Timepix pixel detectors

for imaging and characterization of complex radiation fields around nuclear and particle experiments and in space

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Stanislav Pospíšil[1]

for

J.Jakůbek[1], B.Bergmann[1], M.Campbell[2], J.M.O'Donnel[3], R.Nelson[3], E.Heijne[1,2], C.Granja[1], C.Leroy[4], A.Owens[5], L.Pinsky[6], H.Takai[7], Z.Vykydal[1]

[1] *Institute of Experimental and Applied Physics, CTU in Prague, Czech Republic*
[2] *CERN, Switzerland*
[3] *LANL, USA*
[4] *Université de Montréal, Canada*
[5] *ESA*
[6] *NASA/University Houston, USA*
[7] *BNL, USA*

Work carried out within the CERN Medipix Collaboration

Main goals of the presentation

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- To describe family of ***Medipix2 and Timepix semiconductor pixel detectors*** including corresponding R/O electronics
- To demonstrate capability of the devices for ***high resolution (micrometric and nearly nanometric) radiography and 3D imaging*** by means of X-rays and neutrons for biomedical applications and material research
- 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 show examples of broad ***applications*** of the Timepix detectors ***in physics experiments including ToF technique, in medicine, dosimetry, radiation measurements and space research***

www.cern.ch/medipix

Medipix/Timepix pixel detector device

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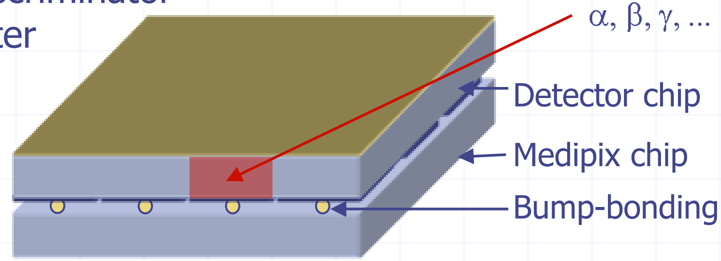
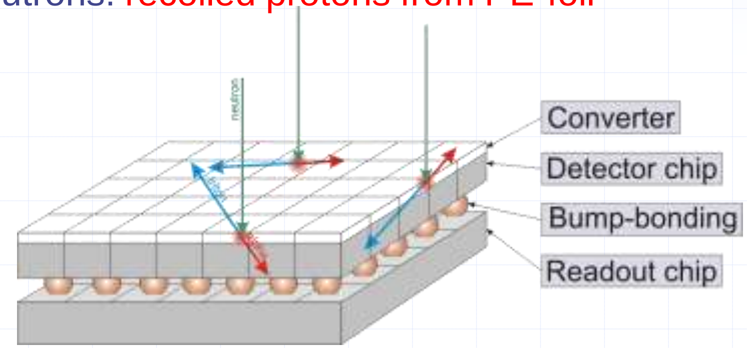
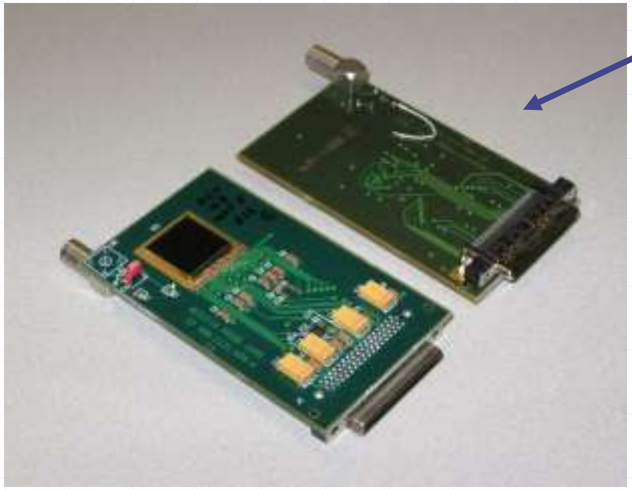
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000μm)
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter

- 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

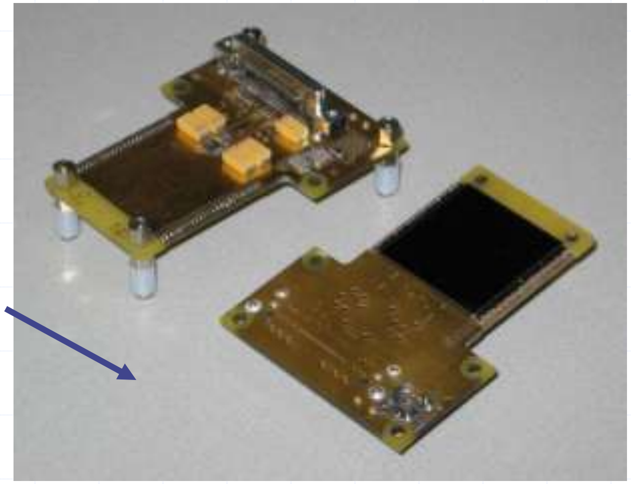






Medipix2/Timepix
Pixels: 256 x 256
Pixel size: 55 x 55 μm^2
Area: 1.5 x 1.5 cm^2

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

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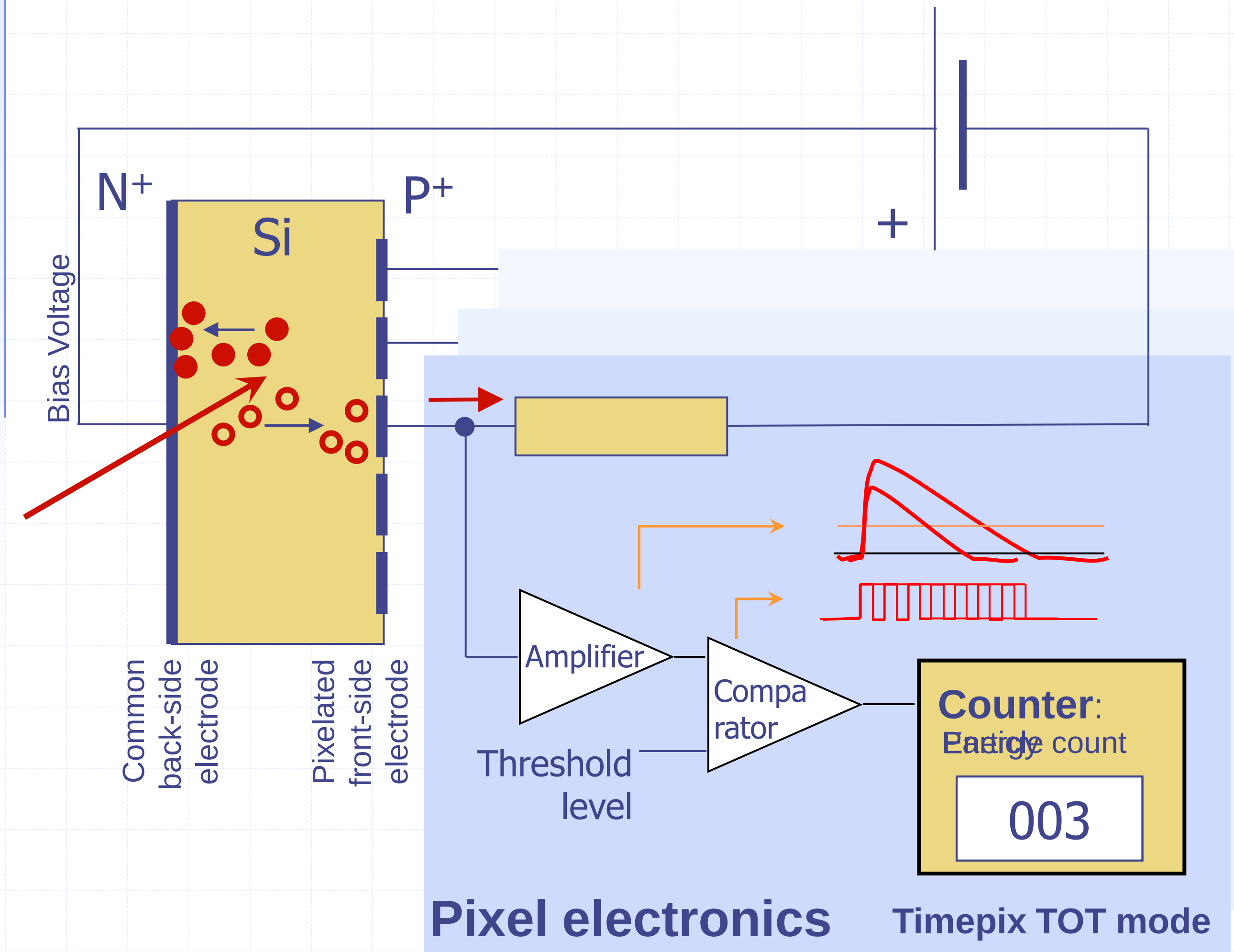

Threshold level above electronic noise
⇒ **No false counting**.

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

Energy calibration (how to deposit defined energy into a volume 55x55x300μm^3?)

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

HISTORY 1995-2011:

MAMOGRAPHY

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

Medipix/Timepix – USB controlled portable device

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- 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).

PIXELMAN SW to control, read and evaluate data

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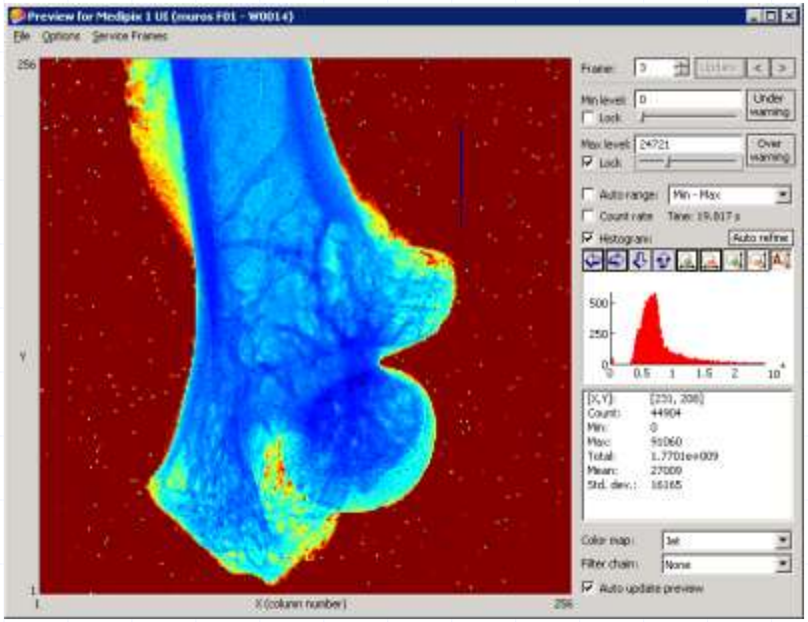
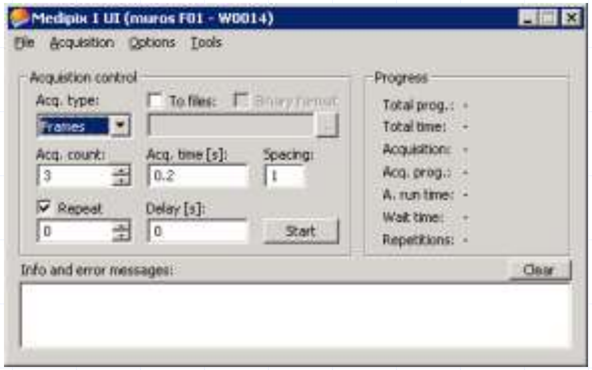
- Software package for Medipix/Timepix acquisition control and data evaluation
- Supports all available Medipix/Timepix based detectors
- Supports all commonly used readout interfaces
- It is designed for maximum flexibility and interoperability with other devices (like stepper motor control unit) to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





Experimental setup

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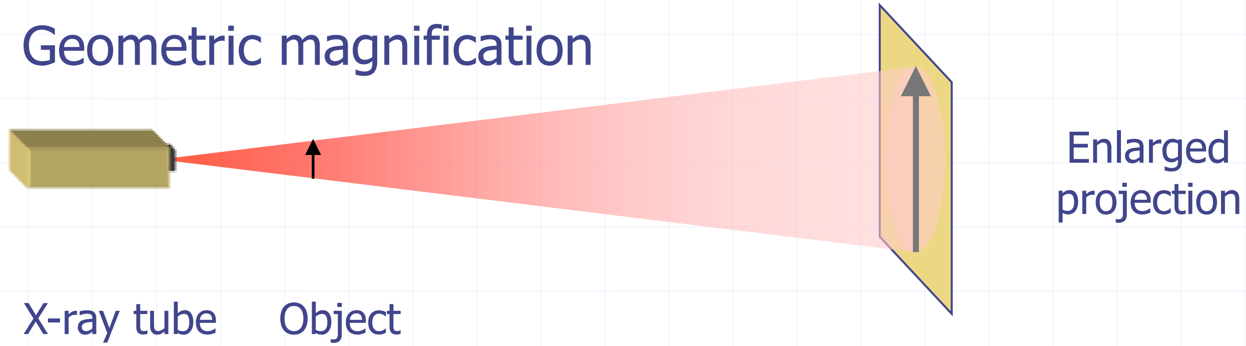
Requirements:

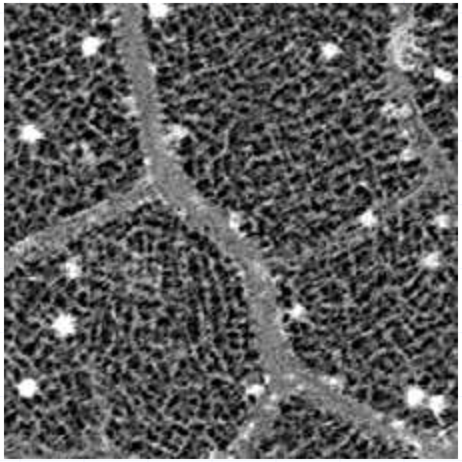
- Microfocus X-ray source to enable geometrical magnification
- Adjustable object holder (three translations + rotation)
- Sample stabilization (temperature, humidity)
- Equipment for automatic calibration of pixel responses
- Detector holder and detector stabilization (temperature, condensing point)

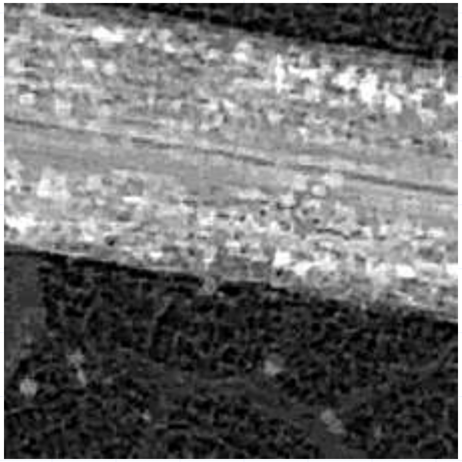


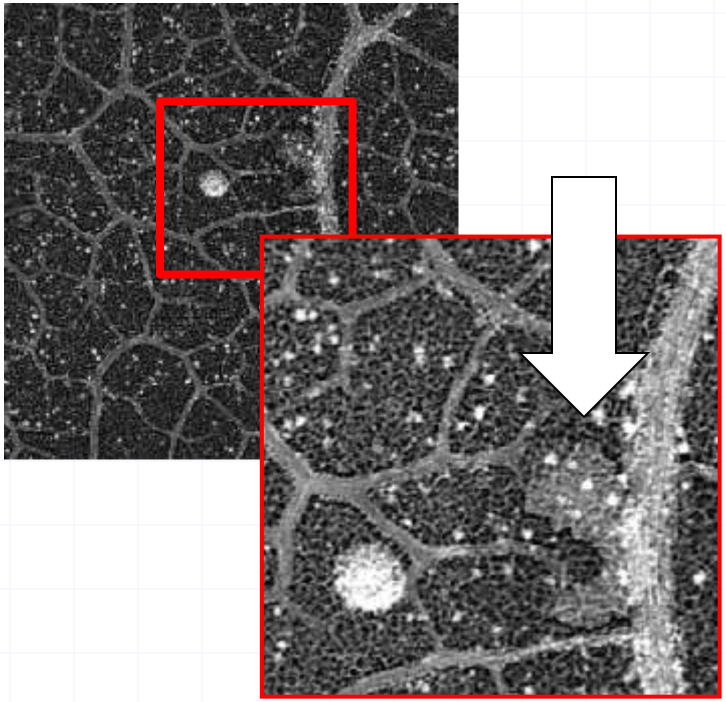
High resolution X-ray radiography:
Example: Leaf Miner story

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)



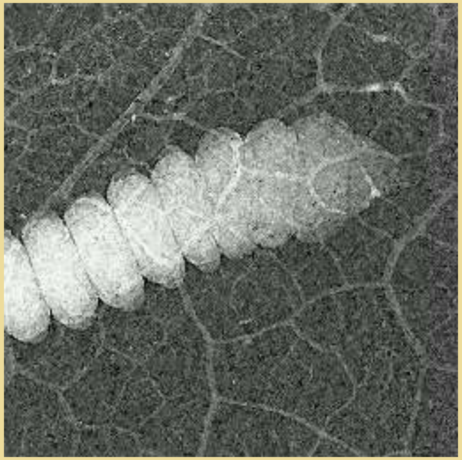
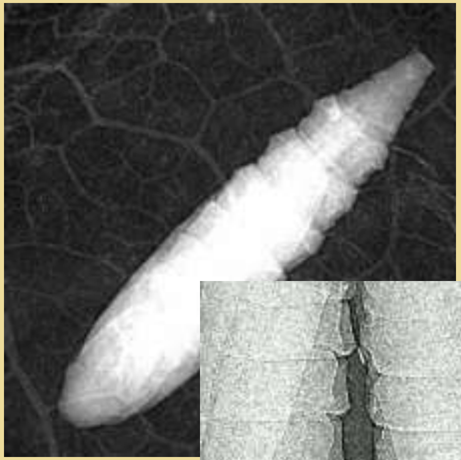




Healthy chestnut tree leaf structure (no parasite) – cellular structure of leaf is nicely observed (resolution below 1 um). The white spots are small drops of resin secreted by the leaf.

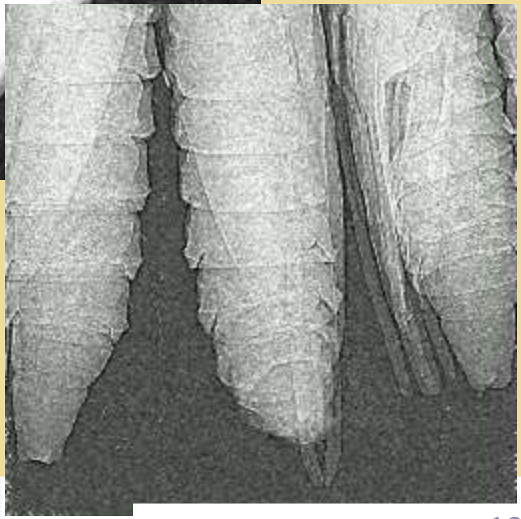
High resolution X-ray radiography:
Example: Leaf Miner story

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

Let's take a look together at the X-ray movie!

Several collected pupas



High resolution X-ray radiography:

Example: Leaf Miner story - Cure

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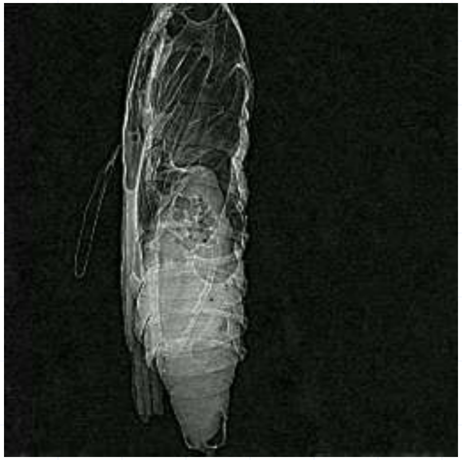
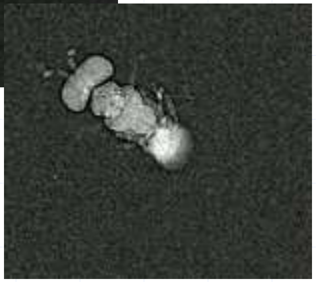
The best cure: natural enemy (parasitic wasp)

Certain small wasps can put eggs into leaf miner pupas

Parasite inside of parasite:



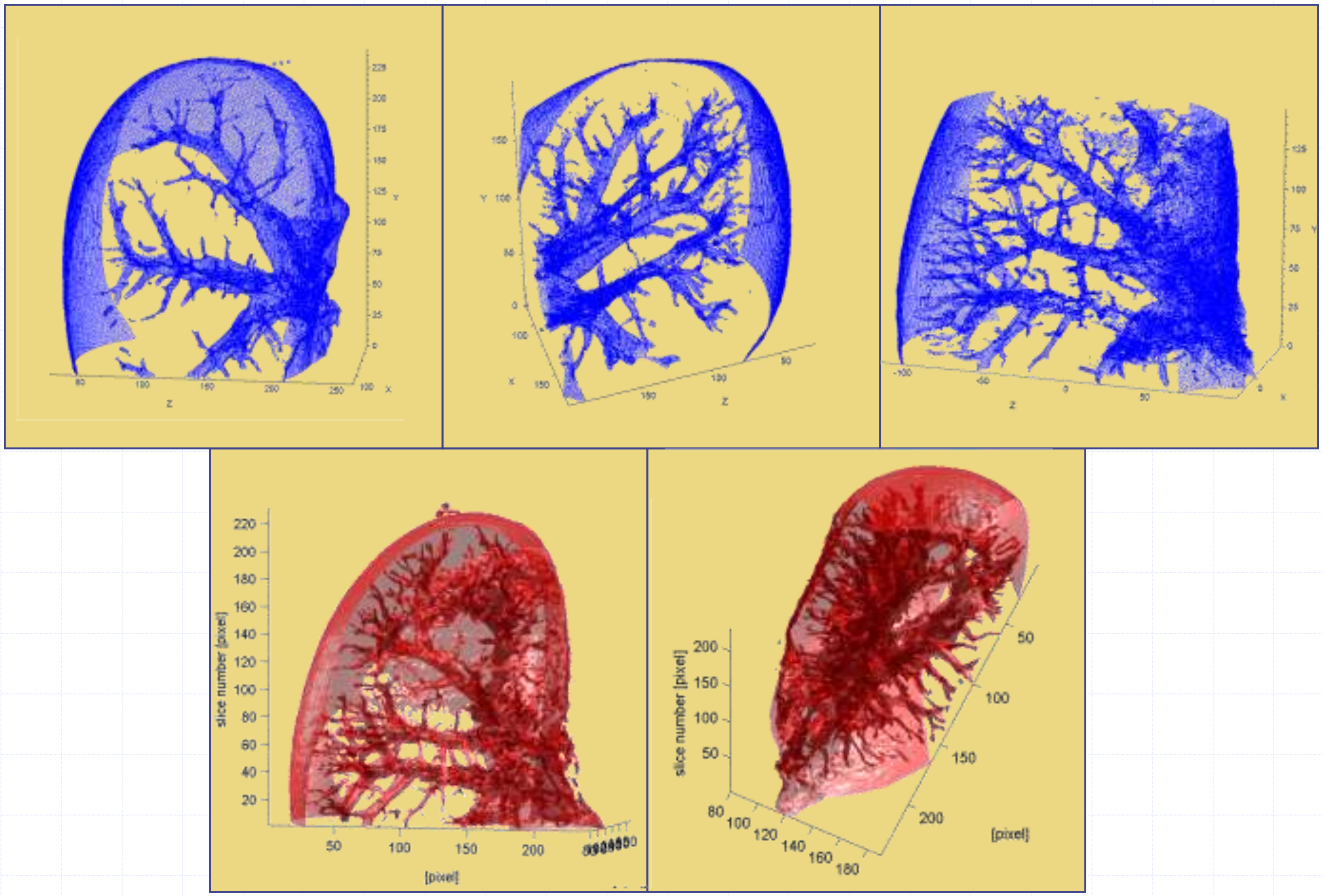


Parasite kills the pupa and leaves it as adult wasp. The life cycle is completed!

Soft tissue X-ray imaging

Mouse Kidney Tomography

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



Science 1, Vol. 339 no. 6119 pp. 510-511, Feb 2013

Small objects:

Radiography of seeds – Science journal competition winner

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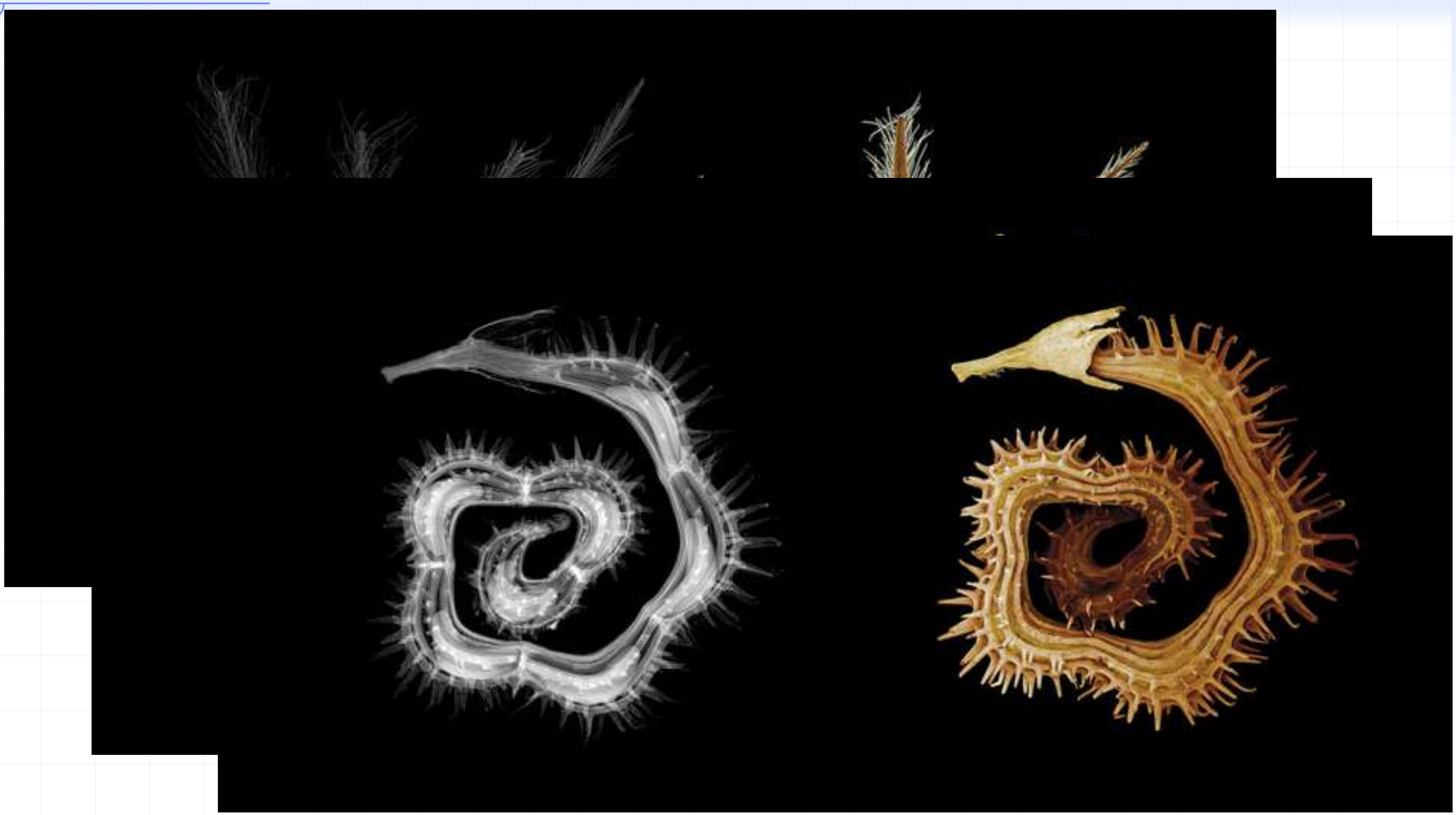
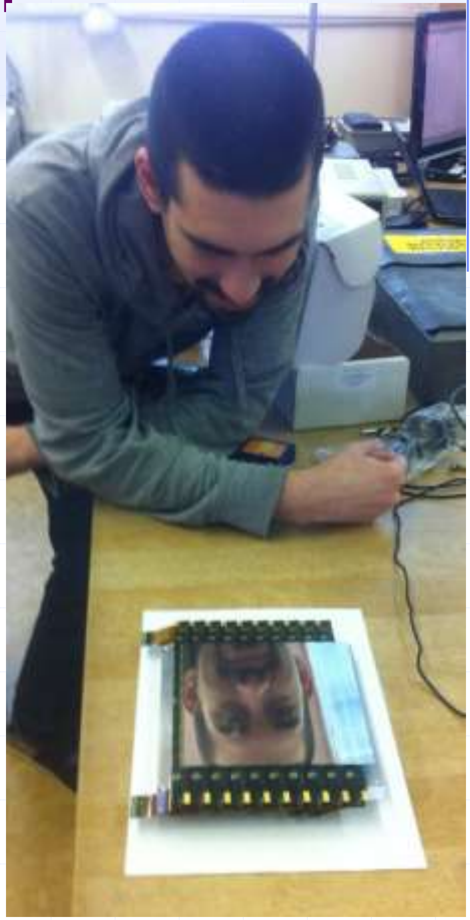


Imaging of large objects: WidePIX 6.5 Megapixel detector

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

Large size objects:
Cockroach with parasite (magnified)

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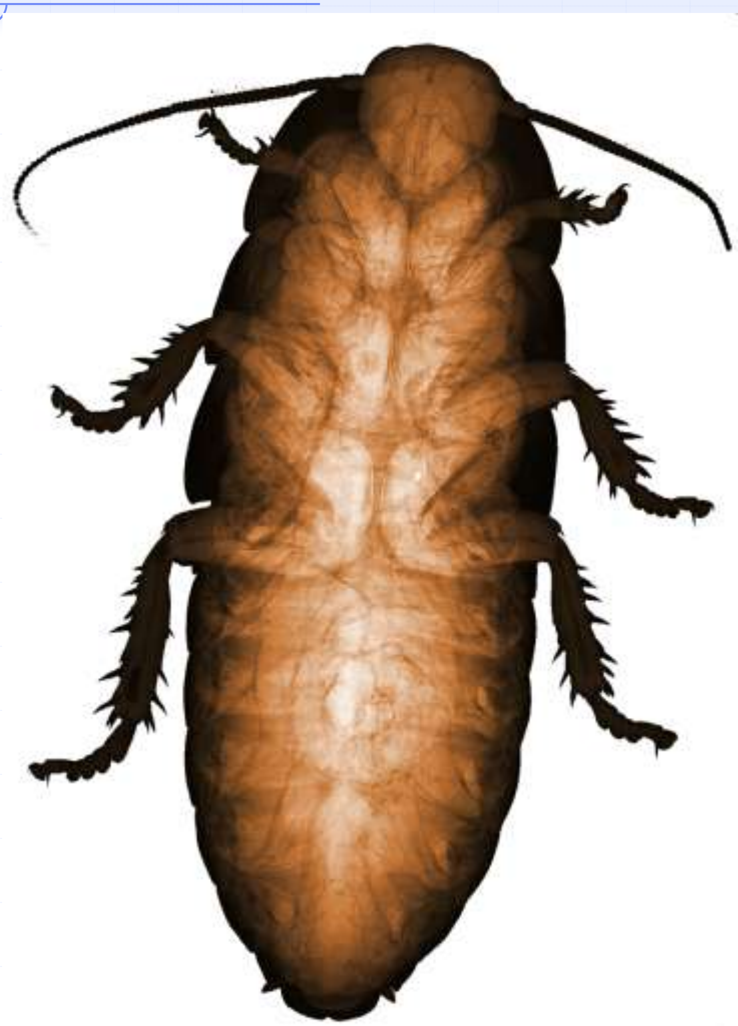
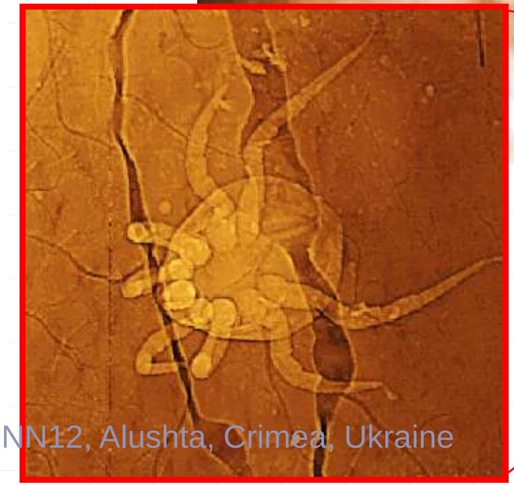
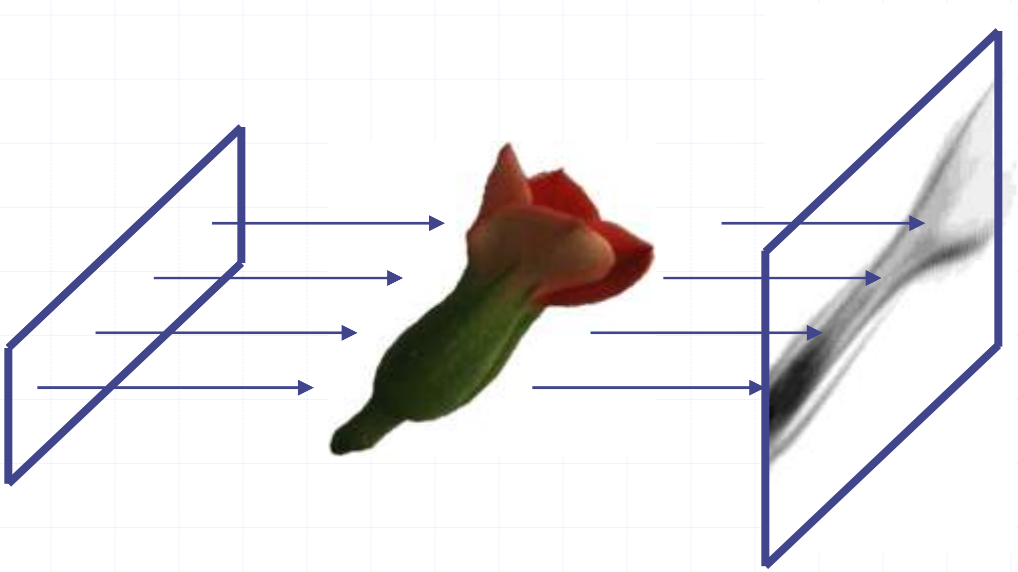
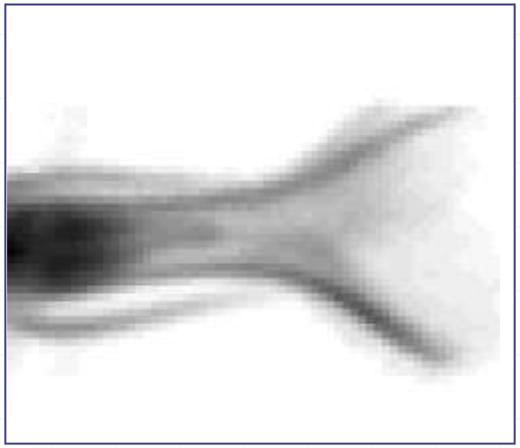




~10μm
resolution

The Neutronography





Parallel beam of thermal neutrons

Specimen attenuating the beam

Shadow on detector plane

Neutronogram

Flower behind Al plate
Look through metal!

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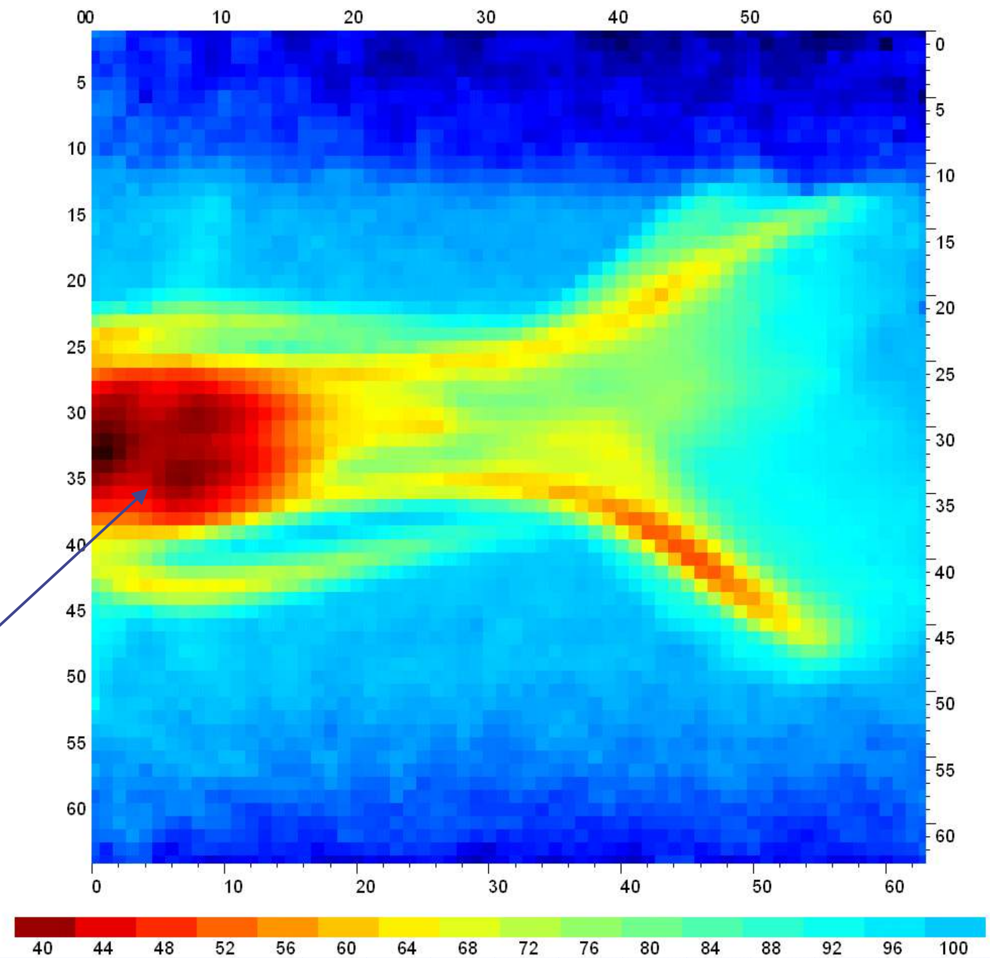

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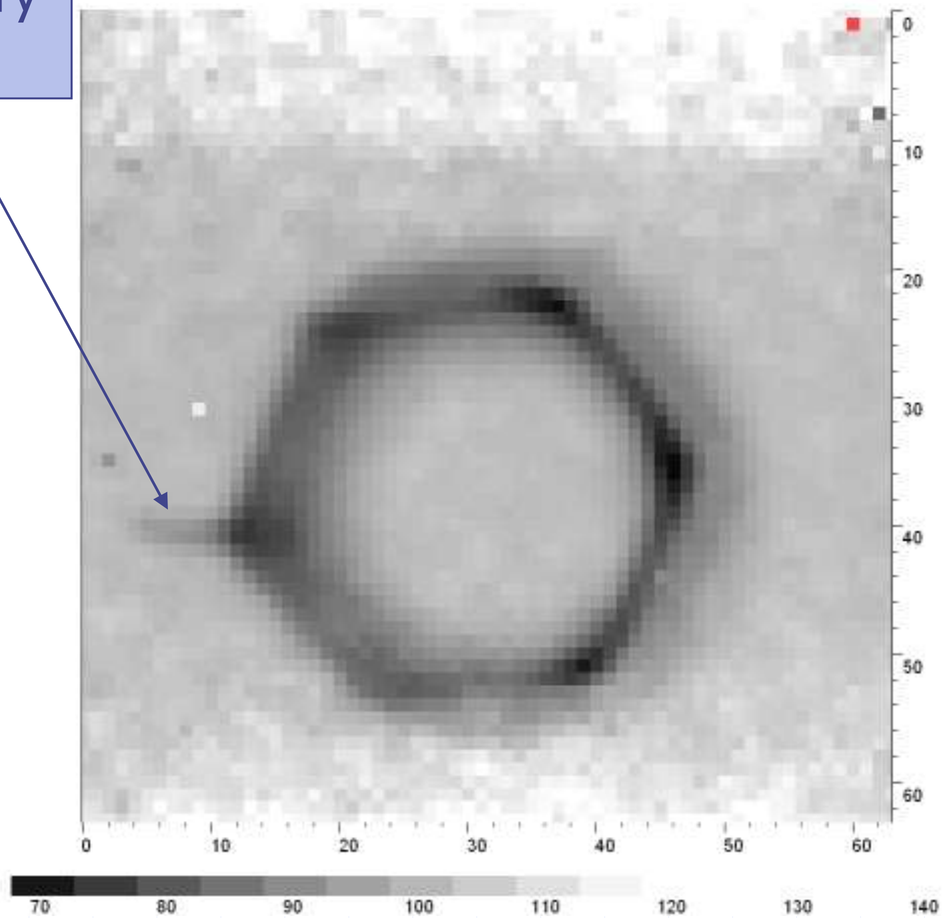
Glued Al pieces

Glue raised through capillary attraction



Cold neutron radiography: Wrist watch

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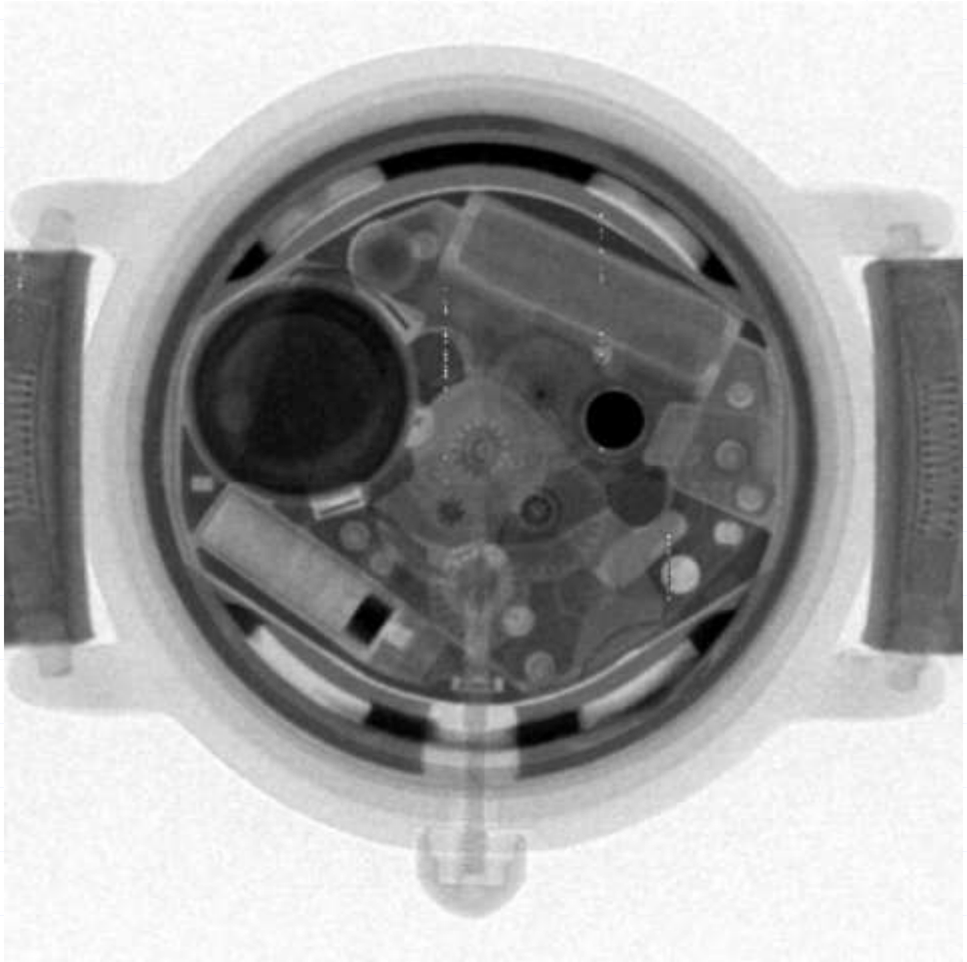

Tracking mode of pixel detector operation

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

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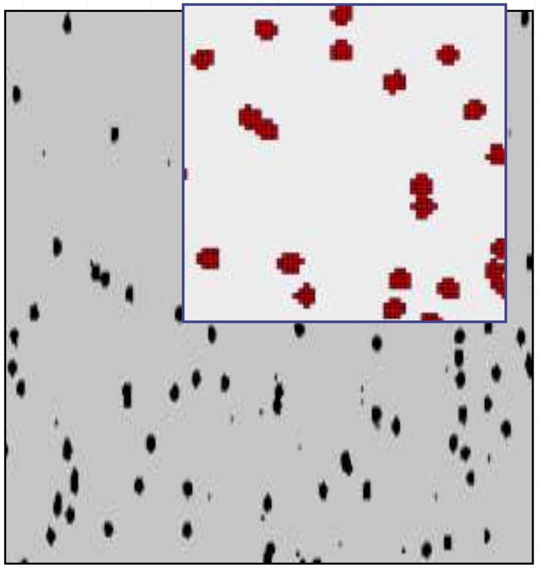

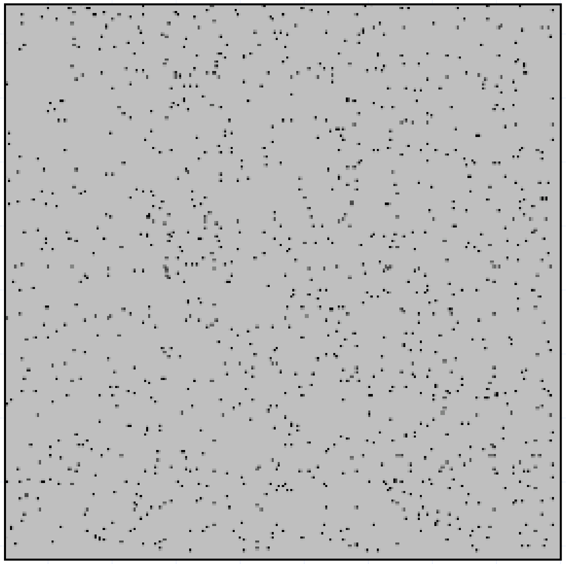

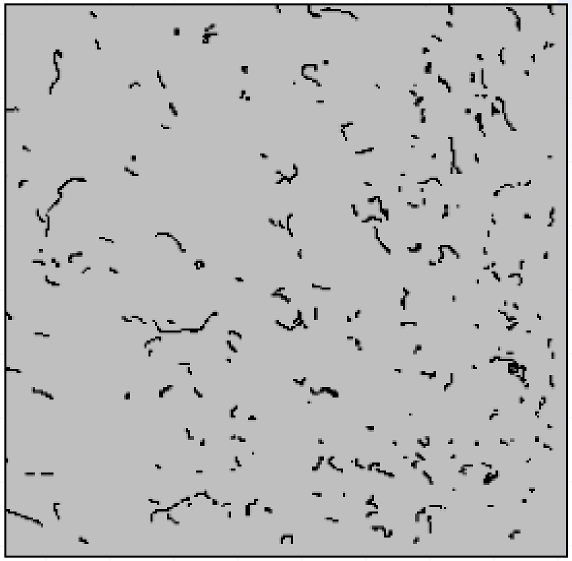

- ^{241}Am alpha source gives clusters of ~5x5 pixels measured with the MEDIPIX-USB device and a 300 μm thick silicon sensor. The clusters are shown in detail in the inlet. The cluster sizes depend on particle energy and threshold setting.
- Signature of X-rays from a ^{55}Fe X-ray source. Photons yield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

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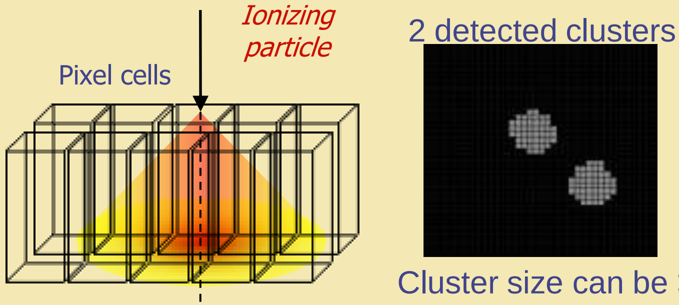
Charge sharing effect - clusters

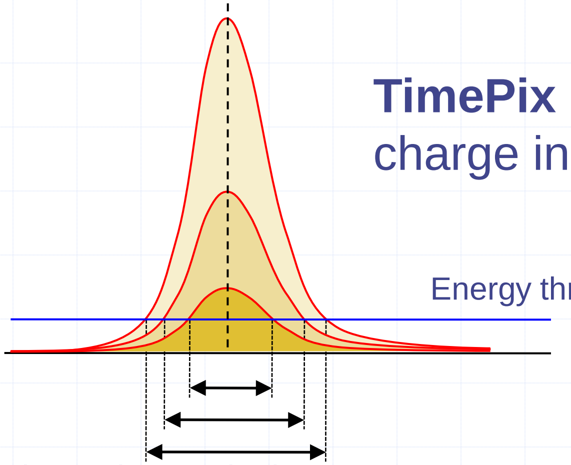
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => **CLUSTER**
- Pixels in a cluster will detect the charge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

The Cluster size depends on:

- Particle Energy
- Depth of interaction
- Detector Bias Voltage
- Local CCE

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





TimePix can measure charge in each pixel

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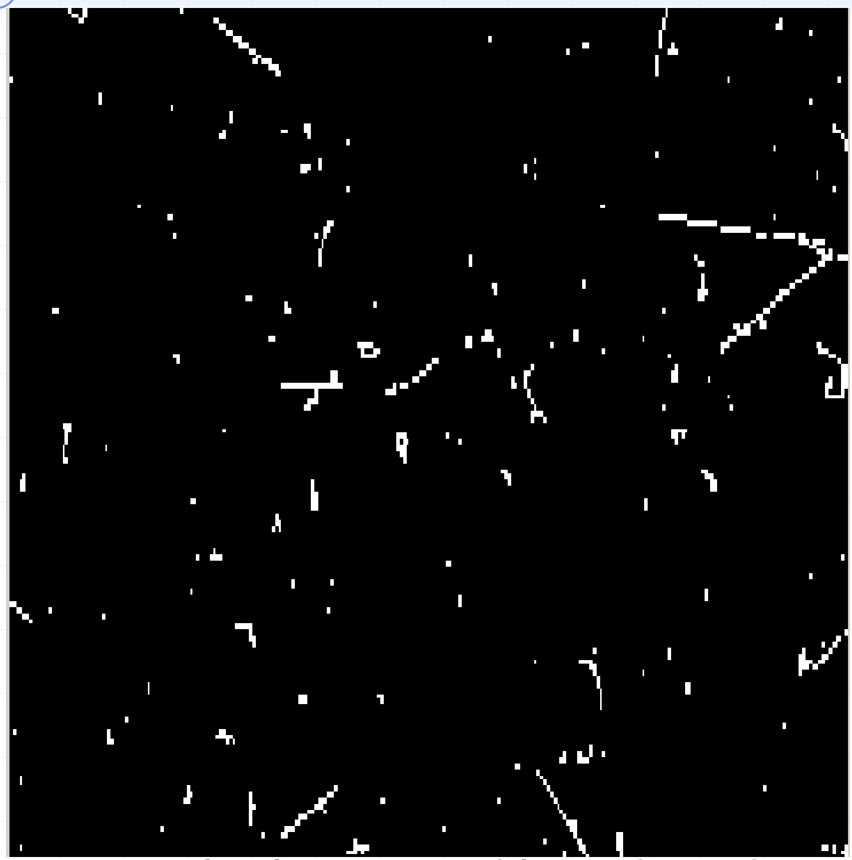
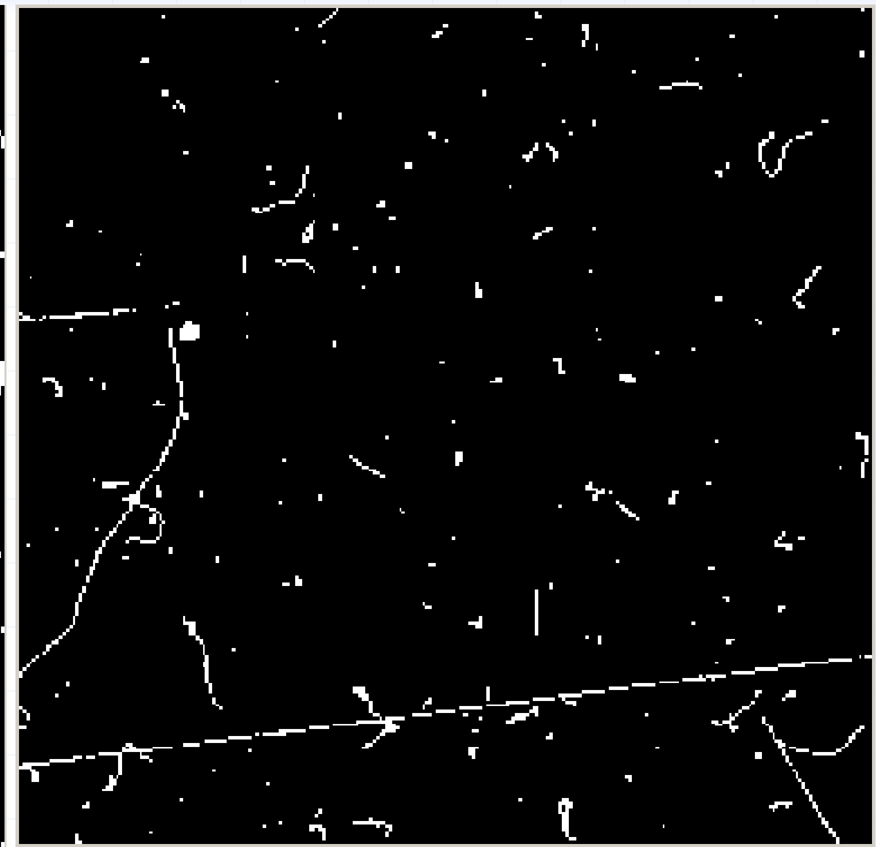
Response of Medipix2 device to natural background radiation





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

Tracks of 11 MeV protons in silicon entering the device under 85°

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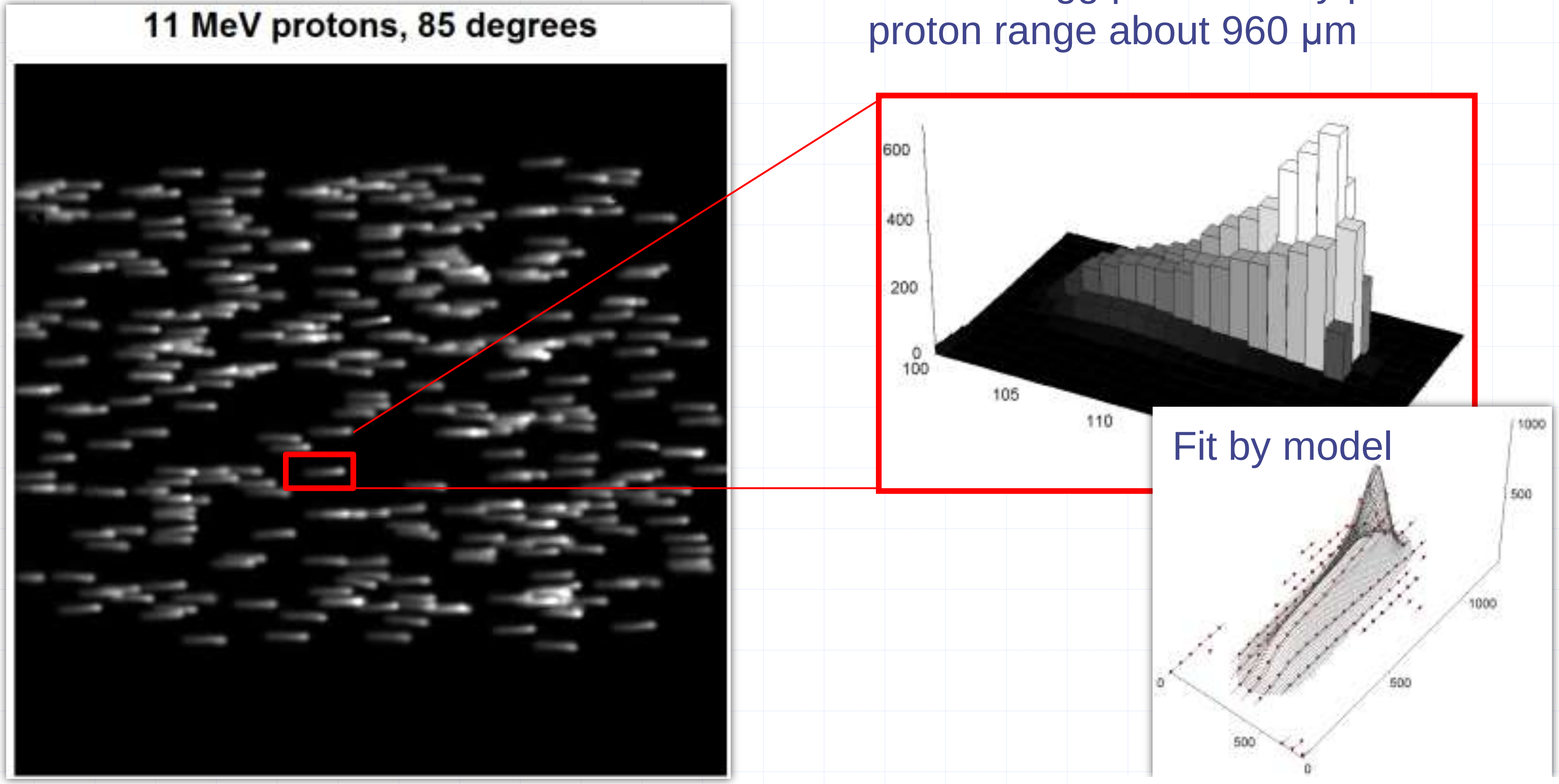
ΔE/Δx Bragg profile nicely pronounced, proton range about 960 μm



Typical observed images in hadron therapy beam

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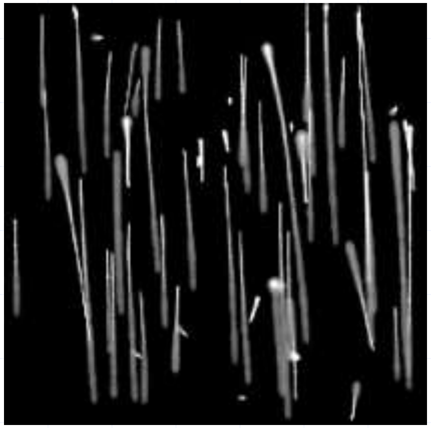
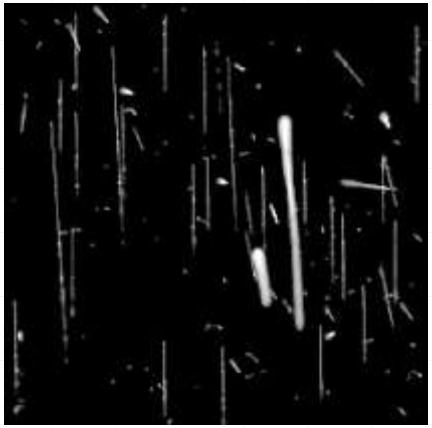
Protons 48 MeV



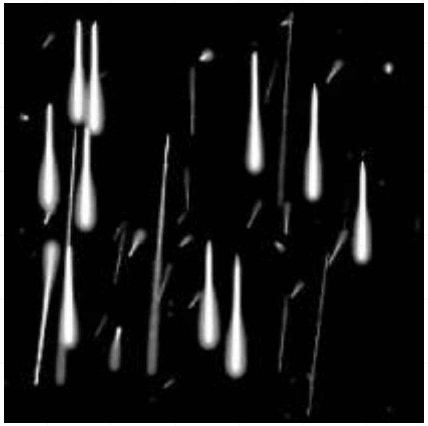
Only protons and their scattering, no secondaries.

Protons 221 MeV



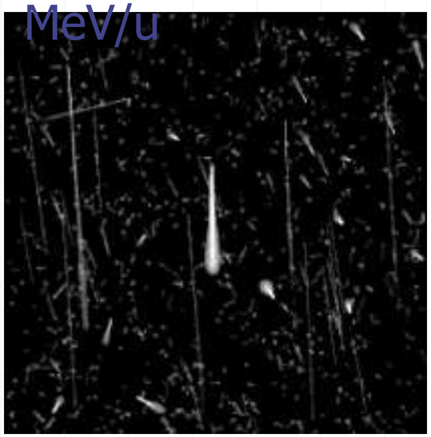
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u



Carbons and many secondaries.

Hadron therapy: Recorded track types

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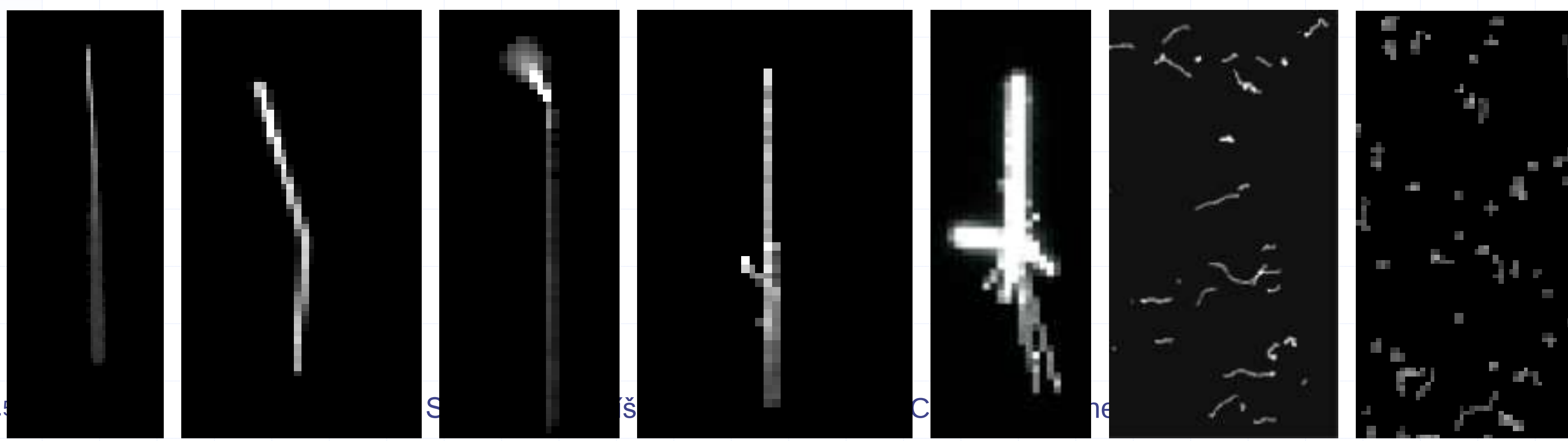
Several basic track types identified:

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



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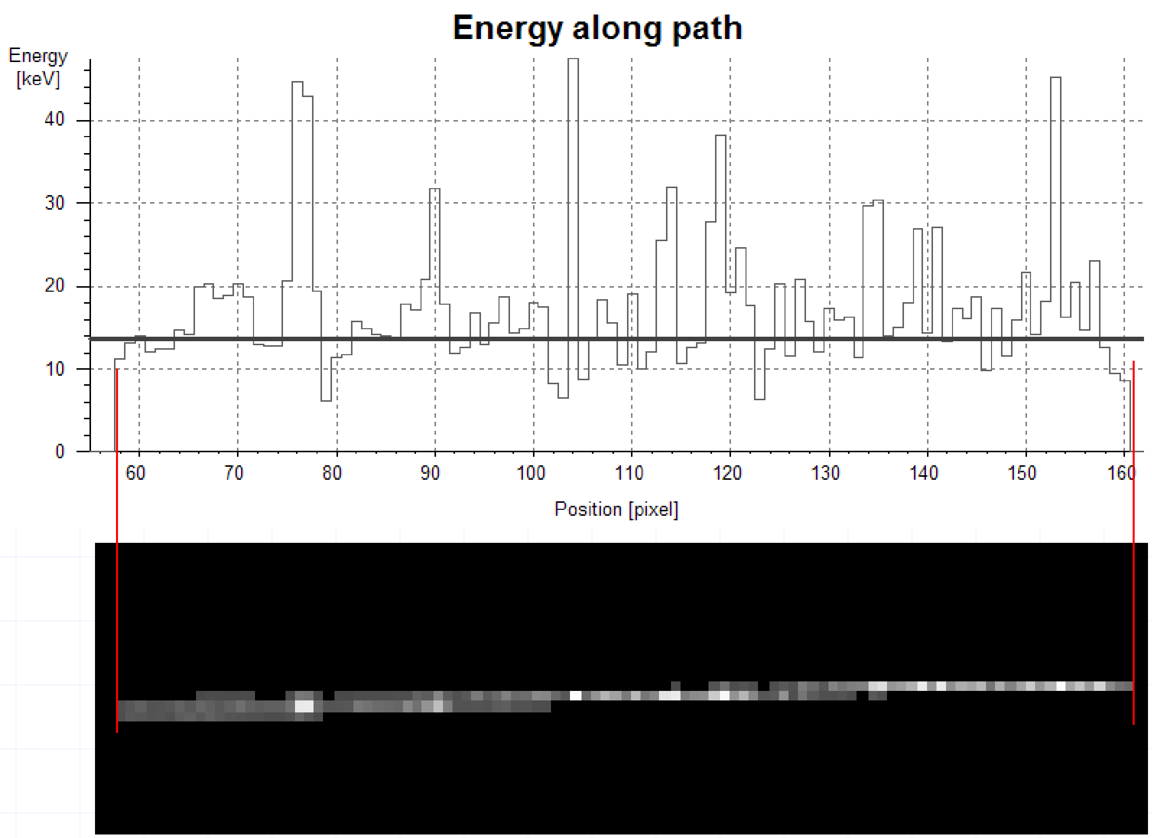
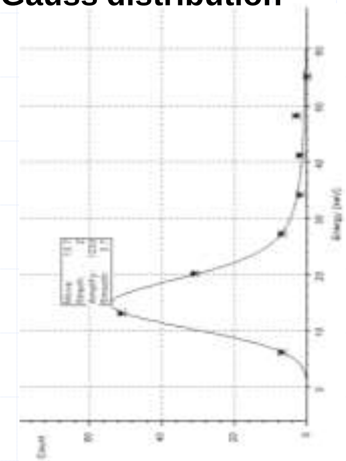
Charge sharing effect:

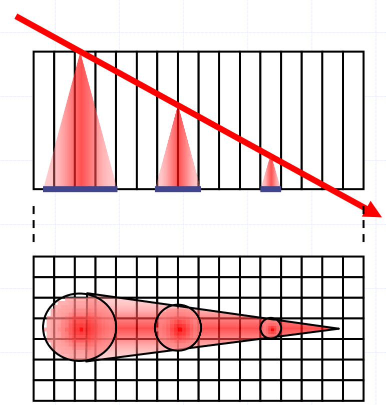
Tracks of MIP particles – Cosmics



Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution



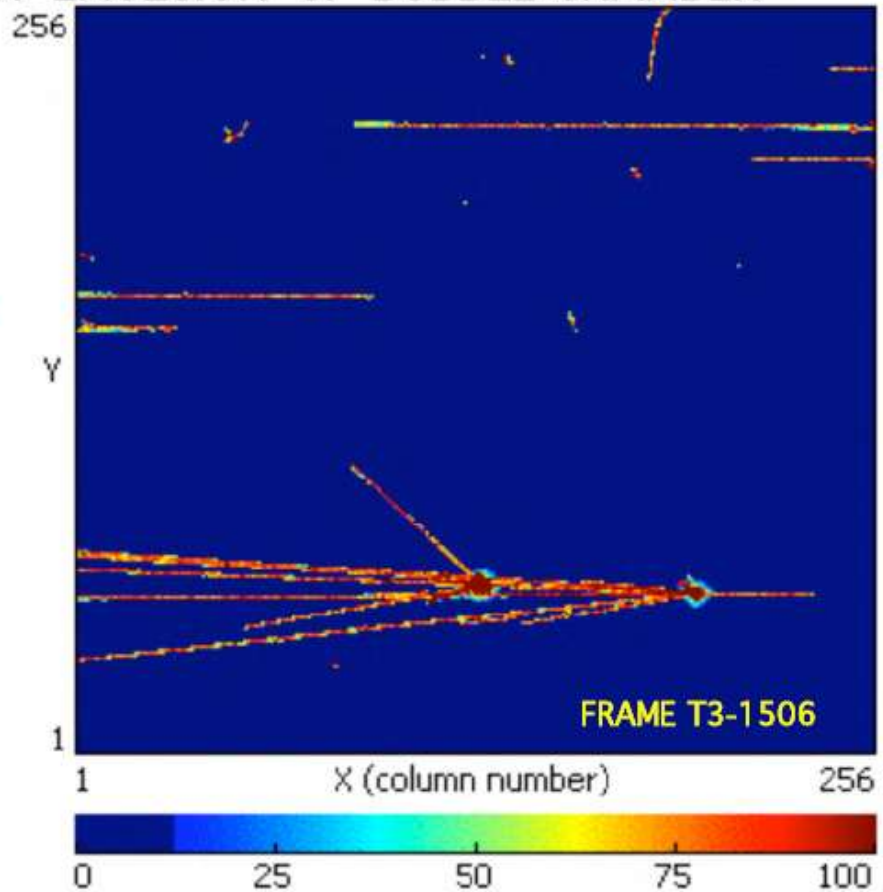


TIMEPIX as SILICON 'EMULSION' or 'BUBBLE CHAMBER'

H6 PION BEAM 2007

INCIDENT from RIGHT

BEAM



with John Idarraga / Montréal

Erik HEIJNE IEAP/CTU & (

Timepix exposed in flight over Atlantic (Santiago-Madrid)

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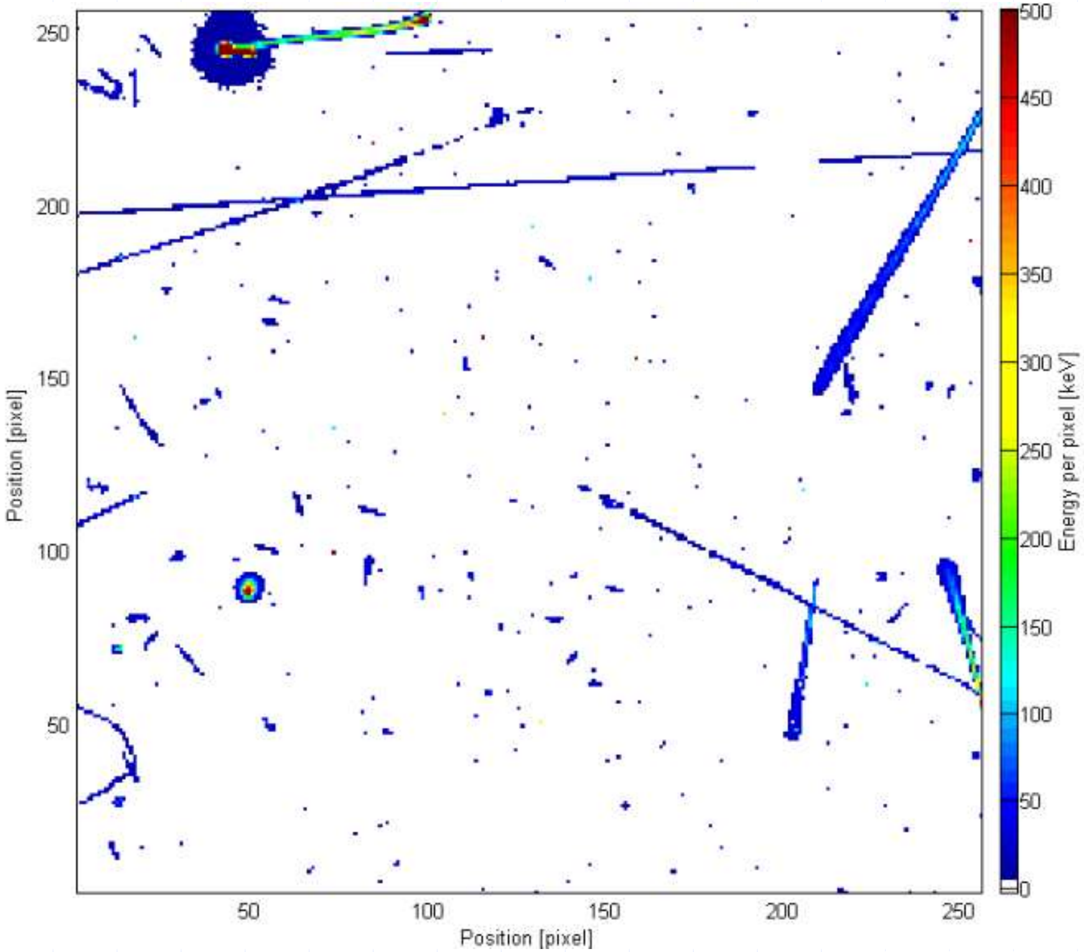
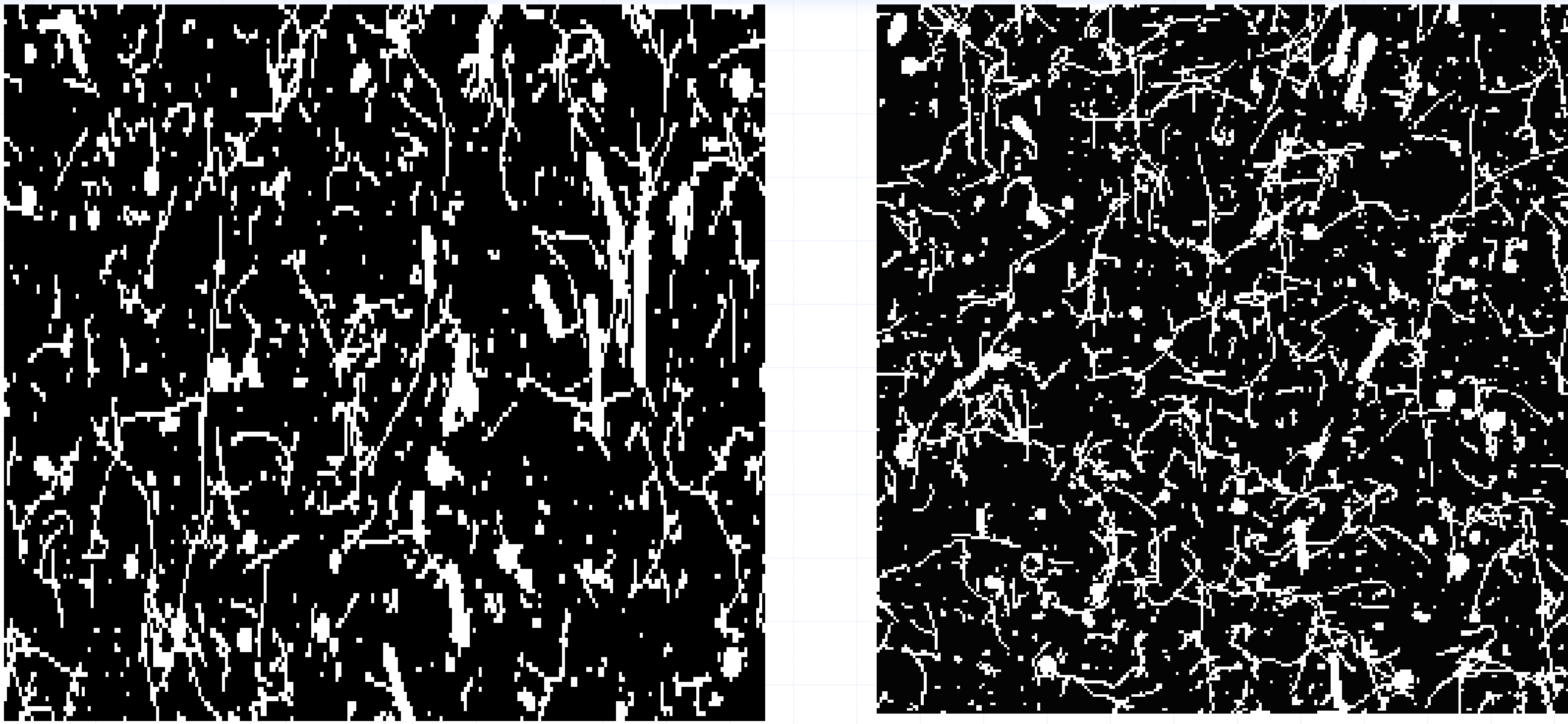


Response of MEDIPIX-USB device with polyethylene converter (on the right hand side) to fast monochromatic neutrons (17MeV)



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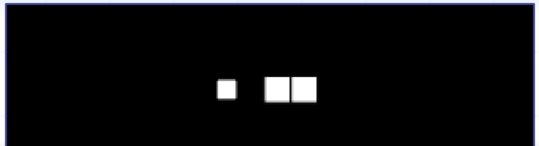
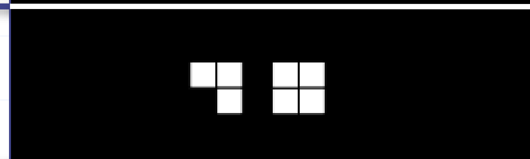
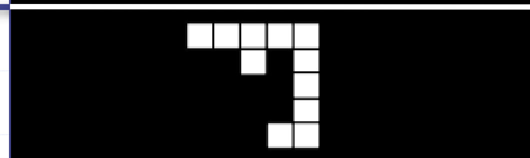
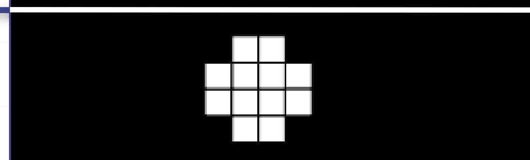
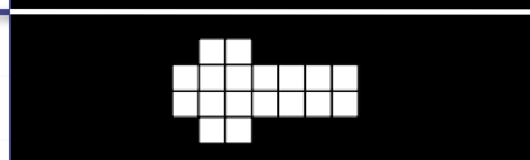
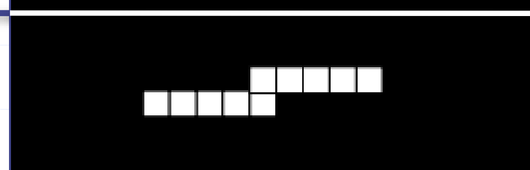
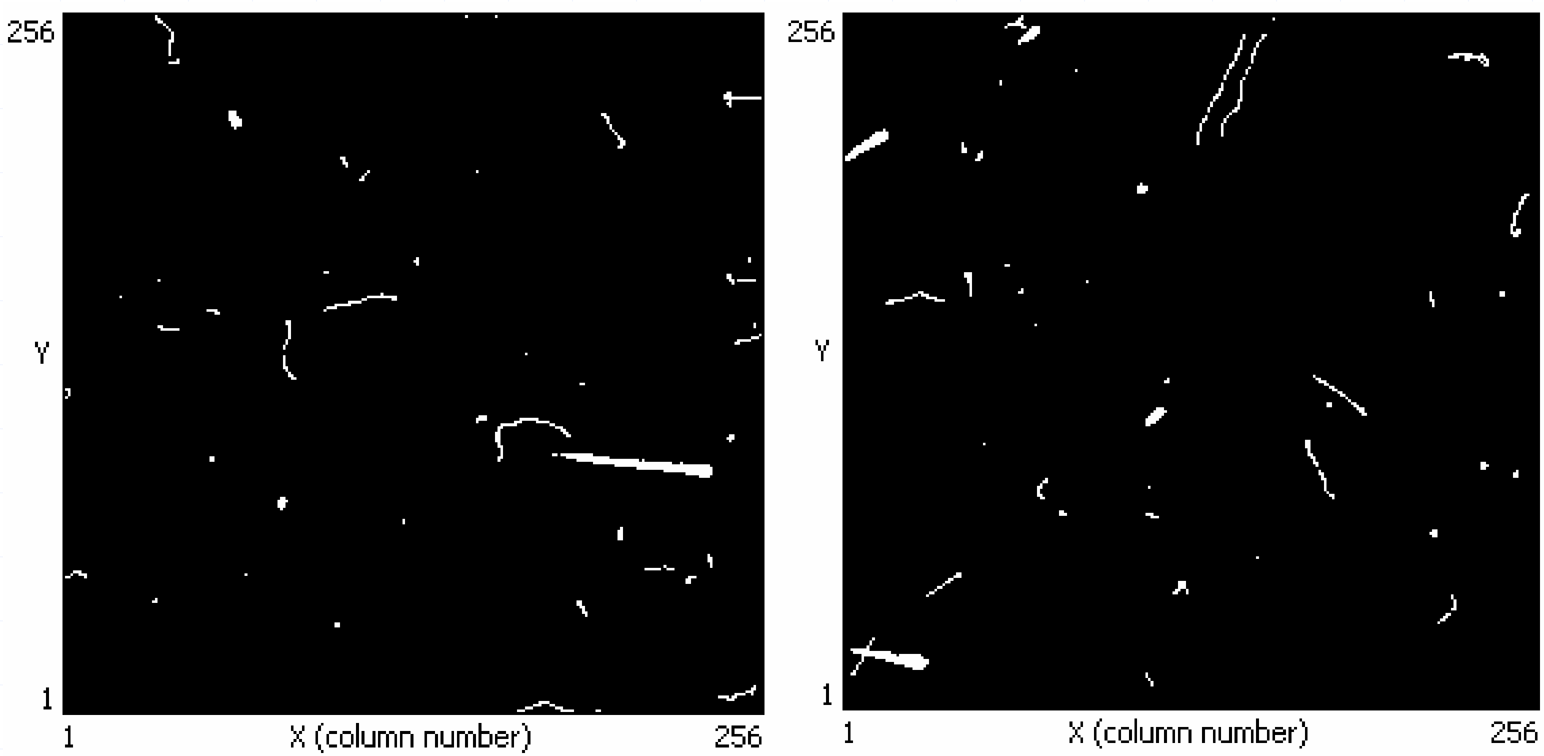
1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with low range (alpha particles,…)
5) Heavy track		Heavy ionizing particles (protons,…)
6) Straight track		Energetic light charged particles (MIP, Muons,…)

Track visualization – pattern recognition of interacting quanta and its energy

Institute of Experimental and Applied Physics
Czech Technical University in Prague



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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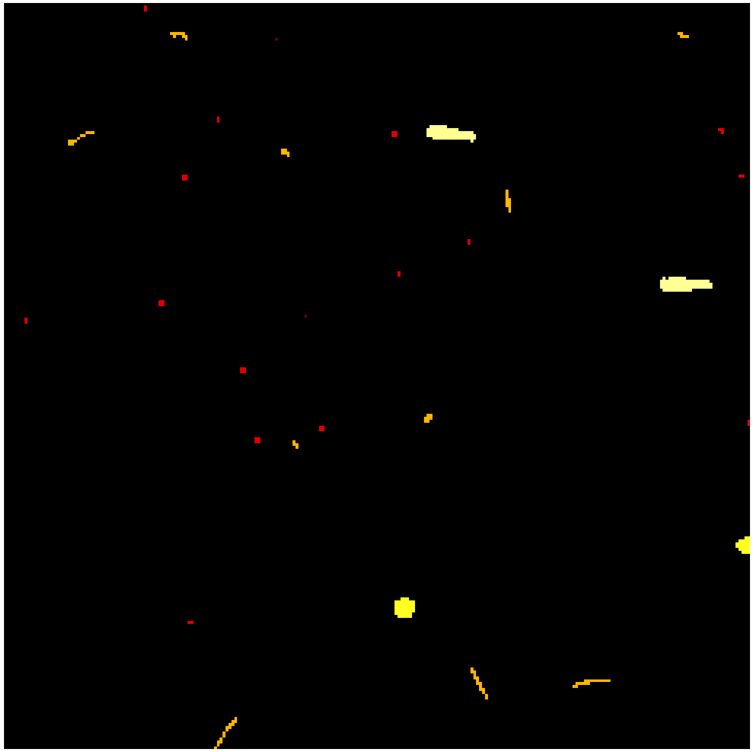
Czech Technical University in Prague



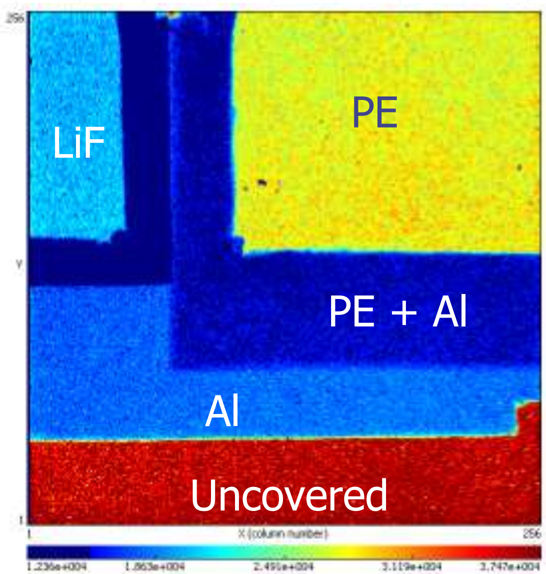
200 frames recognized in 1 sec on standard PC (courtesy of Tomas Holy)

Detail view on conversion layers for neutron detection

Institute of Experimental and Applied Physics
Czech Technical University in Prague

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

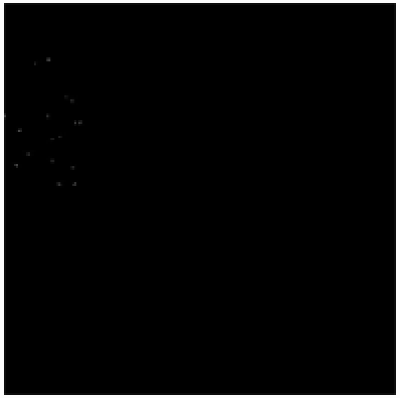


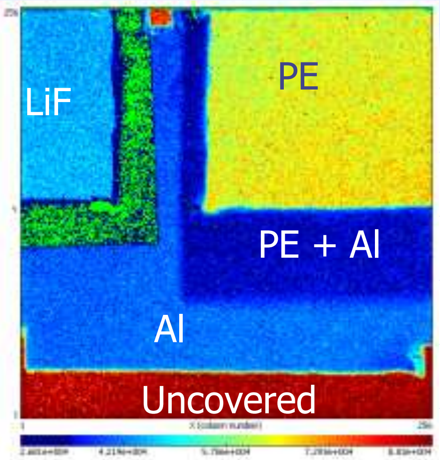
33

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

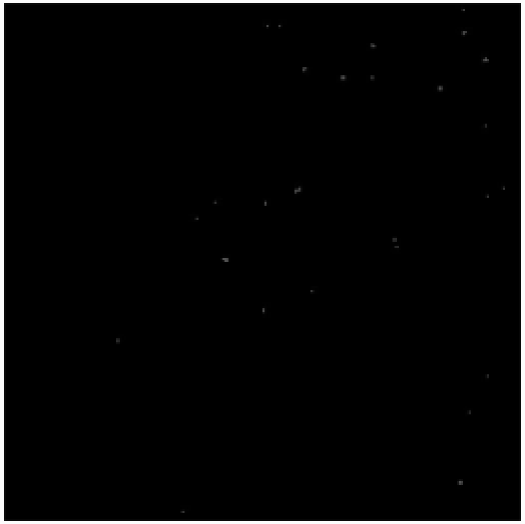
Identification of spectral composition of incoming neutron radiation can be done by comparing responses of different sensitive regions.

Thermal neutrons – 500s





252Cf – 2000s



AmBe – 2000s

17 MeV neutrons at 0^{o}

34

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

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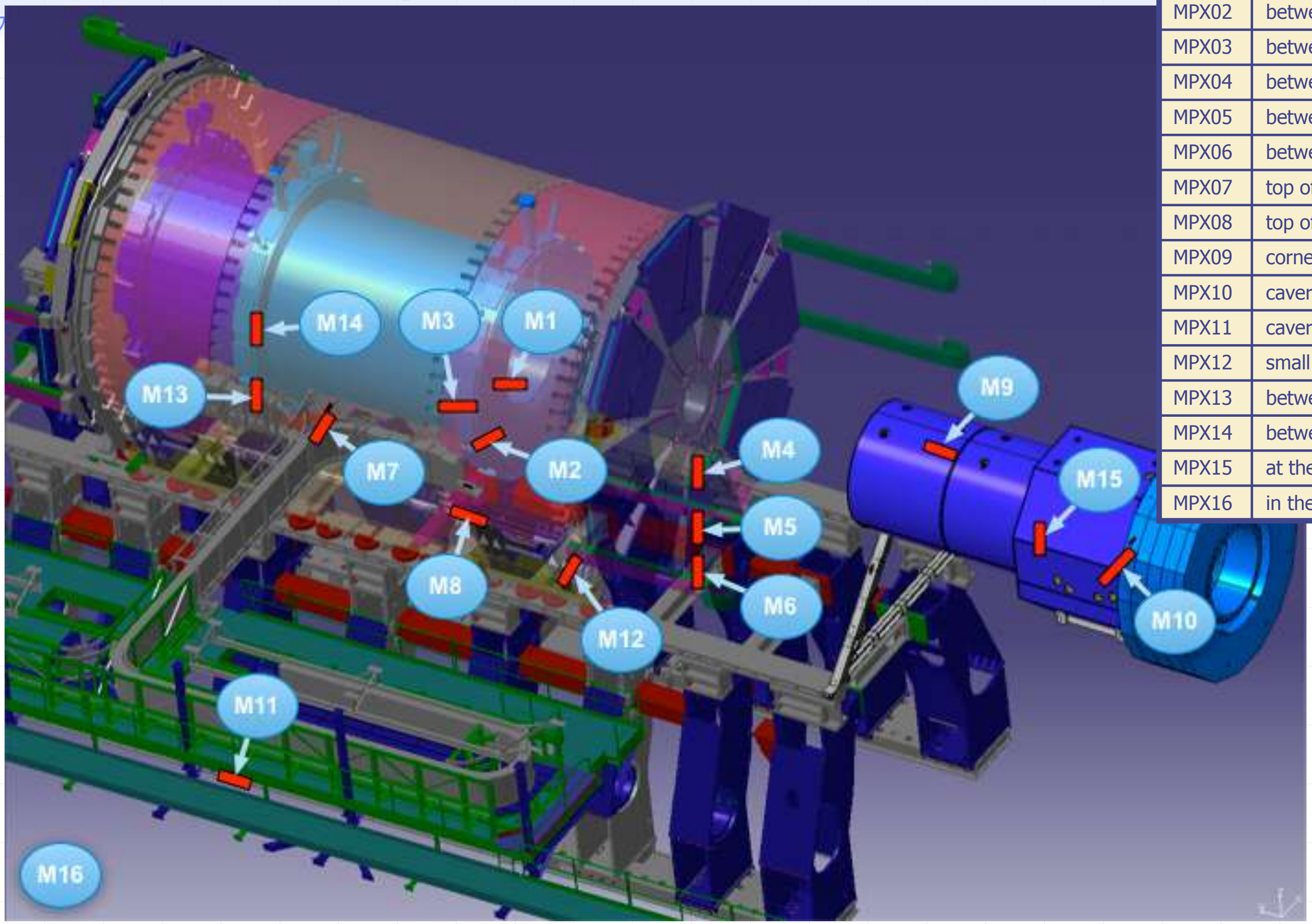
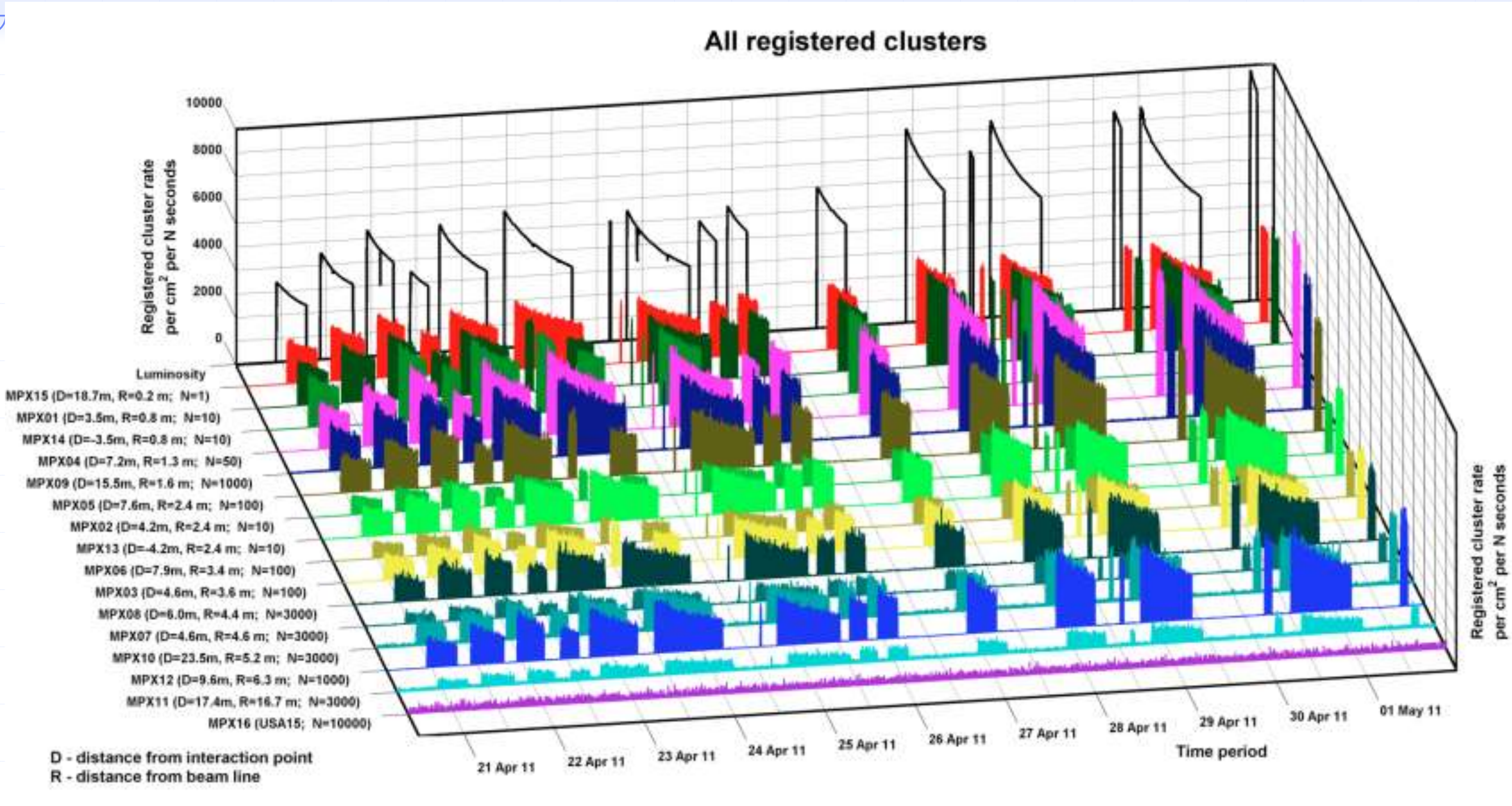


MPX01	between ID and JM plug
MPX02	between ID, LARG and JM
MPX03	between LARG and LARG EC
MPX04	between FCAL and JT
MPX05	between LARG and JT wheel
MPX06	between LARG and JT wheel
MPX07	top of TILECAL barrel
MPX08	top of TILECAL EXT. barrel
MPX09	corner between JF cyl. and hexagon
MPX10	cavern wall A 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

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



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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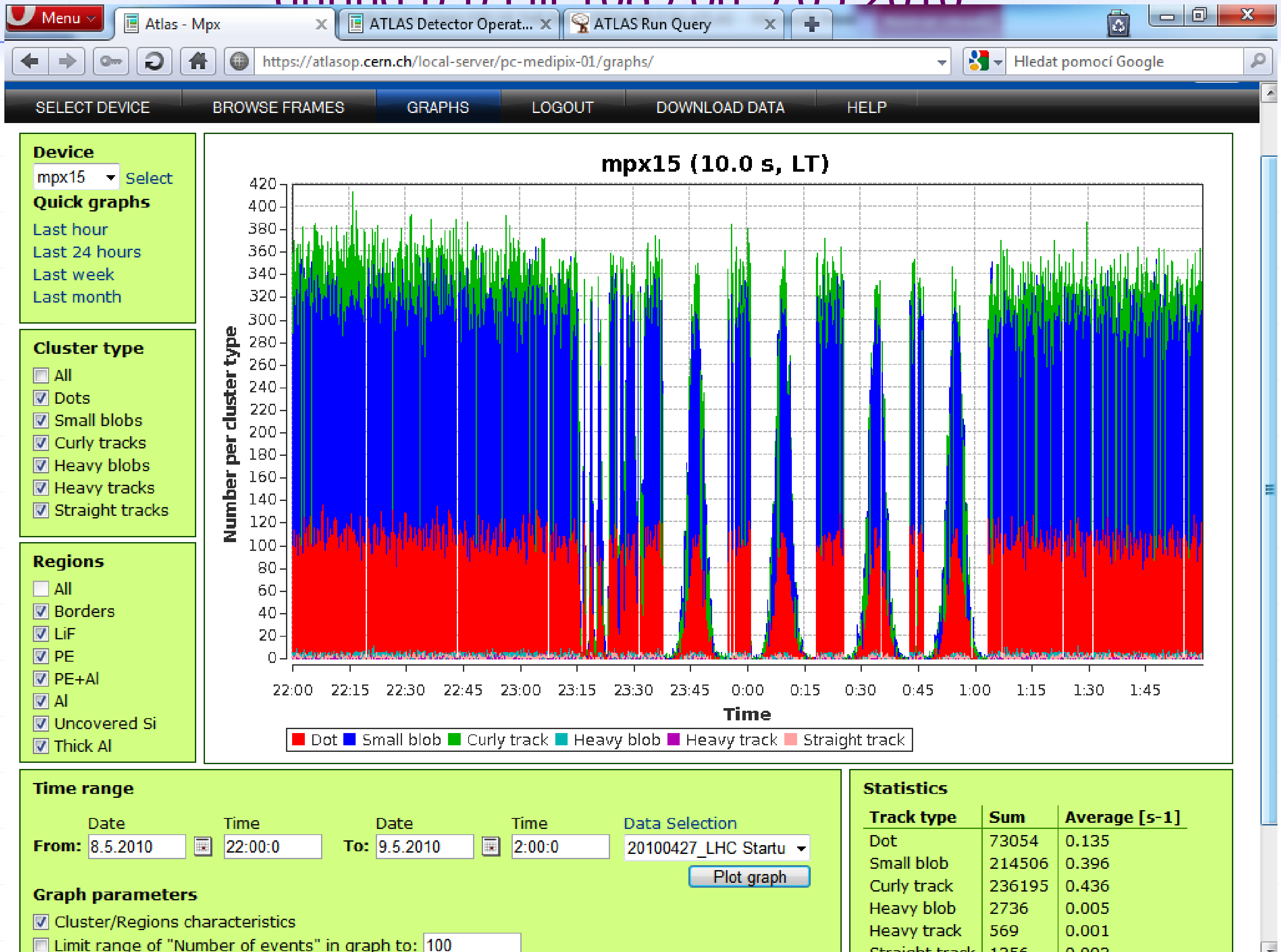

Fast neutron ToF measurement with TIMEPIX

LANSCE neutron sources and nuclear science flight paths

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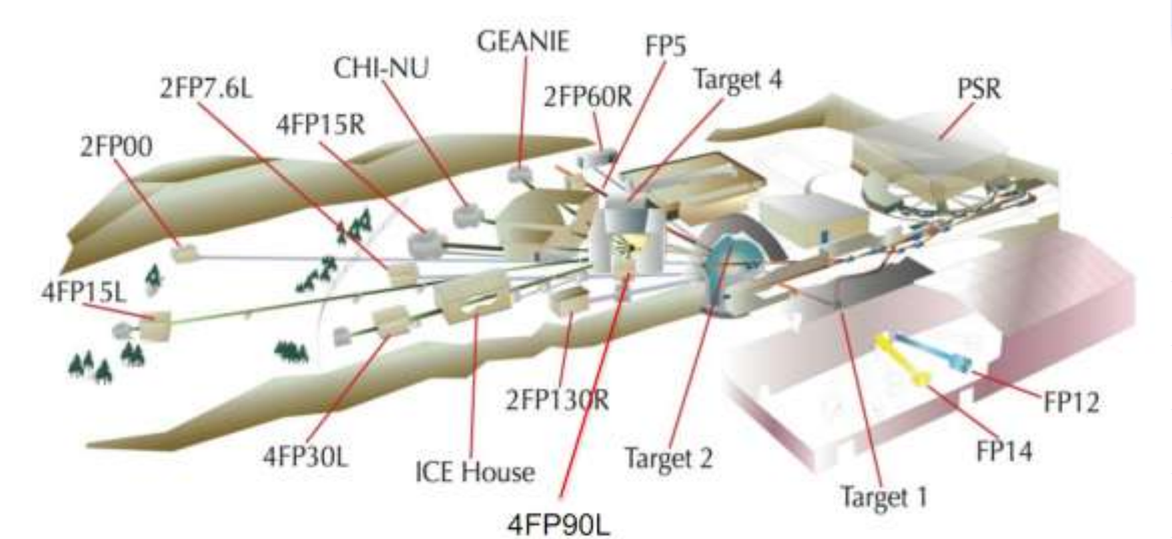
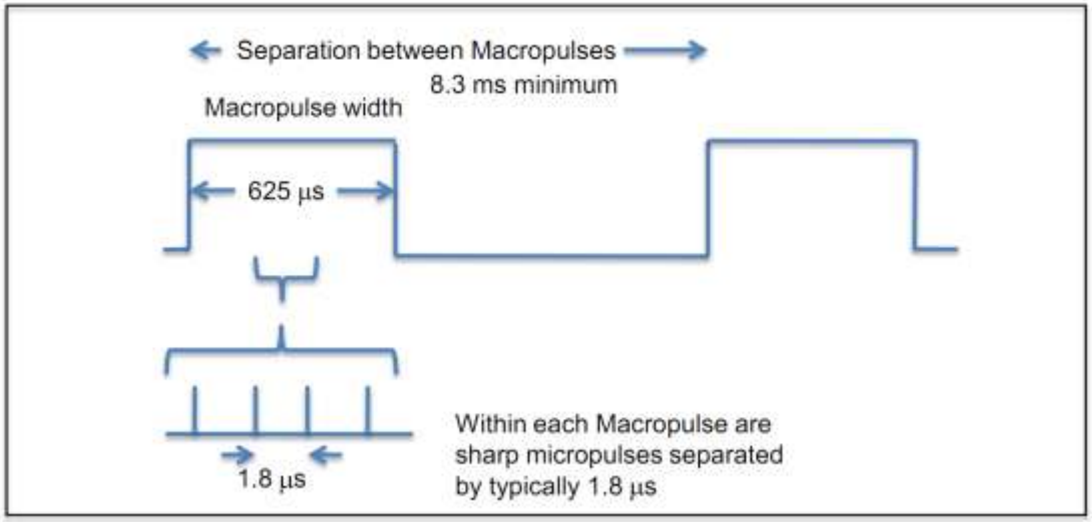
Czech Technical University in Prague

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



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



Fluence of different cluster types over energy

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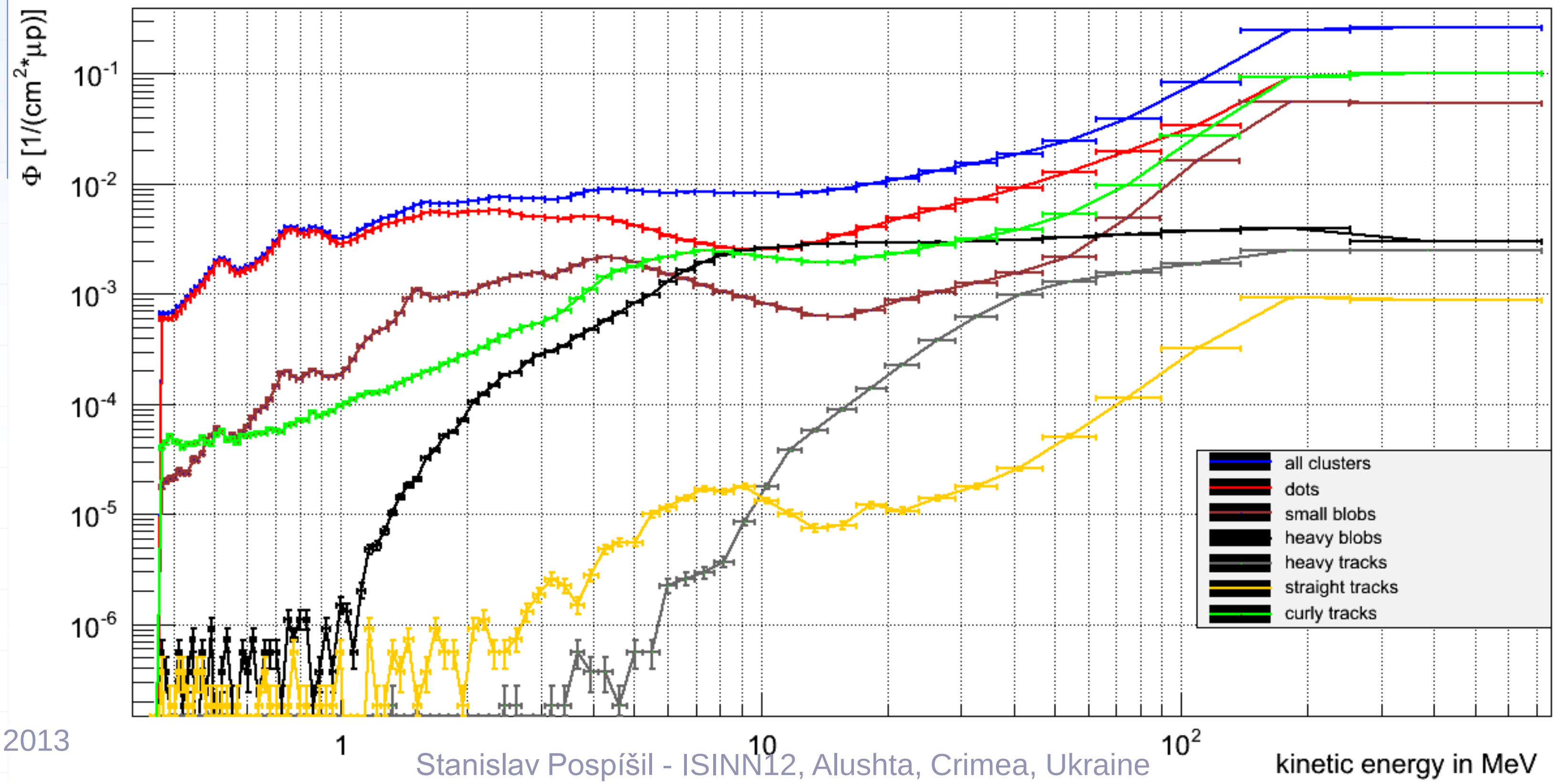
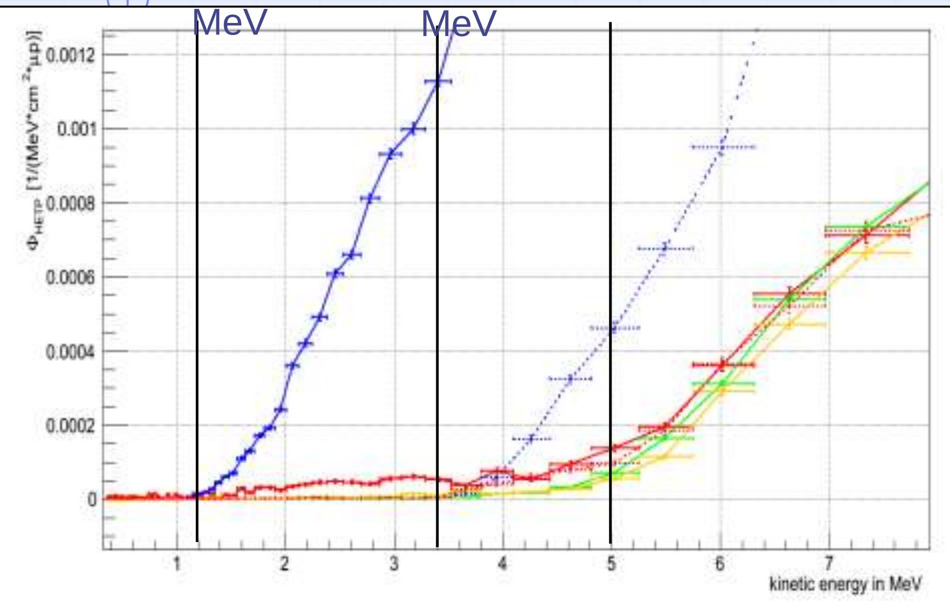
- Curly tracks, dots and small blobs dominate nearly over the whole energy range
- Asymmetric errorbars in x-direction due to binning of the measurement
- Three humps are present at lower fast neutron energies (<1 MeV) -> dots

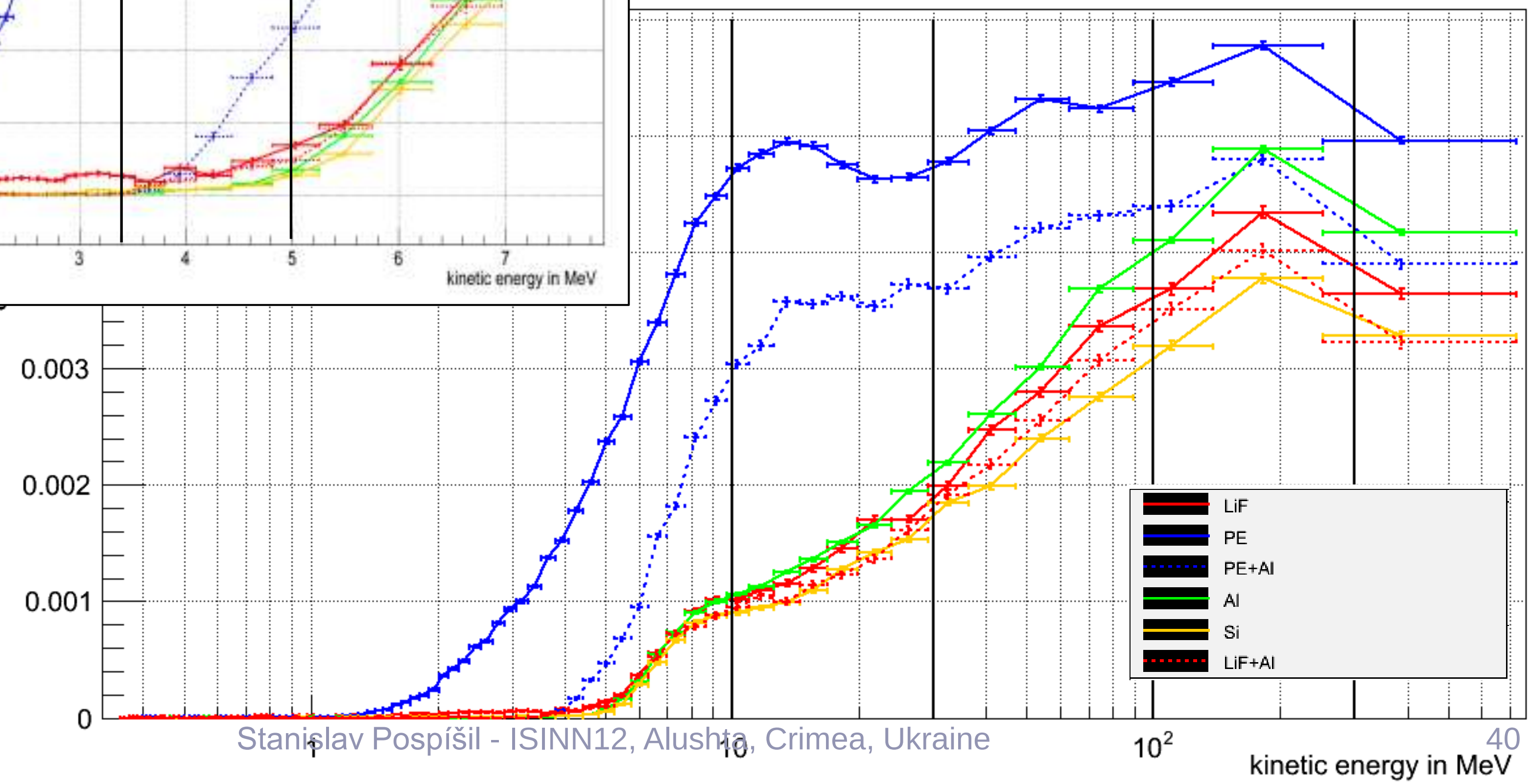


Fluences below different conversion layers

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

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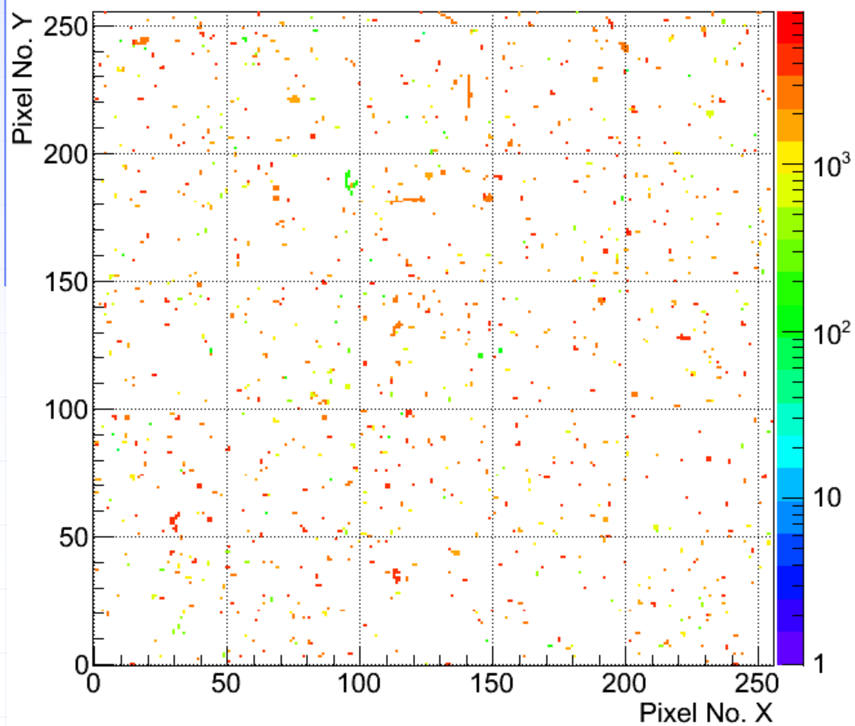
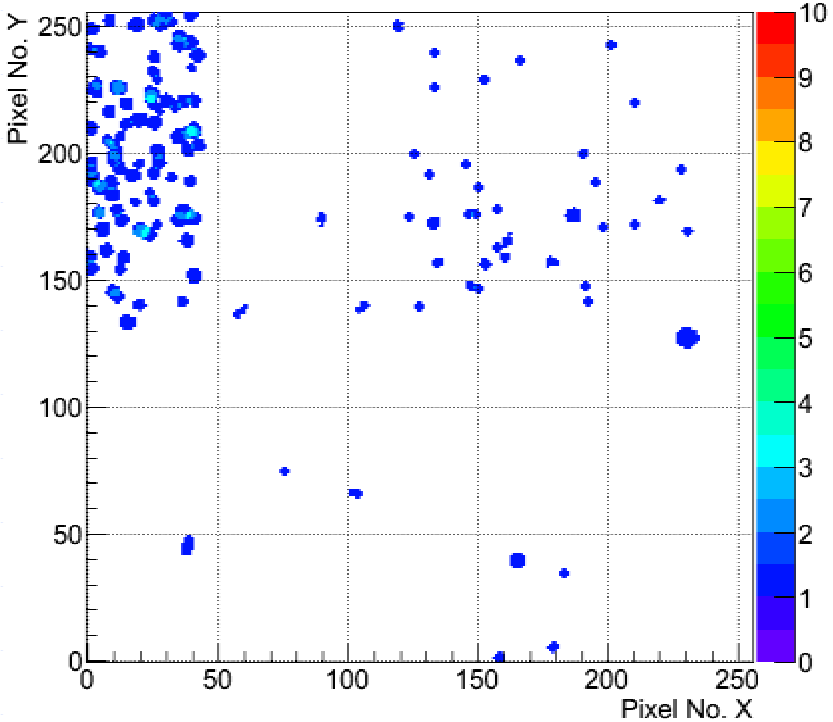
- Mainly dots, curly tracks are found in this energy region
- Heavy blobs below LiF indicate presence of thermal neutrons
- Also PE region shows slightly enhanced count rate



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)

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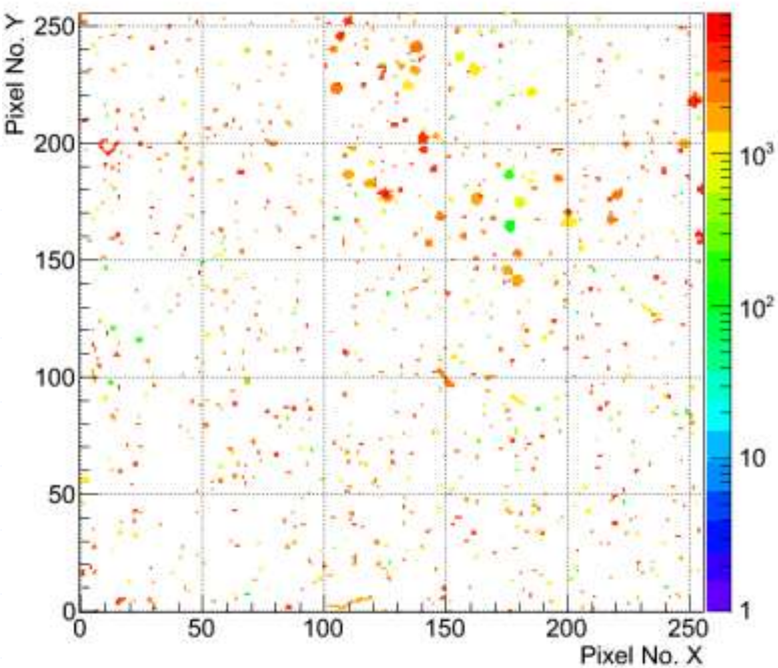
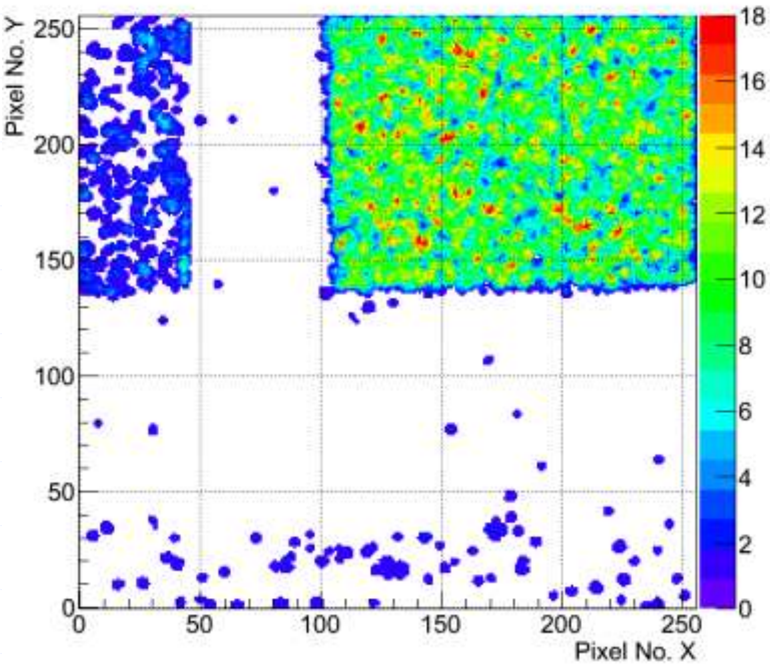
Response of Timepix: Energy region 1.2 – 3.4 MeV

- Heavy blobs below LiF indicate presence of thermal neutrons
- Clear signal of HETP below PE
- uncovered area shows also a few events



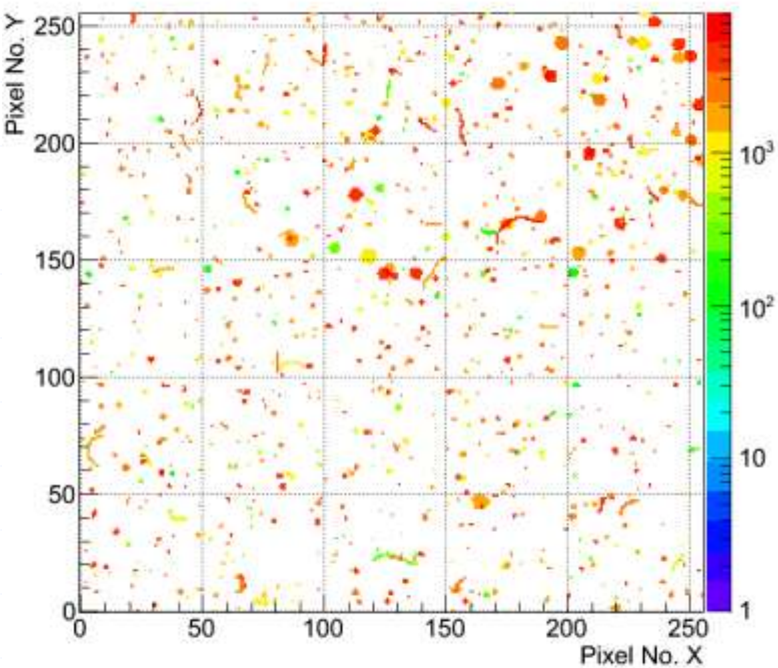
All types of clusters in this energy region integral picture (1000 events were considered)



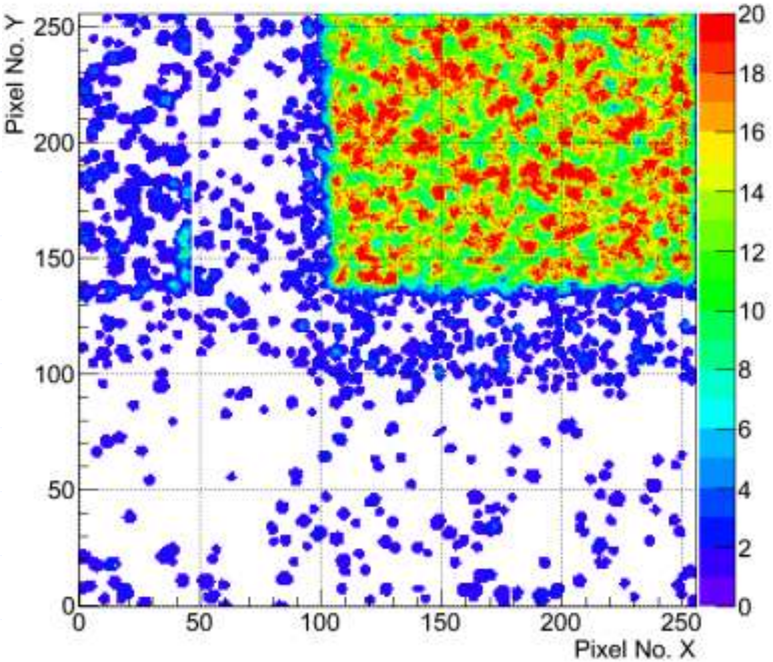
Heavy tracks and heavy blobs in this energy region (full statistics - 10259 events were found)

Response of Timepix: Energy region 3.4 – 5.0 MeV

- Clear signal of HETP below PE
- Also PE+Al region becomes 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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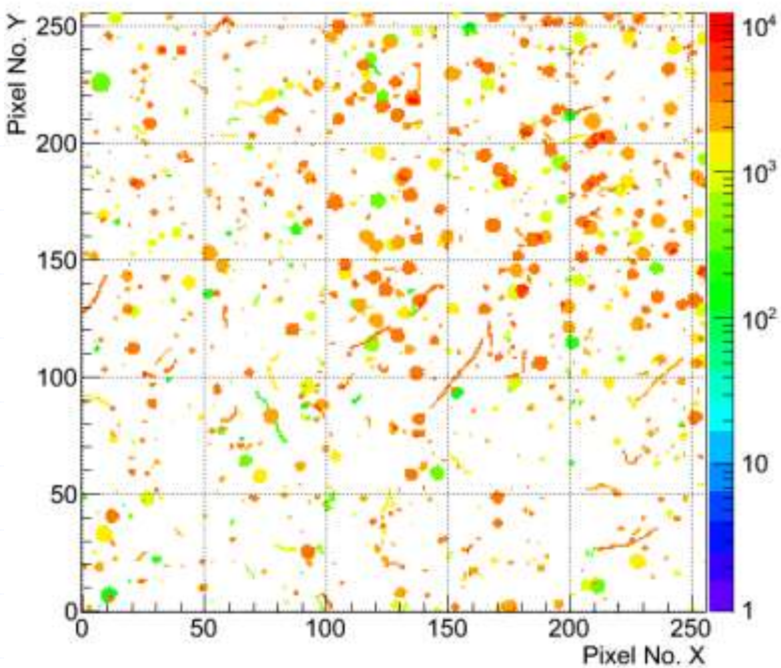
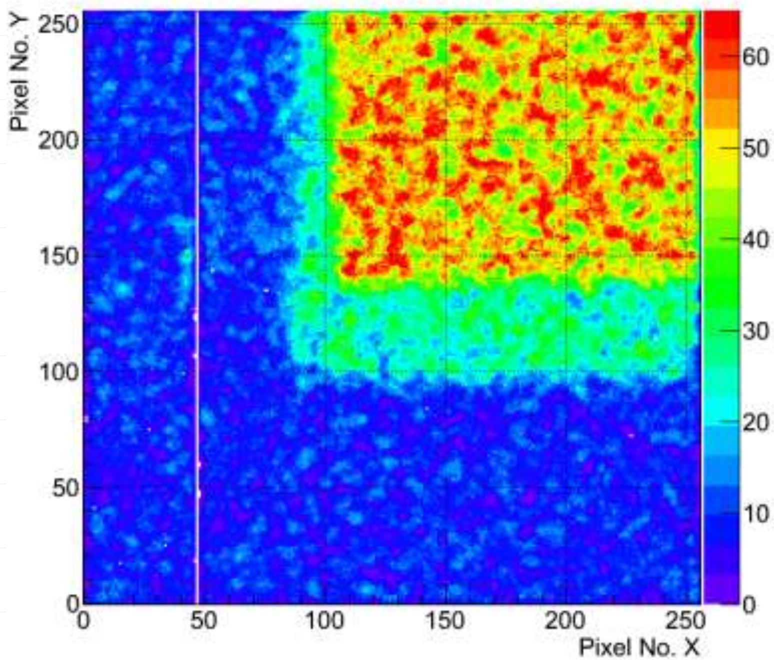
- Higher HETP count rate below PE and PE+Al
- HETP: cluster still look roundly shaped
- No enhancement below LiF



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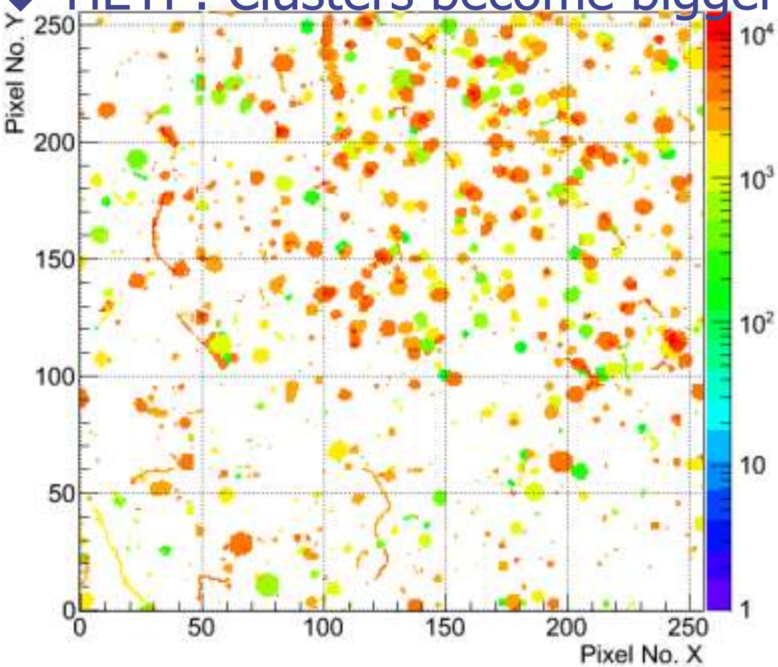
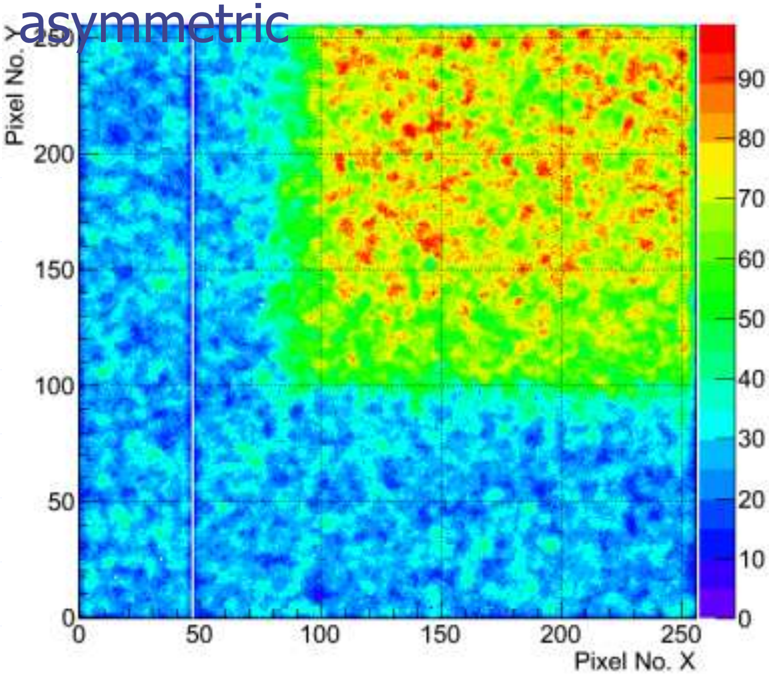
- Higher HETP count rate below PE and PE+Al (contrast to other regions begins to decrease)
- HETP equally distributed below all other regions
- HETP: Clusters become bigger and asymmetric



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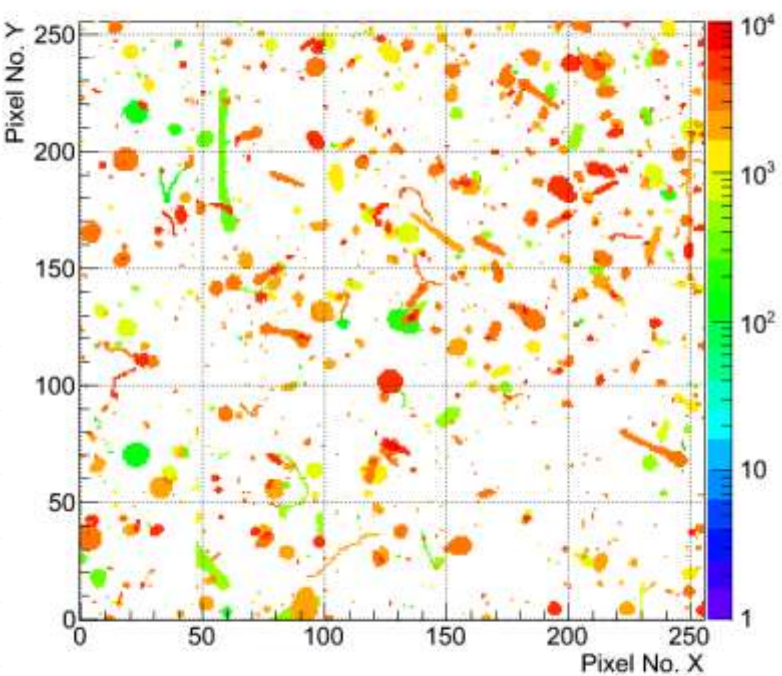
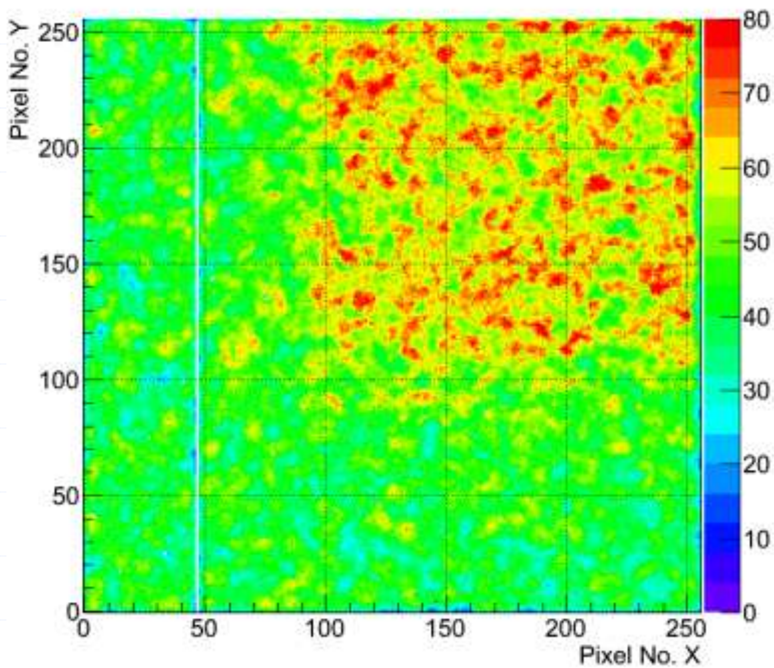
- Still enhanced response below PE and PE+Al
- Contrast to all other region is decreasing
- Cluster are getting bigger and more and more asymmetric



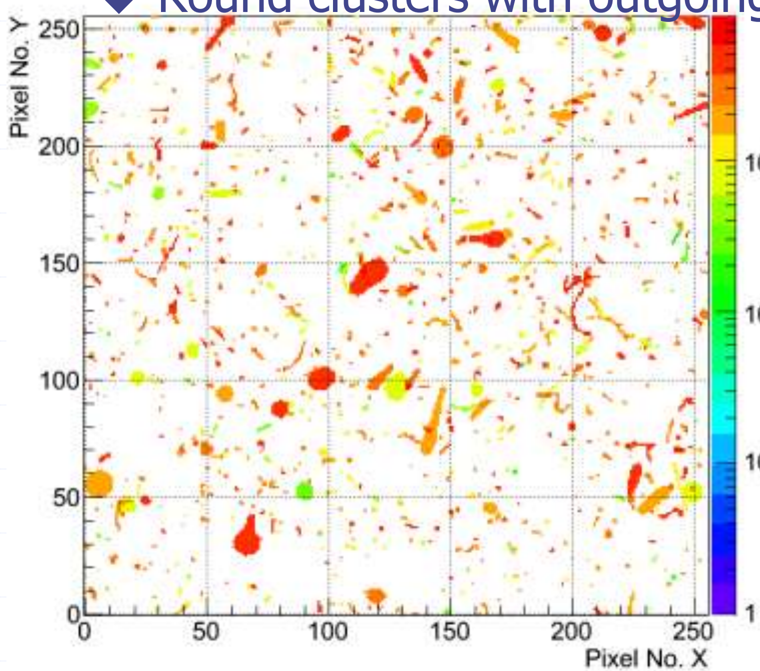
All types of clusters in this energy region integral picture (1000 events were considered)



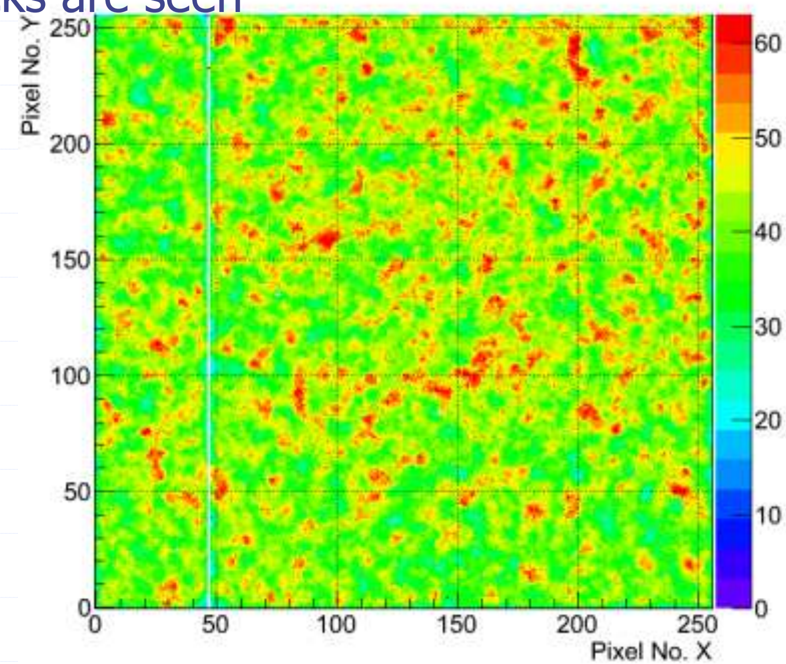
Heavy tracks and heavy blobs in this energy region (full statistics - 93227 events were found)

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)

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Response of Timepix: Energy region 300 MeV +

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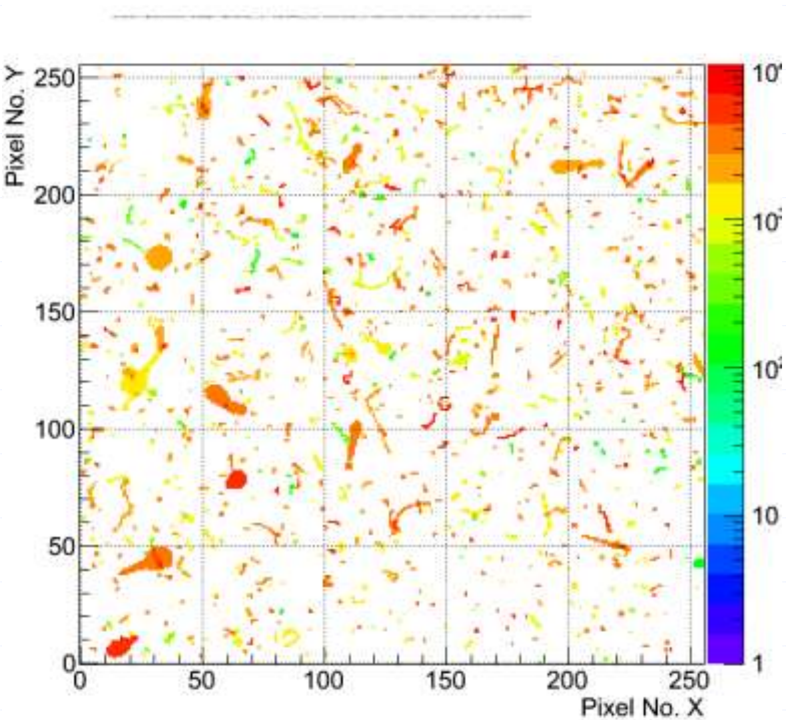
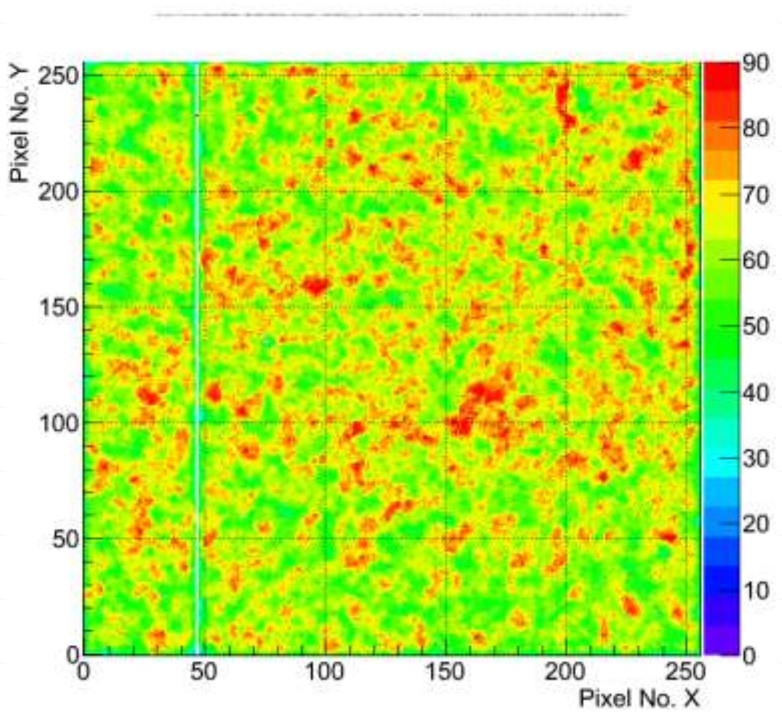
- HETP nearly equally distributed below all regions



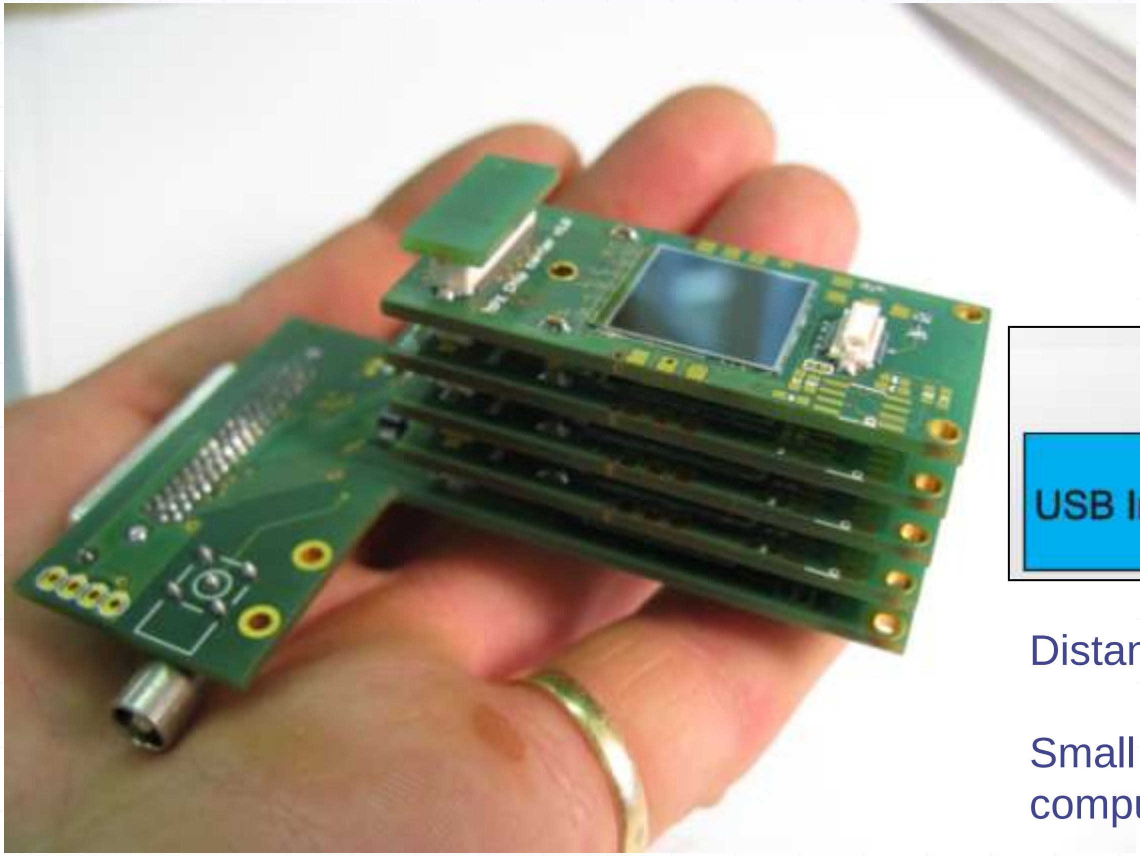
All types of clusters in this energy region integral picture (1000 events were considered)

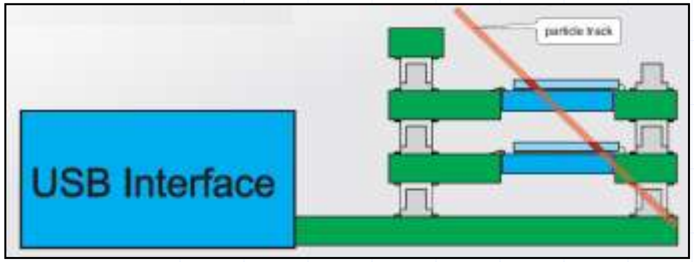


Heavy tracks and heavy blobs in this energy region (full statistics - 29634 events were found)

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

Medical application:
Hadron therapy - Experimental setup

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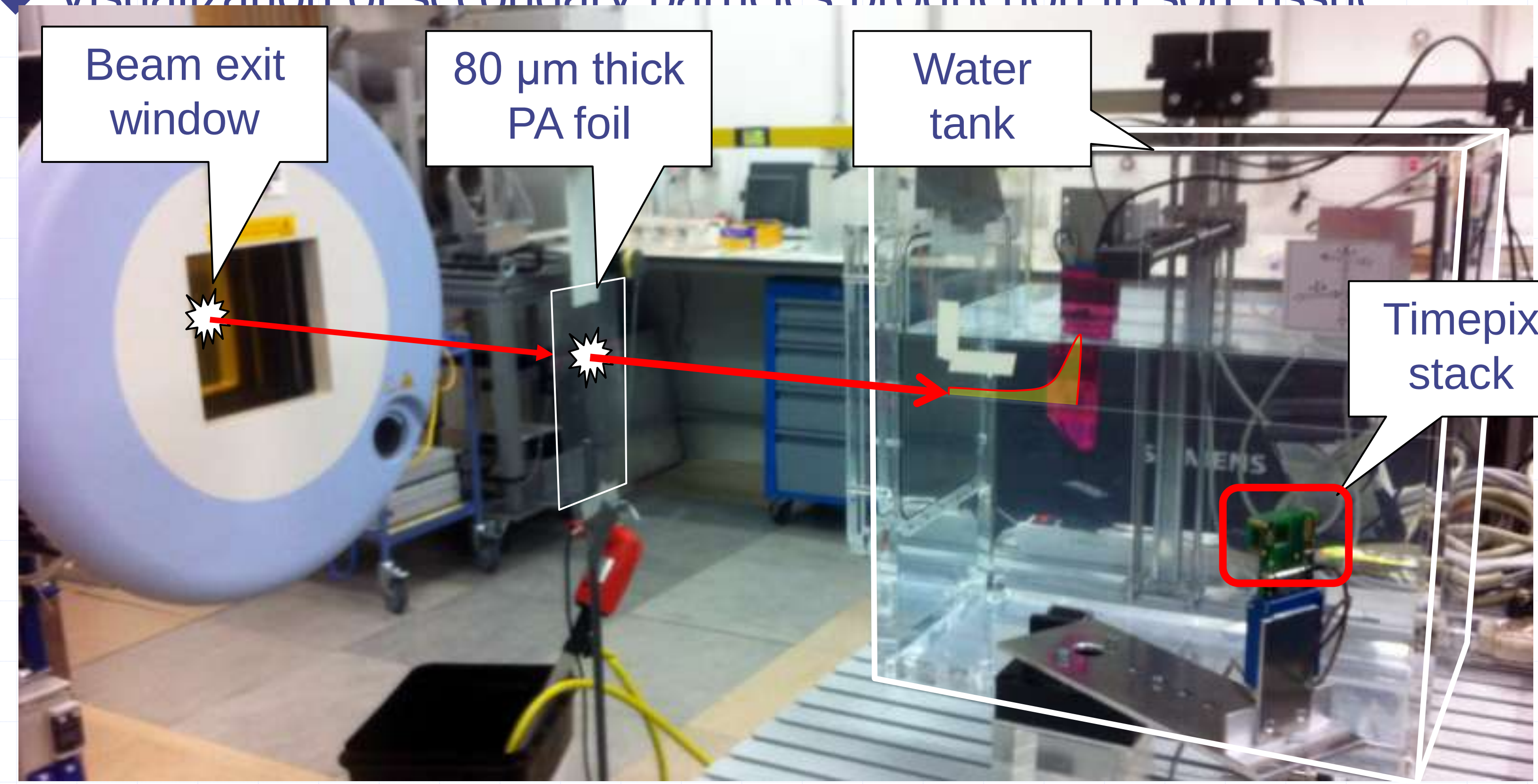
Czech Technical University in Prague

- Visualization of secondary particles production in soft tissue



Medical application:

Hadron therapy - Beam line can be imaged

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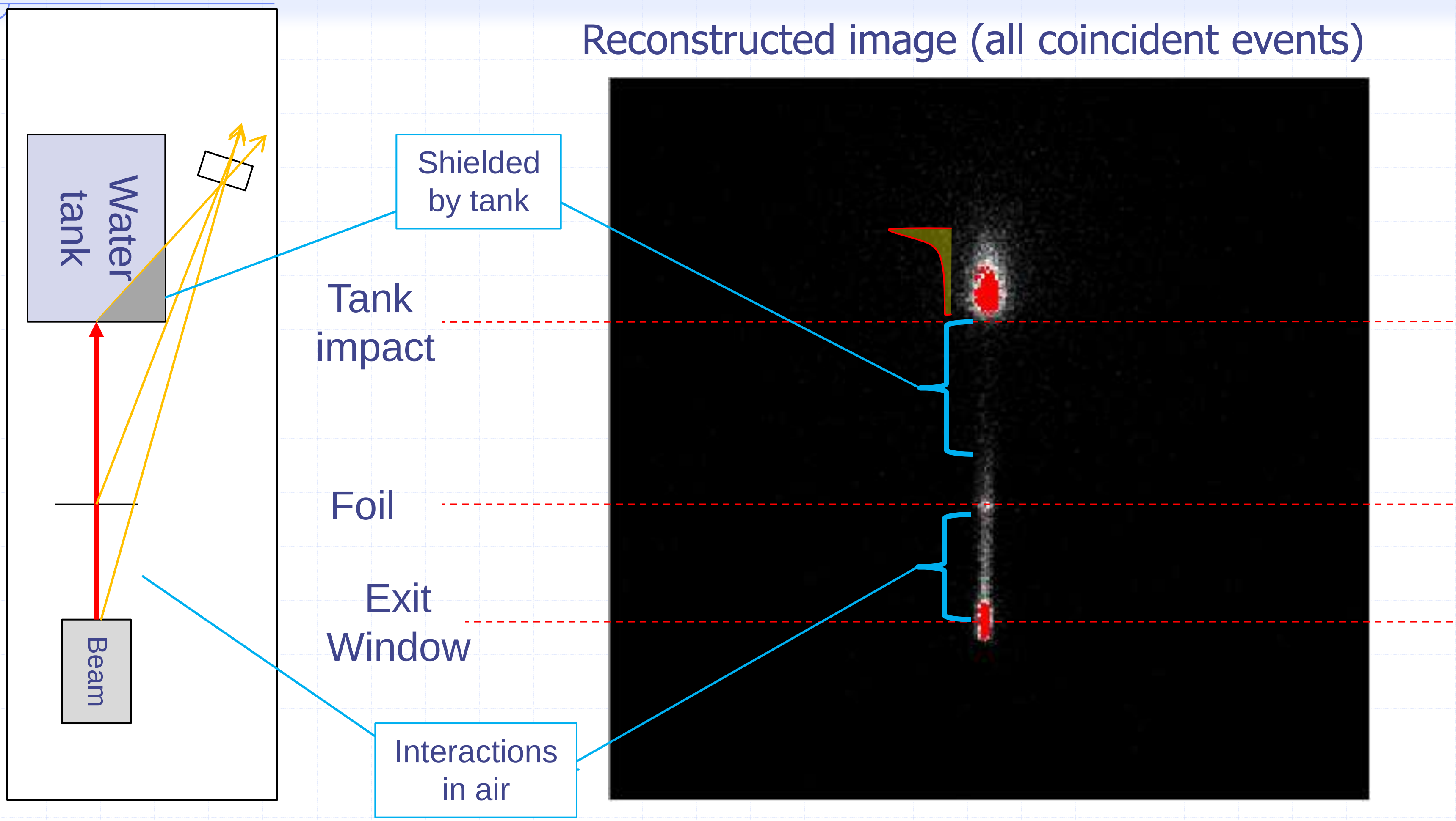

Single ^{8}He ion decay sequence recorded by Timepix

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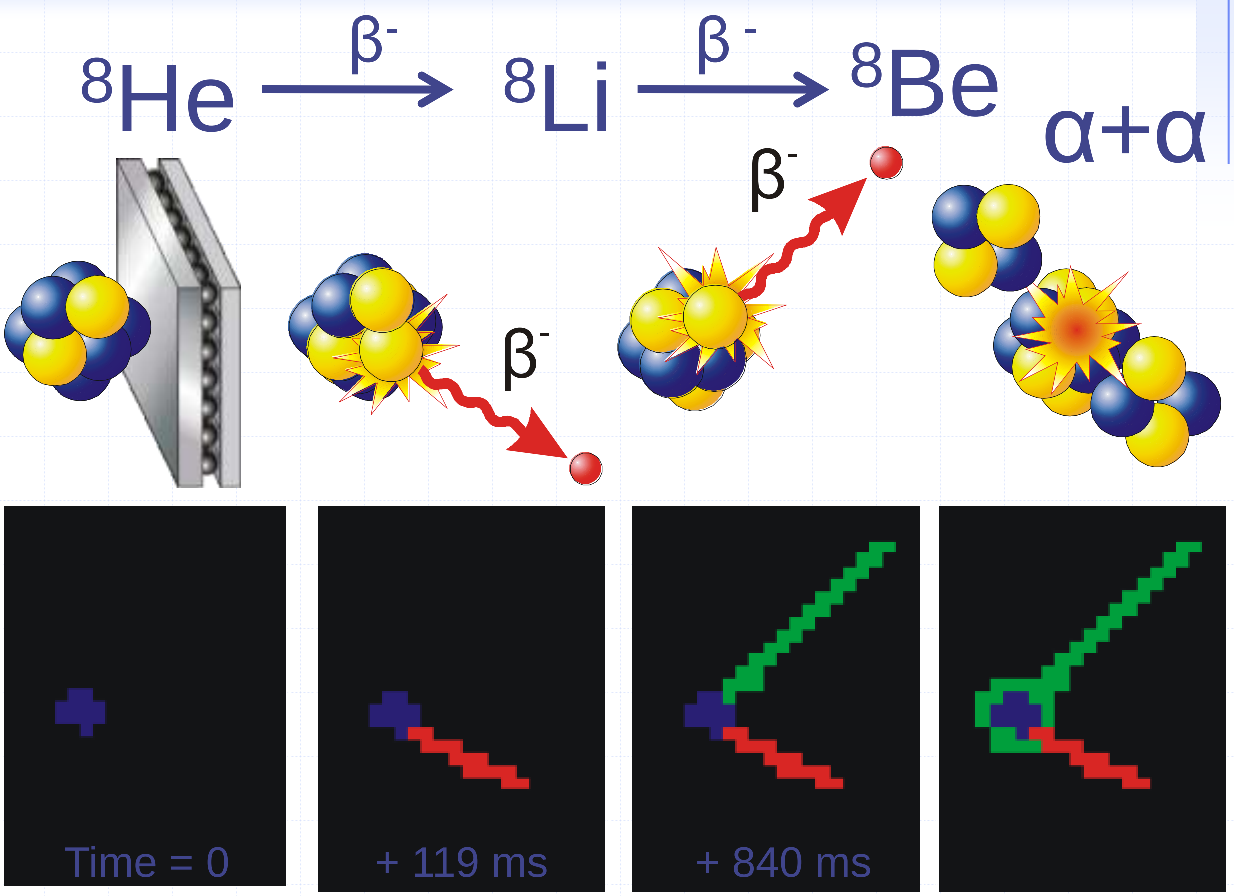
Ion hits the Timepix

First β-decay

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



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

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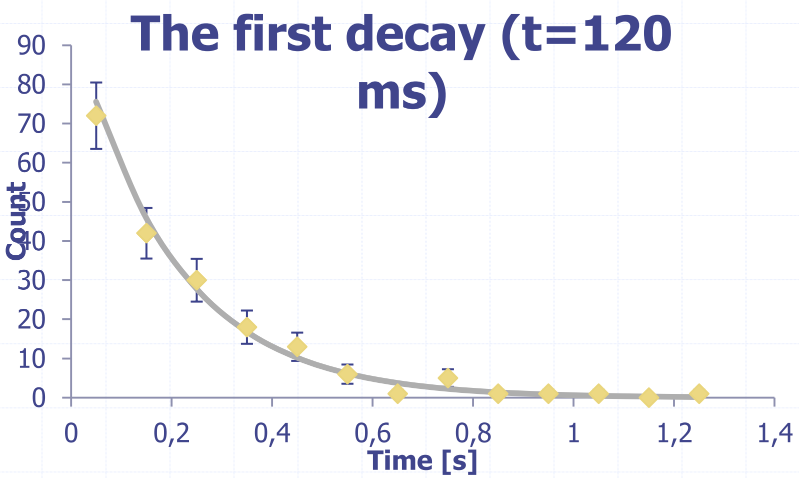

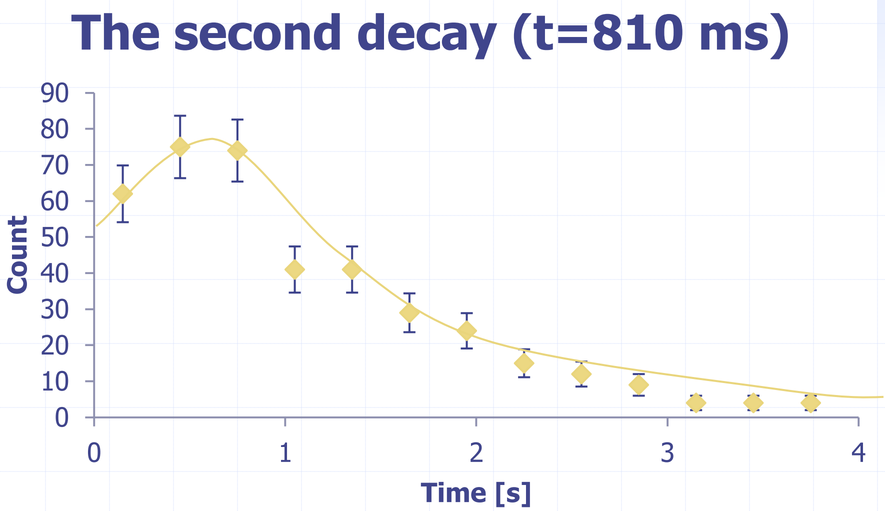

Time and spatial coincidence technique permits:
- observation and measurement of decay of individual nucleus
- in range from microseconds to seconds (and longer).

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

Dosimetry in space on ISS

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

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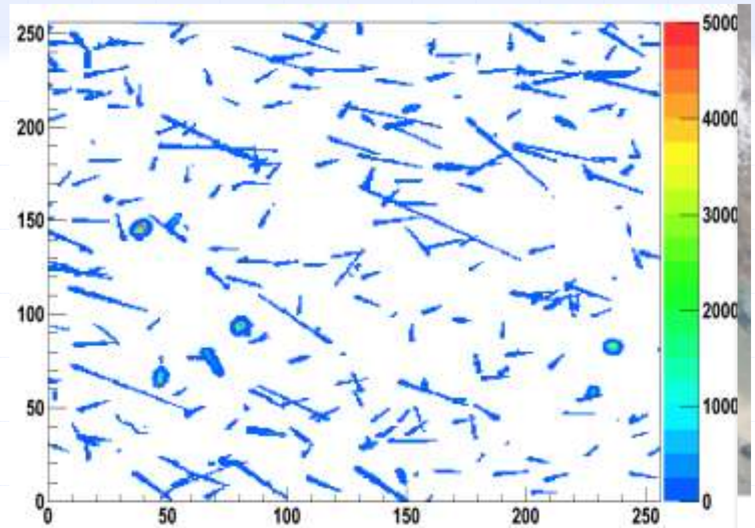

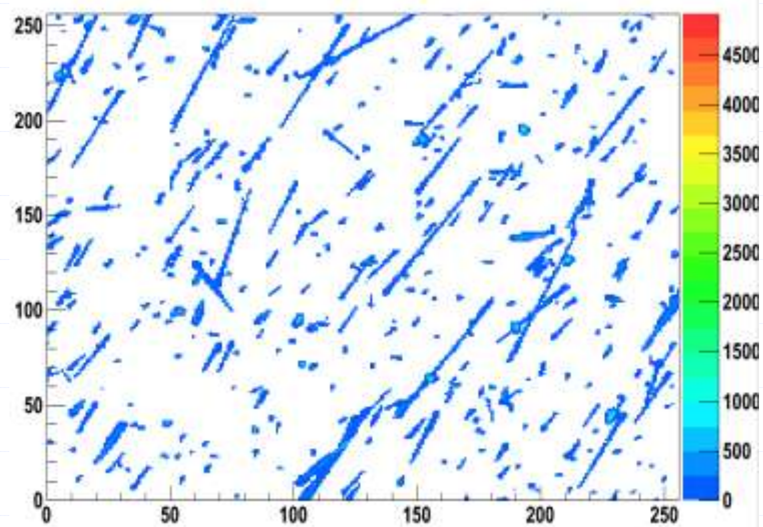

Timepix device for space applications

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.

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Dosimetry in space:
SATRAM – ESA Proba-V satellite

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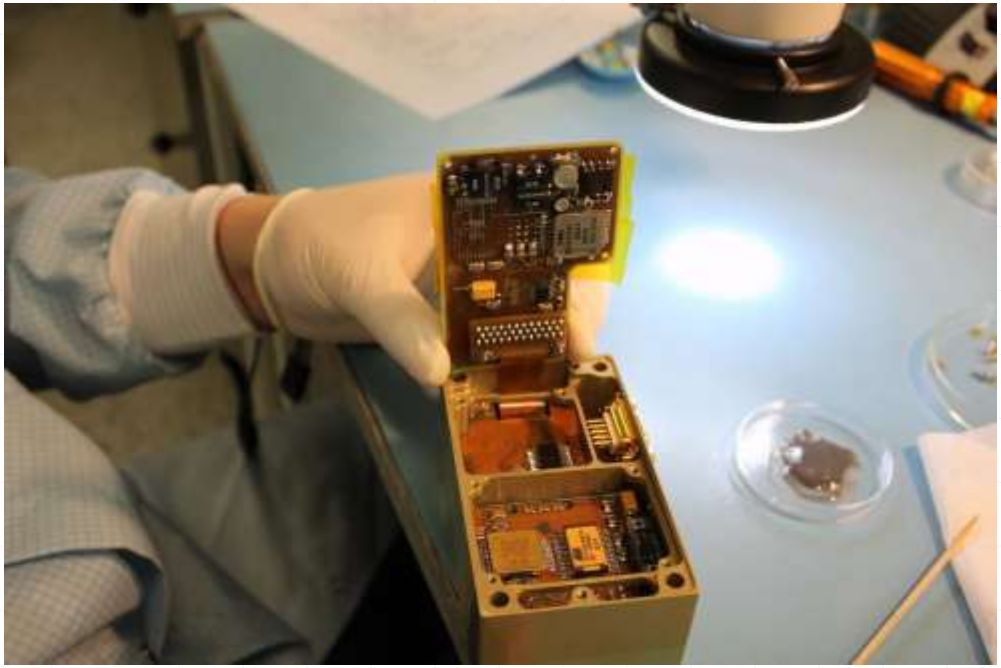
Czech Technical University in Prague

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

- Altitude ~ 800 km
- Timepix for the first time outside in the space
- Launched last week!



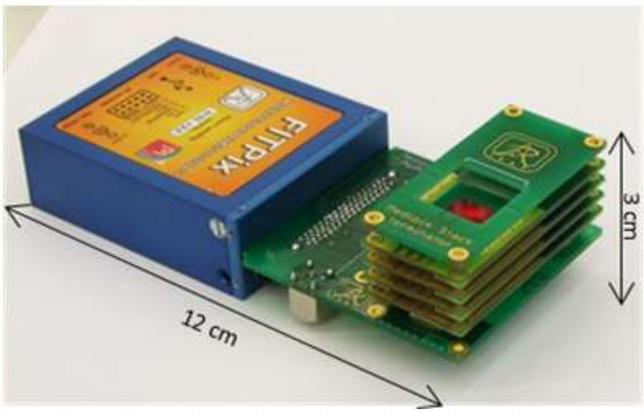
proba VEGETATION

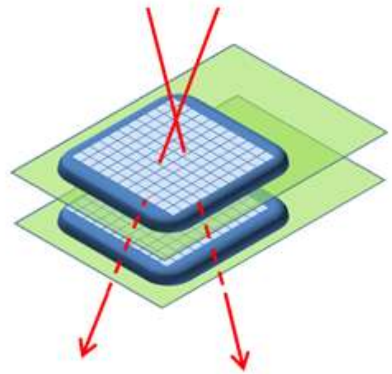
RISESAT

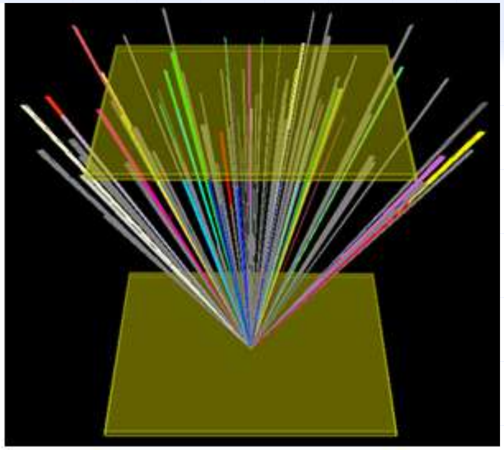
Rapid International Experimental Satellite
Timepix particle μ-tracker particle telescope

東北大学
TOHOKU UNIVERSITY

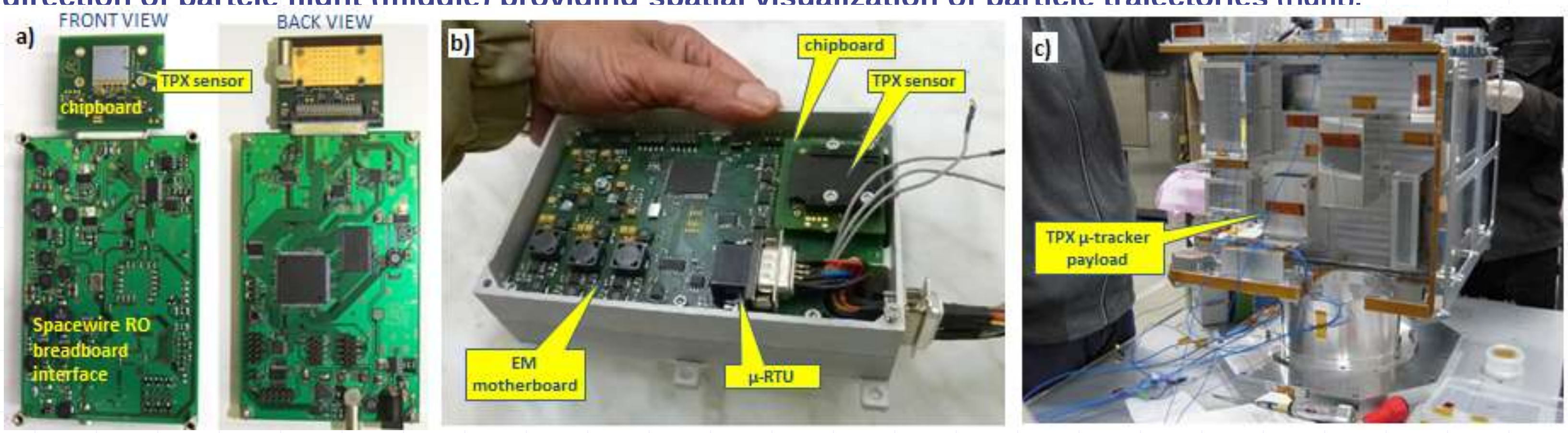
Institute of Experimental and Applied Physics
Czech Technical University in Prague







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).

Summary

- The capability of the Medipix/Timepix devices for ***high resolution submicrometric radiography and tomography*** with X-rays and neutrons has been demonstrated.
- It has been also shown, that ***Timepix device operating in tracking mode represents high resolution position sensitive and spectroscopic 3D detector, which enables a full visualization of individual ionizing particle tracks in solid state***.
- ***Protons with precisely determined tracks represent microprobes to study radiation defects and inhomogeneities of sensors.*** What about use of such ***„proton microscopy“ for SEE studies?***
- For an effective utilization of pixel detectors in tracking mode:

  - the ***Fast readout*** (USB 2.0 based interface with 100-800 s^{-1} frame rates is available);

  - ***Off-line single event analysis*** (for pattern recognition and analysis of every track to get its coordinates and energy).
- A portable ***high resolution camera for energy sensitive detection of*** single X- photons, neutrons, protons and any other energetic charged particles has appeared. The camera is effectively used in many physics experiments and for space research (ESA, NASA) as well.