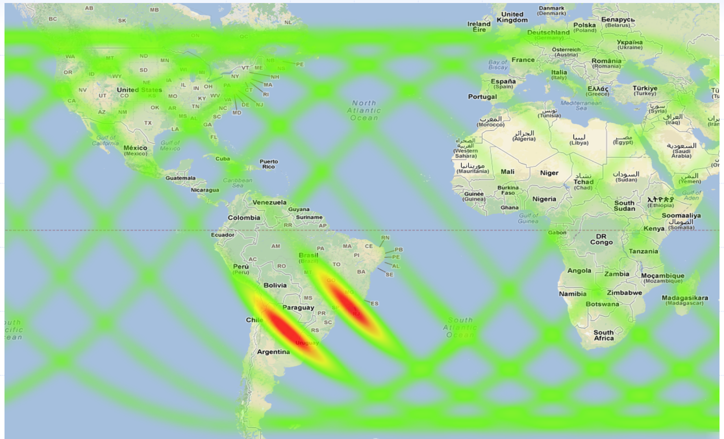
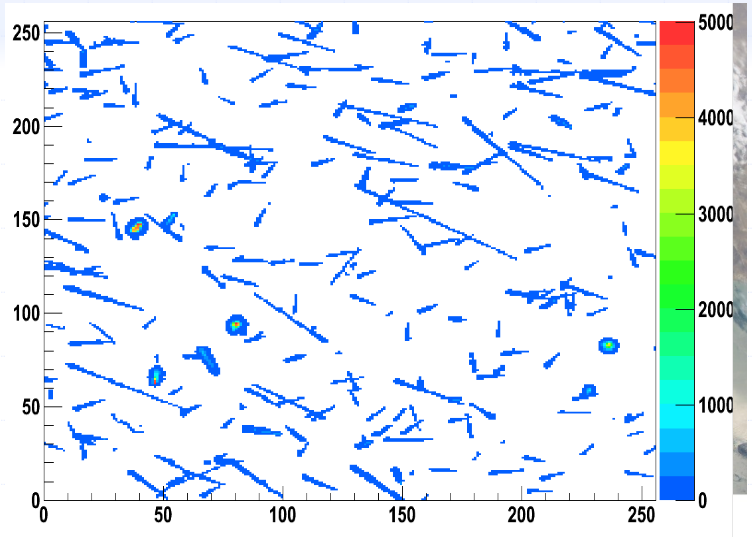
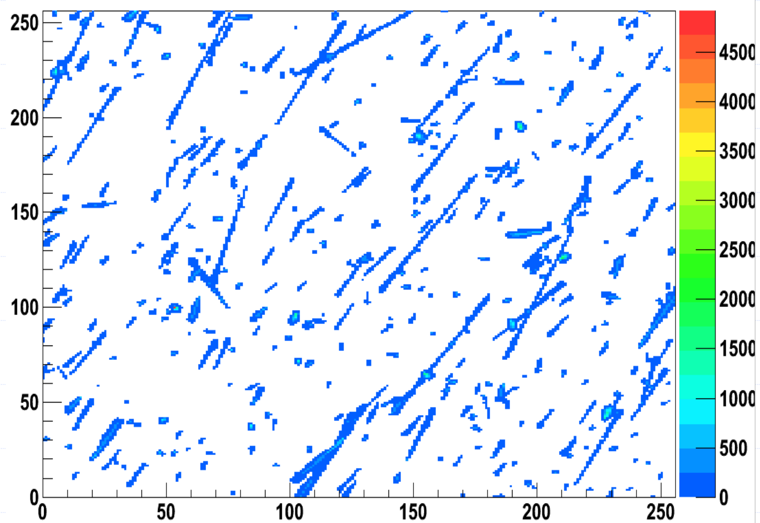
Dosimetry in space on ISS

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







Dosimetry in space: SATRAM – ESA Proba-V satellite

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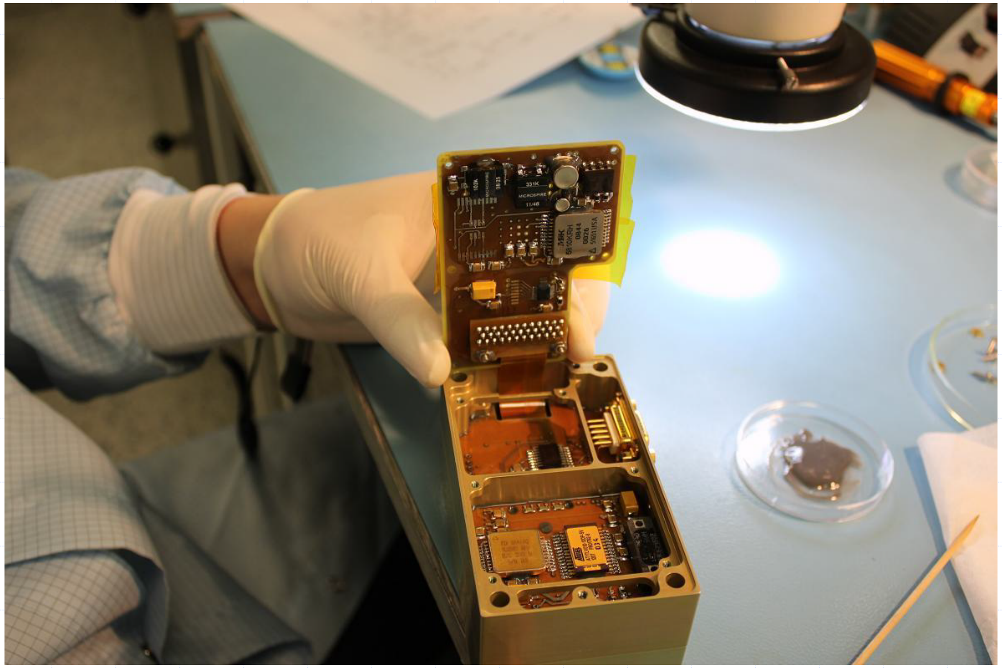
Characterization of mixed radiation field on low orbit of PROBA-V satellite

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

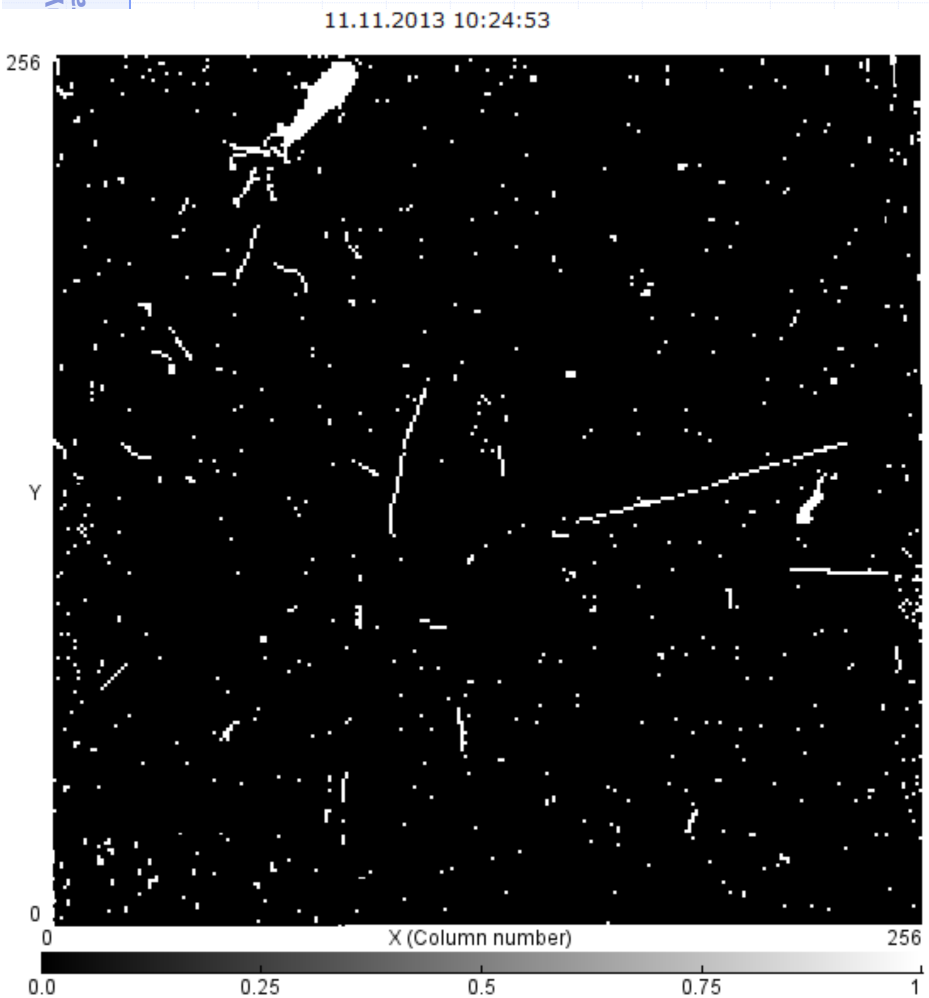


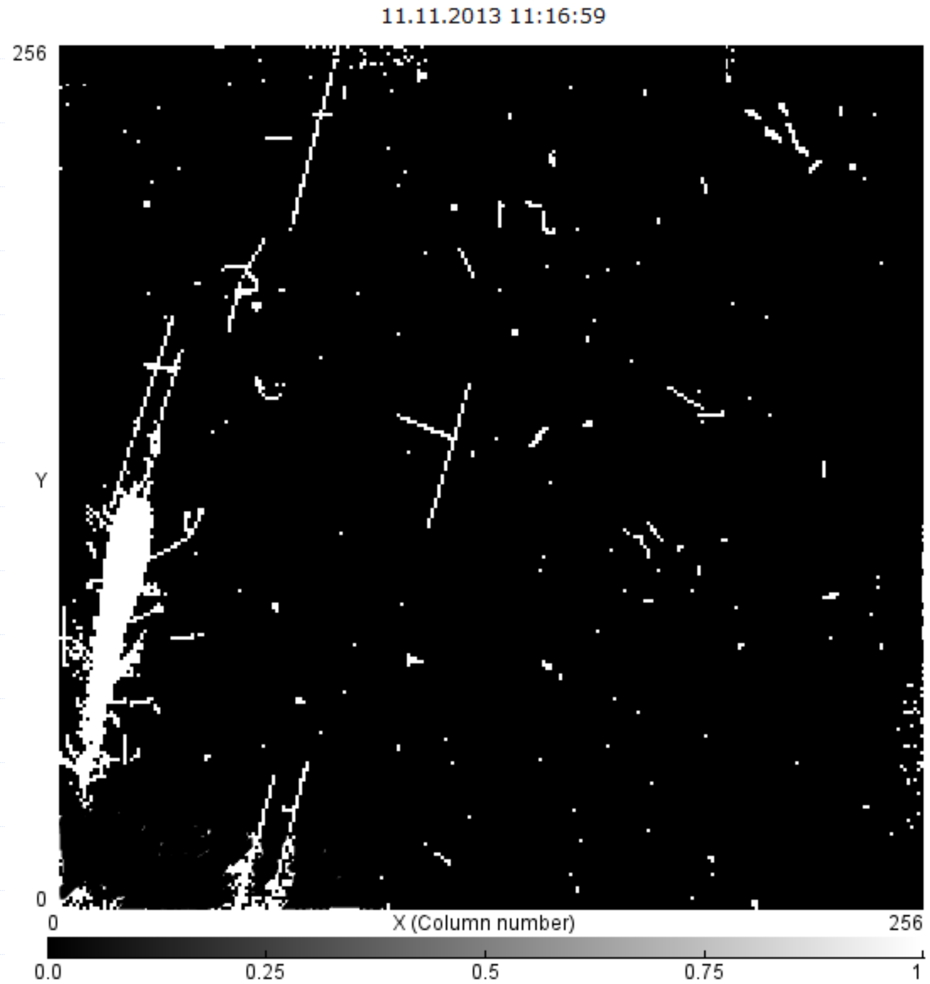
proba VEGETATION

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

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

Energetic heavy charged particles (ions)





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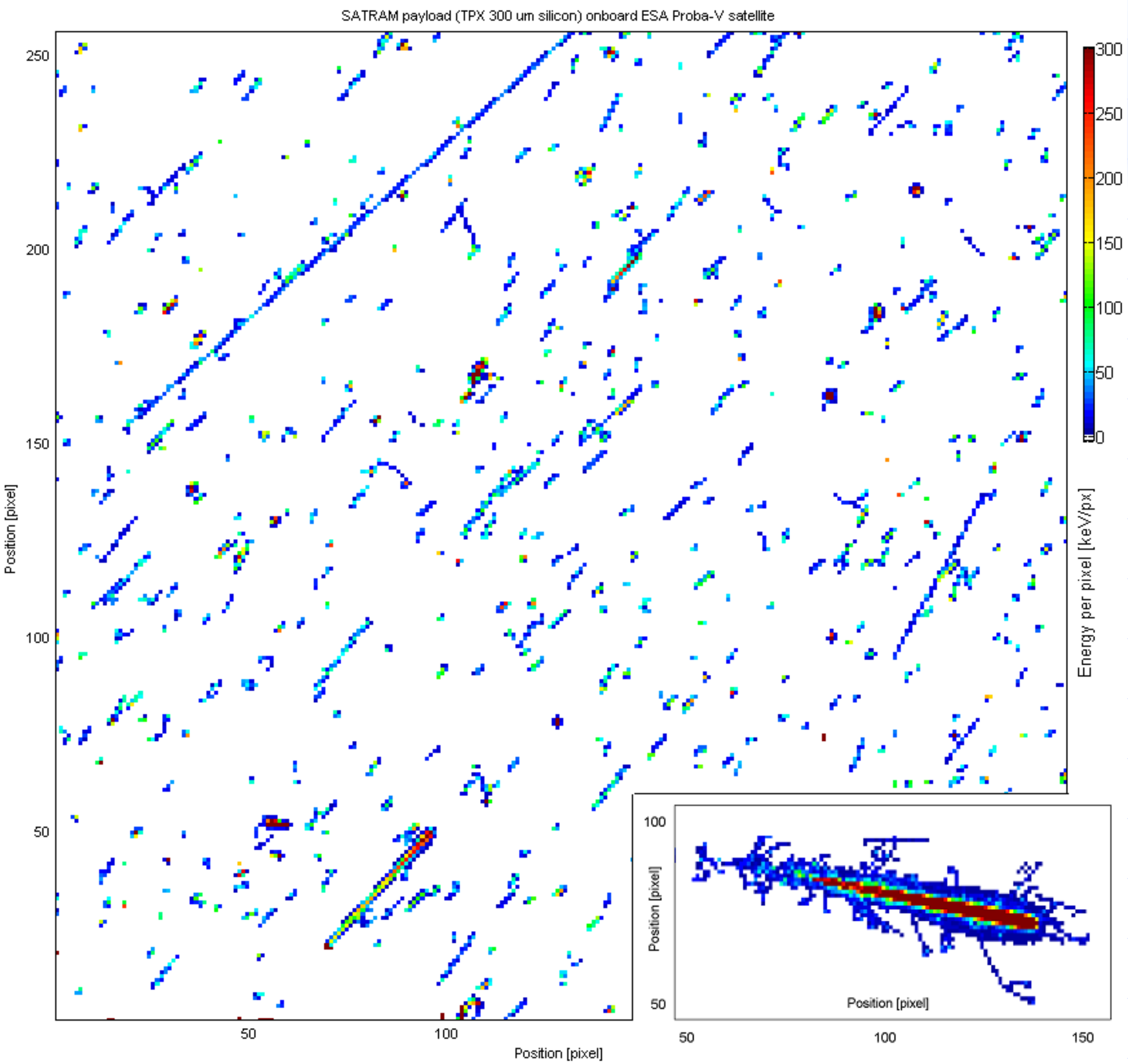

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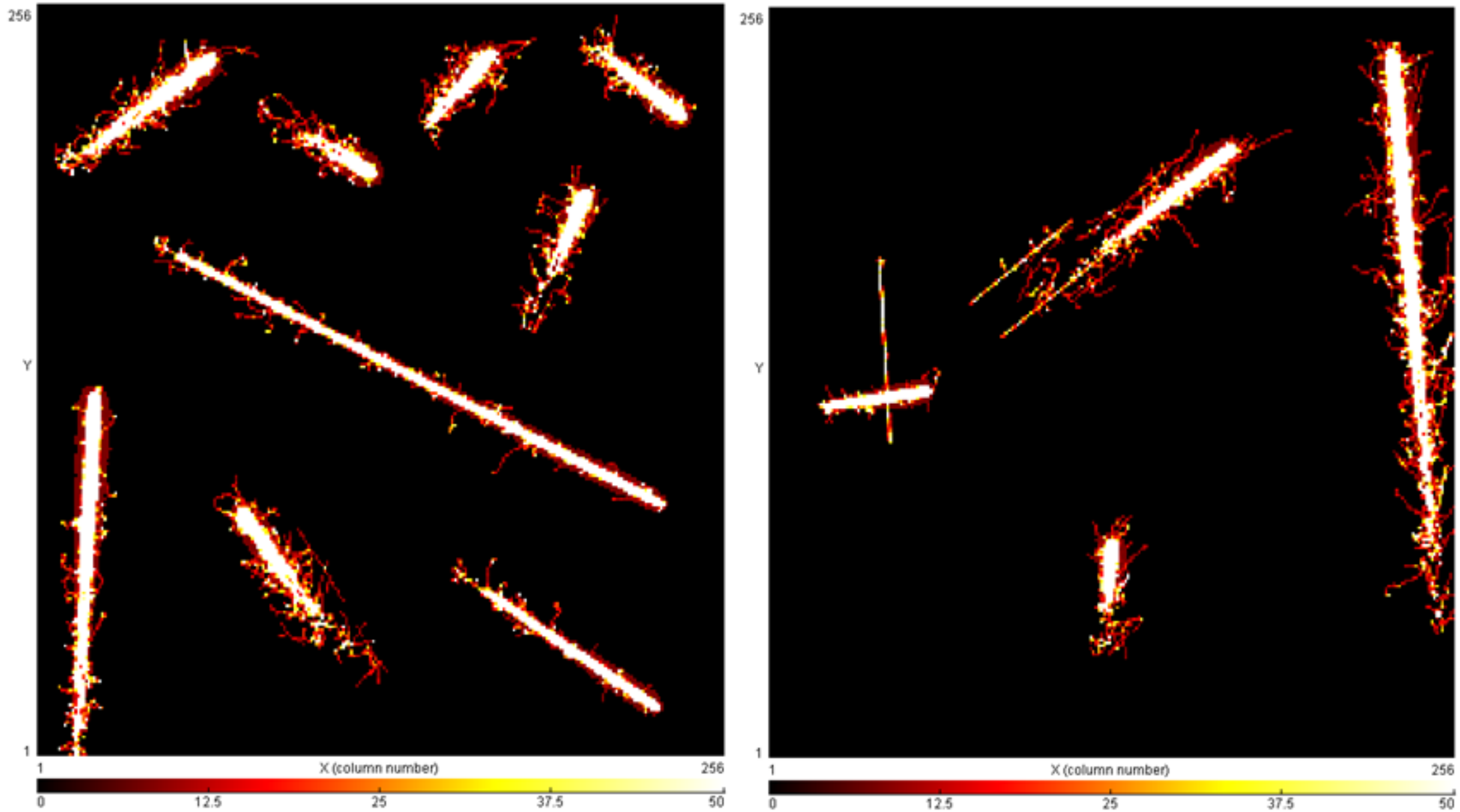
Timepix/ESA Proba-V:
LEO space radiation @ 820 km

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



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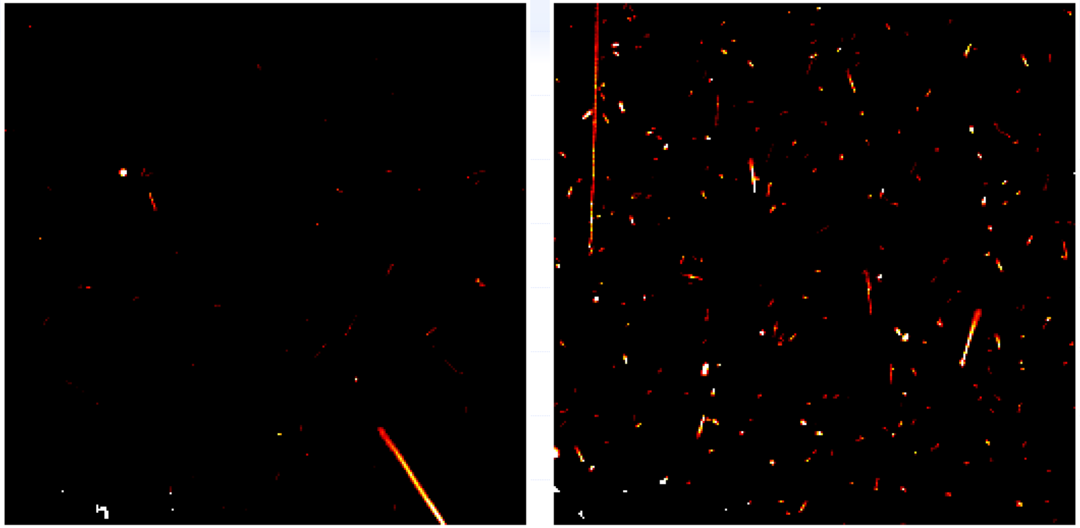
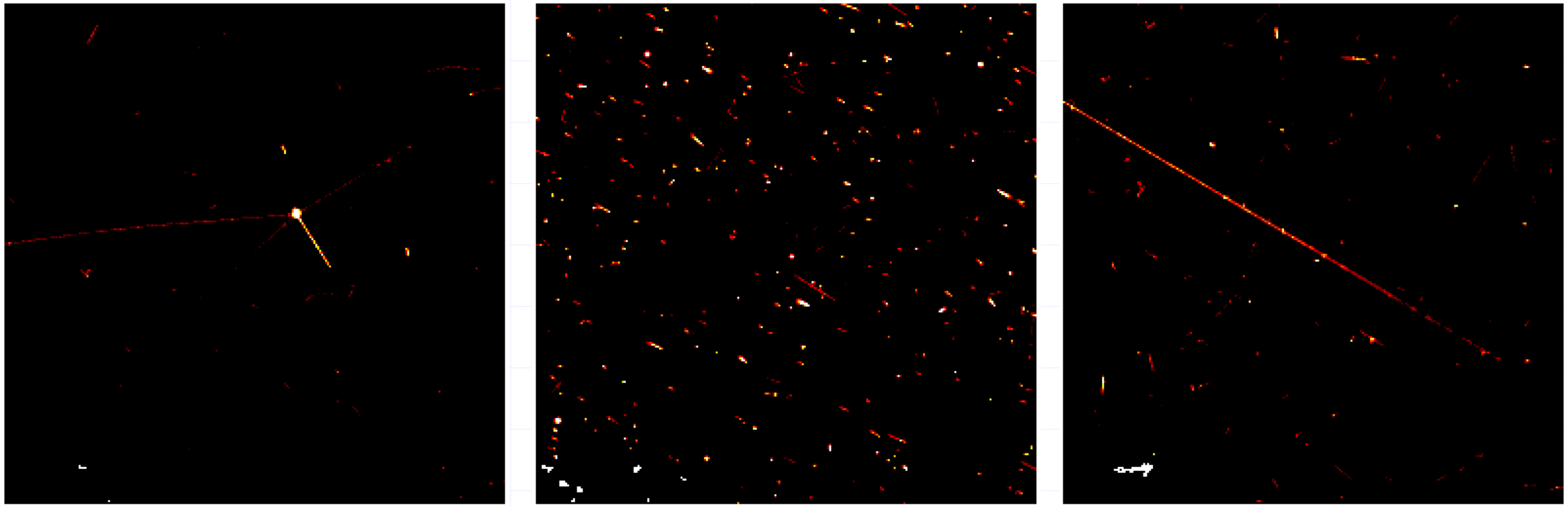
SATRAM – Measured frames

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

- Commissioning phase
- Data from 15th May 2013
- Detection threshold of 10keV





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

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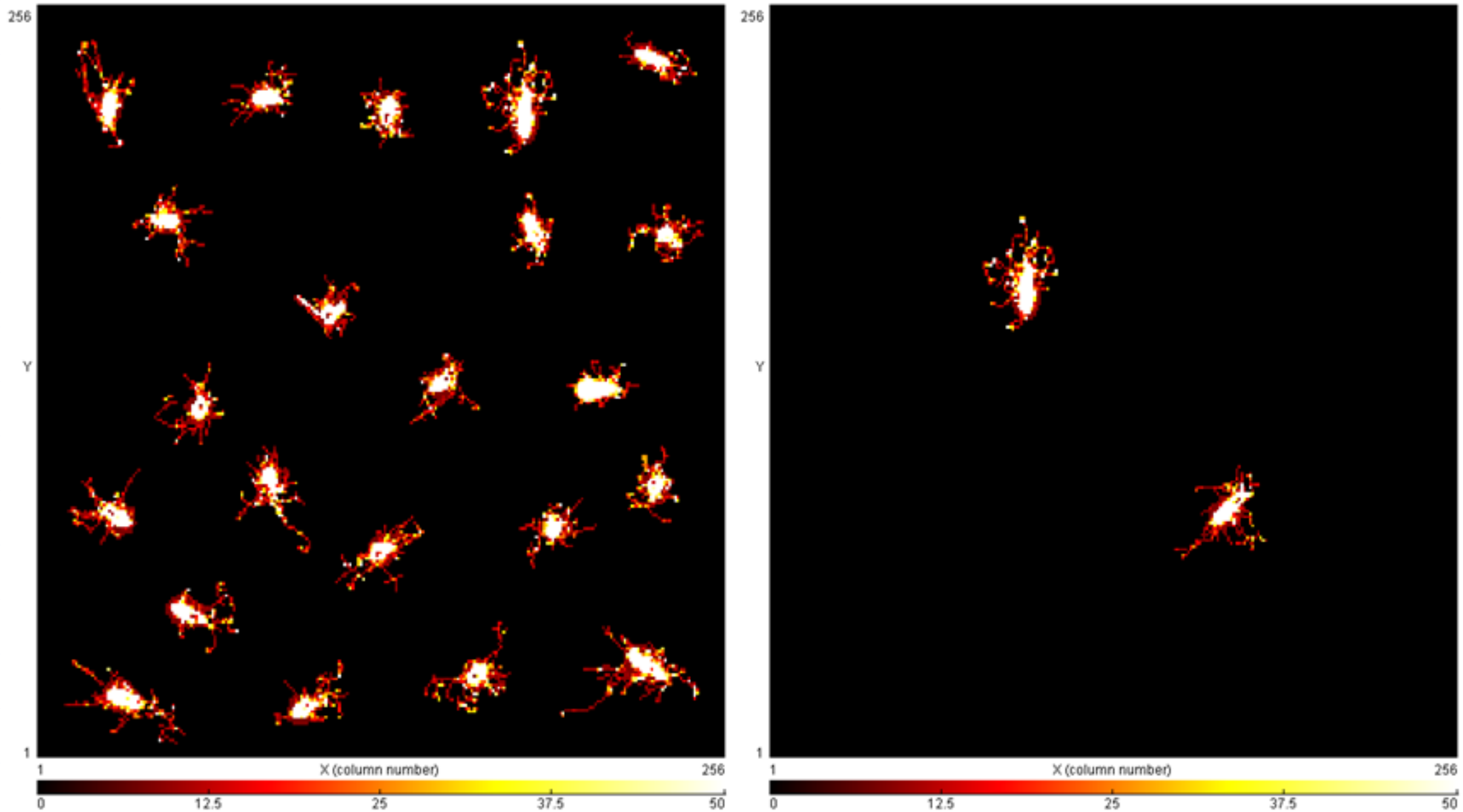
HETPs: Highly energetic heavy charged particles (ions) → HZE's



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

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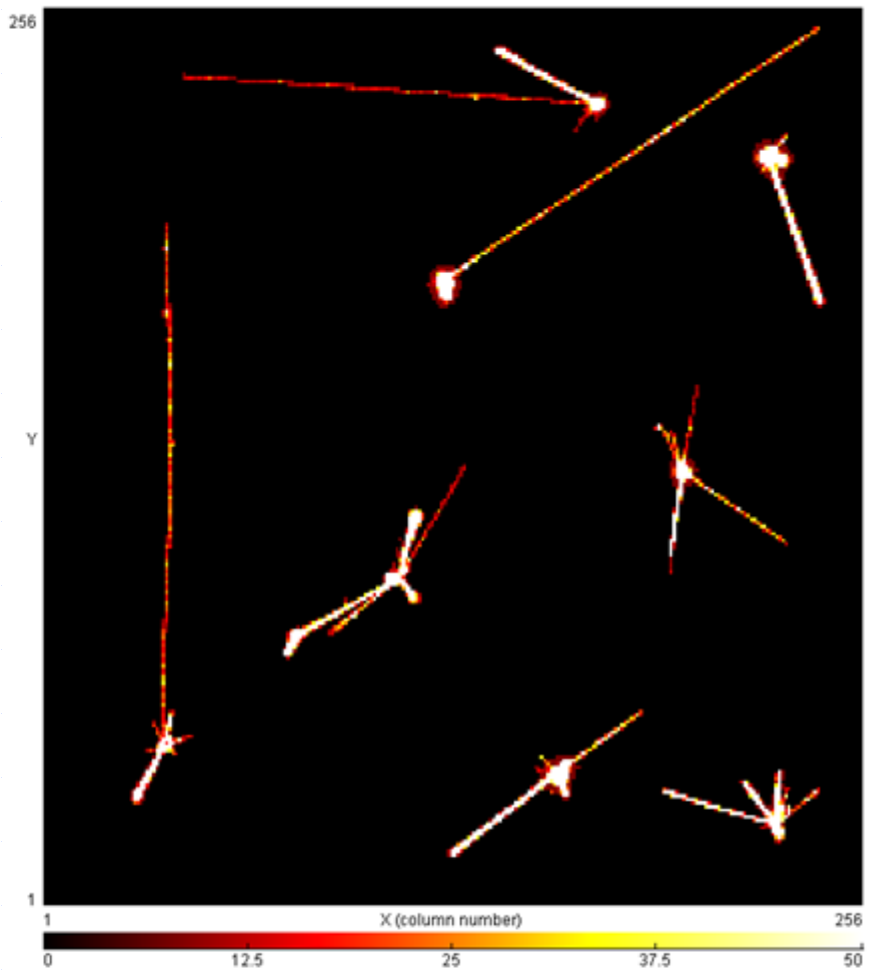
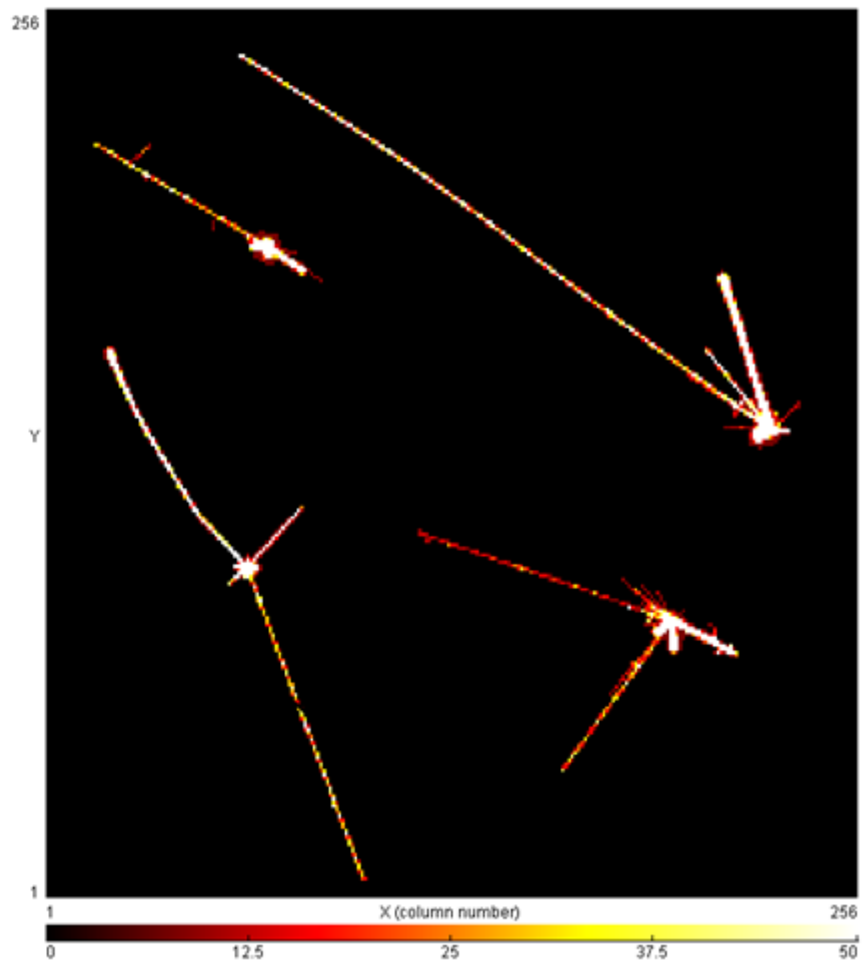
LETPs: Energetic light charged particles (I) + nuclear interactions





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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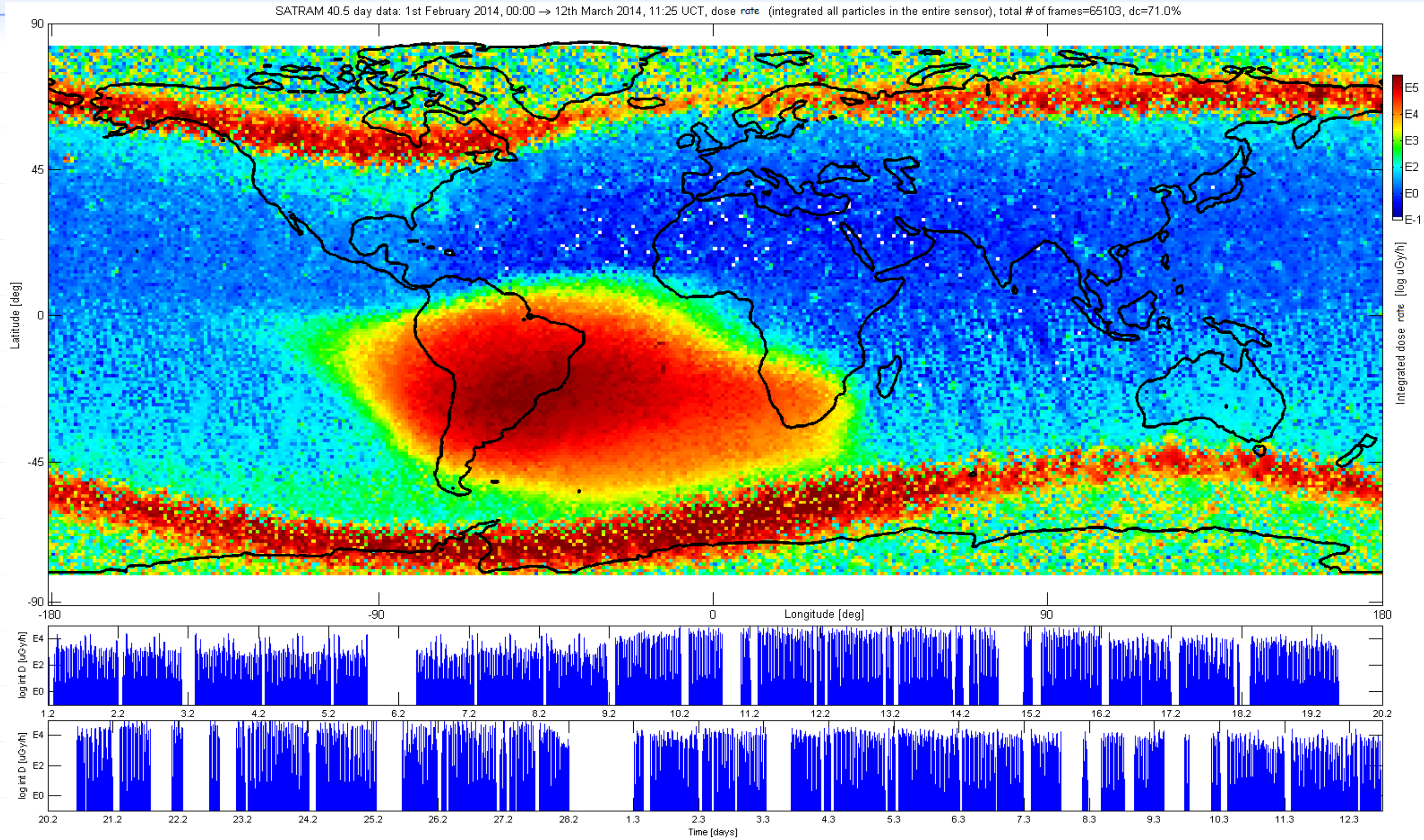
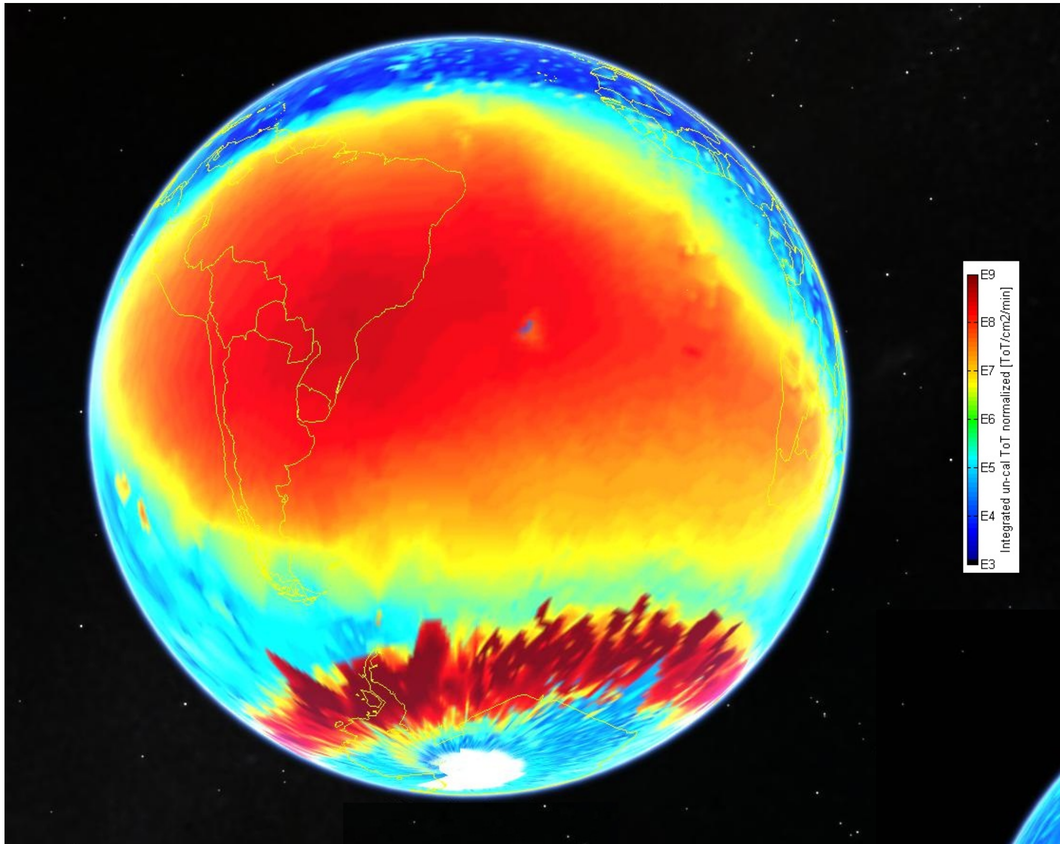
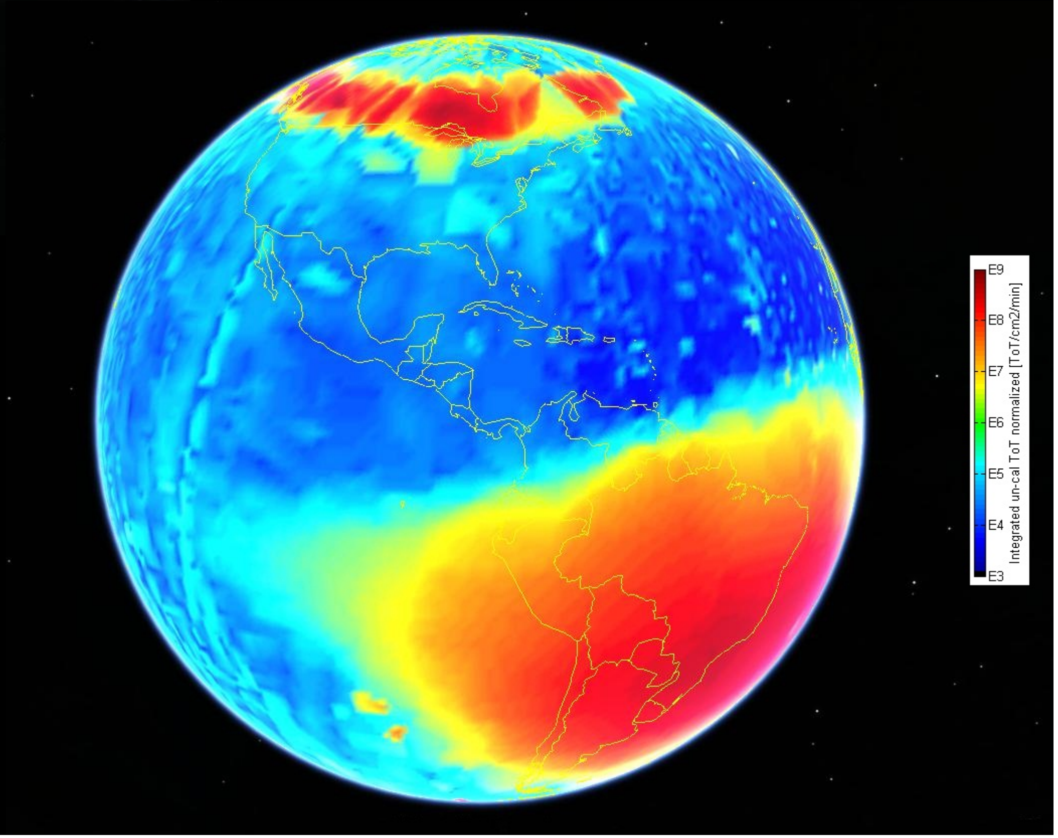


SATRAM – Proba-V



South America, Antarctica, South Atlantic Anomaly SAA

The Americas



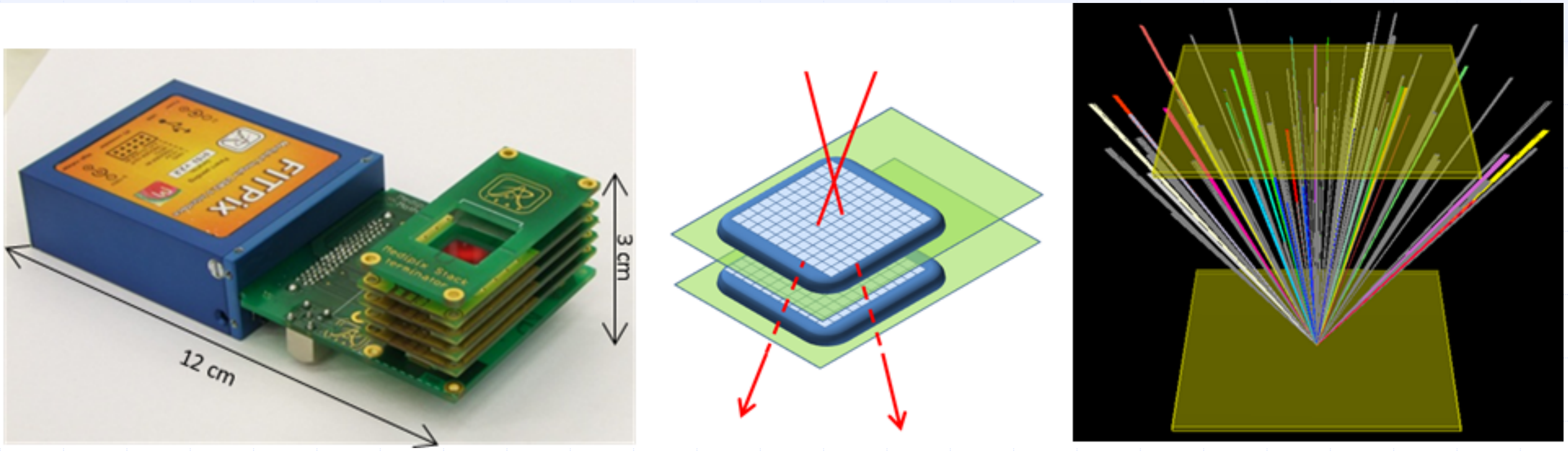
Radiation field Earth map spatial distributions measured by Timepix onboard ESA Proba-V satellite LEO orbit 820 km altitude displaying all radiation components integrated over 5.5 months

RISESAT

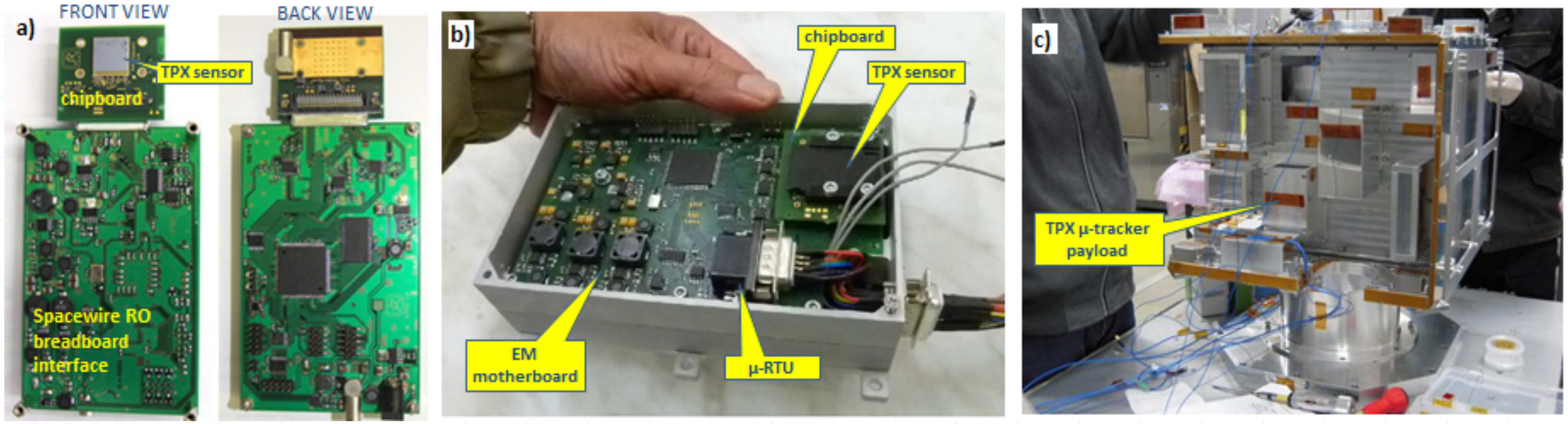
Rapid International Experimental Satellite
Timepix particle μ-tracker particle telescope

東北大学
TOHOKU UNIVERSITY

Institute of Experimental and Applied Physics
Czech Technical University in Prague



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 partcle 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).

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How to proceed further to improve position resolution, detection efficiency, R/O speed?

- Sensor technologies
- R/O chip technologies
- R/O interfaces for data transfer
- SW for data evaluation

Some examples follow!

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Promising candidate for neutron imaging: CdTe sensor ?

- 1mm thick CdTe bonded on Medipix2 chip (cooperation with Napoli University – Prof. Paolo Russo)
- Opaque for slow neutrons => almost all neutrons are captured
- Secondary radiation to be detected:
  - 558 keV photons
  - 558 keV electrons of internal conversion (about 3%)

- What imaging properties would have such neutron detector?

Monte-Carlo Simulations: Gamma Ray Interactions - CdTe

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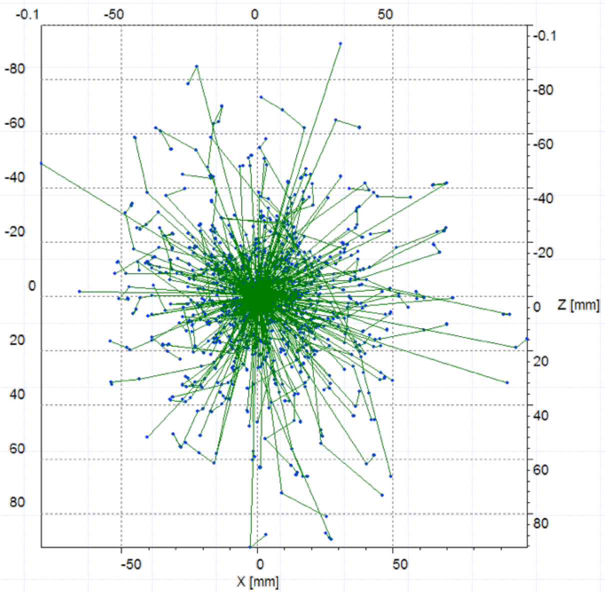
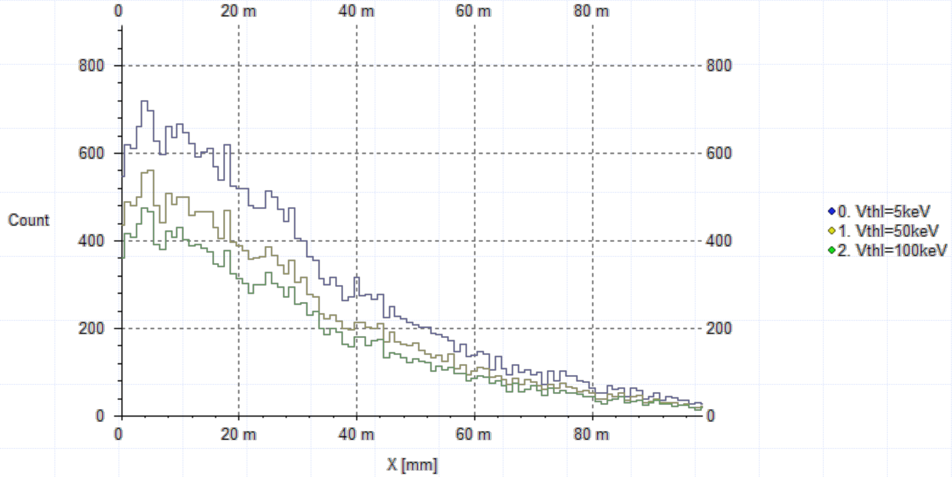
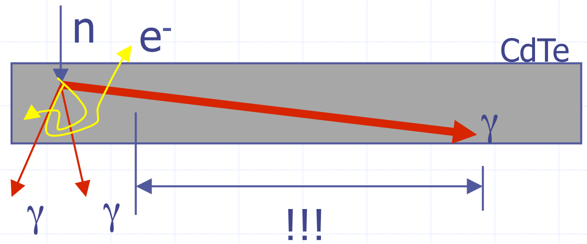
10 000 tracks of 560 keV photons in CdTe crystal have been simulated in MCNP.





Range of 560 keV gamma photons exceeds Medipix size
=> background signal in images



Drawback – a lower efficiency of the planar geometry

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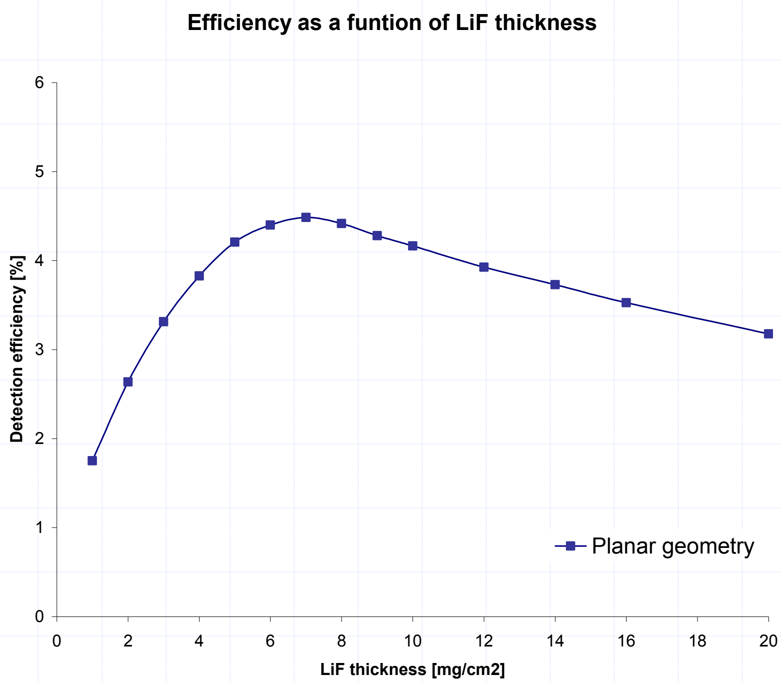
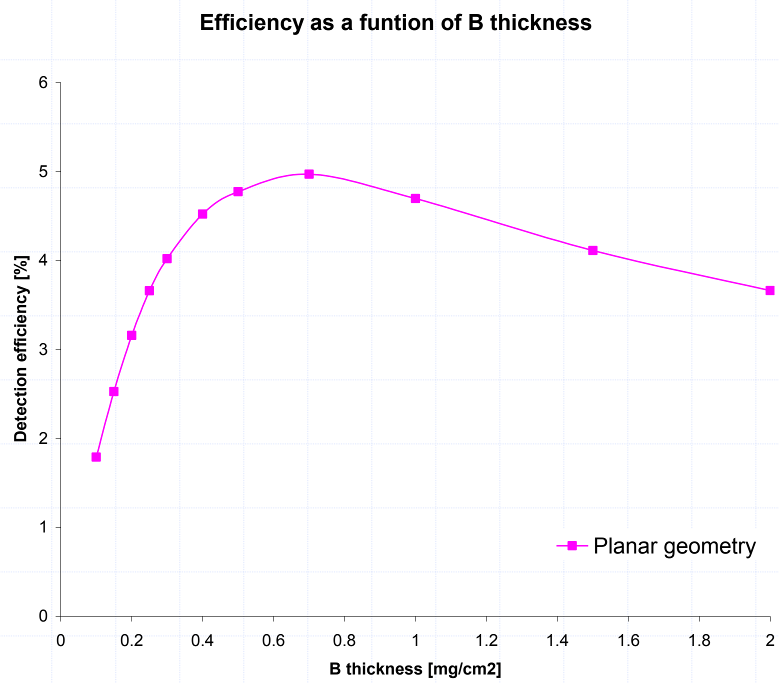
^{6}LiF, enrichment 90%



Amorphous ^{10}B, enrichment 80%



Efficiencies are comparable. Higher cross section of ^{10}B does not spawn a significant increase of efficiency.

Detection efficiency of the planar detector can not be more than ~5%!

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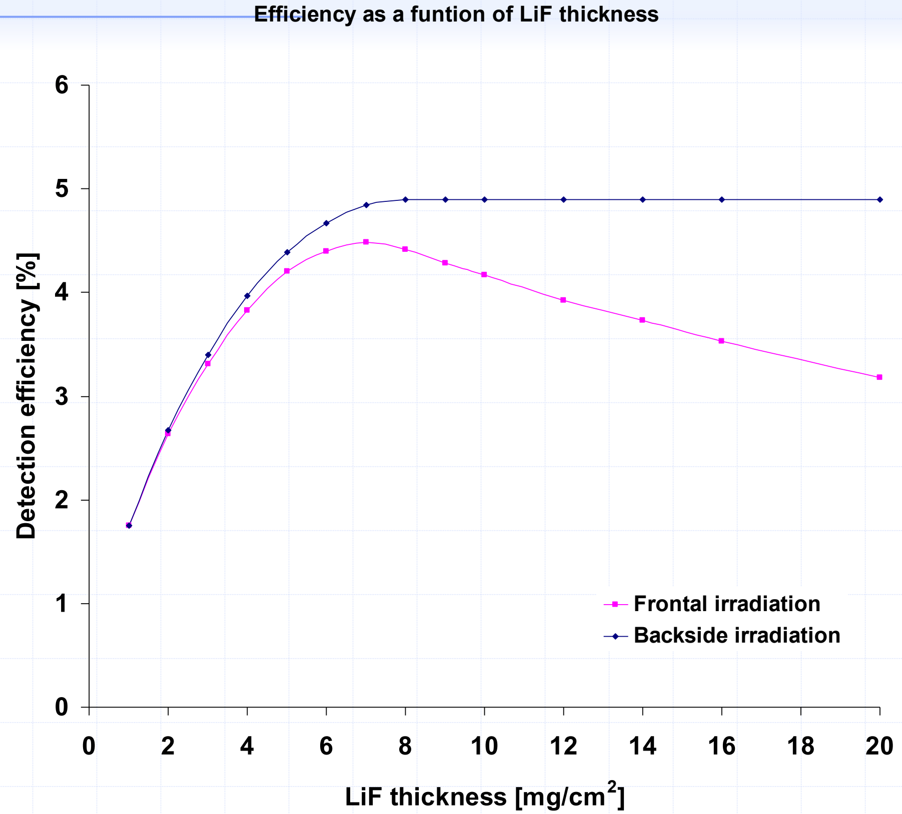
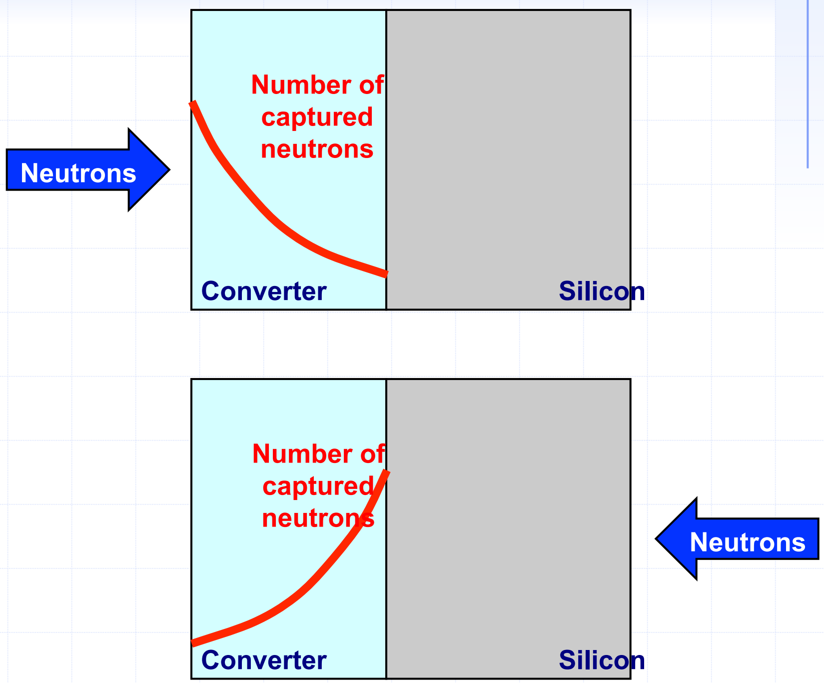
Obverse and adverse irradiation





Irradiation from back side is useful especially when comparing different detectors and converters – the effect of self-shielding and the necessity of precise converter layer thickness control are eliminated.

2D neutron array modification

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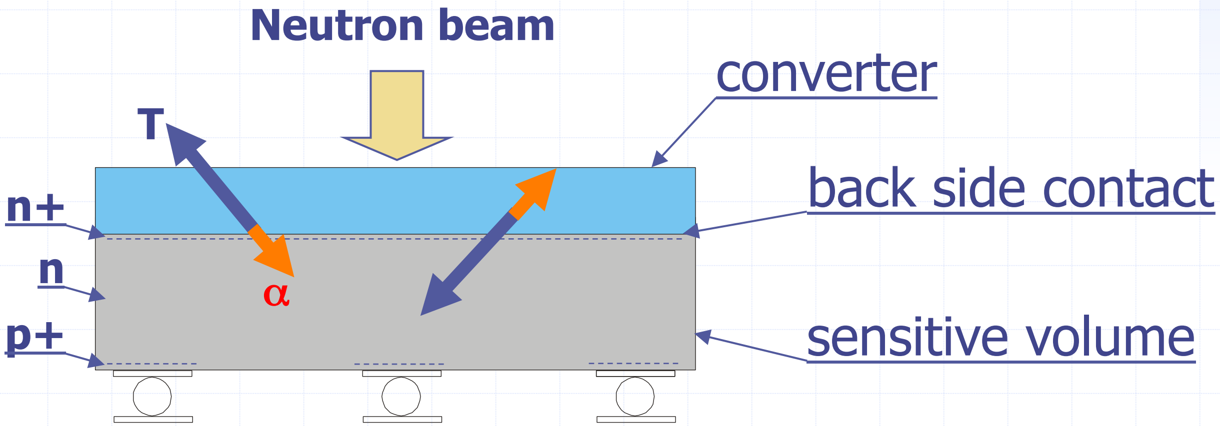
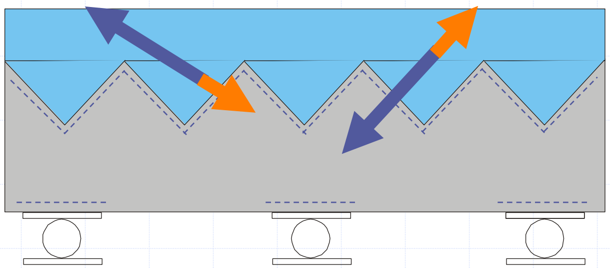
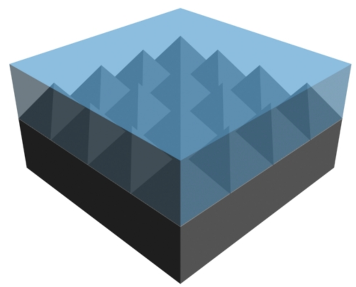
"Standard" 2D type



"Egg plate" 2D type
(with enlarged surface to increase
the detector efficiency)





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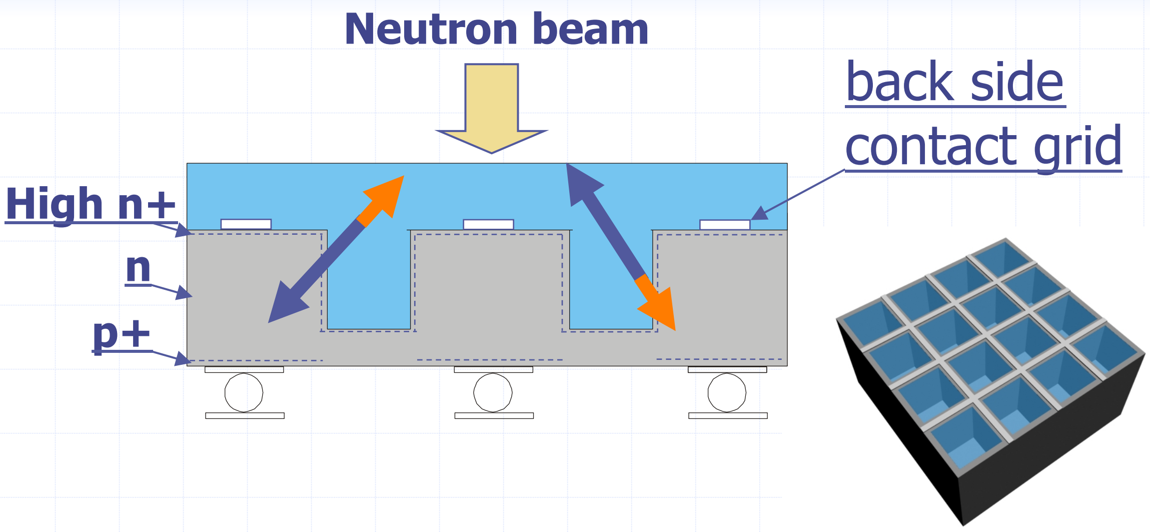
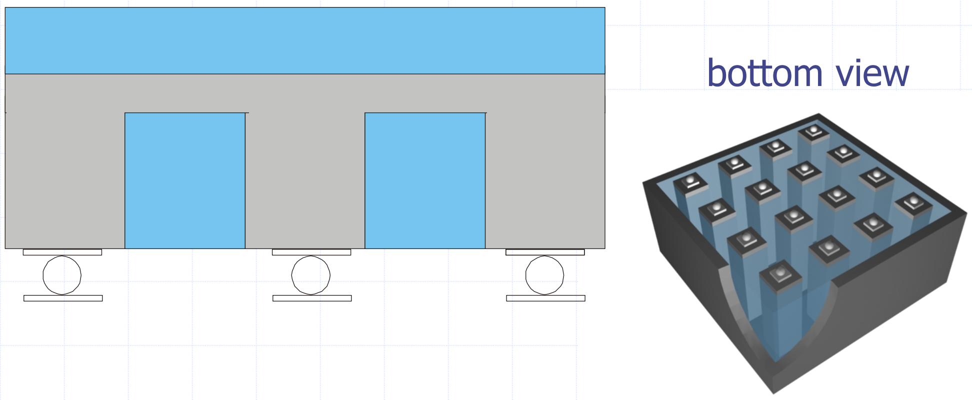
Neutron array modification

"Channel" 2D type
(maximized filling)



"3D inverse" structure
(there are pillars instead of pores)



Measured and simulated spectra of deposited energy

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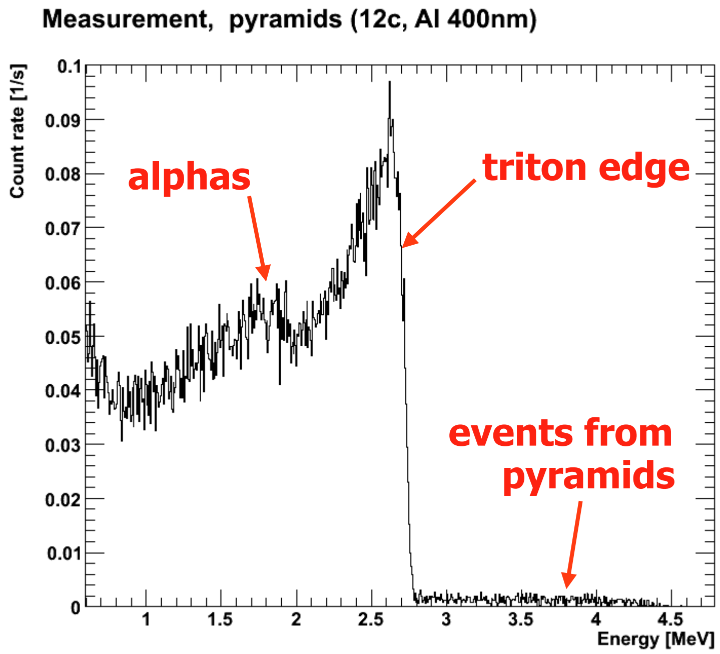
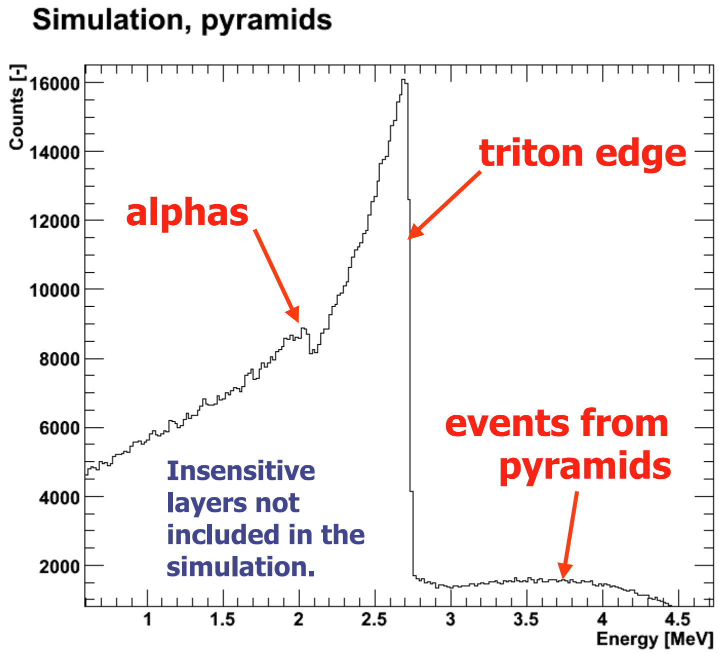
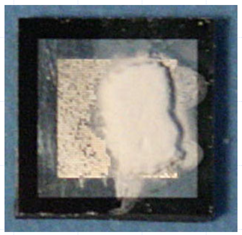
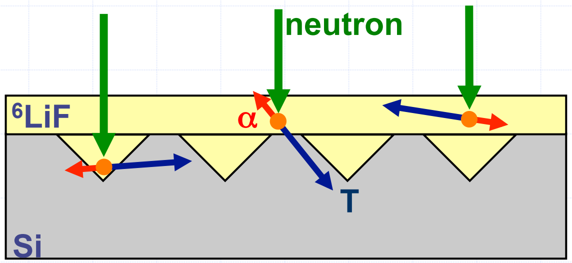






Fabricated at Mid-Sweden University, Sundsvall



T and α from pyramids can reach Si at the same time => events above 2.72 MeV

Neutron beam parameters:

Horizontal channel (neutron guide) of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague. Intensity about 10^6 neutrons/(cm^2s) at reactor power of 8MW

3D geometry arrays
- comparison of cylindrical vs. square ^{6}LiF converter

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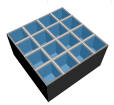
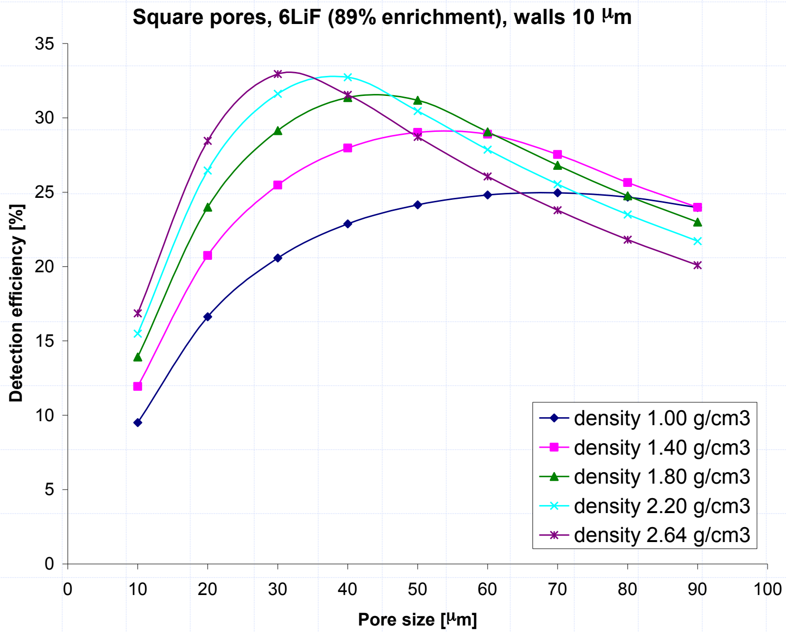
Fixed wall thickness – variance in the converter / cell size

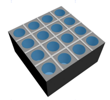
Square

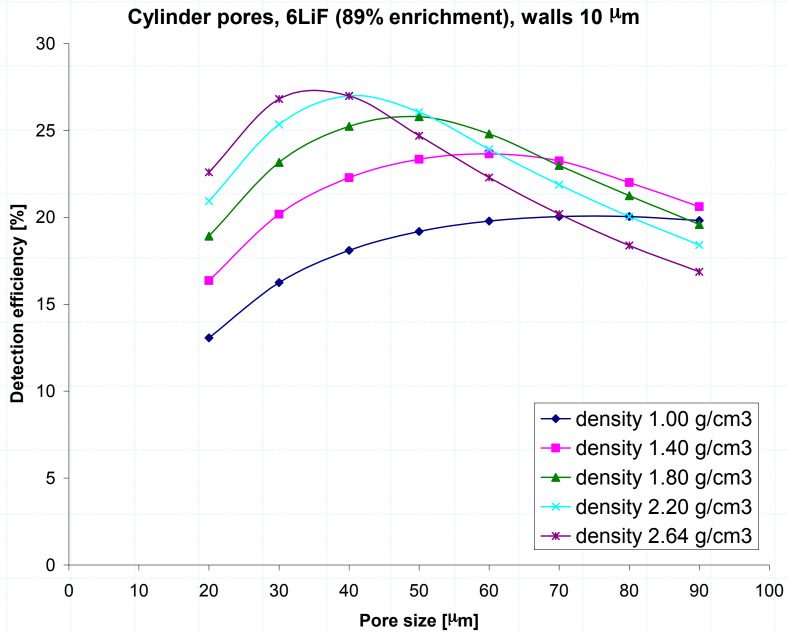




Maximal efficiency: ~32%

Cylinder





Maximal efficiency: ~27%

3D geometry arrays
- comparison of cylindrical vs. square ^{10}B converter

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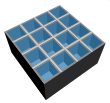
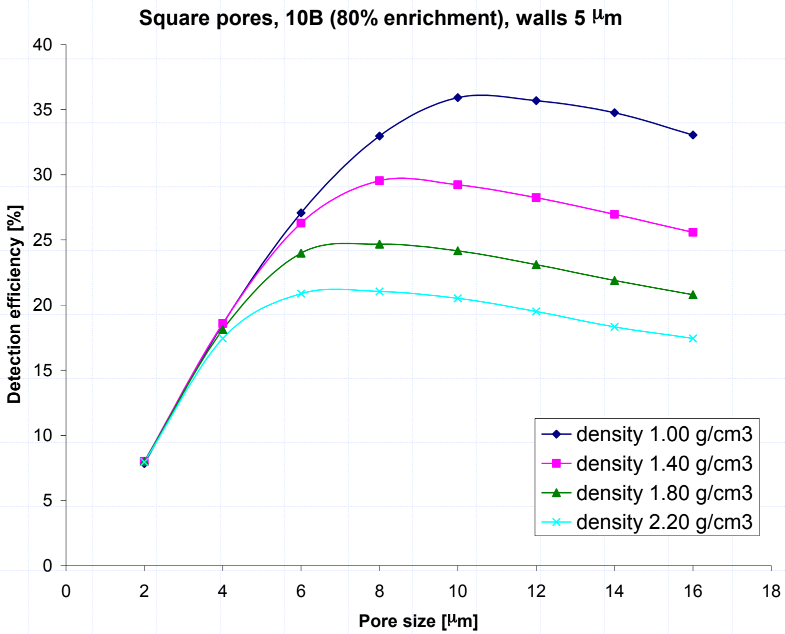
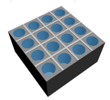
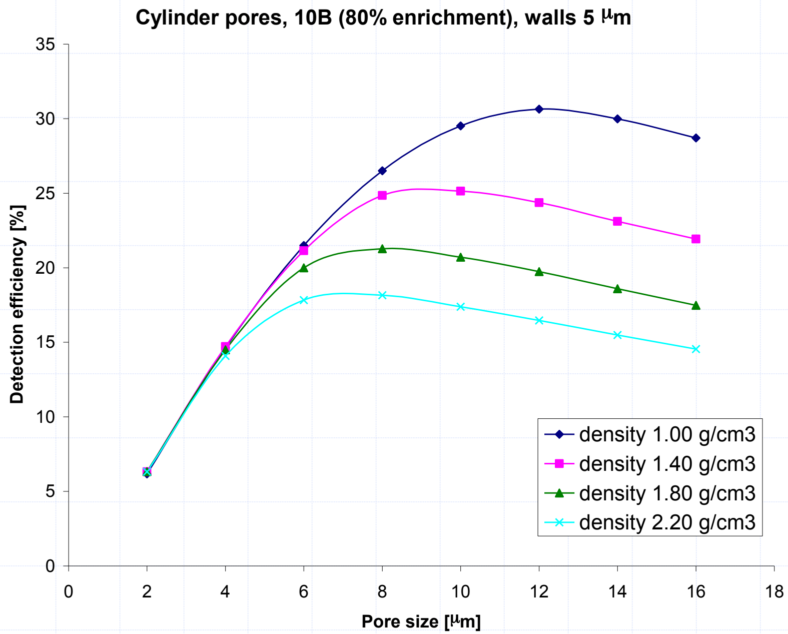
Fixed wall thickness – variance in the converter / cell size

Square 



Maximal efficiency: ~36%

Cylinder 



Maximal efficiency: ~31%

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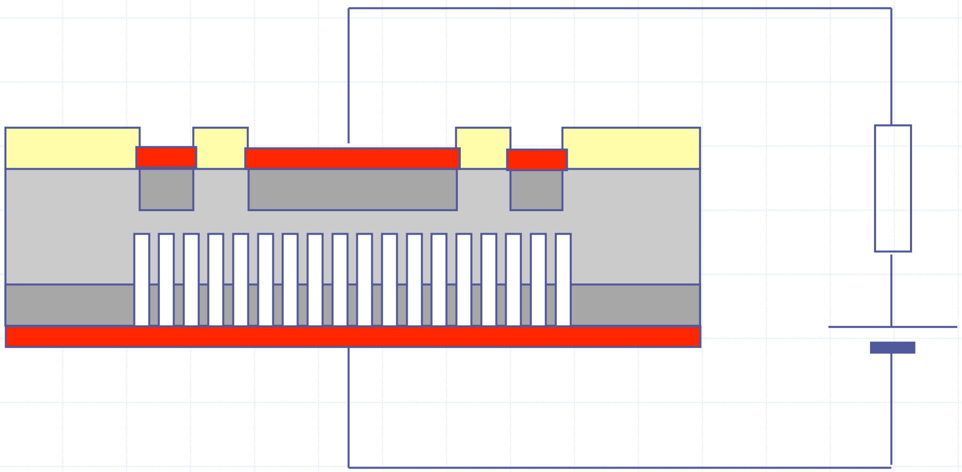
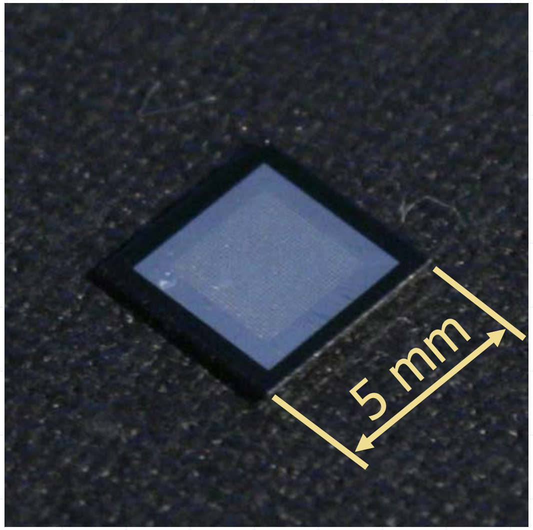
3D stuffed detector

- A next step in the development would be 3D detector diode with etched pores filled with a neutron converter.



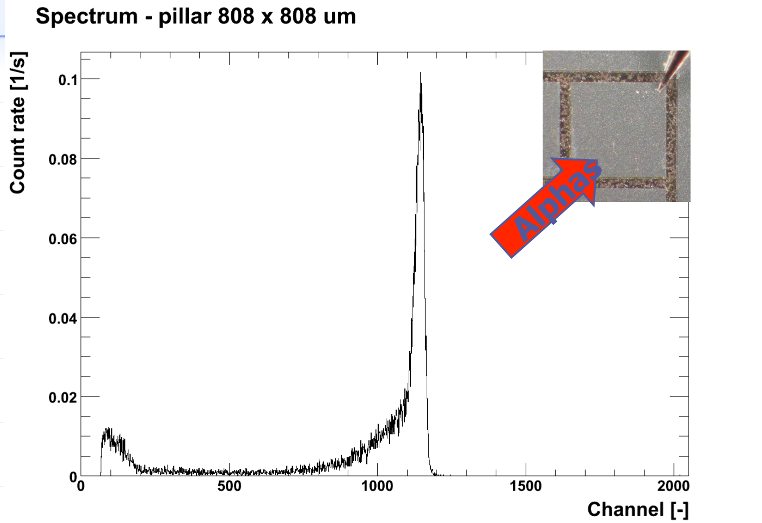
3D stuffed detector

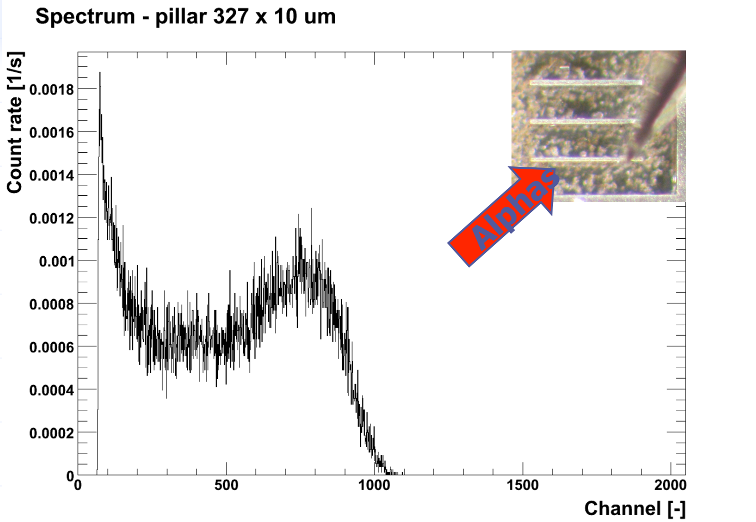
intermediate step

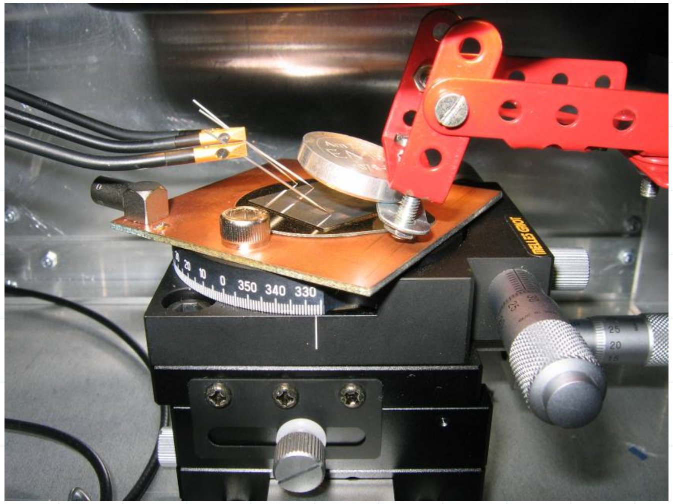


"Inverse pyramids" detector (KTH)

^{241}Am alpha spectra of 80 μm tall pillars







Range of 5.41 MeV alphas from ^{241}Am in silicon is 28.2 μm => they deposit only part of their energy in the thin wall.

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Spectroscopic response of 3D sensors bump bonded to TimePix chip

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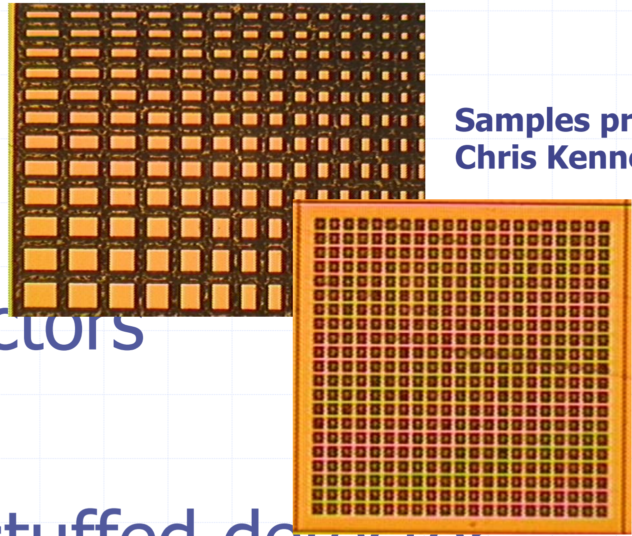
Future work

- Simulation software improvements
- Charge collection tests
- Tests of 3D stuffed detectors
- Medipix device with 3D stuffed detector



Samples prepared by
Chris Kenney, SLAC

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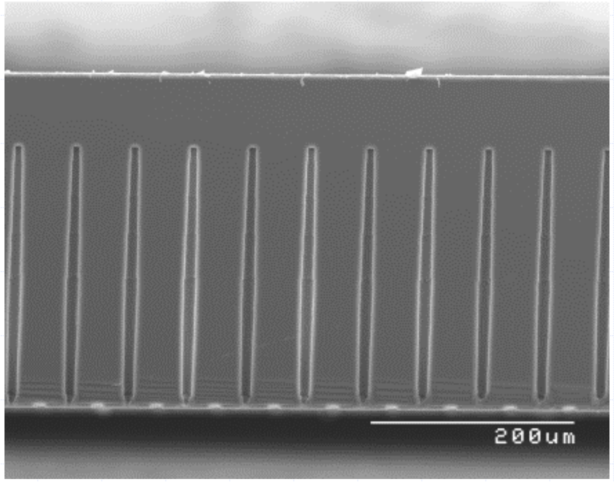
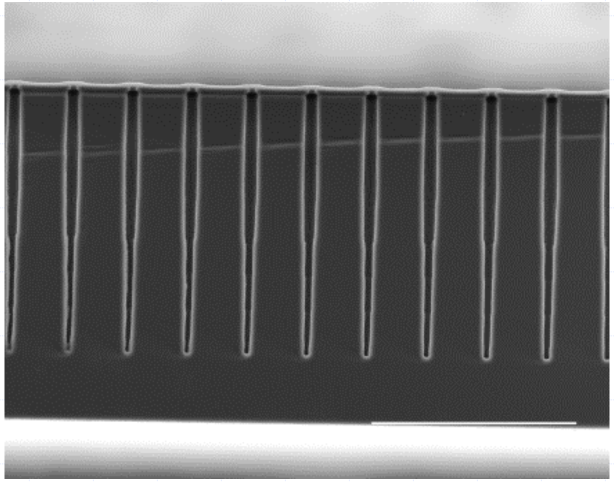
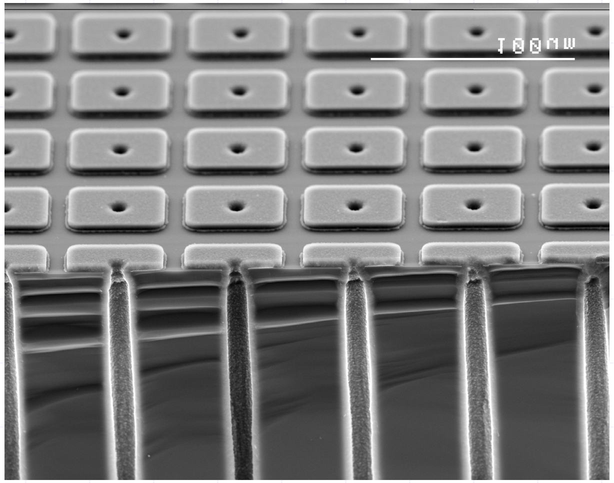
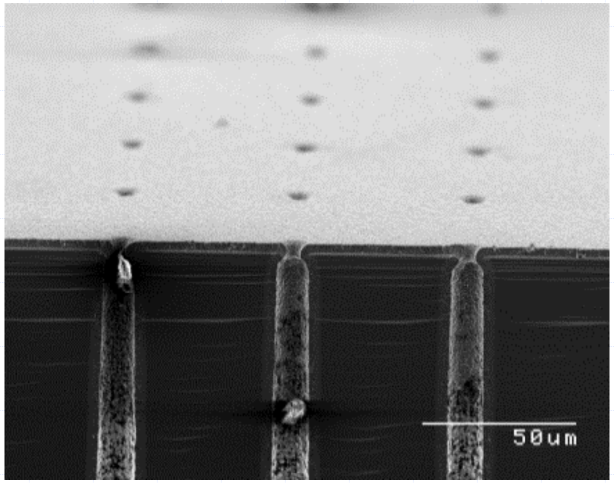
Tested sensor geometry

- Designed and fabricated at CNM Barcelona

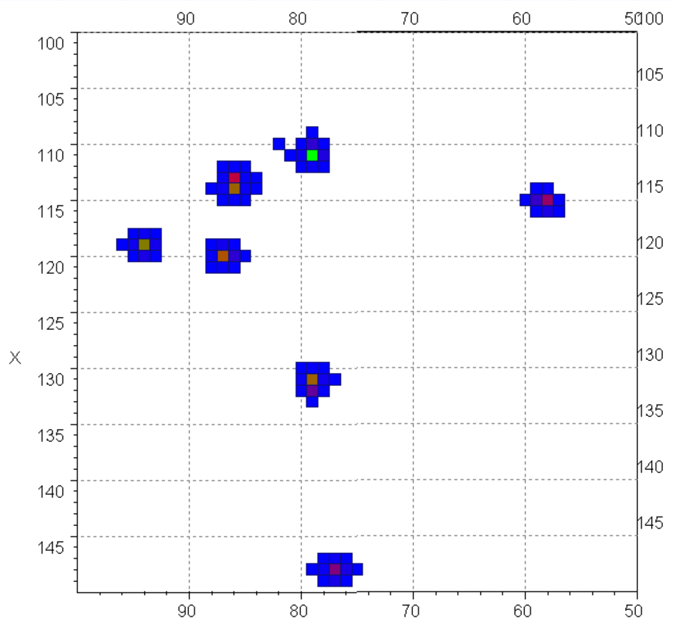


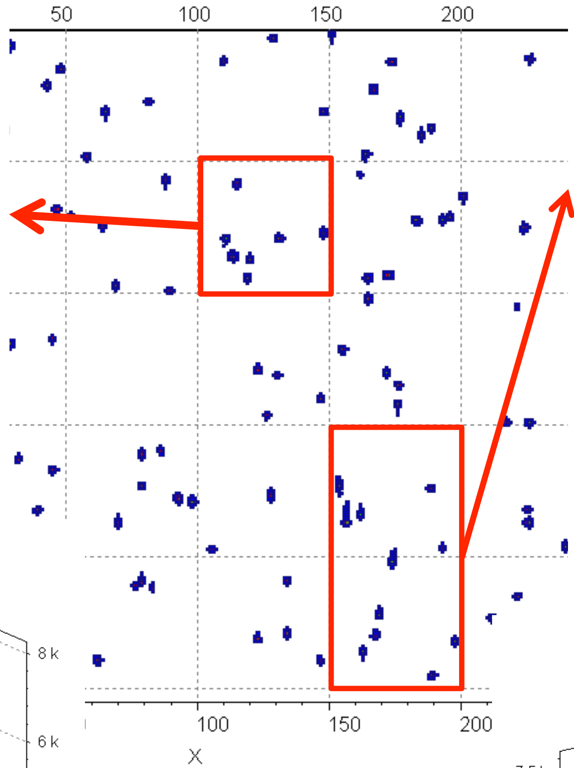


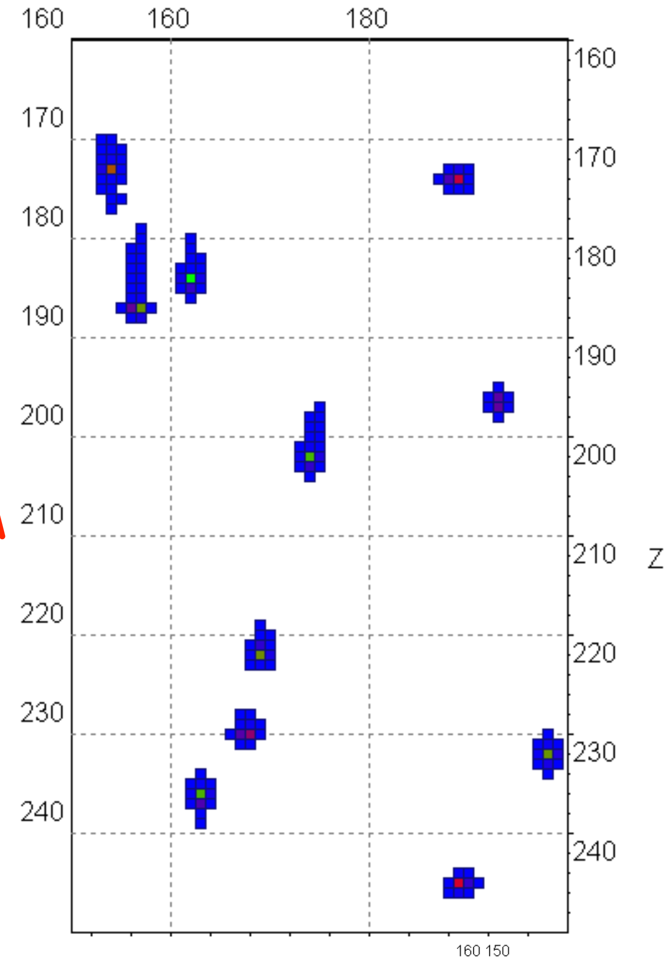


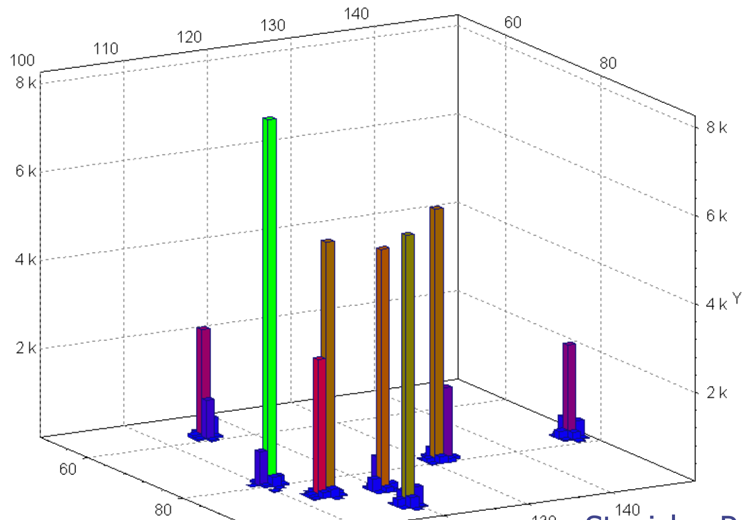


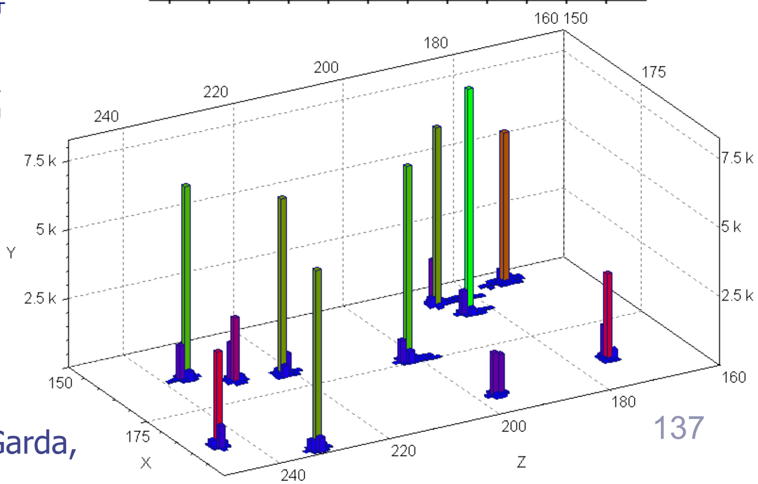
Examples of alpha clusters

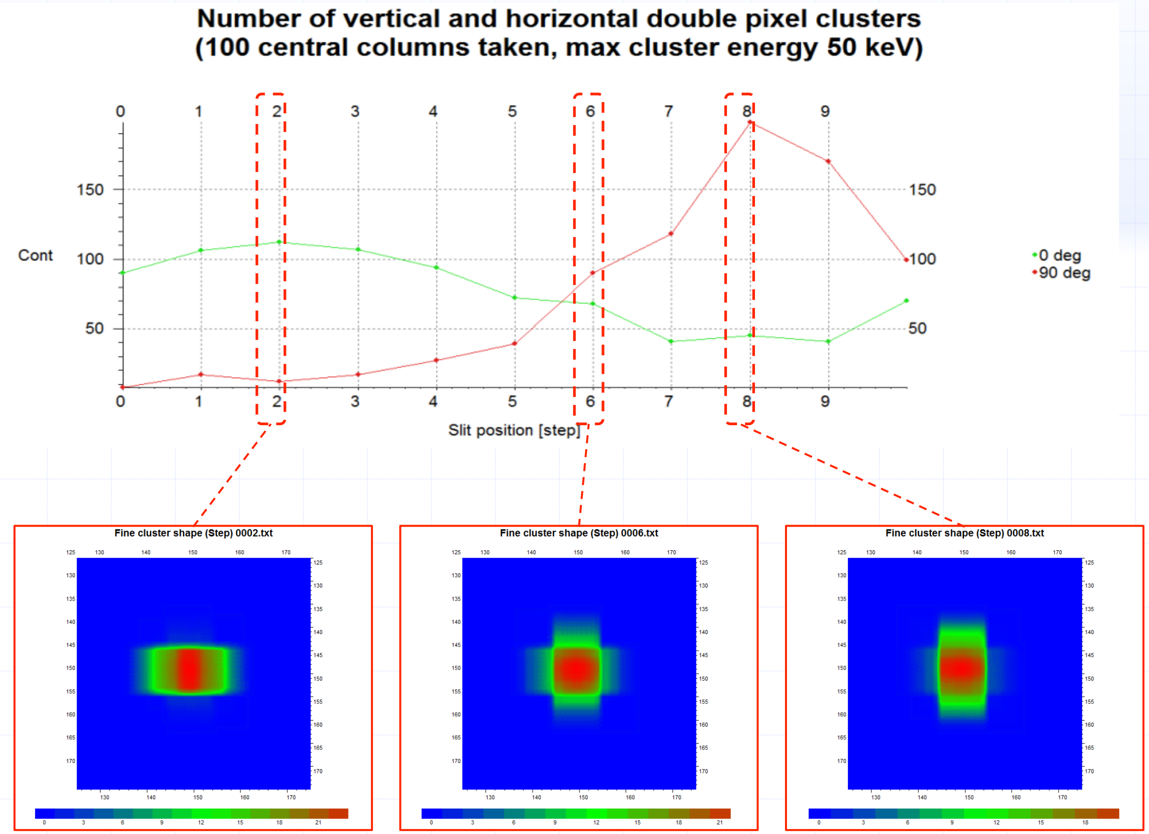


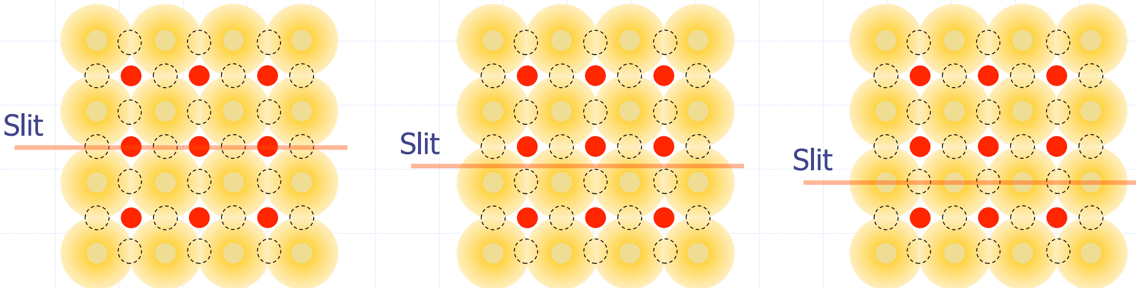












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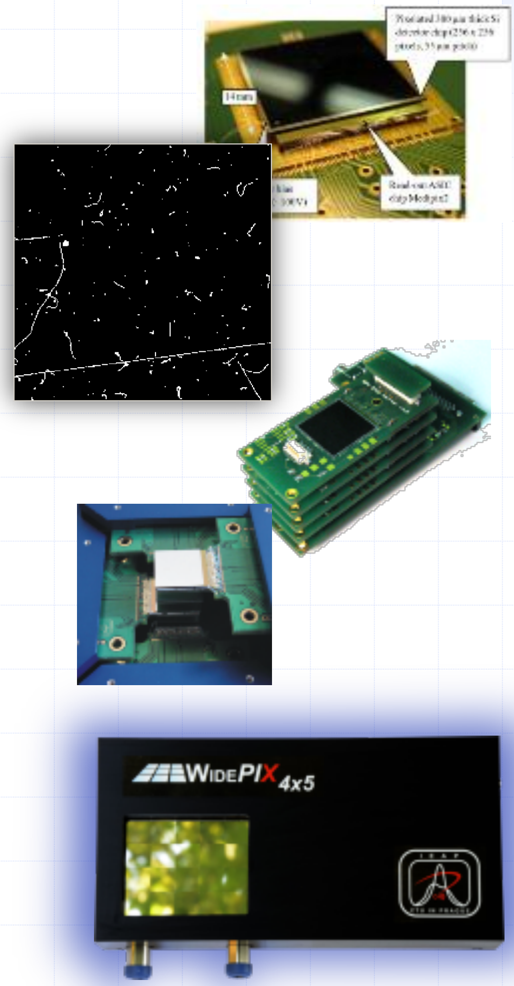
R/O systems

Introduction & Motivation
- Timepix pixel detector
- Energy sensitive imaging with pixel detectors

Multidetector systems based on Timepix
- Telescope
  - Particle tracking: Hadron therapy
  - Selective neutron detection
- Modular system based on edgeless technology
  - Concempt and parameters
  - Neutron imaging based on tracking
- Large area detector with edgeless sensors
  - WidePIX 4x5 1.3 Mpixels: Neutron imaging

Summary and future work



Timepix pixel device

single particle counting pixel detector

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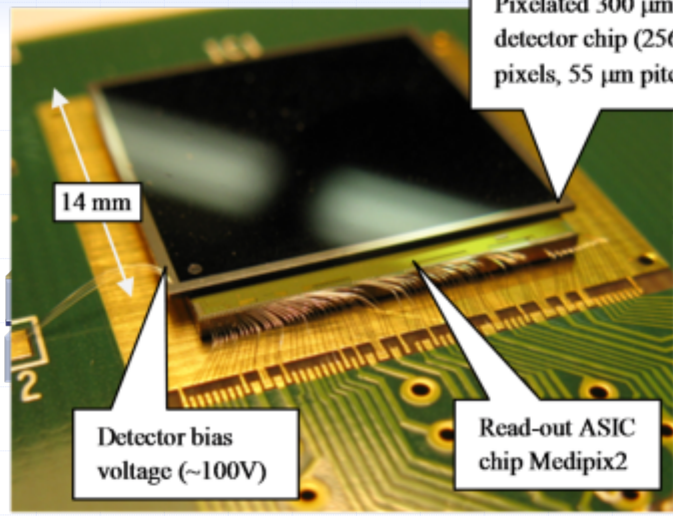
- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or ADC or **Timer**
- Multichip assemblies with common sensor: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)
- Multichip detectors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



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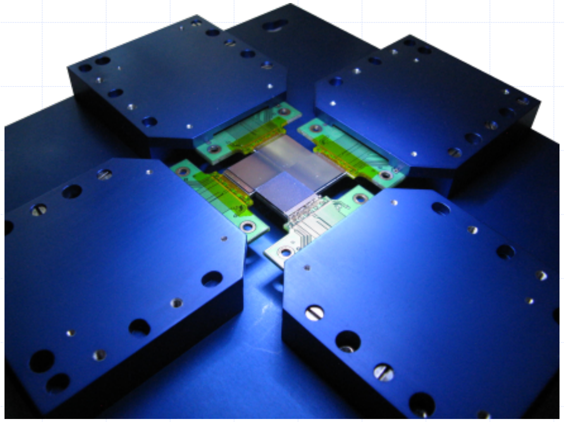
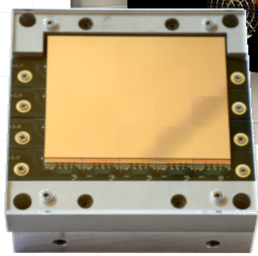
Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2





WidePIX$_{10x10}$ detector properties

- **Features**:
  - **2560 x 2560 square pixels of 55 μm**,
  - Photon counting => Superior image quality without instrumental noise => ultra-high contrast even for light material objects
  - **Large fully sensitive area without any gaps** between sensor chips,
  - Energy discrimination allowing **"color" radiography**,
  - Frame rate: 2 fps

Operation Modes and Free Parameters:

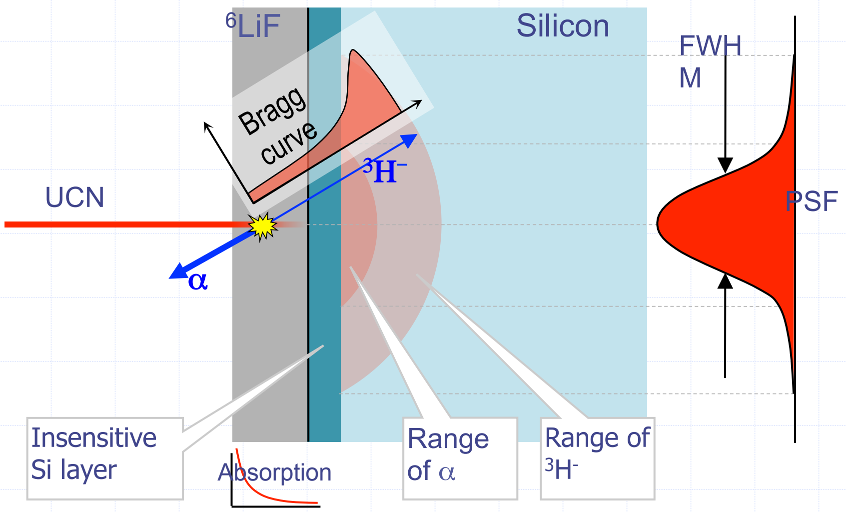
- Counting mode or energy integrating mode can be selected for each pixel
- Threshold can be set for each of 100 tiles individually
- Threshold can be adjusted locally for each pixel (4 bits => 16 levels)

Problem: Threshold equalization

How to adjust the threshold level for each tile and each pixel to assure their same meaning in energy.

Monte-Carlo simulations

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



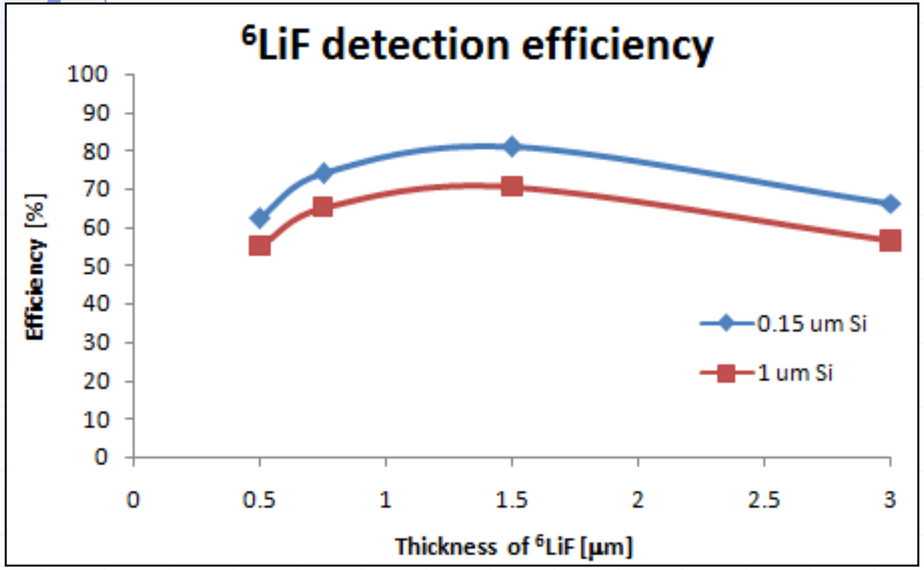
Geometry used in simulations

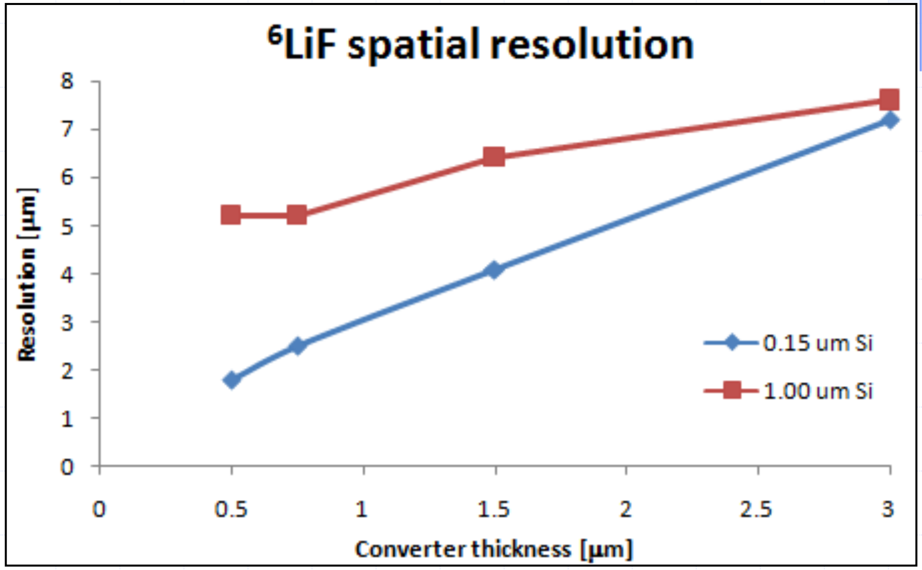
Expected UCNs velocity: 500 cm/s. For such neutrons the cross section of ^{6}Li increases to **0.34 Mbarn**. The cross section of ^{10}B reaches **1.67 Mbarn**.

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.

Simulation results for ^{6}LiF





The converter thickness maximizing efficiency is about 1.5 um thick. Resulting efficiency is 81% for Si layer of 0.15 um resp. 71% for Si layer of 1 um.

Dependence of spatial resolution (in terms of FWHM of PSF) on thickness of ^{6}LiF coating. The resolution for 1.5 um thickness is about 4.1 um for Si layer of 0.15 um resp. 6.4 um for Si layer of 1 um.

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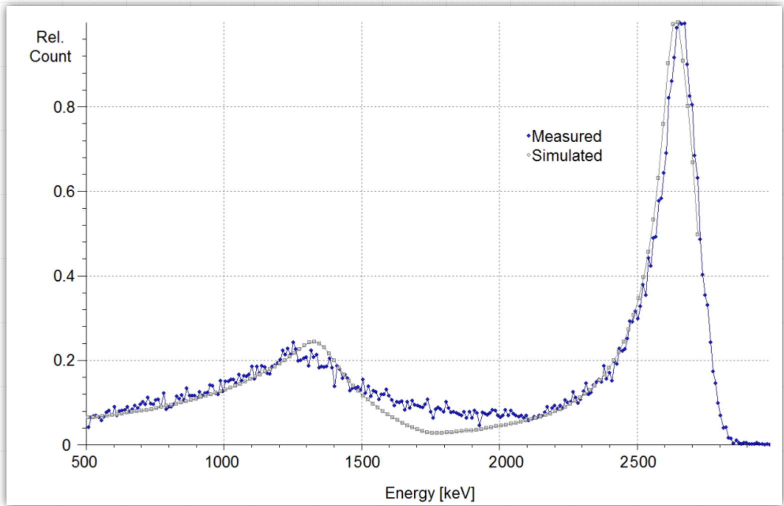
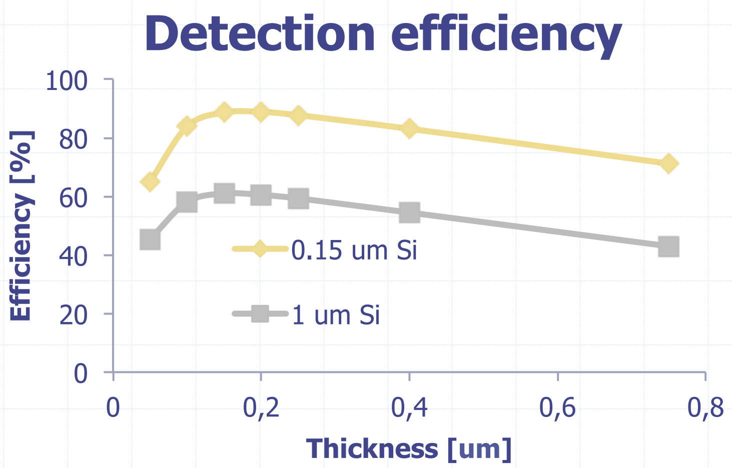
Experiment 2: Deposited layer of ^{6}LiF

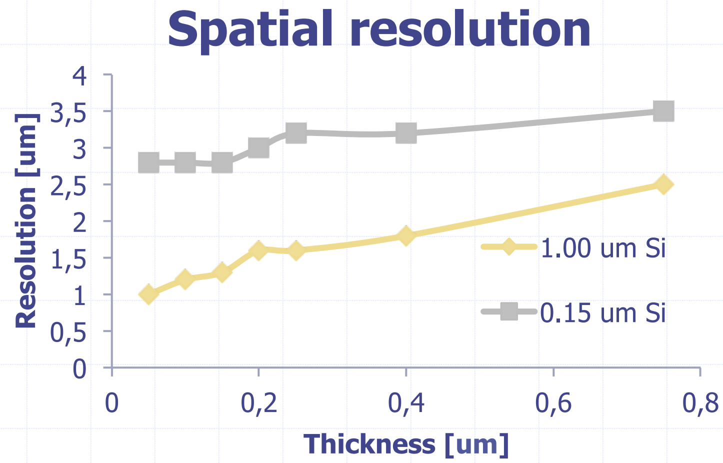
- 400 ug/cm^2 of ^{6}LiF was deposited onto Timepix sensor surface by evaporation (~ 1.5 um).
- Spectrum was measured and compared with simulation (thickness of insensitive Si layer tuned to achieve the best agreement).



- The insensitive layer thickness is ~ 1 um.
- Detection efficiency ~ 70%.

Simulation results for ^{10}B





The converter thickness maximizing efficiency is about 1.5 um thick. Resulting efficiency is 89% for Si layer of 0.15 um resp. 61% for Si layer of 1 um.

The resolution for 1.5 um thickness is about 1.6 um for Si layer of 0.15 um resp. 3.0 um for Si layer of 1 um.

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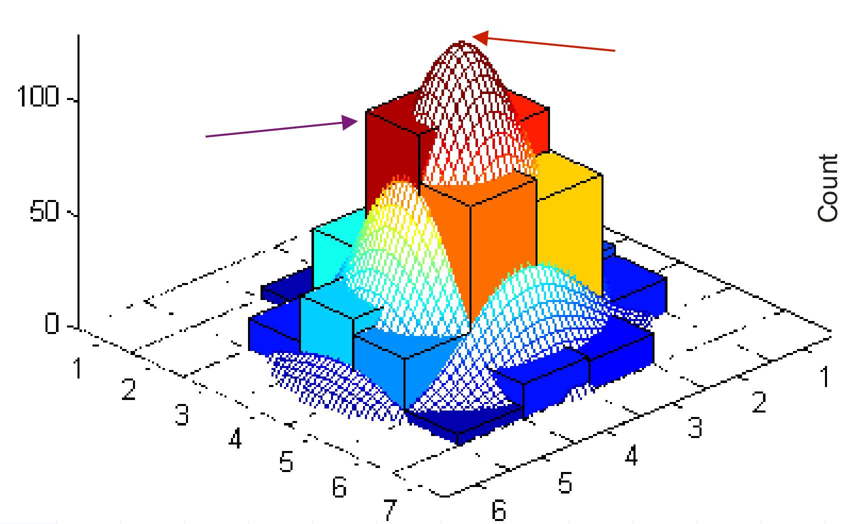
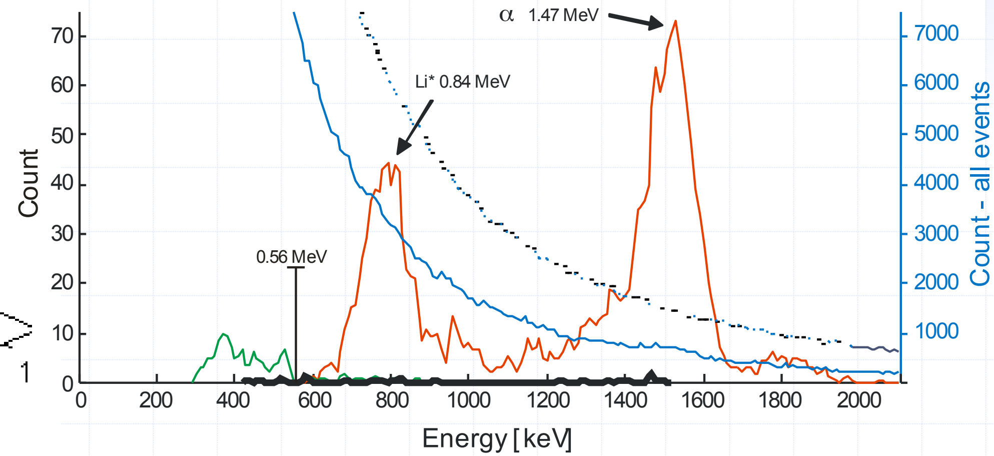


Pixel detector response to every charged article (alpha and 7Li) in a form of 3D-cluster with a shape corresponding to convolution of Gaussian and individual pixel resonses



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

Siemens star - test of spatial resolution of Medipix2 system with cold neutron beam

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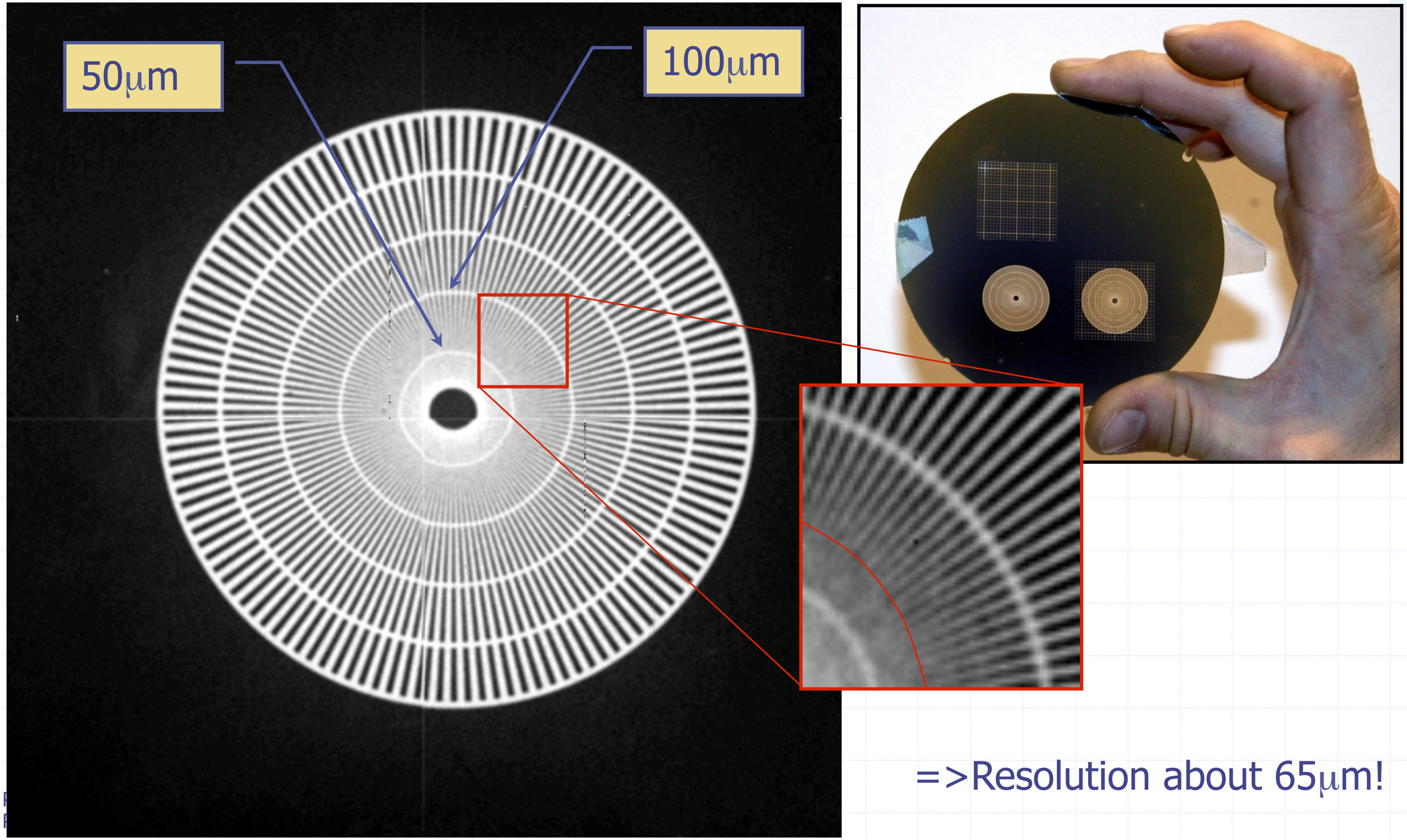

=>Resolution about 65μm!

Siemens star, ^{6}LiF thin converter, Timepix R/O chip

Clusters of both particles centroiding

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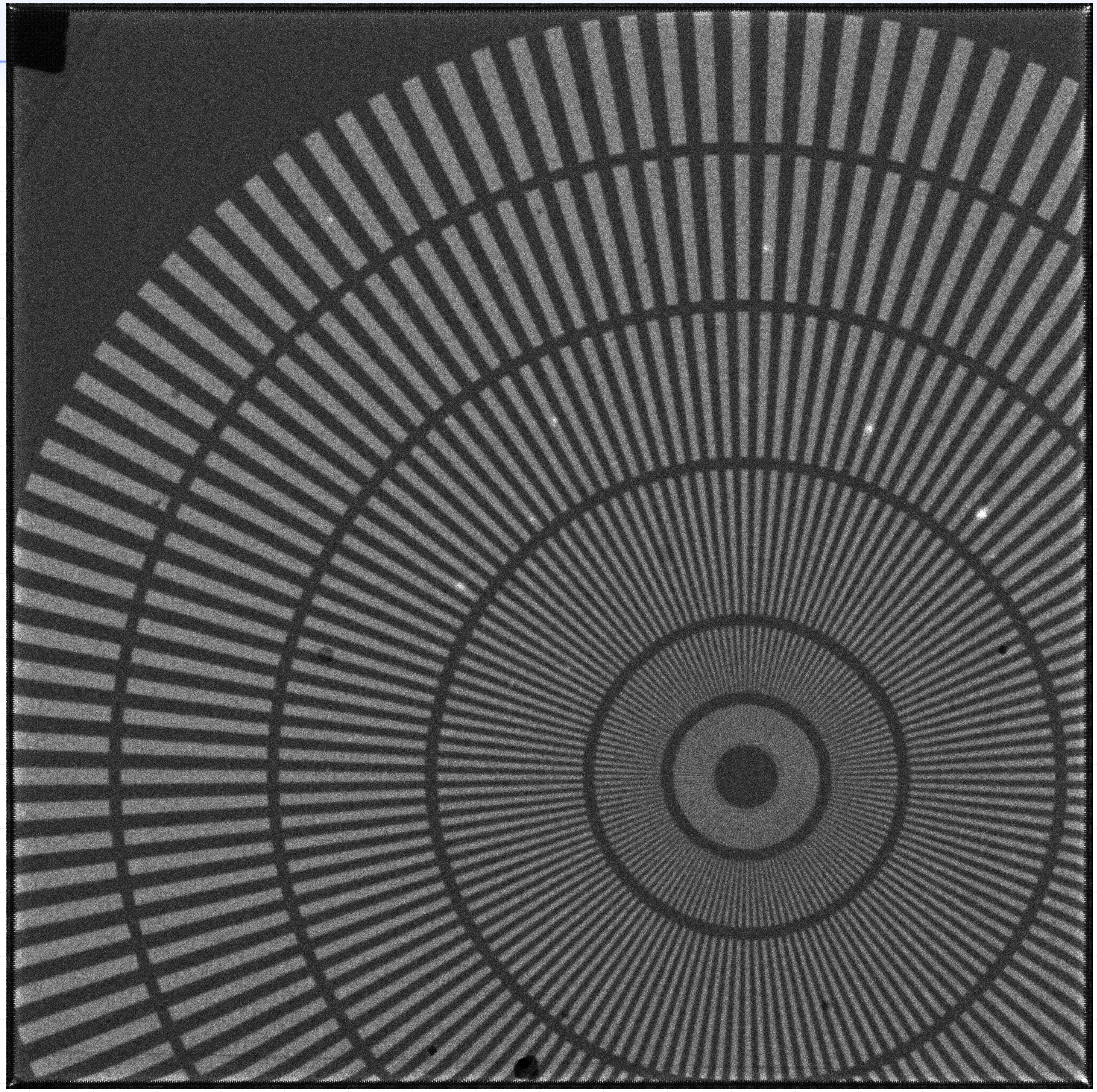

Alpha clusters centroiding only, resolution ~ 3 um

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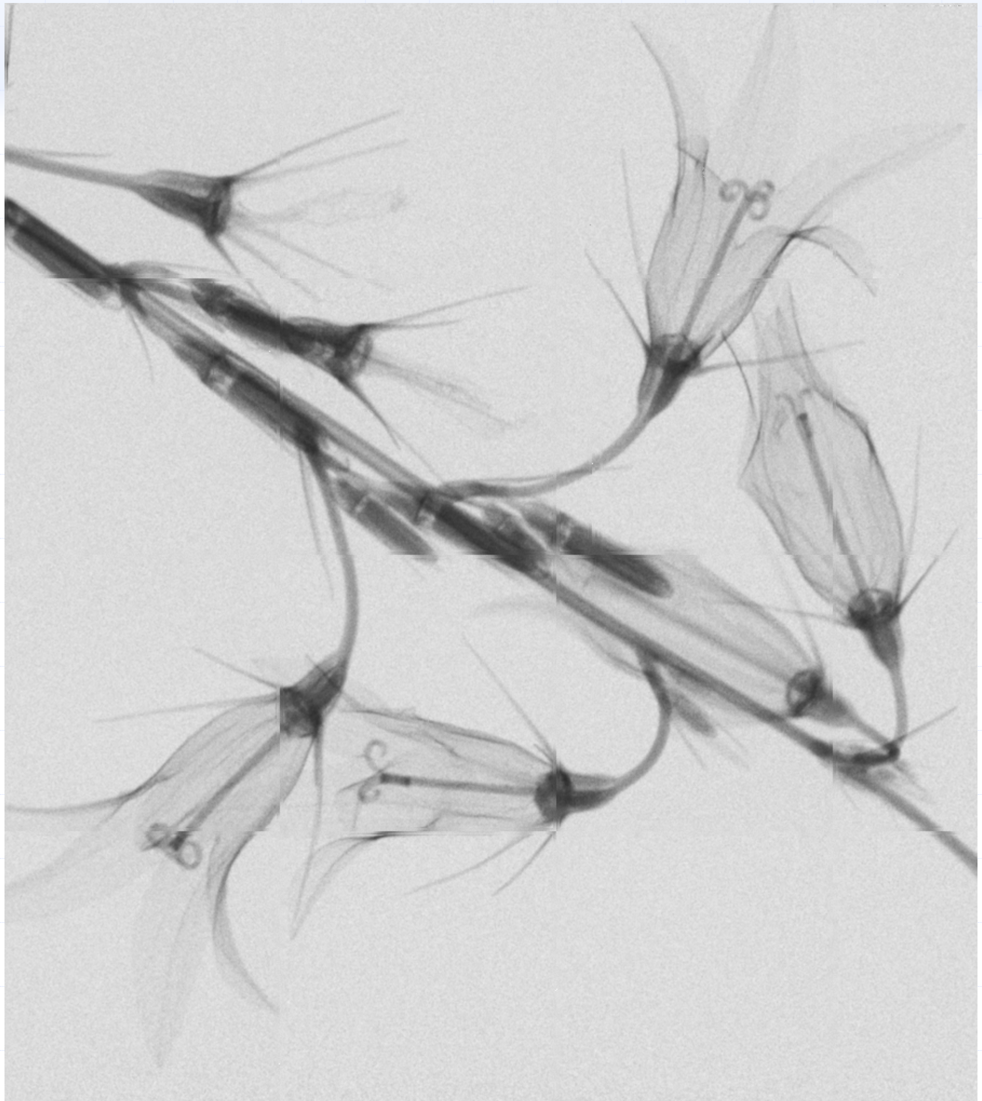
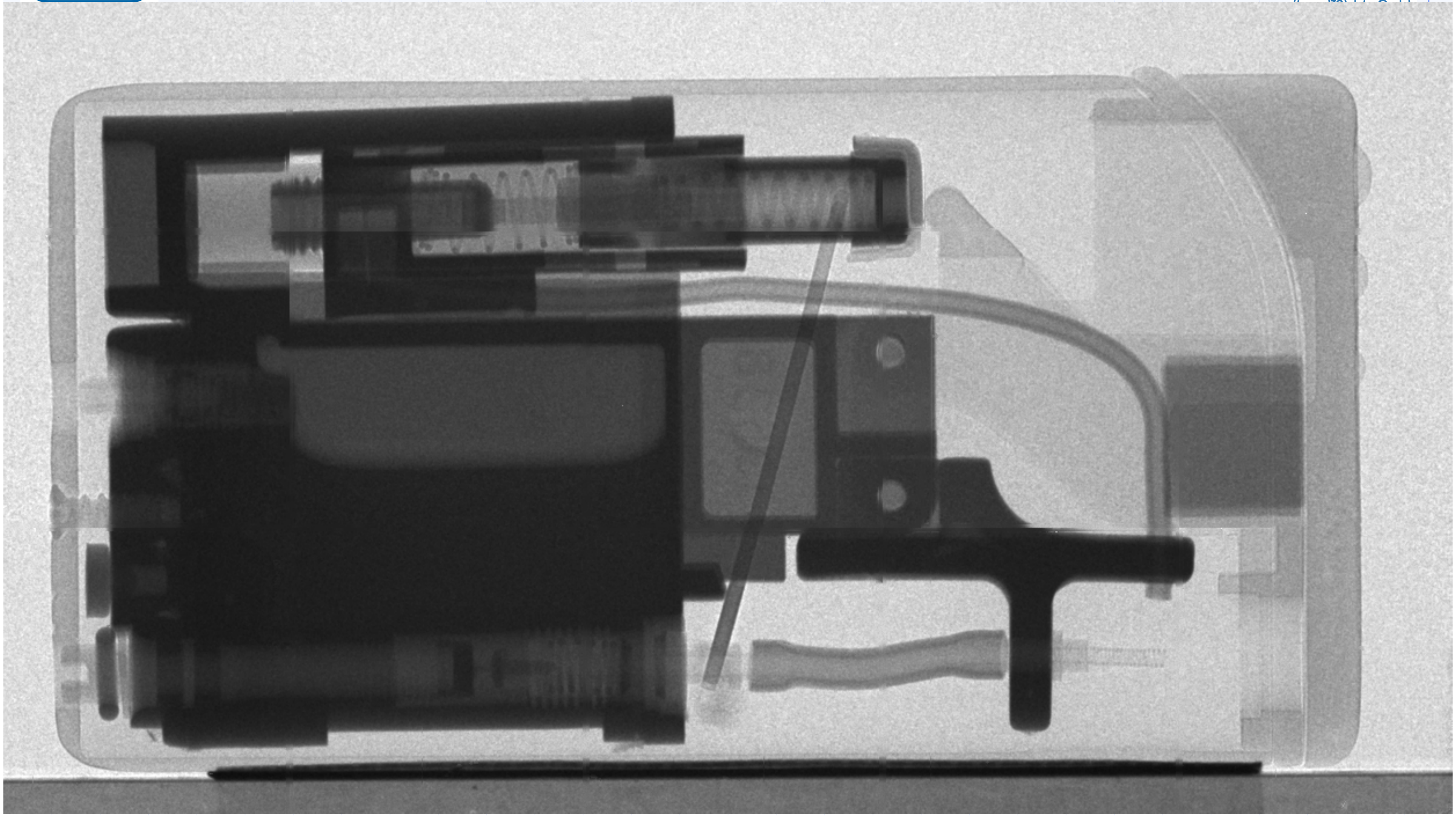
Bellflower



Lighter



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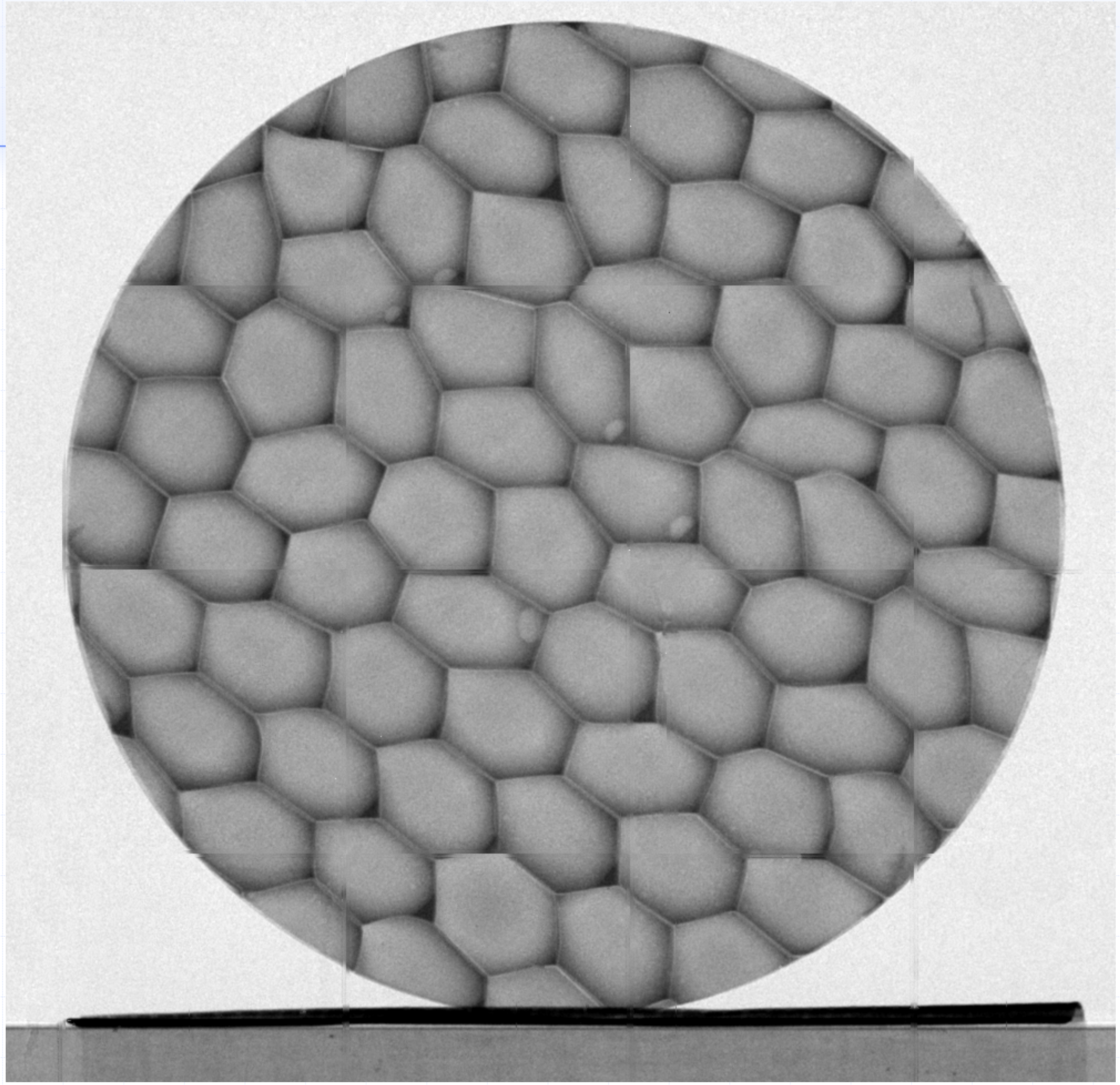
Composite metallic core



Acknowledgement

The presented results have been born out of research and development activities grown at IEAP CTU in Prague. Their achievement would not be possible without extensive cooperation in the program Medipix2@3, which has been coordinated through CERN since 1999 with significant contributions of the following colleagues:

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[8] Manchester University, UK
[9] MidSweden University, Sundsvall, Sweden
[10] ESS, Sweden
[11] PSI, Switzerland

Thank you!