Journey with hybrid pixel detectors from biomedical imaging through particle physics up to extraterrestrial space

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on behalf of Medipix2/3/4 collaborations

Lecture outline

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- To remind briefly the development of ***Medipix/Timepix hybrid semiconductor pixel detectors*** and methodology of their use for ***high resolution (micrometric and nearly nanometric) imaging by means of X-rays and neutrons***.
- To document development of Timepix pixel detector for ***visualisation of individual particle tracks in solid state*** similarly to nuclear emulsions, cloud chambers, bubble chamber, Micro-Pattern Gaseous Detectors etc.
- To present some results of ***microscopic investigation of interactions of charged particles and neutrons in silicon sensors*** in a broad energy range (500 keV up to GeV region) by means of ***ToF technique.***
- To demonstrate broad ***applications of Timepix detectors for measurements of composition and spectral characteristics of mixed radiation fields around physics experiments (ATLAS, MoEDAL) and in space.***
- To reveal ***the latest achievement in 3D high resolution particle tracking and ToF applications of Timepix3 detectors for particle accelerator experiments, hadron therapy and astroparticle physics***

Medipix/Timepix hybrid pixel detector device

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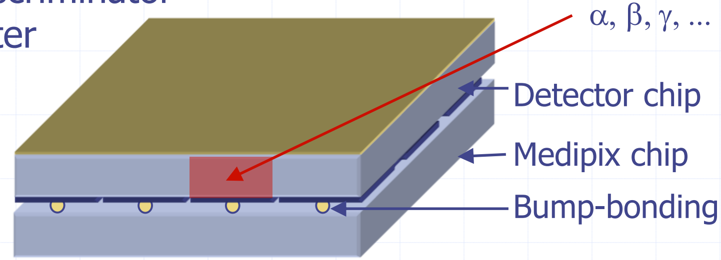
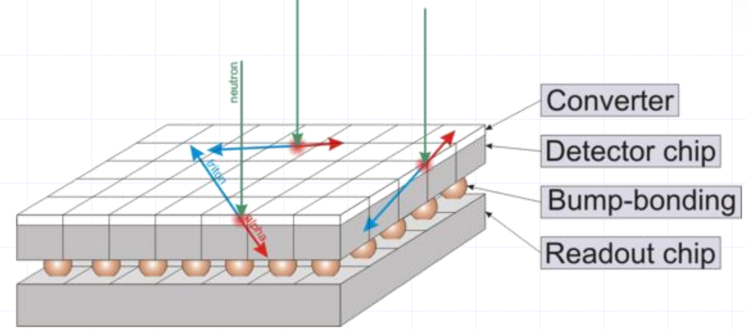
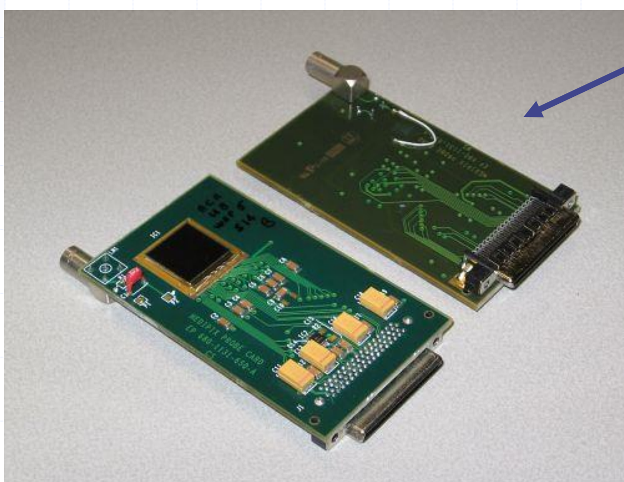
- Planar pixellated detector (Si, GaAs, CdTe, thickness: 300/700/1000μm)
- Bump-bonded to Medipix readout chip containing in each pixel cell:
  - amplifier,
  - double discriminator
  - and counter

- 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

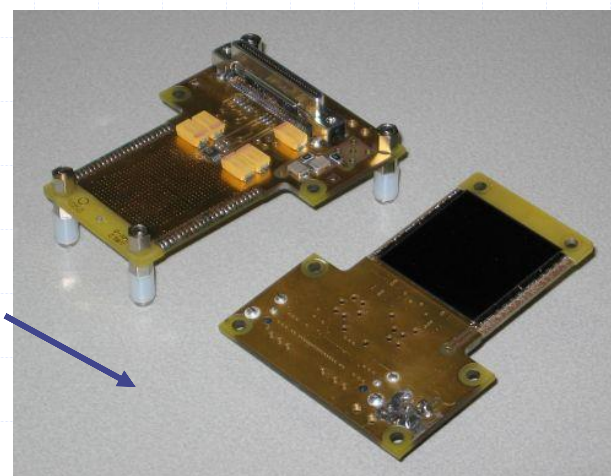






Medipix2/Timepix
Pixels: 256 x 256
Pixel size: 55 x 55 μm^2
Area: 1.5 x 1.5 cm^2

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

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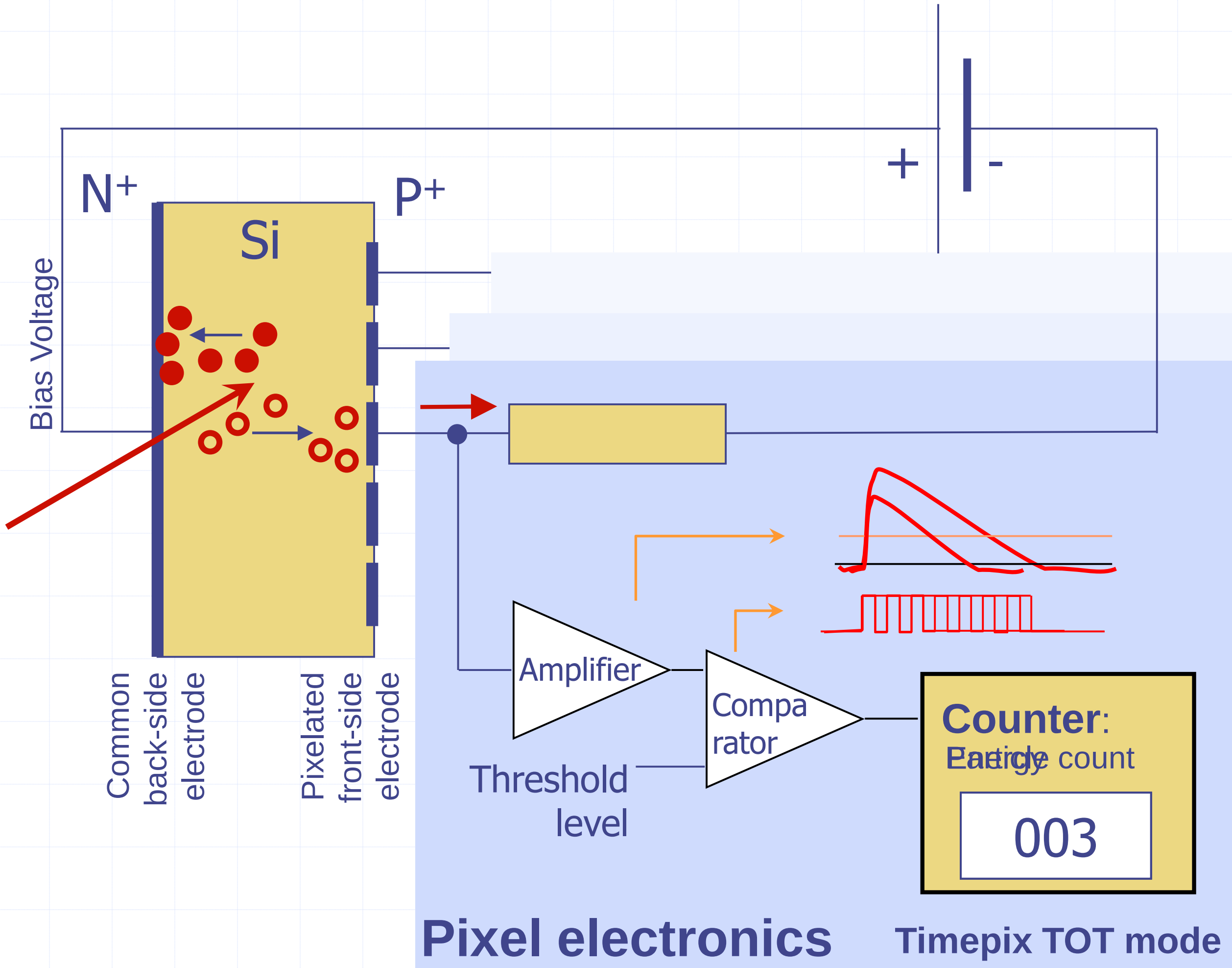

Threshold level above electronic noise
⇒ **No false counting**.

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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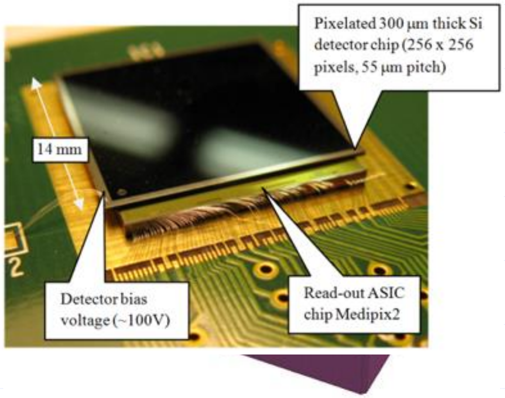
Particle counting pixel detectors

Pilatus - PSI

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

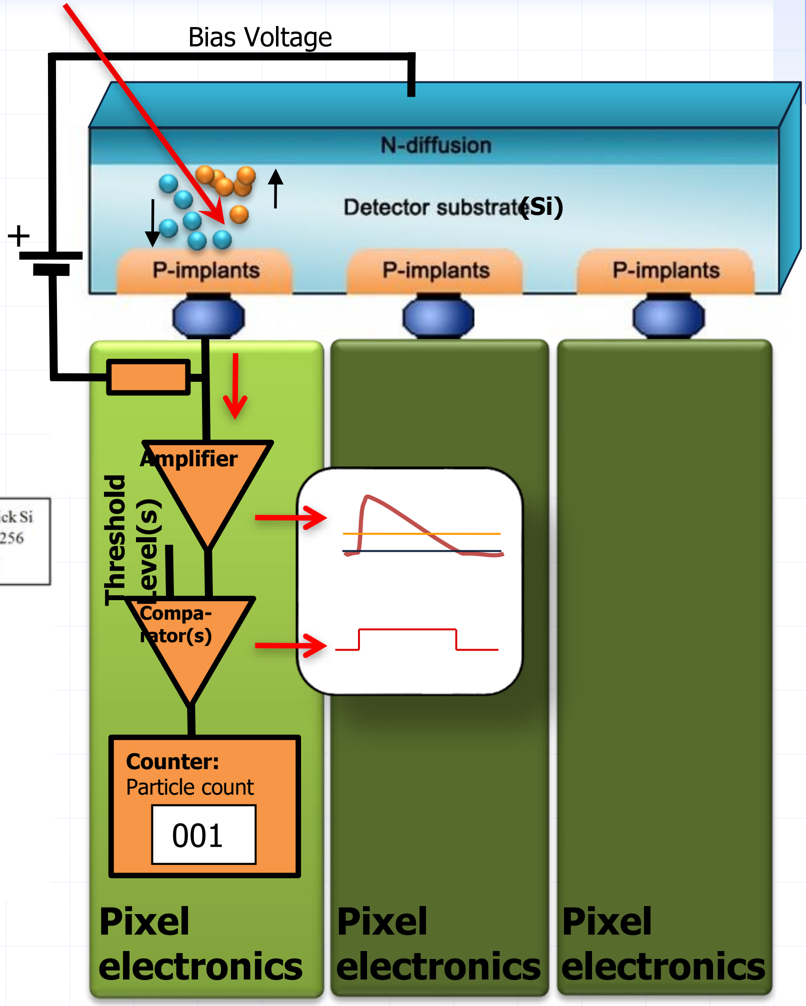
Medipix2 – CERN

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



Timepix - CERN

- Time stamp
- ToT mode



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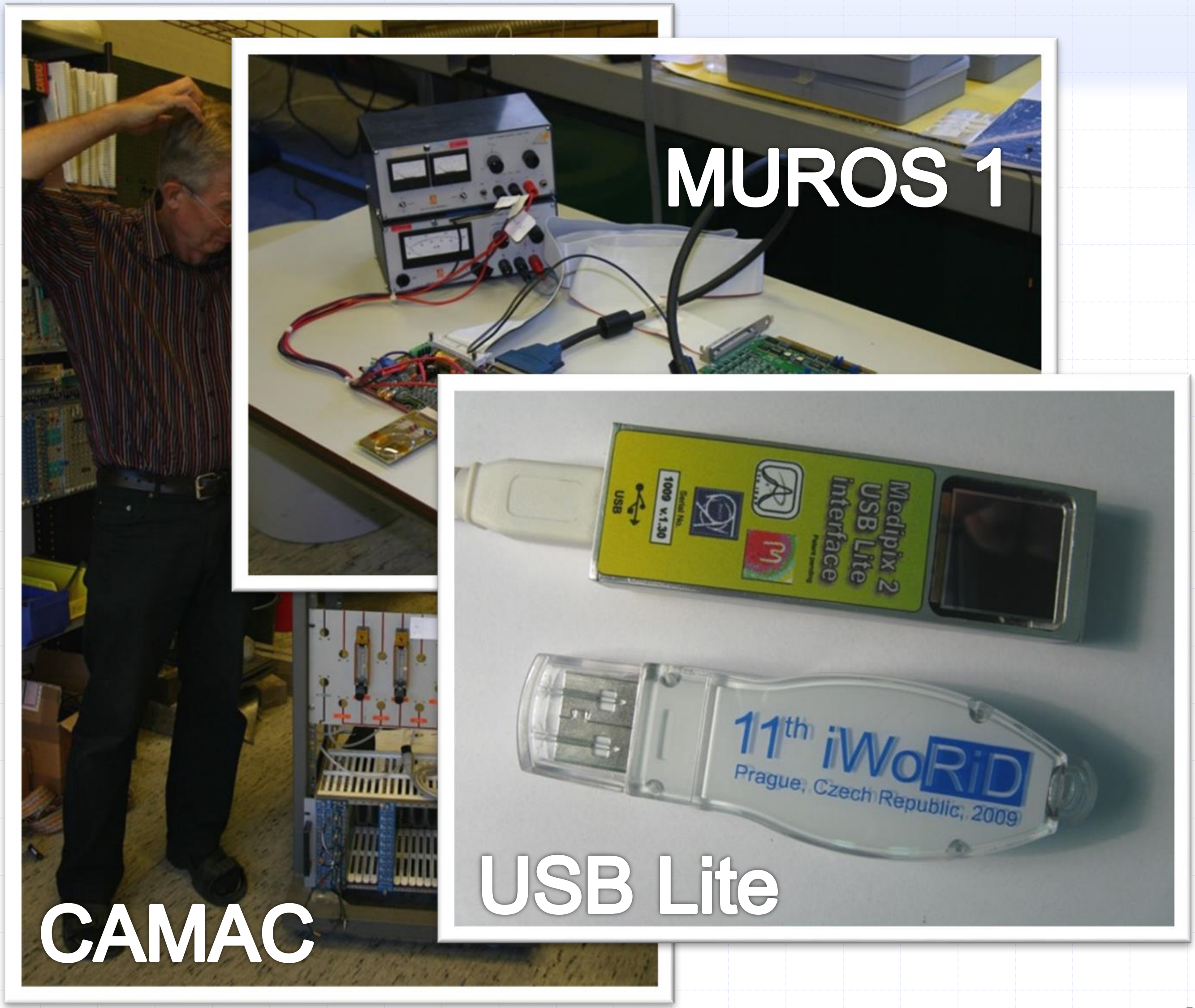
Miniaturization of R/O interfaces for Medipix/Timepix/Timepix3 devices

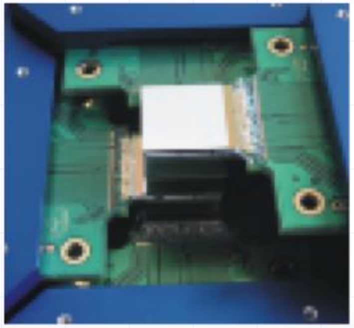
HISTORY from 1999:

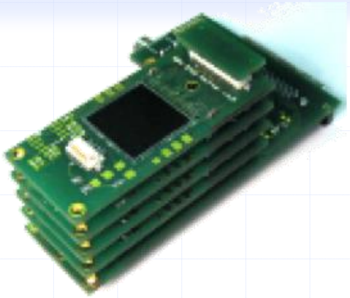
- CAMAC/VME
- MUROS (Nikhef)
- USB1
- USB Lite
- MARS (NZ)
- USB2
- TPX Lite
- Fitpix
- Raspix
- RAL
- ILL
- DESY
- Spidr
- Katrin
- Advacam
- ----

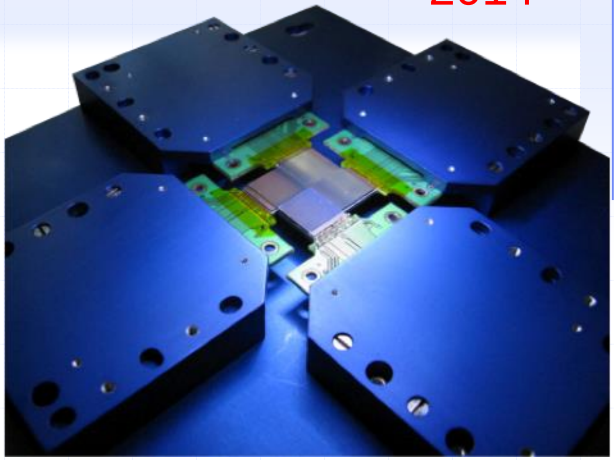


Timepix based devices developed and tested in IEAP CTU

2014





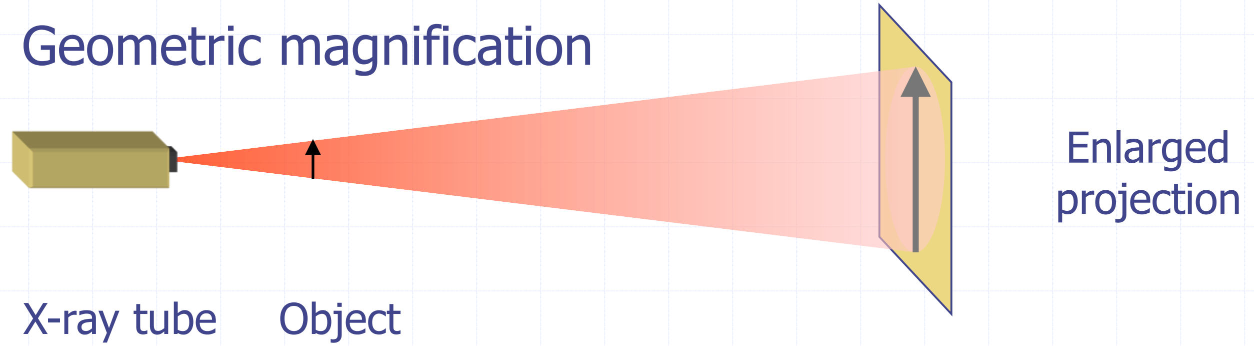


High resolution X-ray radiography

Experimental setup

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)



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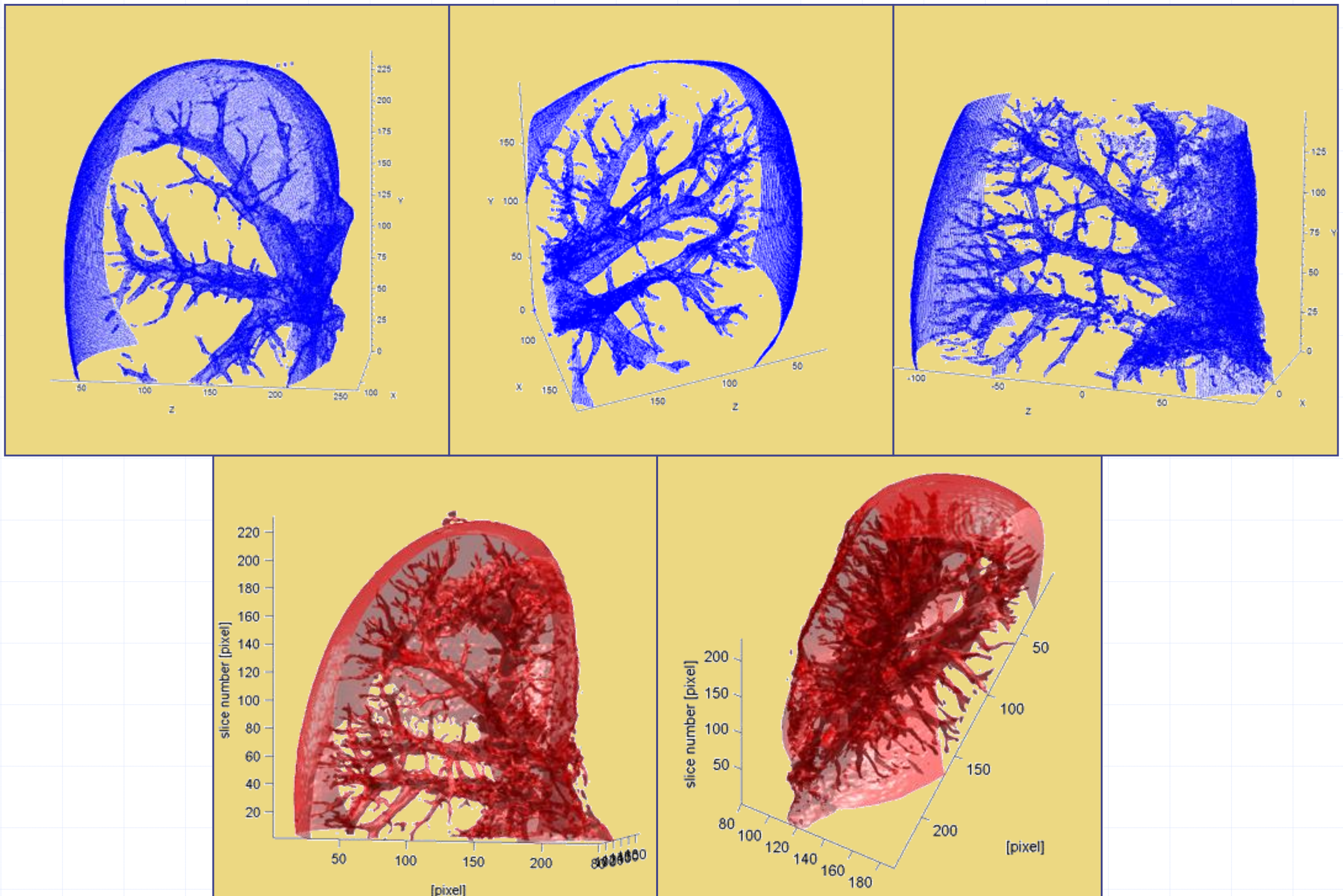
Soft tissue X-ray imaging

Mouse Kidney Tomography

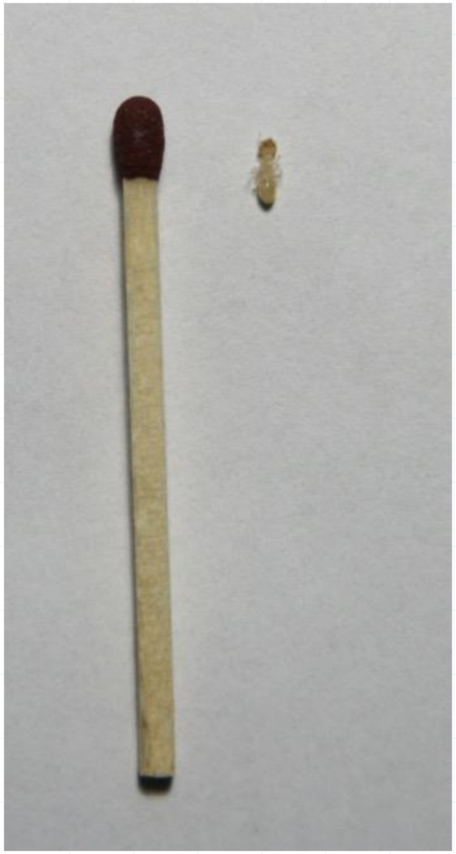
2006

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



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

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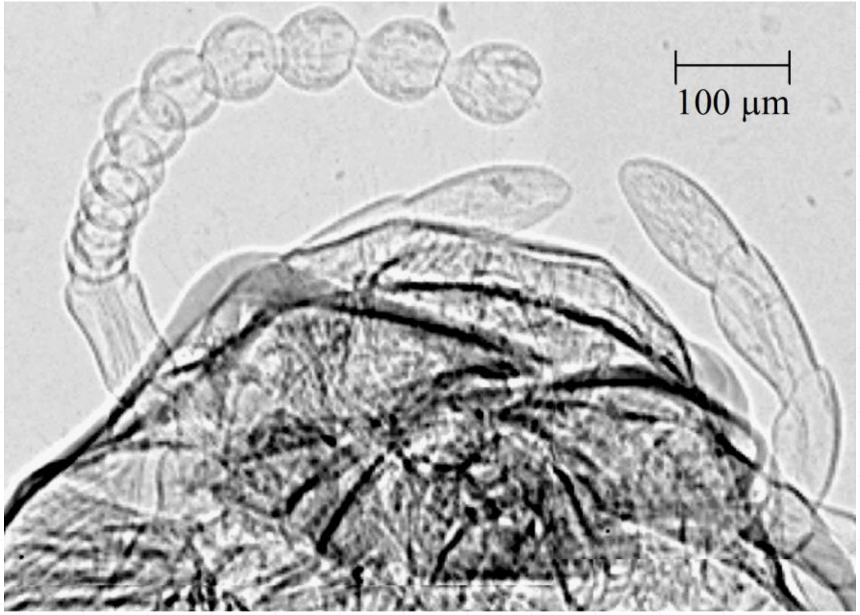
X-ray transmission image of termite worker body (left) and detail of its head (bottom). Even fine internal structure of the antennae is recognized.

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



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High resolution X-ray radiography:
Imaging of Living Termites

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:

Leaf Miner story

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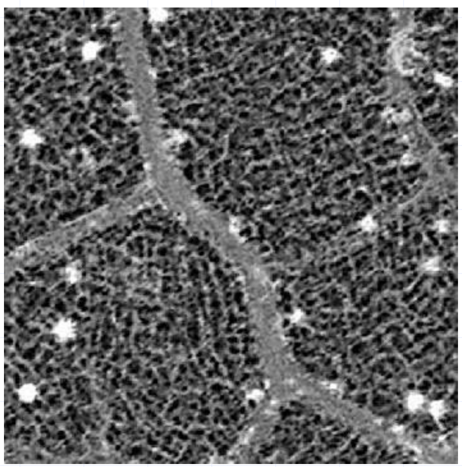
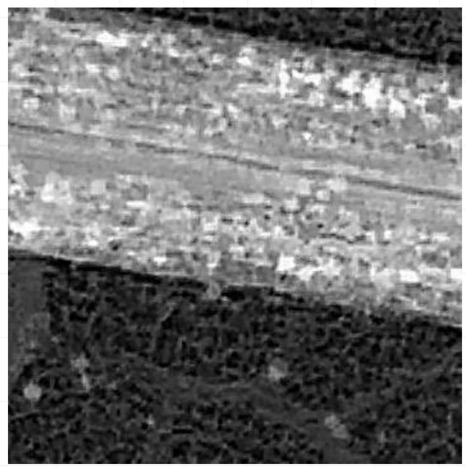
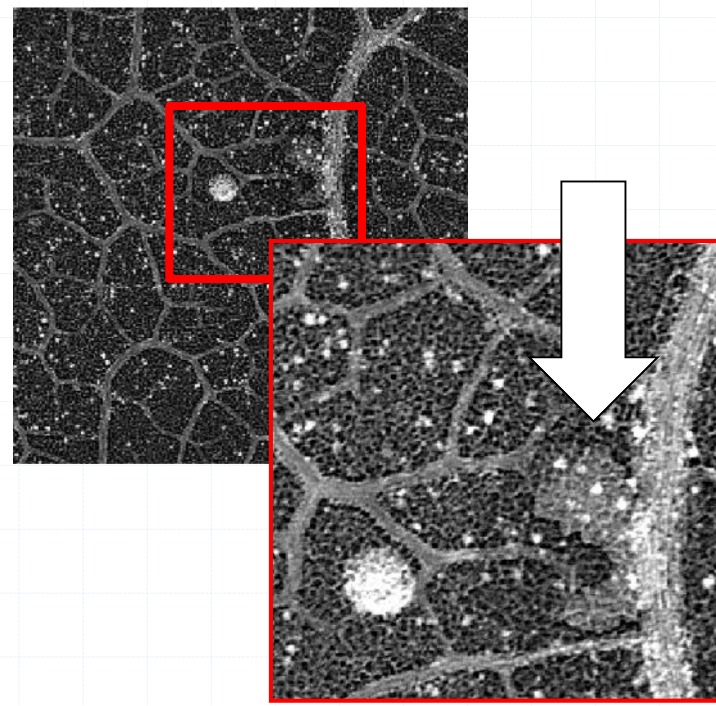
Leaf miner (*Cameraria ohridella*) - small moth. In larvae stadium it lives inside of chestnut tree leafs making "mines" and causing serious problems to the tree. Indication: chestnut leafs get brown, dry and fall down early.

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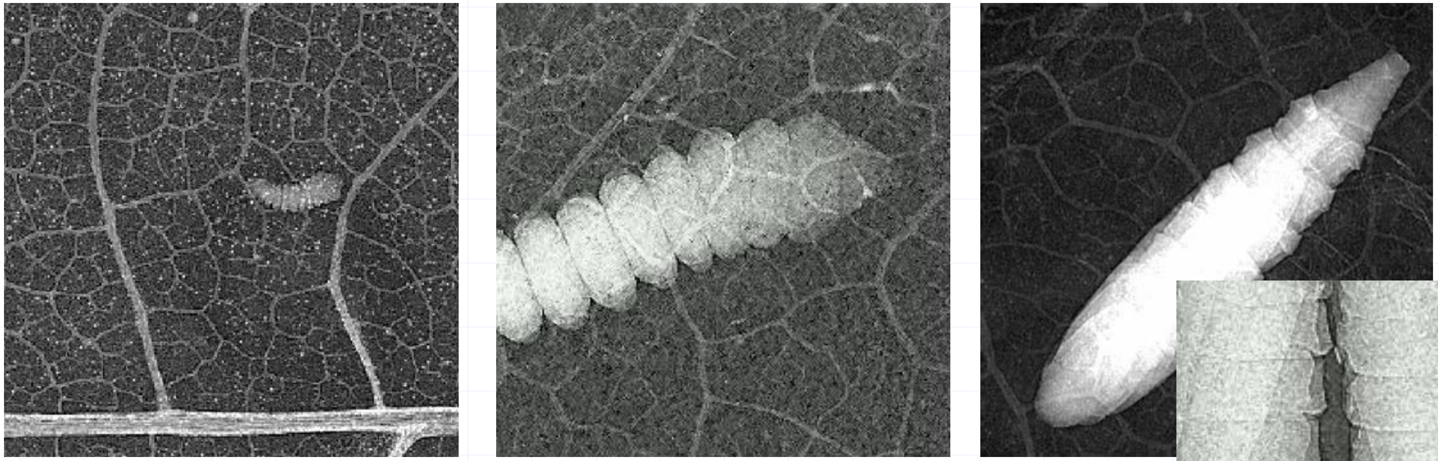
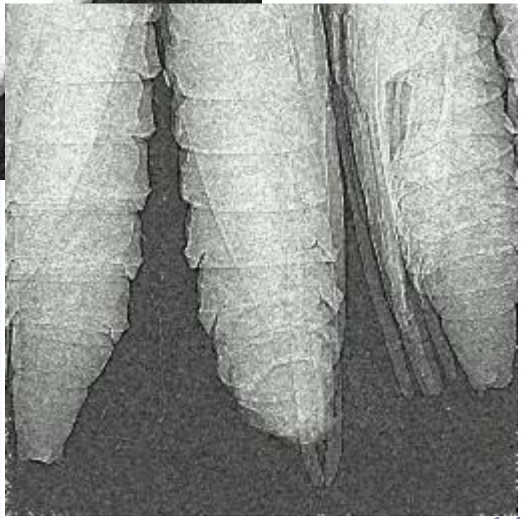
Worms are growing up and after three feeding instars larvae build-up a silken cocoon (pupae)





Several collected pupas

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

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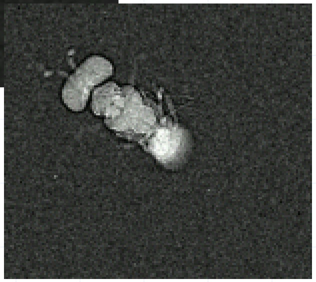
The best cure: natural enemy (parasitic wasp)

Certain small wasps can put eggs into leaf miner pupas

Parasite inside of parasite:



Parasite kills the pupa and leaves it as adult wasp

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Attenuation coefficients for X-rays

Attenuation coefficients with X-ray [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8	8	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.

Attenuation coefficients for 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

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

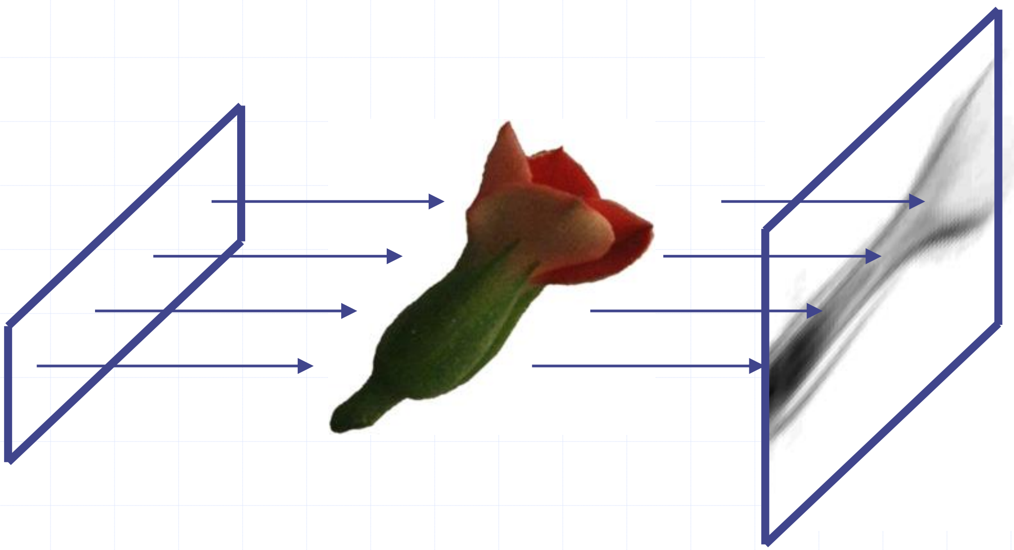
σ-total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.
and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada 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.

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

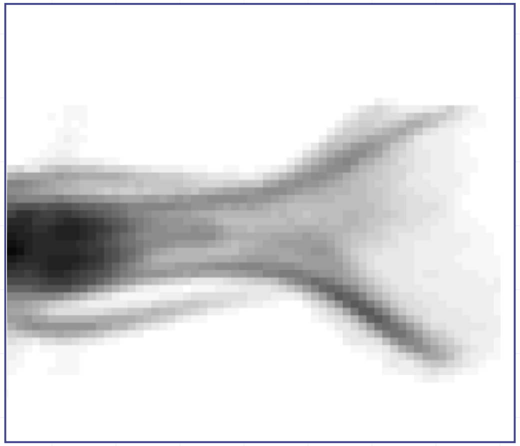
(energetic charged products define interaction with deeply subpixel resolution)



Parallel beam of thermal neutrons

Specimen attenuating the beam

Shadow on detector plane



Neutronogram

Medipix2 with neutron converter: Visualization of explosive encapsulated in a copper cartridge

2004

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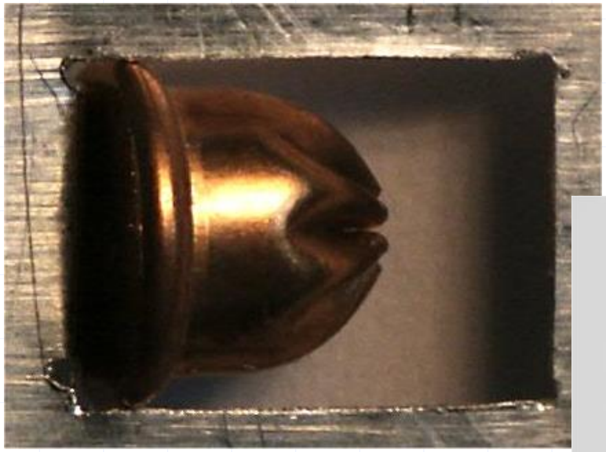
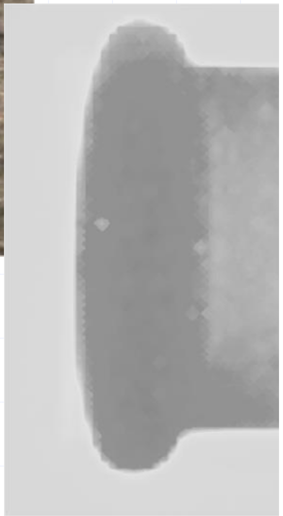
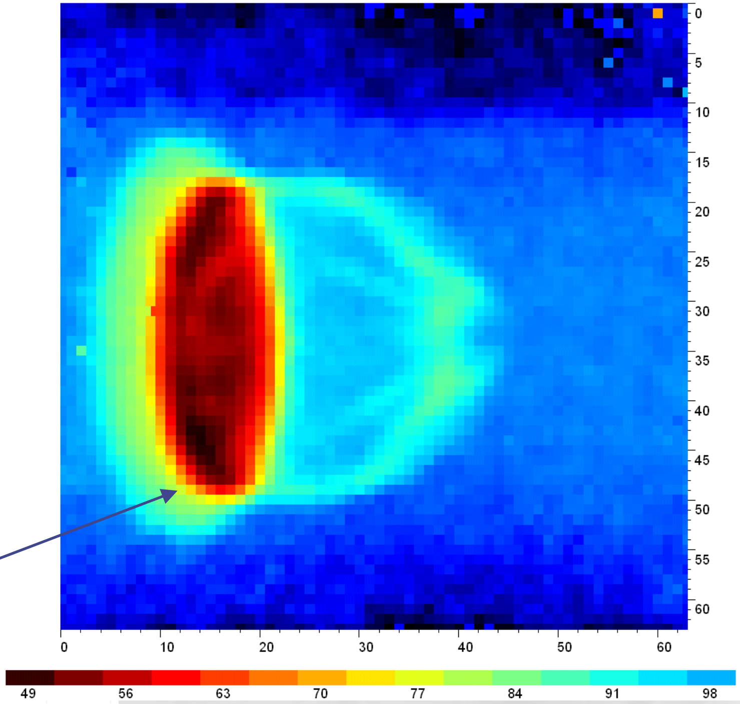
Photography



Blank shell (cartridge)

Roentgenogram

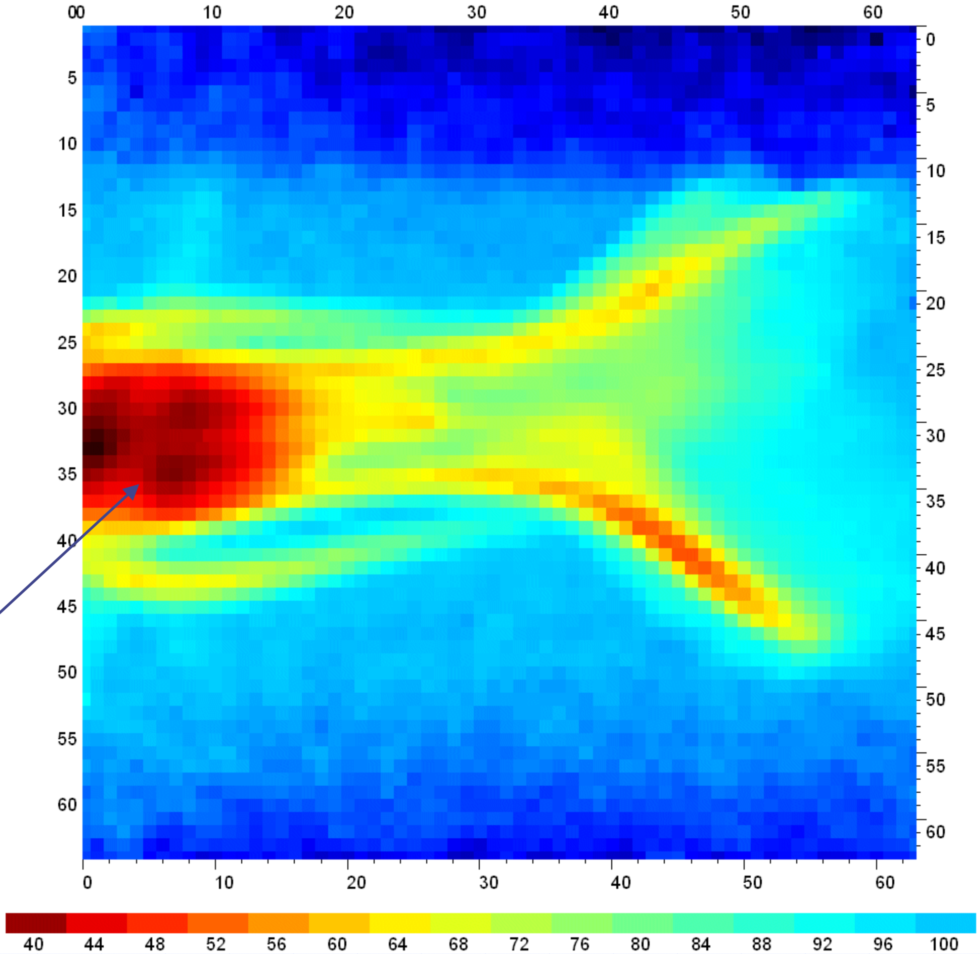




Explosive filling

Flower behind Al plate

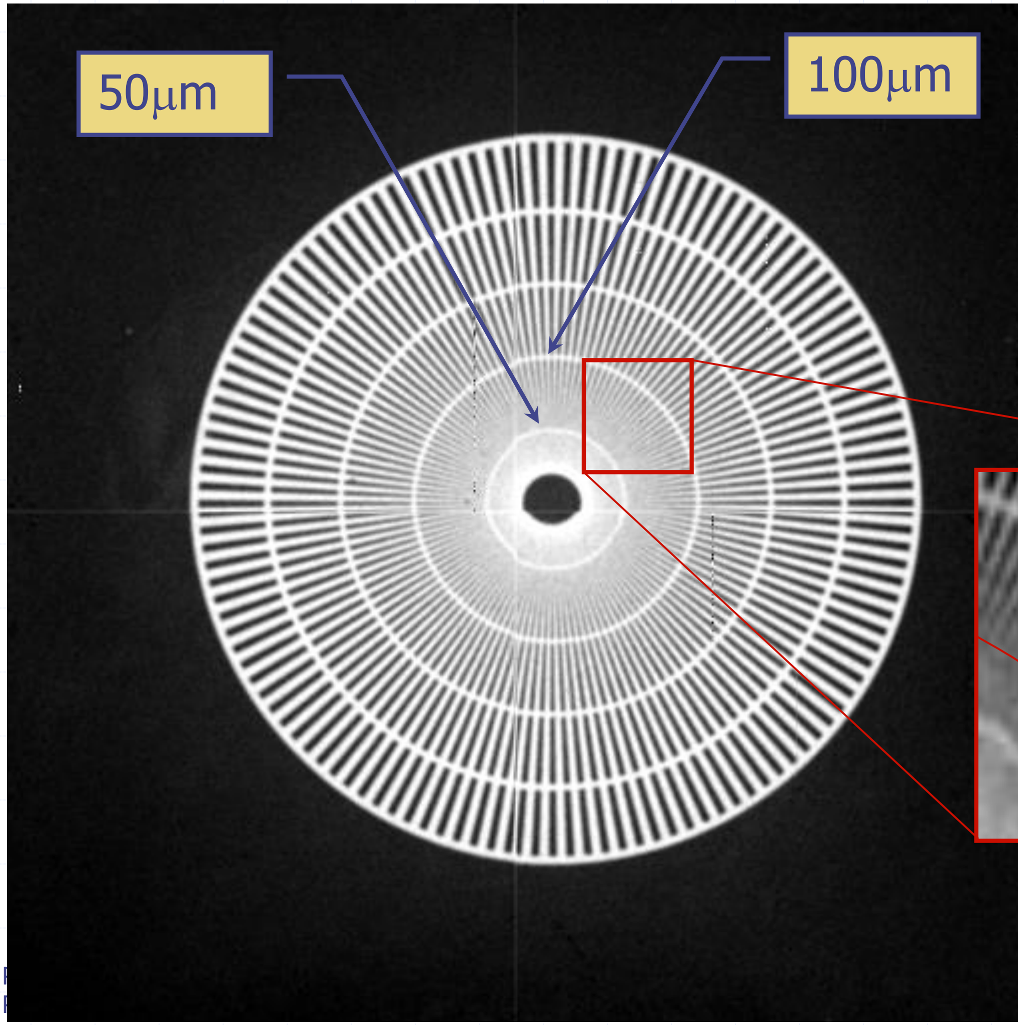
Look through metal with thermal neutron beam at NPI Rez

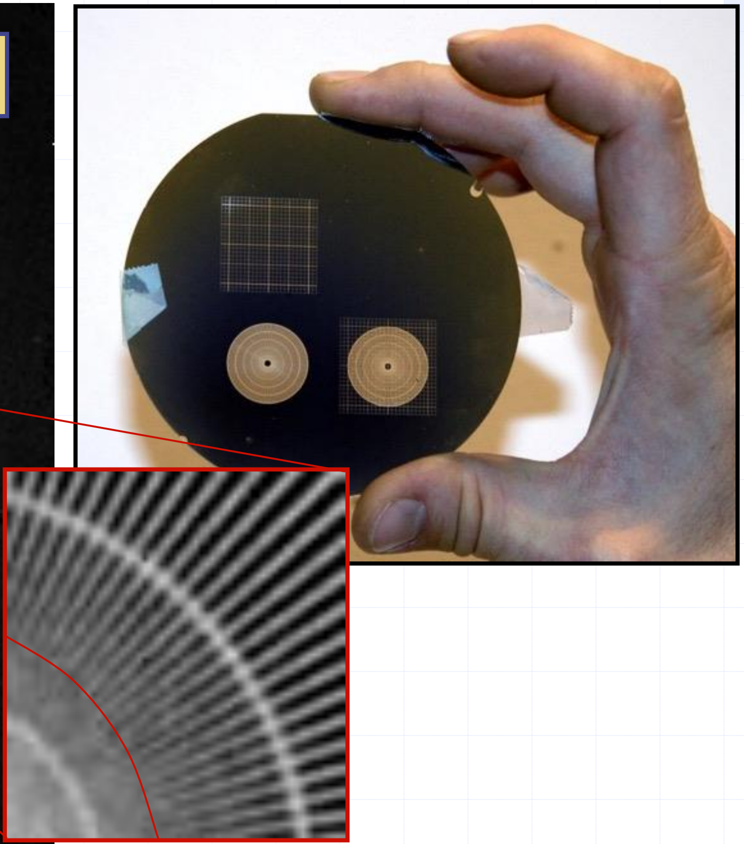


Test of Spatial Resolution

(Medipix2 Quad system and cold neutrons)

2008





=>Resolution about 65μm!

Detail view on conversion layers

added for a neutron detection in mixed radiation fields

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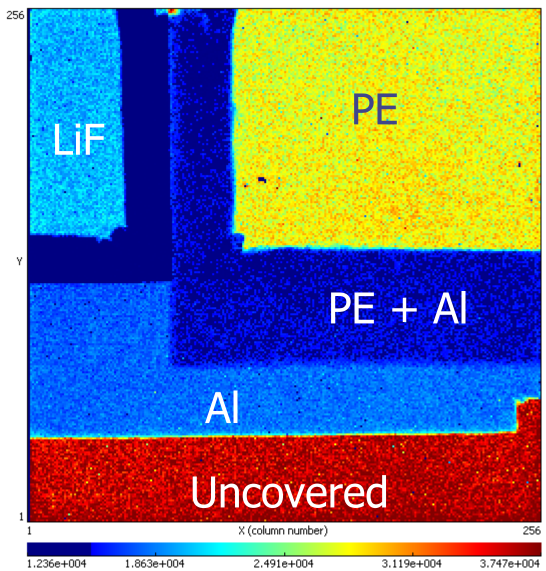
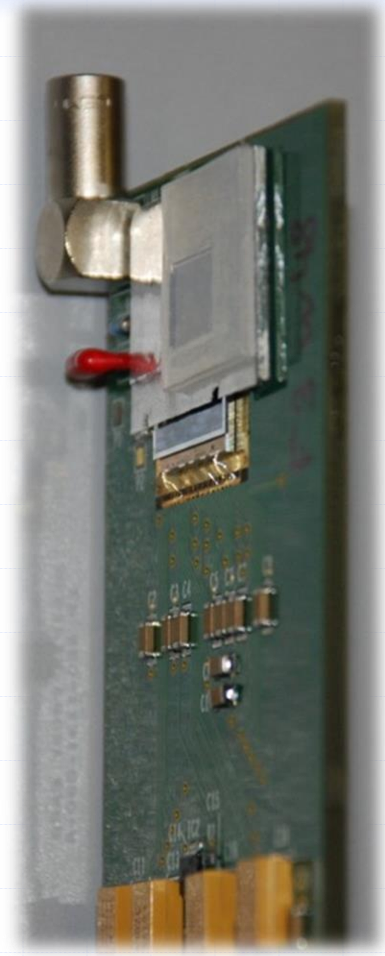
Several different regions:

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





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

2007

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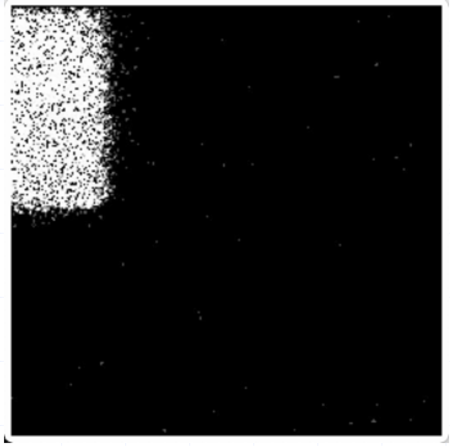
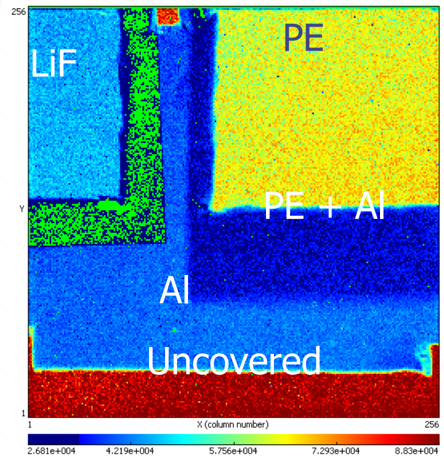
Identification of spectral composition of incoming neutron radiation can be done by comparing responses of different sensitive regions.

Thermal neutrons – 500s





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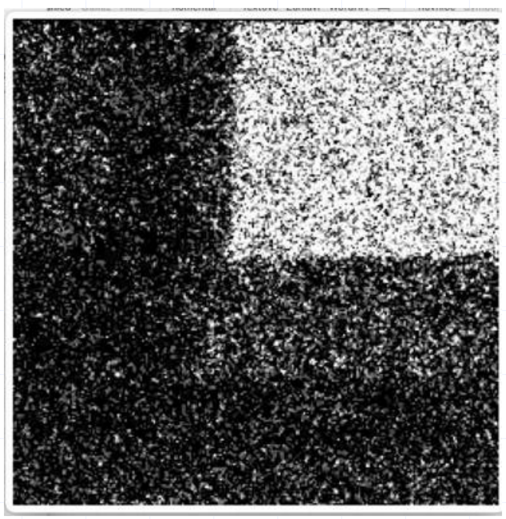
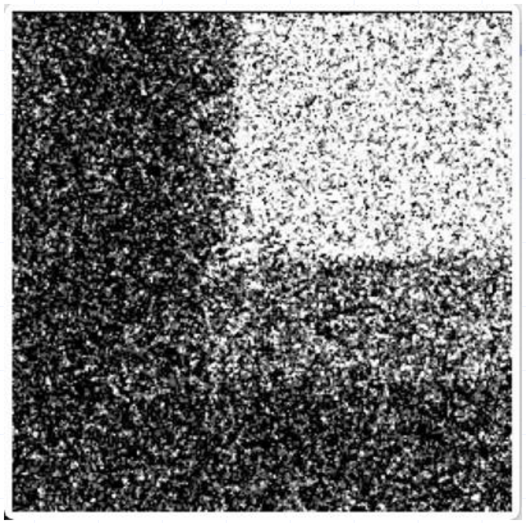
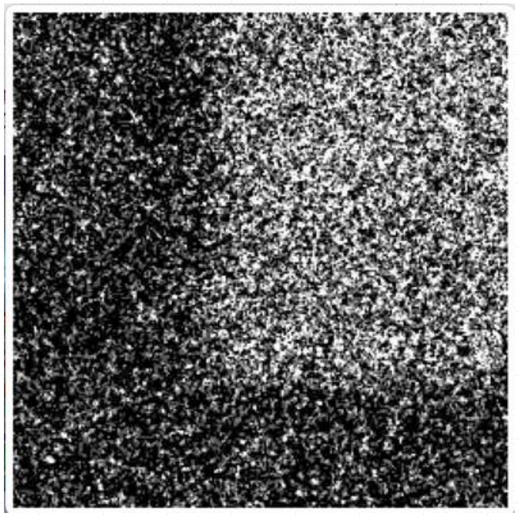


AmBe



17 MeV neutrons at 0º



Typical response of Medipix2/Timepix device to natural background radiation

2005

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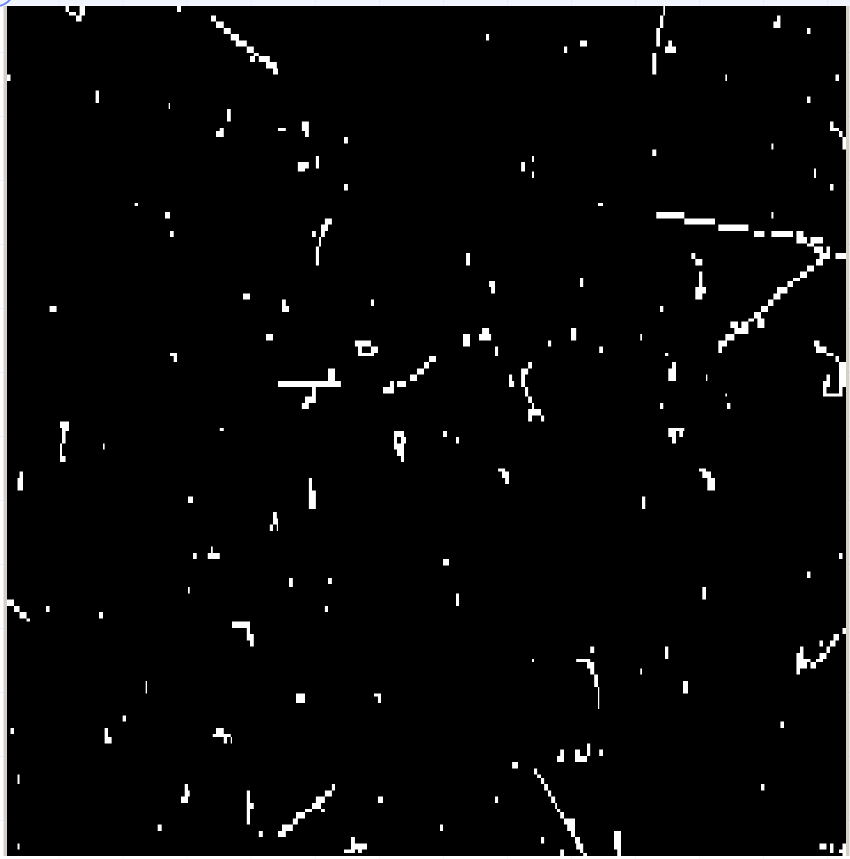

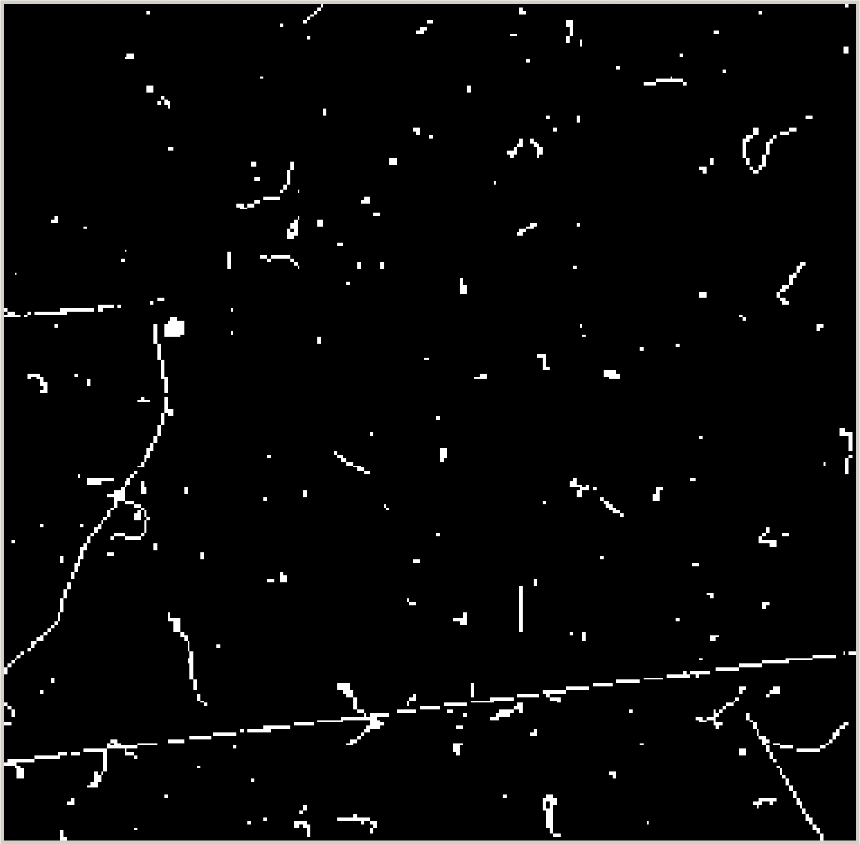

Clearly recognizable tracks and traces of X-rays, electrons generated mostly by gamma rays, alpha particles, muon, including electron-positron pair, … . Muon tracks can be recognized by submicrometric precision.

Tracking mode of pixel detector operation

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

2005-6

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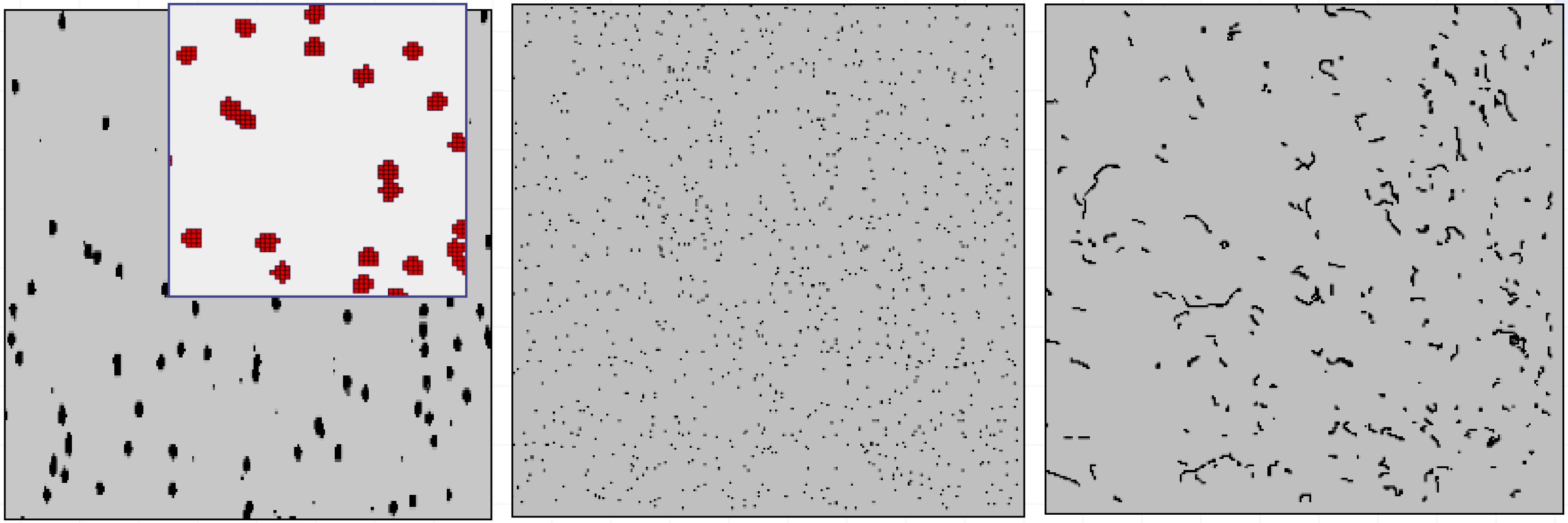

- ^{241}Am alpha source gives clusters of ~5x5 pixels measured with the MEDIPIX-USB device and a 300 μm thick silicon sensor. The clusters are shown in detail in the inlet. The cluster sizes depend on particle energy and threshold setting.
- Signature of X-rays from a ^{55}Fe X-ray source. Photons yield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

Charge sharing effect - clusters

Cluster area brings analog information on energy deposited by a radiation quantum in the sensor

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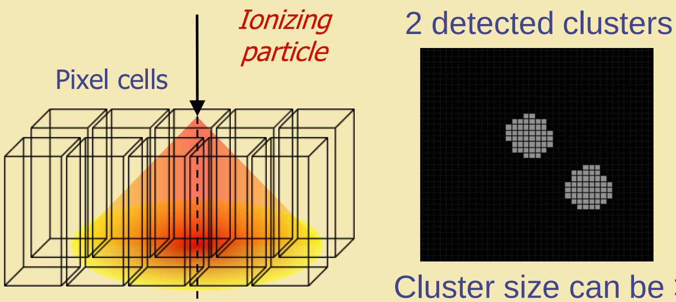
2005-6

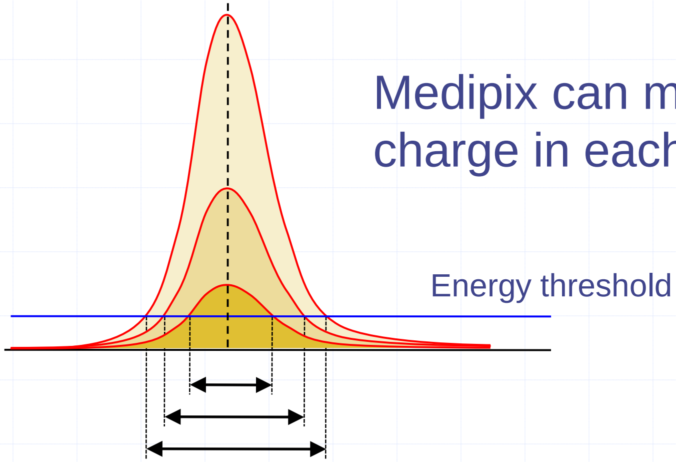
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => **CLUSTER**
- Pixels in a cluster will detect the charge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

Ionizing particle can creates huge charge signal in several adjacent pixels forming **cluster**.
Cluster area 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)



Medipix can measure charge in each pixel!

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

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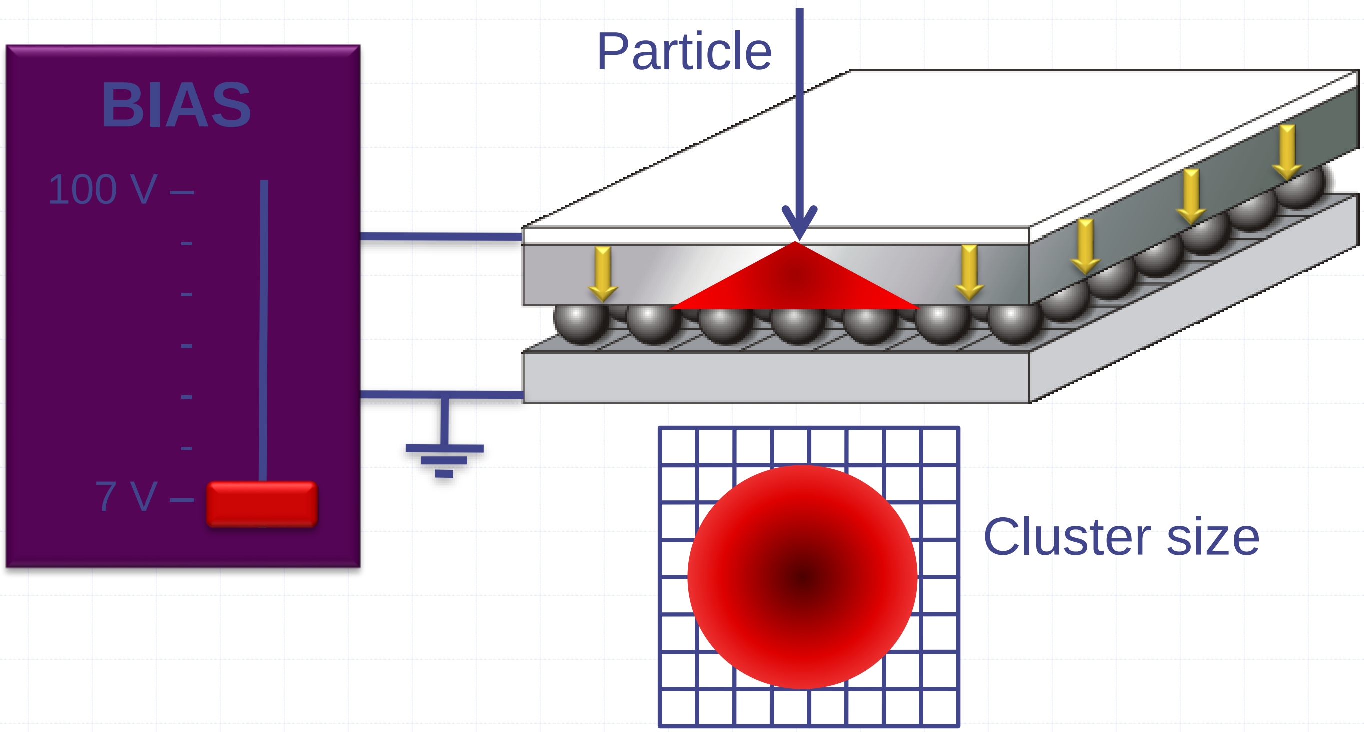

4.93 MeV proton tracks recorded byTimepix silicon detector in Time-over-Threshold mode.

Illumination under different angles and different applied detector biases.

2007

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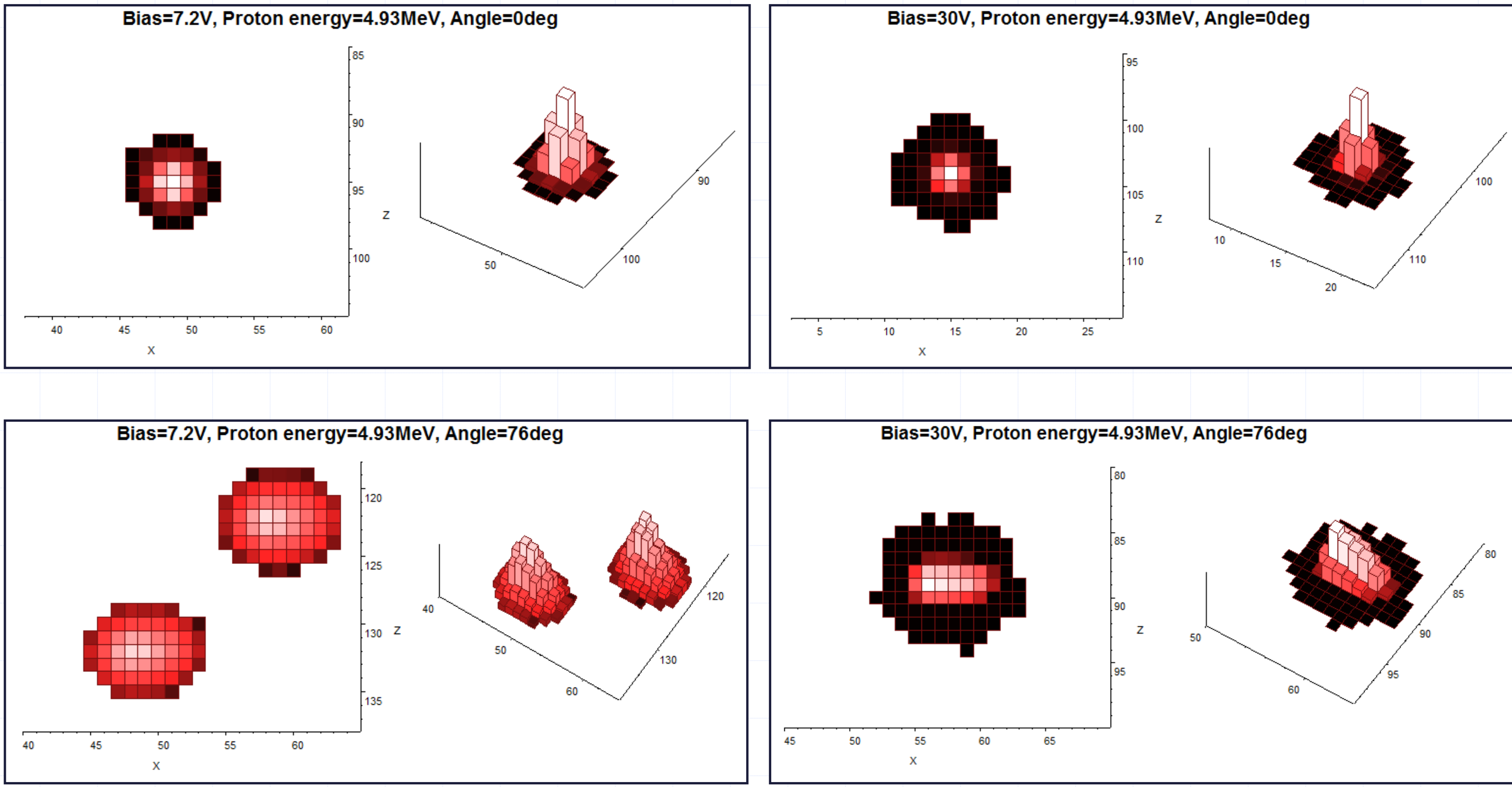

What is the spatial resolution? X- and Y-coordinates are determined with a precision of about 500nm. Determination of angle is with a precision of about 1°. It needs additional experiments.

Radiography with highly ionizing particles

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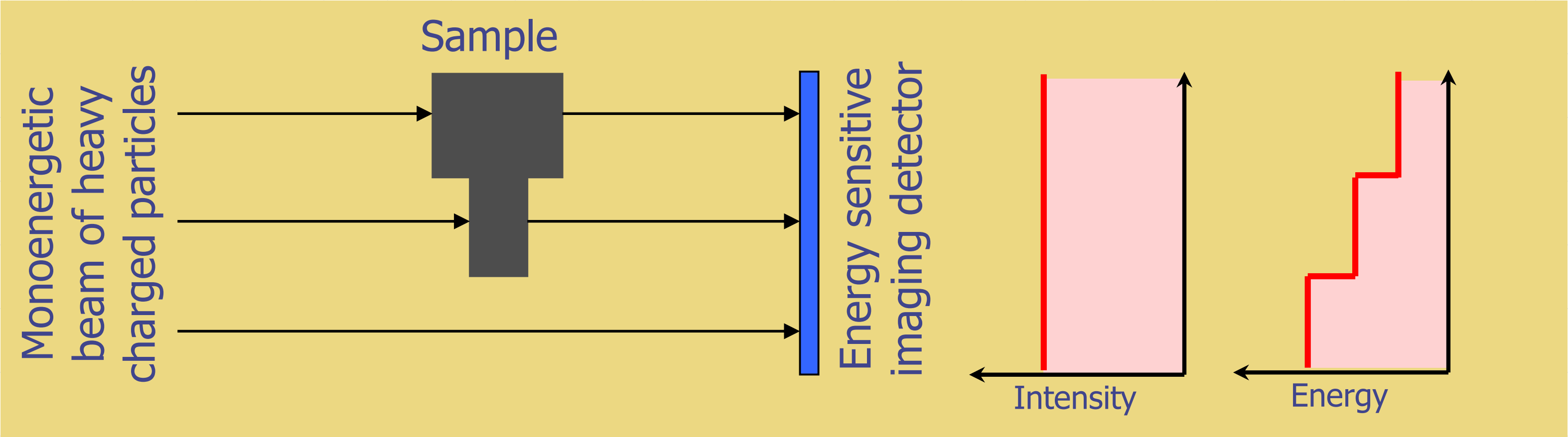
2006



- **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**.

Simple alpha radiography with Medipix2

2006

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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)

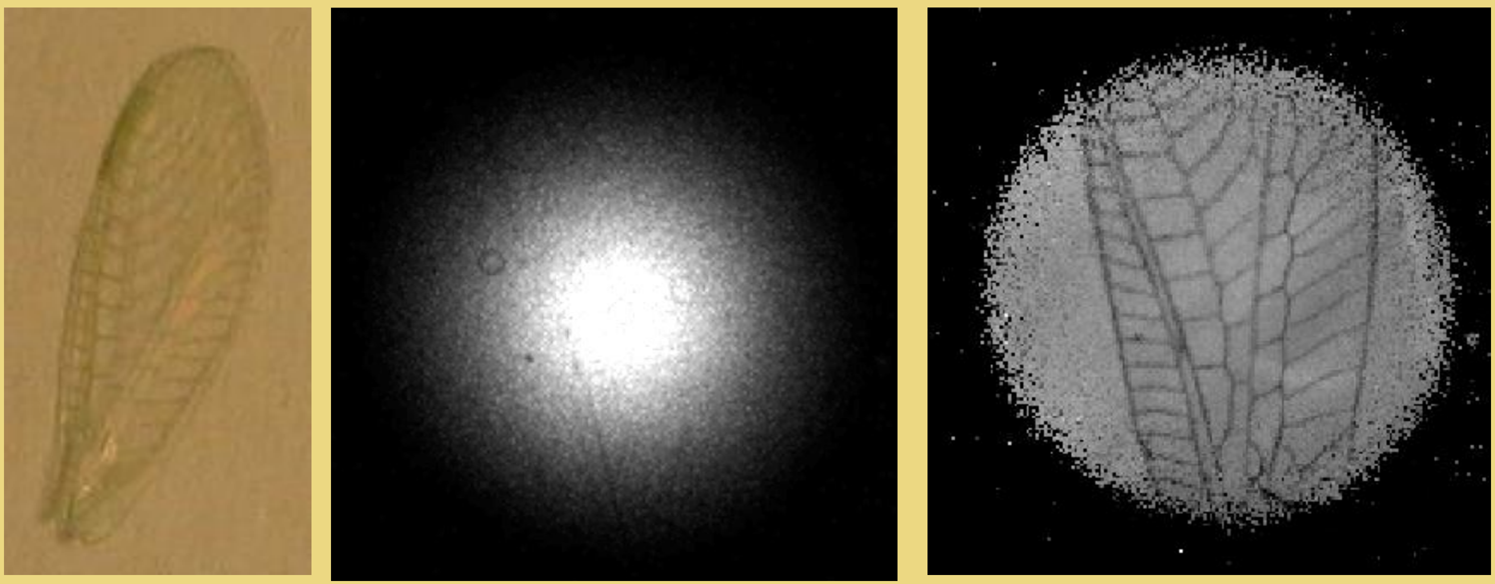

Photo Intensity Energy

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)

2008

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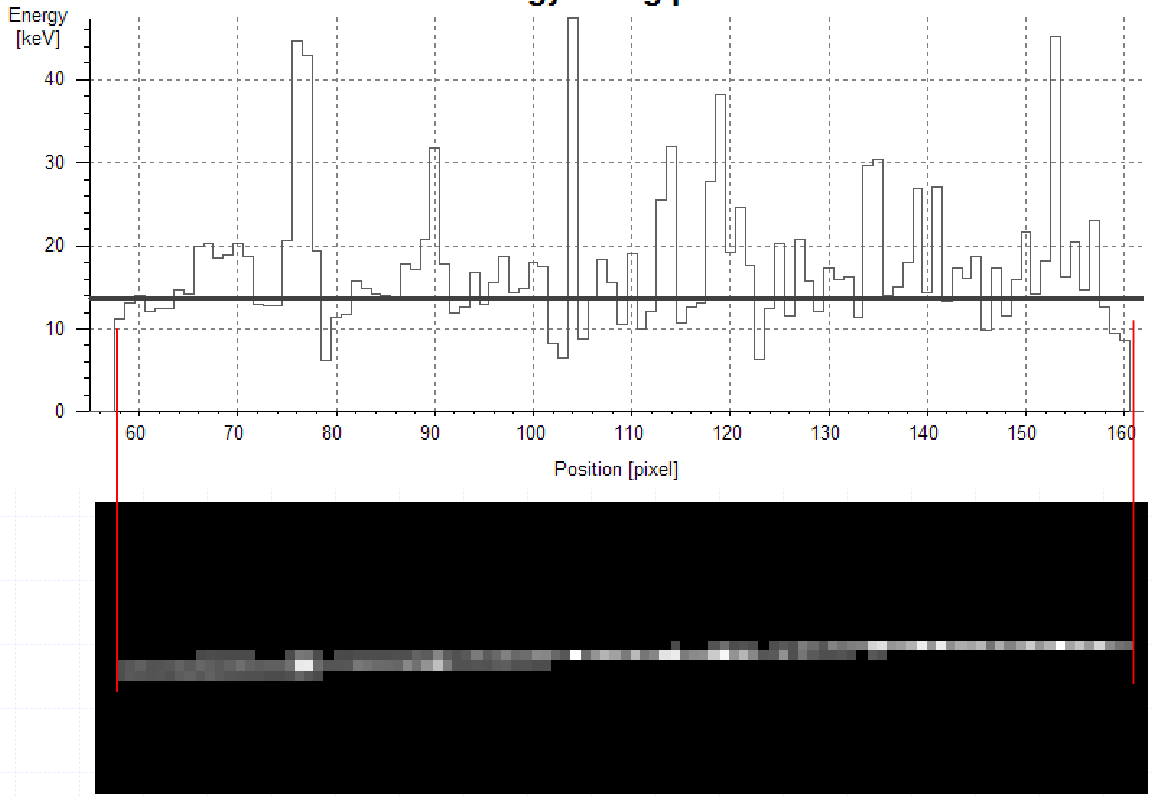
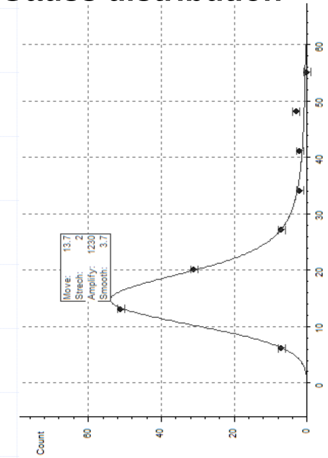
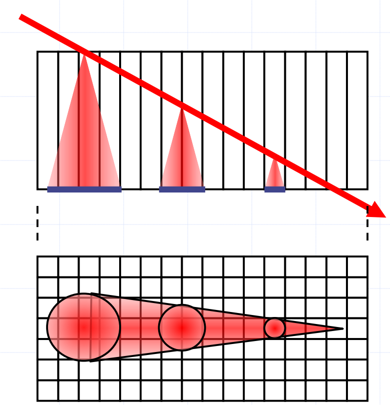
Energy along path



Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution

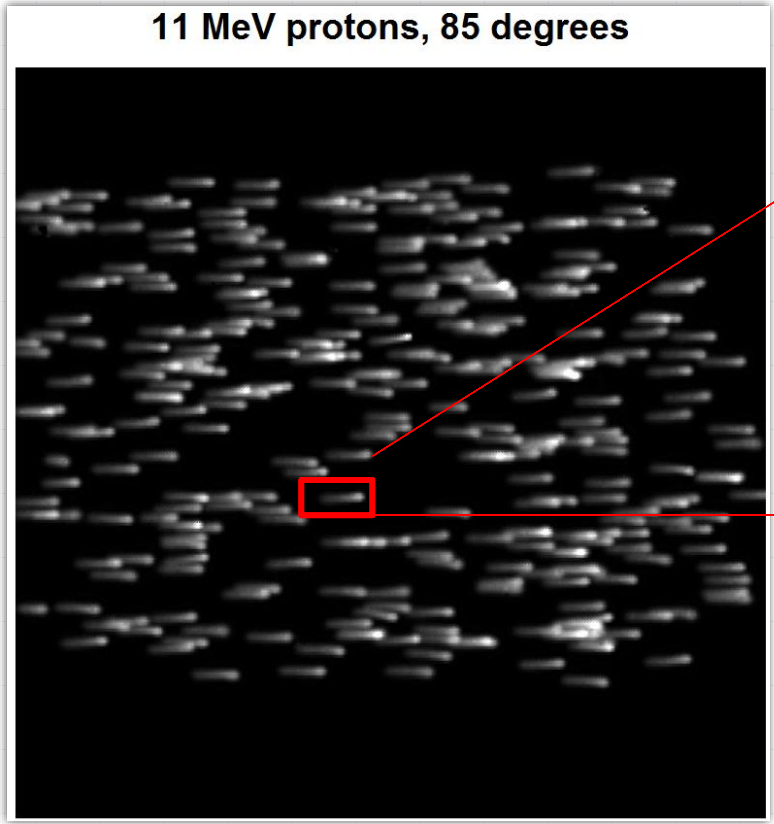


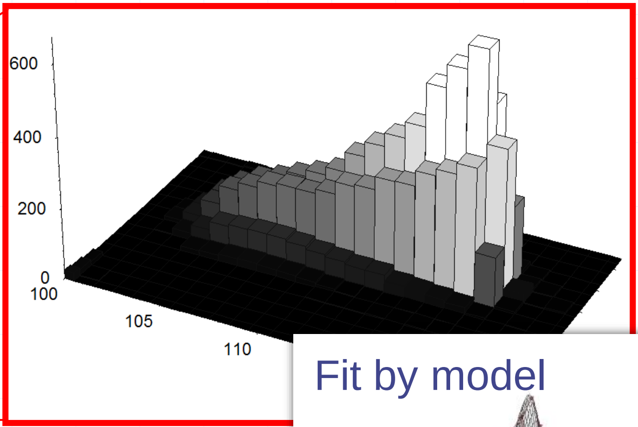


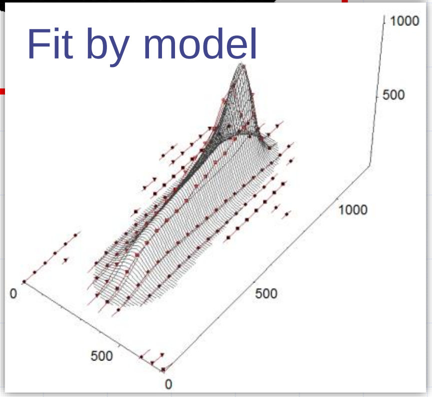
Flock of 11 MeV protons entering the silicon sensor under 85°

2009

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







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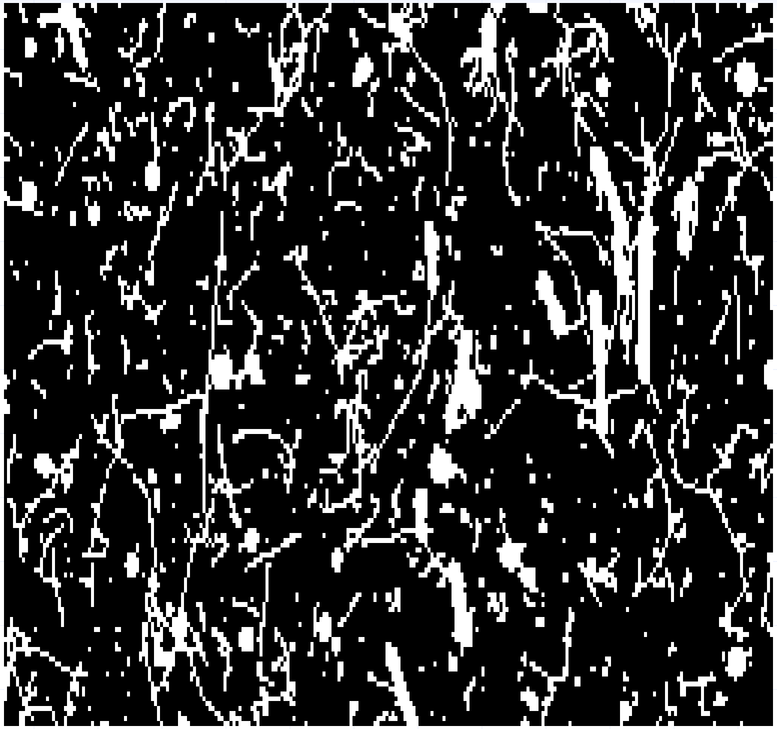
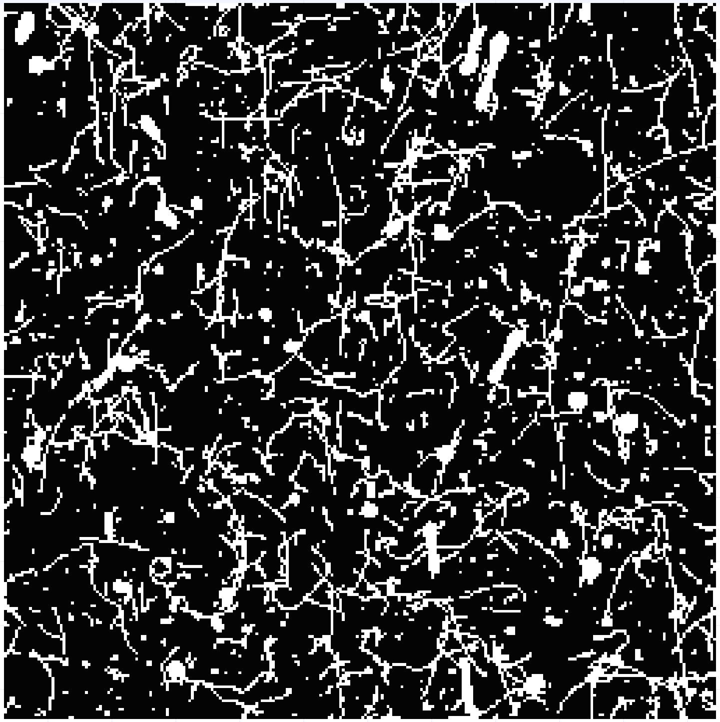
Response of MEDIPIX-USB device with polyethylene converter (on the right hand side) to fast monochromatic neutrons (17MeV)

2005





- 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 - track pattern recognition

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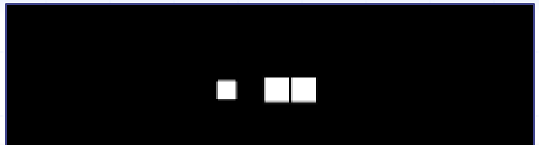
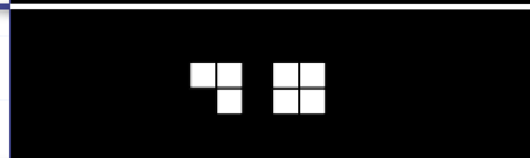
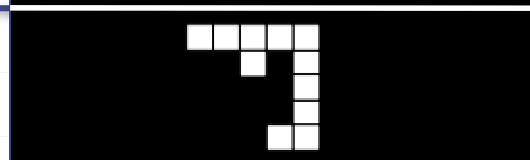
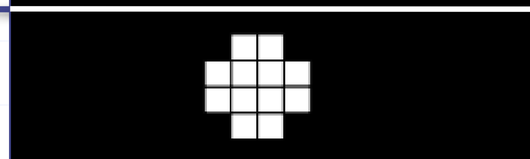
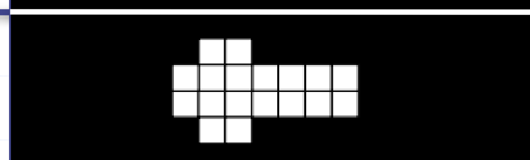
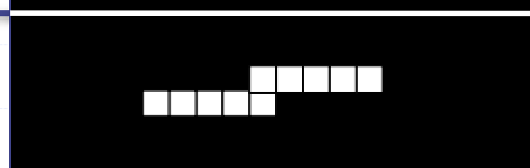
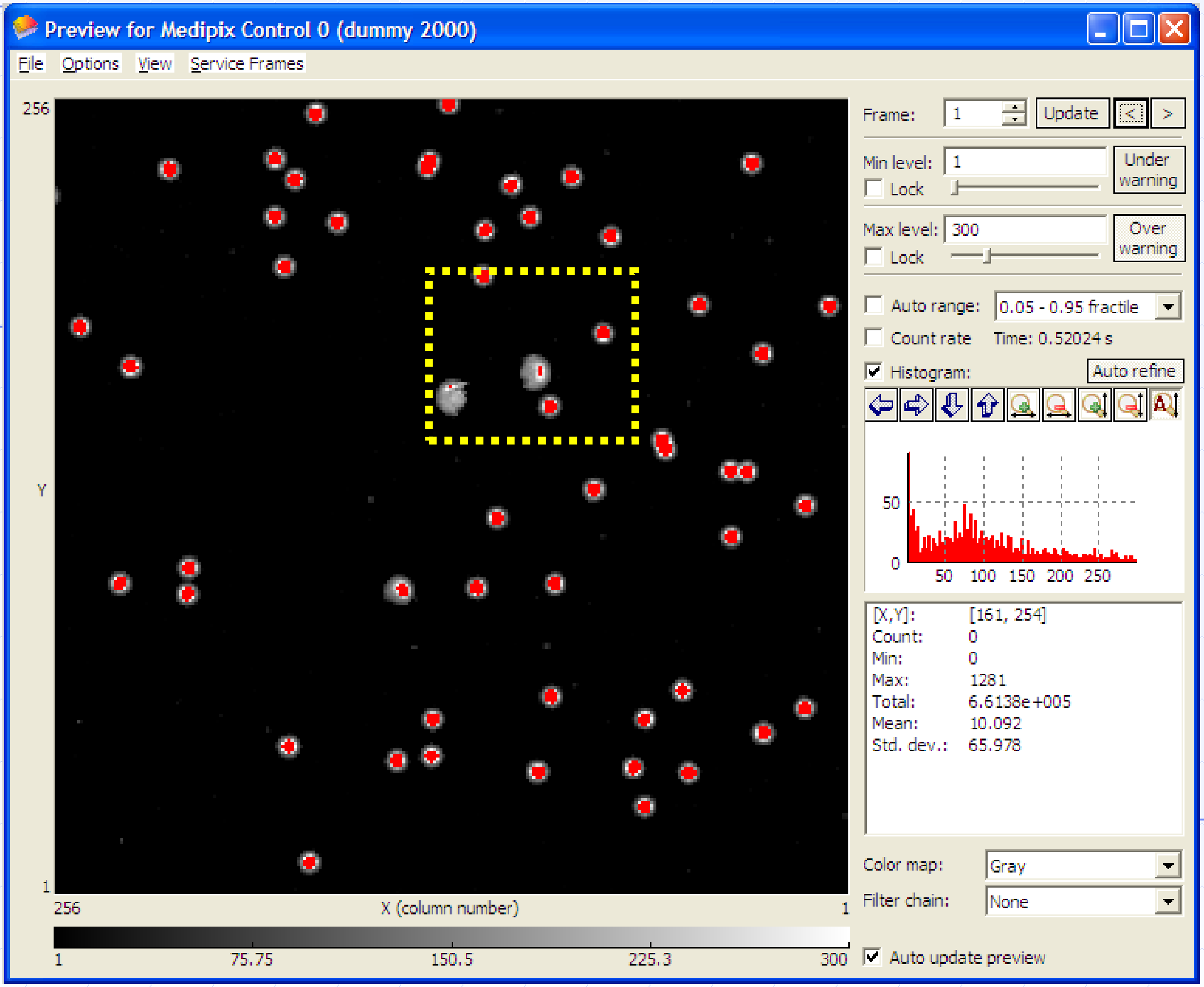
2007

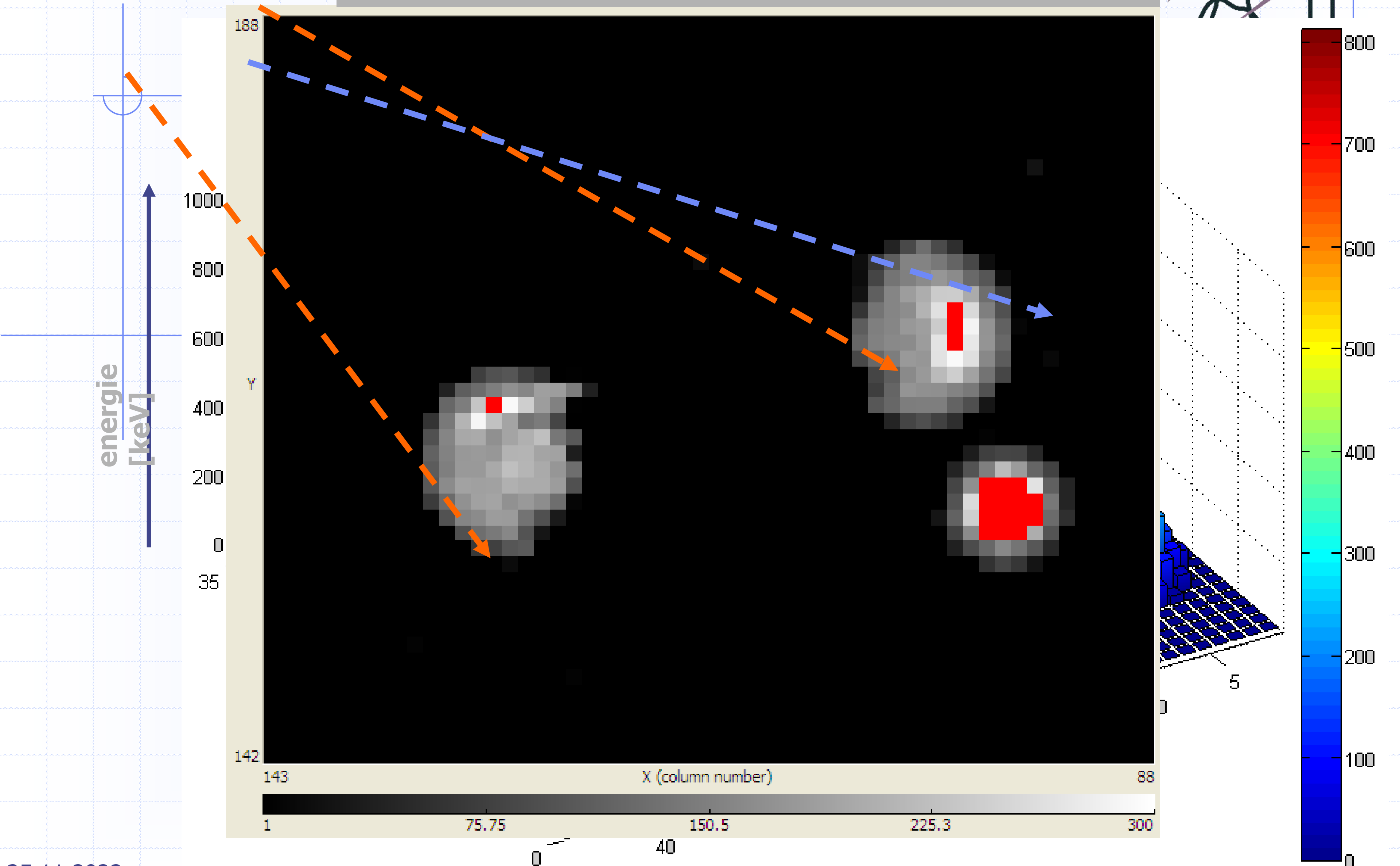
1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with low range (alpha particles,…)
5) Heavy track		Heavy ionizing particles (protons,…)
6) Straight track		Energetic light charged particles (MIP, Muons,…)

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

2008



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



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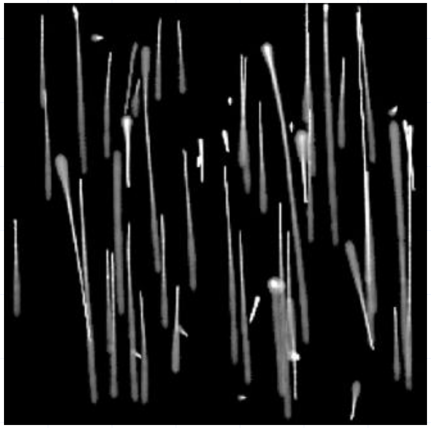
Typical observed tracks of particles used for hadron therapy beam

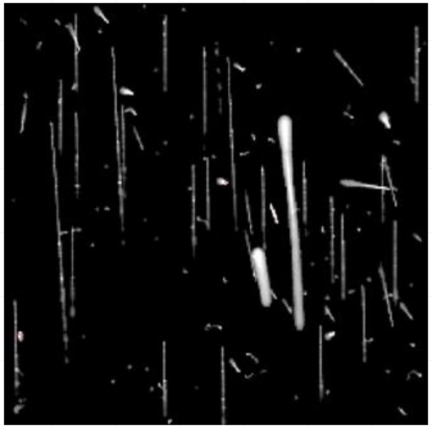
2010

Protons 48 MeV



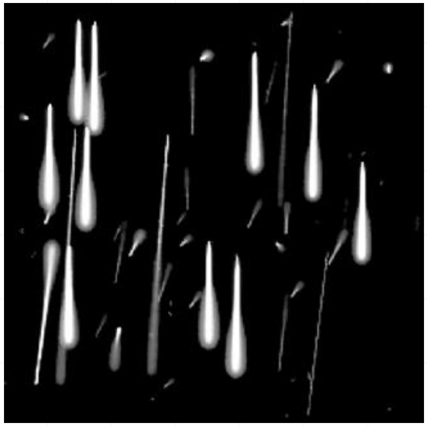
Only protons and their scattering, no secondaries.

Protons 221 MeV



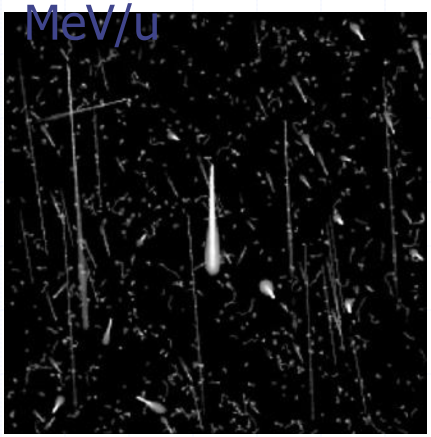
Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



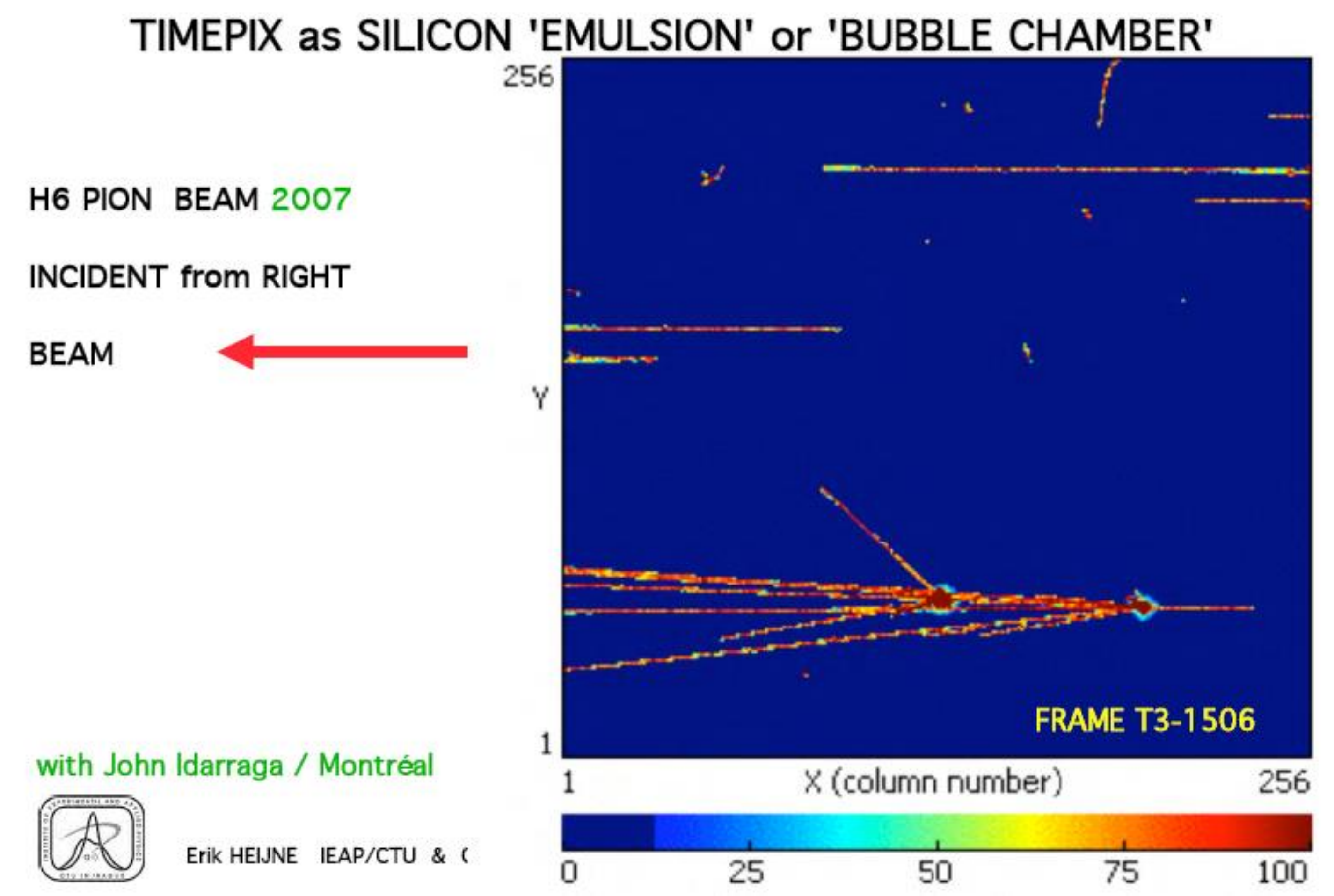
Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u



Carbons and many secondaries.

Detailed visualization of interactions in the Silicon sensor



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

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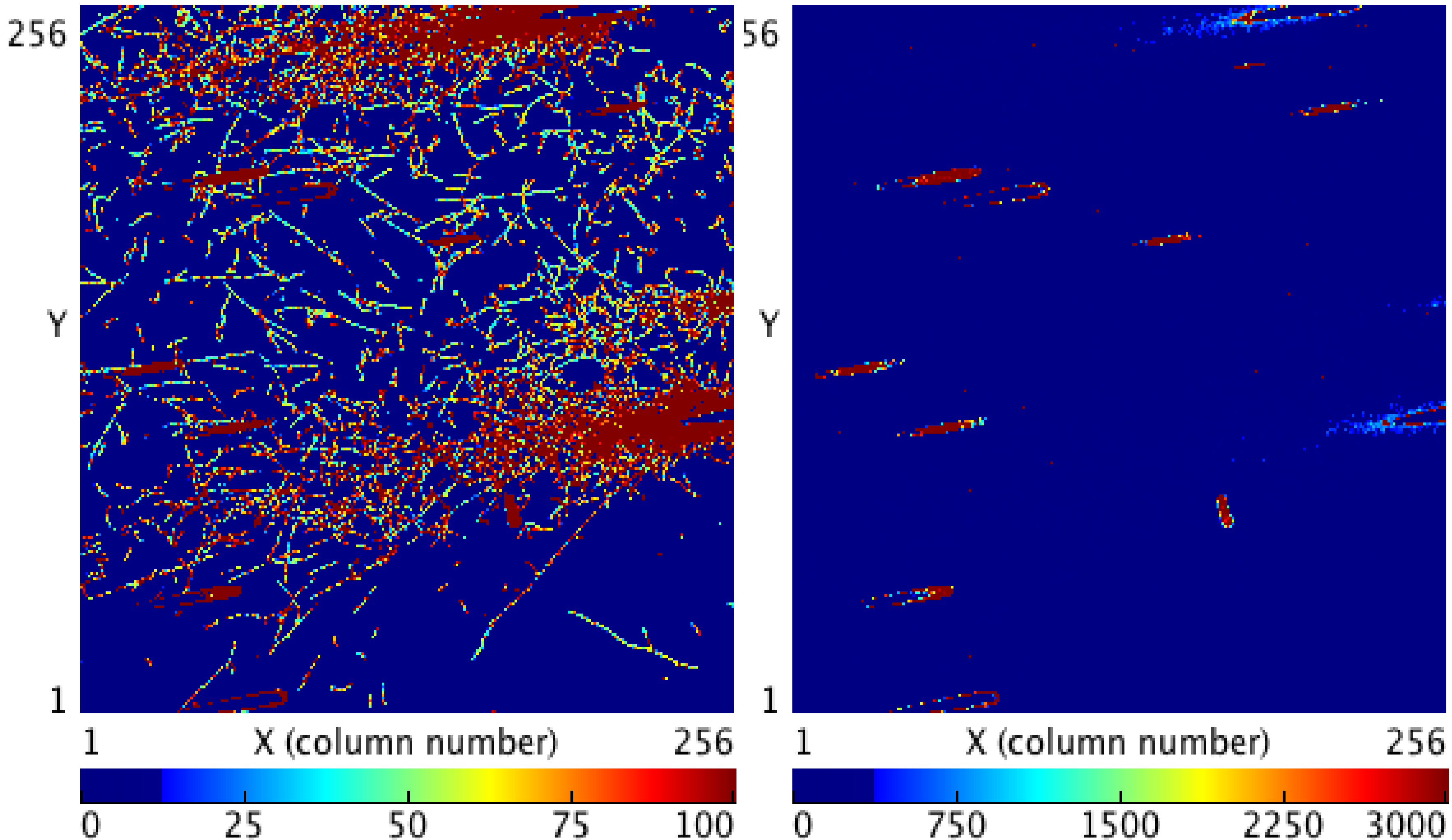

scale 100

scale 3000

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

Relativistic Ions @ small (grazing) angles

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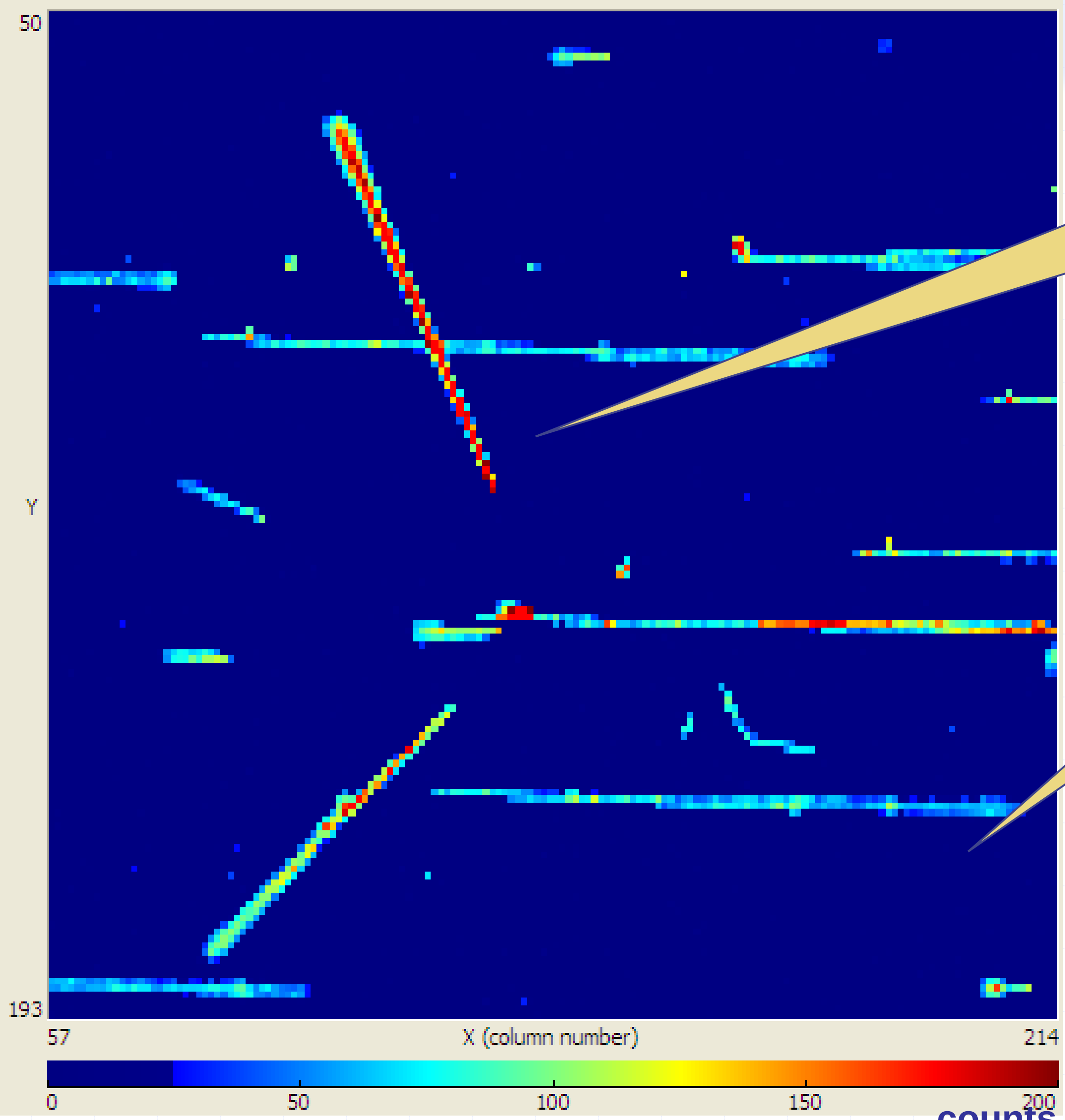
^{2}H

angle = 3º



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

2010

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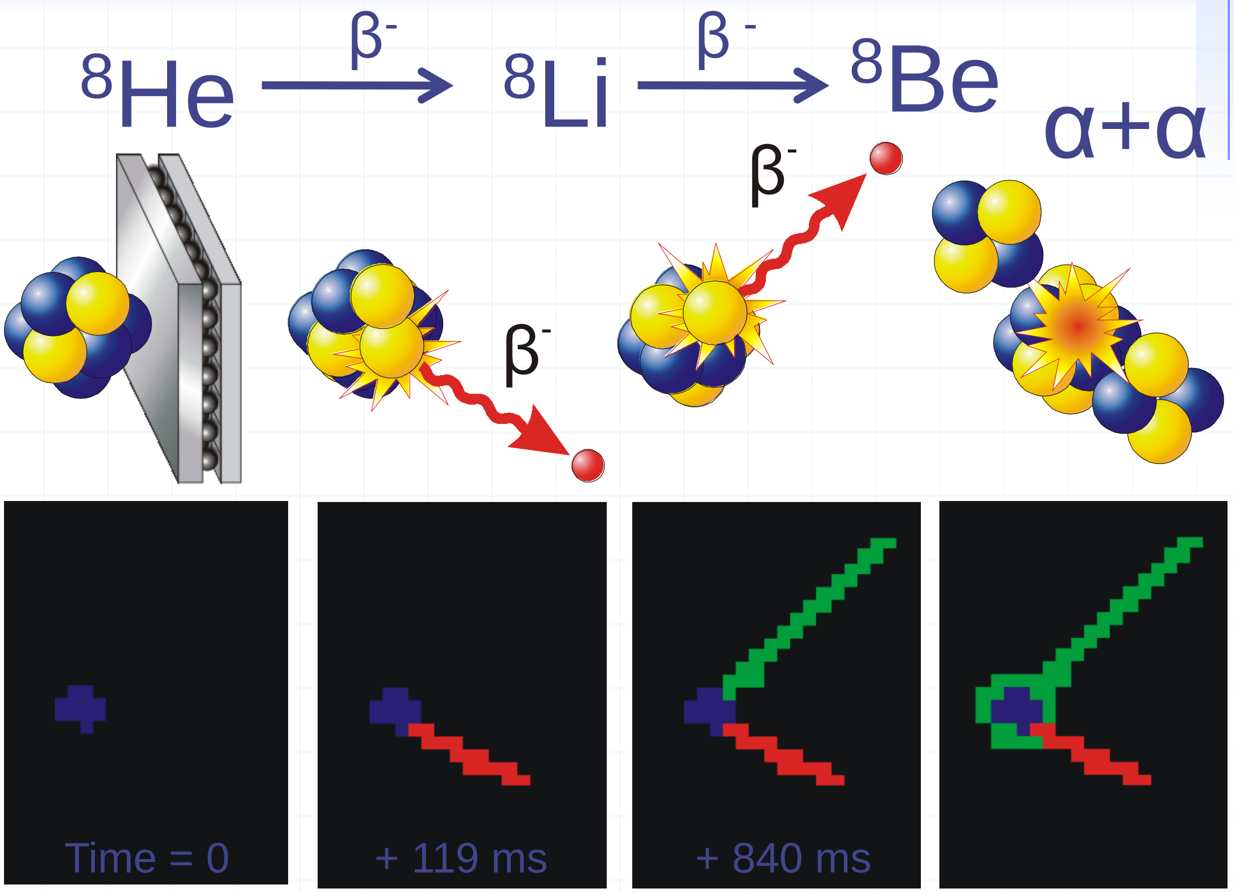
^{8}He ion hits the Timepix sensor where undergoes β-decay

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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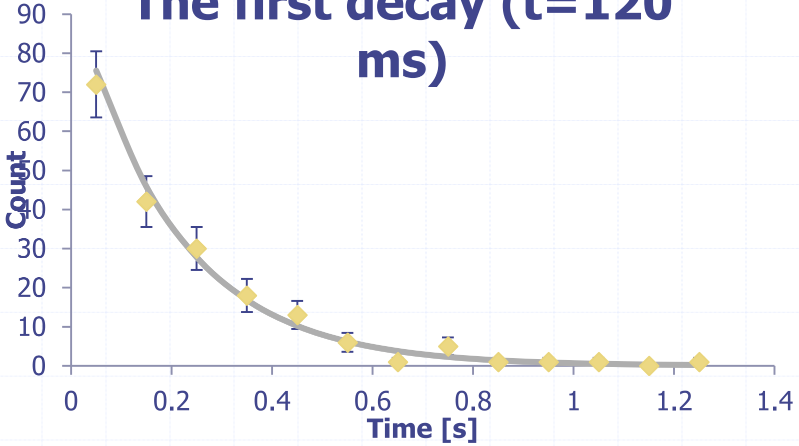
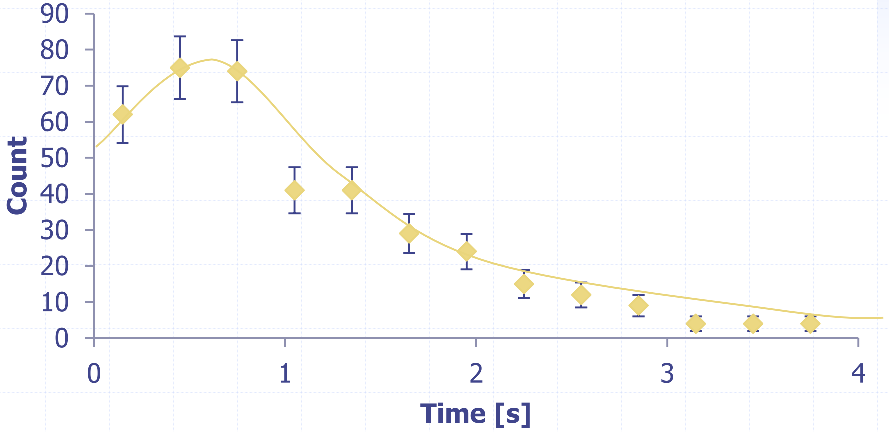
The first decay (t=120 ms)



The second decay (t=810 ms)



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?

Spectroscopy of $^{10}B(n,alpha)^{7}Li$ or $^{6}Li(n, alpha)^{3}H$ products applied for **thermal neutron high resolution imaging** with high S/N ratio in mixed n-gamma radiation fields

2010

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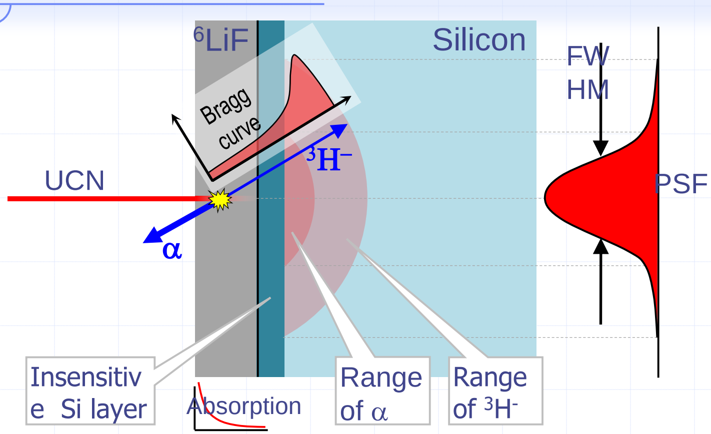
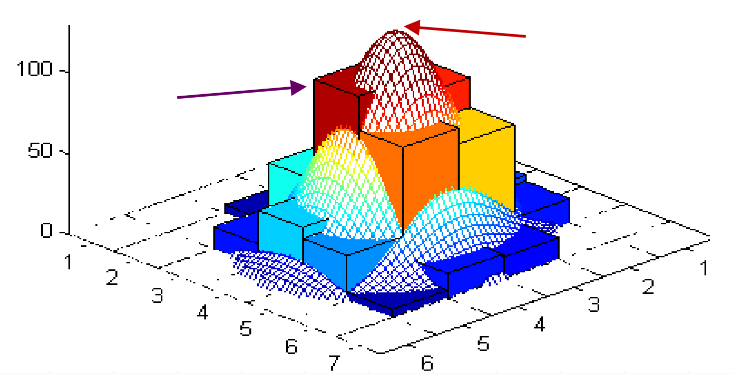
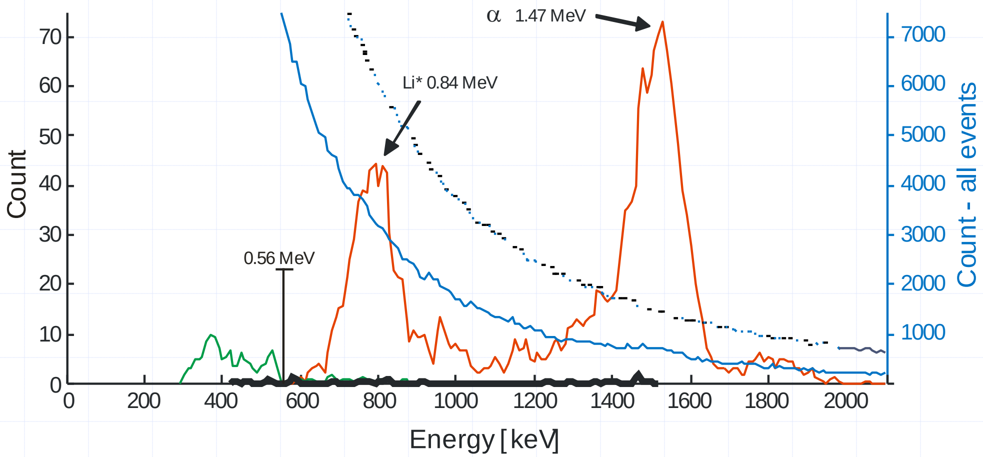


Simulation of pixel detector response to a charged particle (alpha, triton, 7Li) in a form of



3D-cluster with a shape resulting from convolution of Gaussian and the particle track

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



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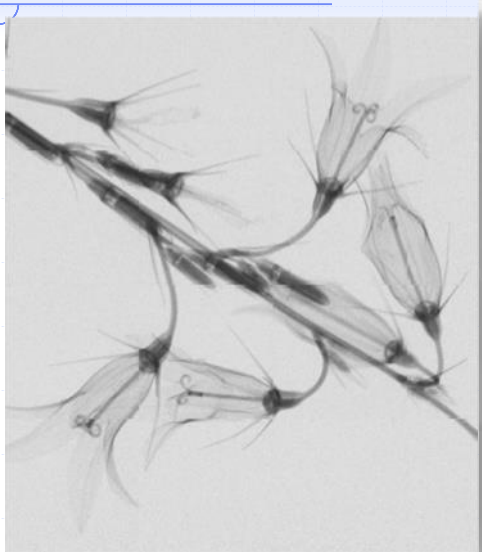
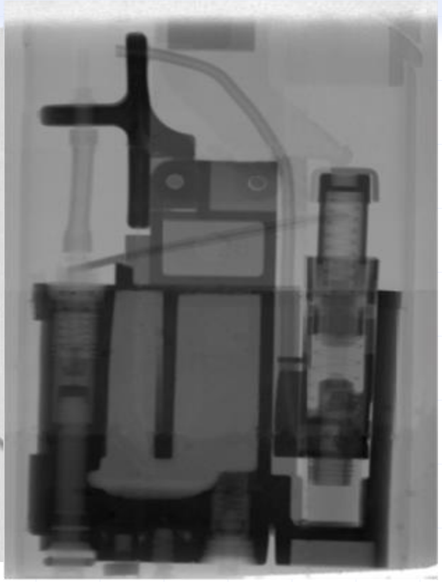
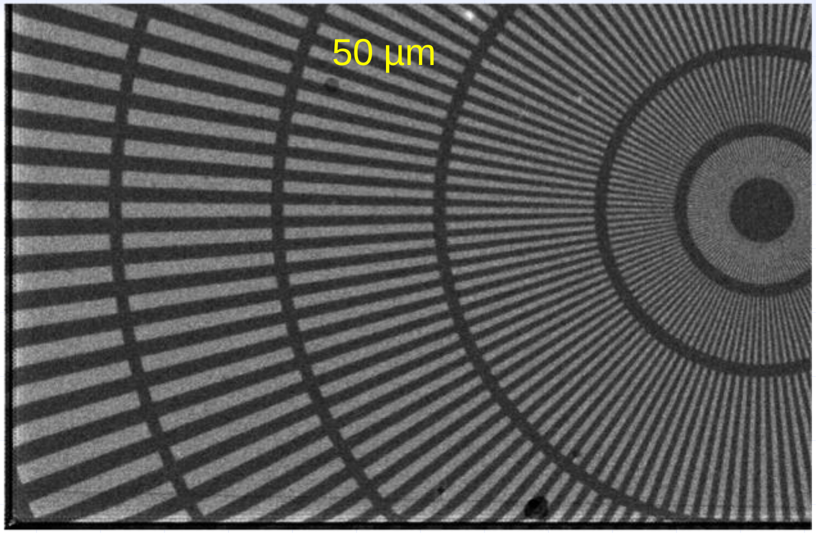
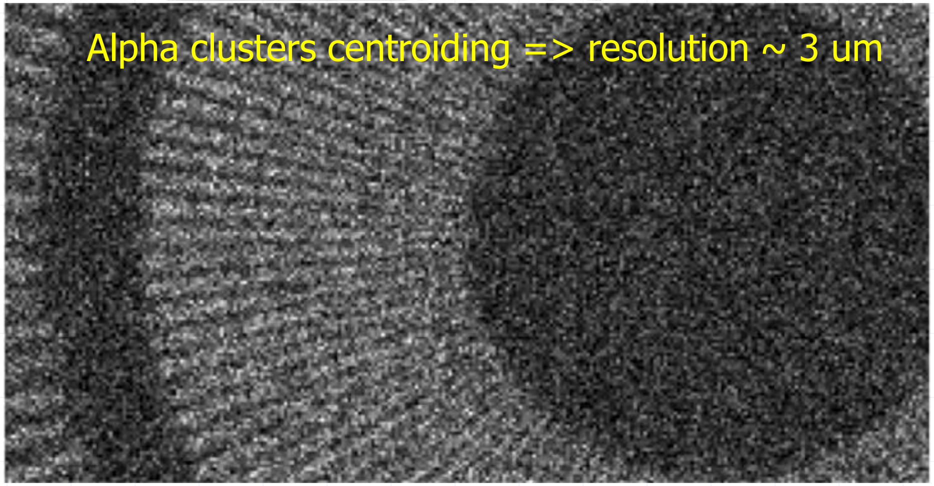
Neutron images with Timepix detector and resolution calibrated by Siemens star









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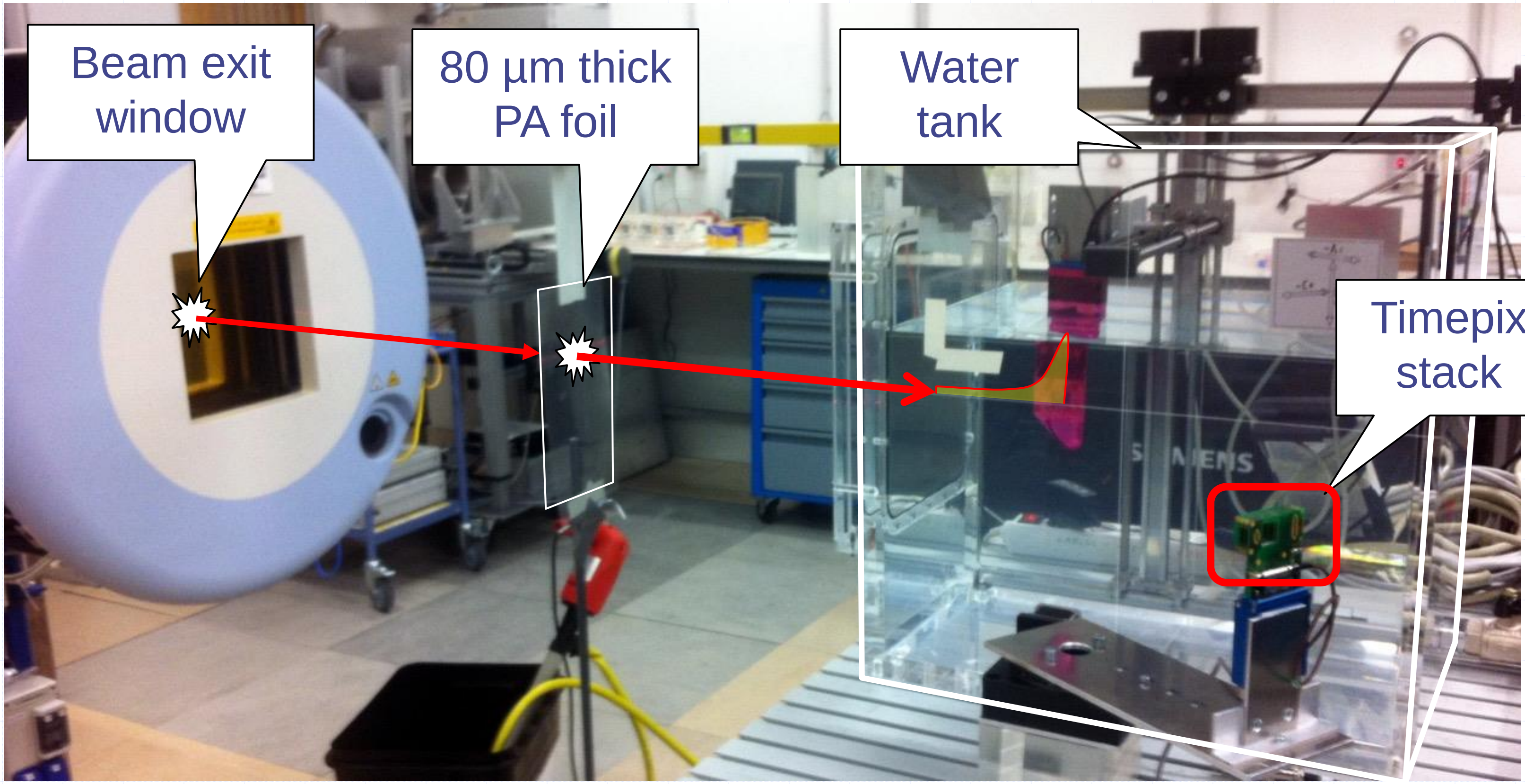
Medical application:
Hadron therapy - Experimental setup

2011



Visualization of secondary particles produced by the beam

Visualization of particle beam in air and in the phantom

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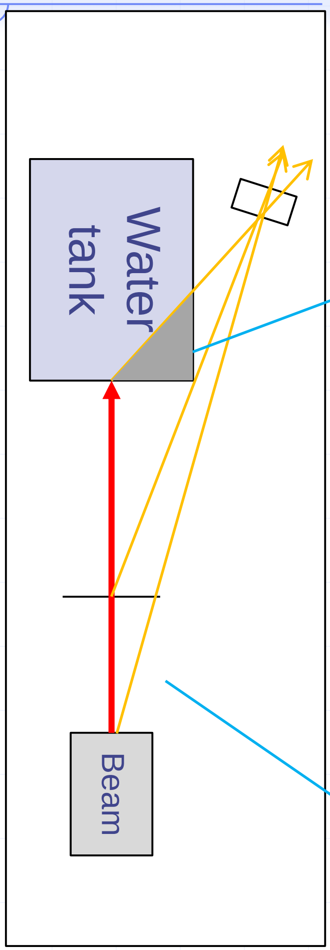
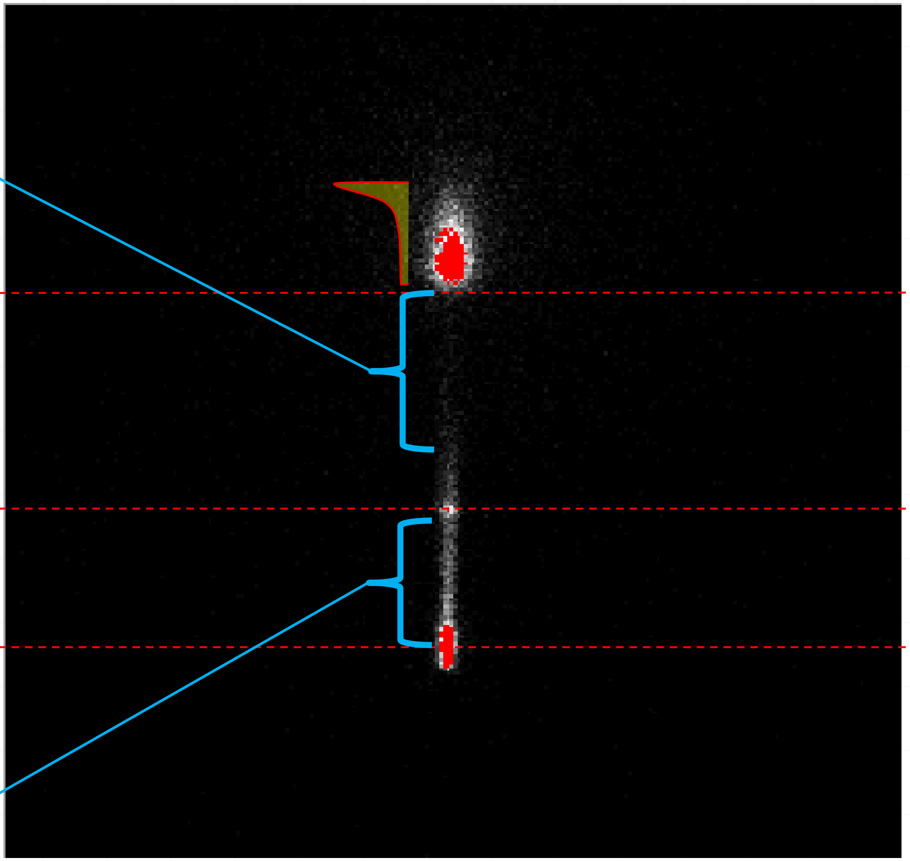


Reconstructed image (all coincident events)



TIMEPIX3

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

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It can be effectively used for simultaneous measurement

- of Time-of-Flight of detected particle,
- Energy of this particle deposited in the sensor and
- a drift time of charge in the sensor

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

Timepix3 CERN chip board

Fast neutron ToF measurement with TIMEPIX

LANSCE neutron sources and nuclear science flight paths

(combined ToA and ToT modes)

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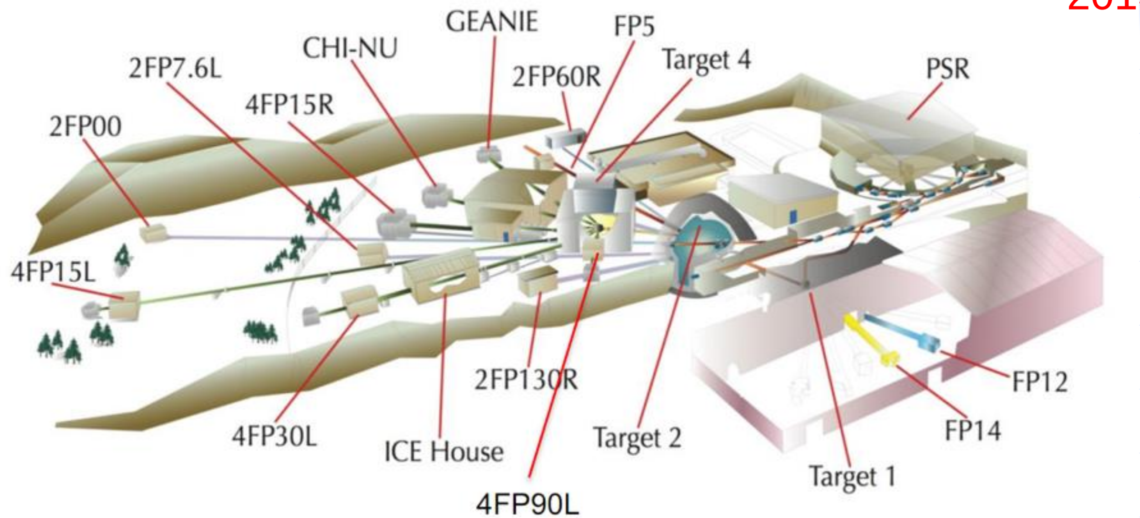
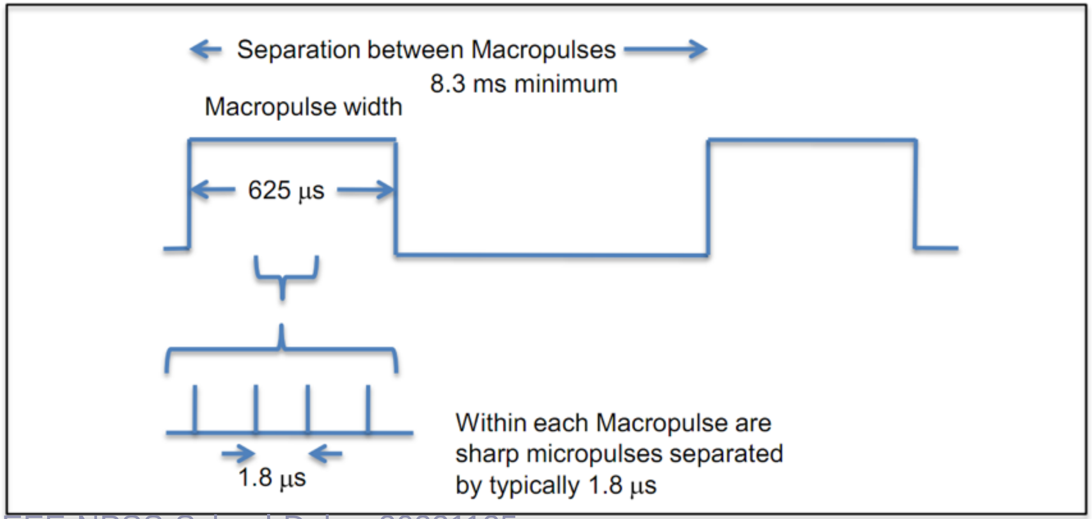
2013

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



- Time structure of the proton beam for typical Target-4 operation 1.8 ns pulses every 1.8 μs



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

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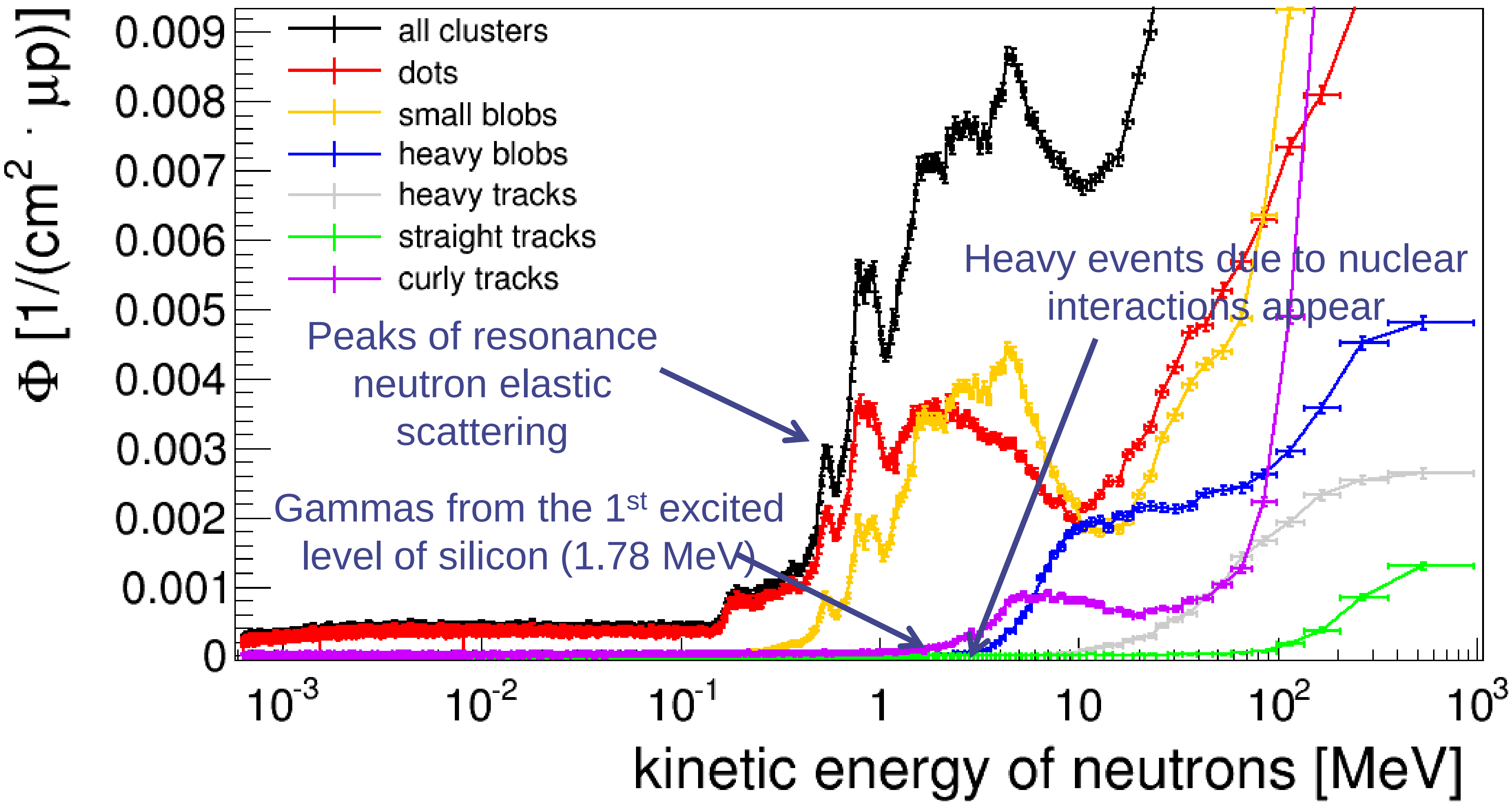
Czech Technical University in Prague

- 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

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

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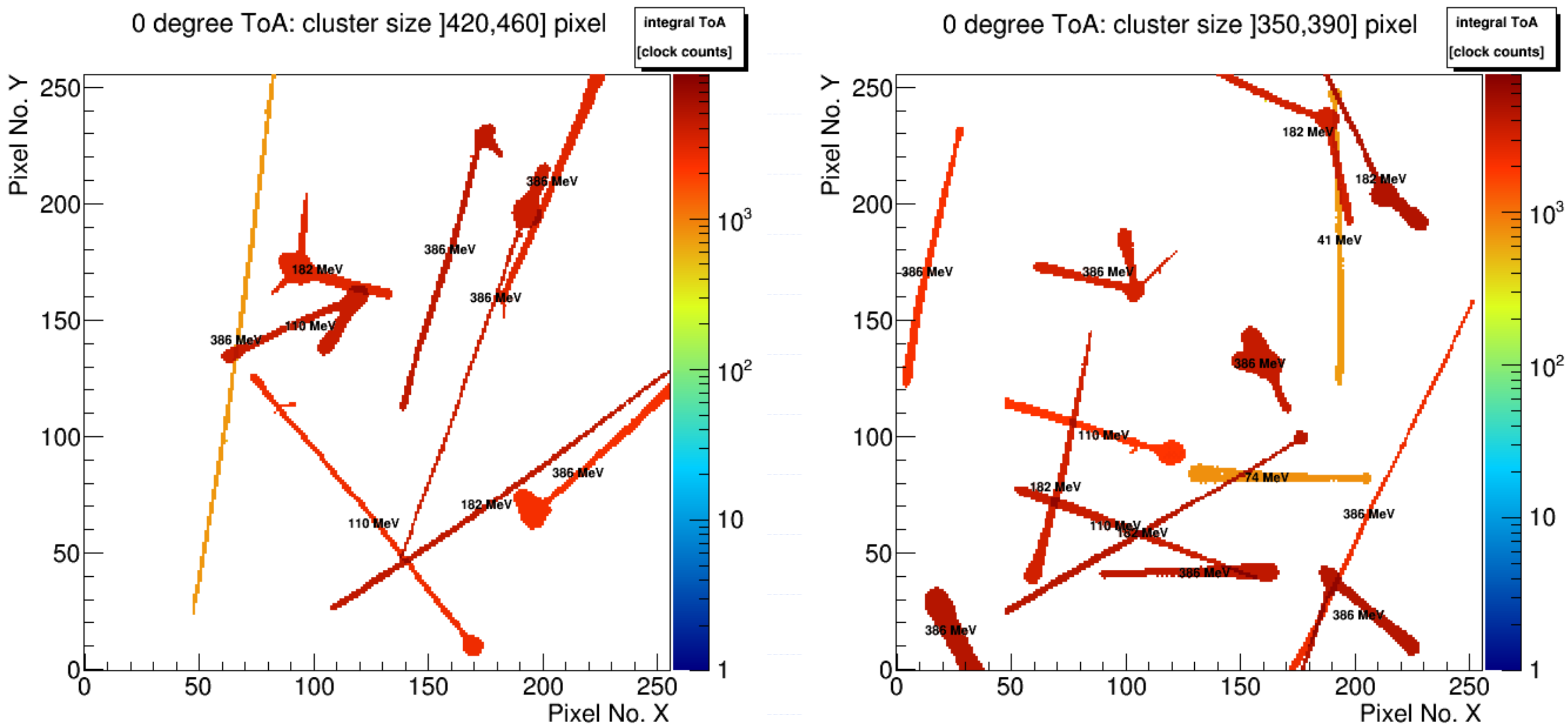

Different colors and black numbers assigned to individual clusters indicate the energy of incoming neutrons as measured by means of the TOF technique

Energy spectra corresponding to elastic and/or inelastic scattering of neutrons on Si nuclei "Neutrons billiard with niclei of silicon"

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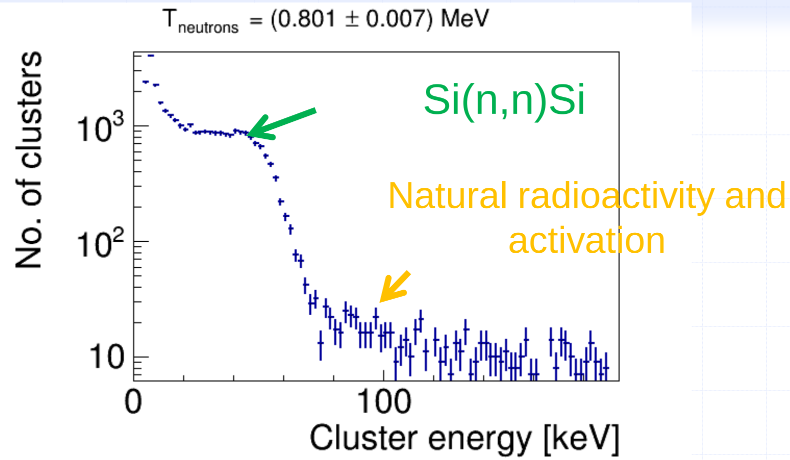

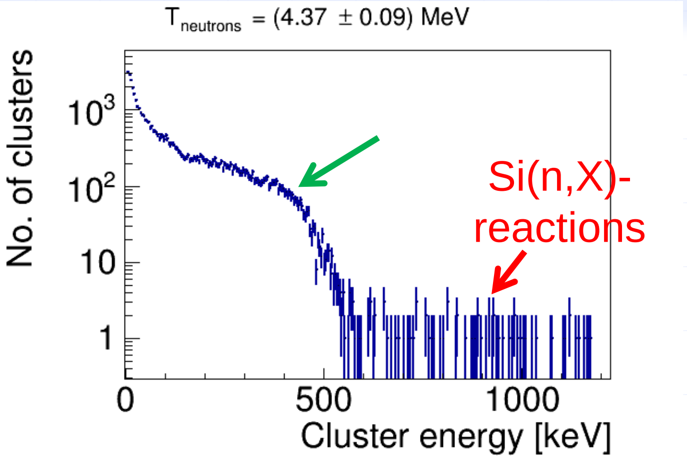

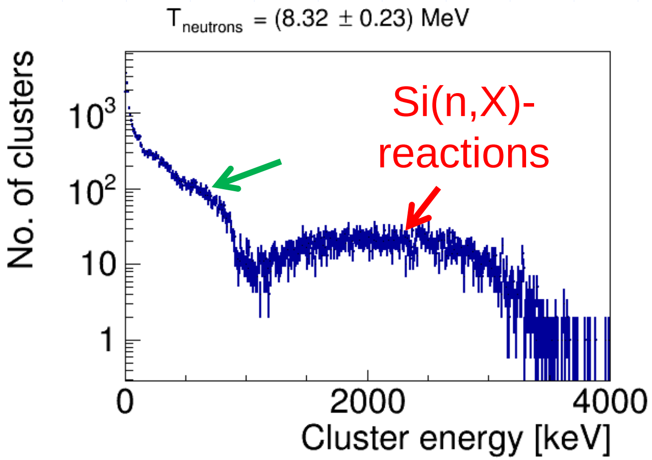

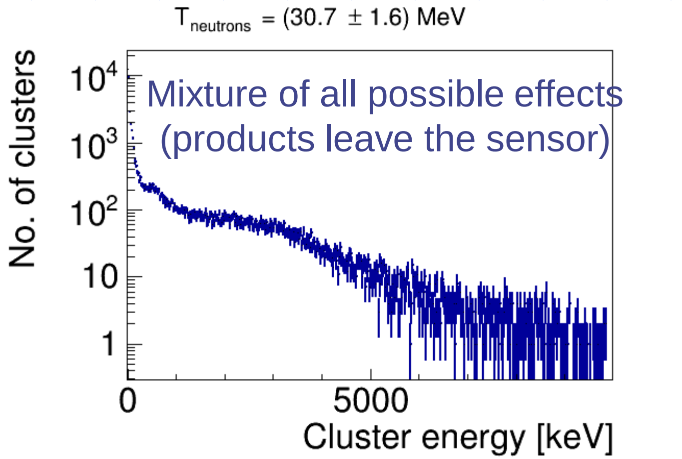

3D-visualisation of particle tracks in Timepix3 detector with CZT sensor

It operates as TPC and/or real time bubble chamber (measured at CERN SPS)

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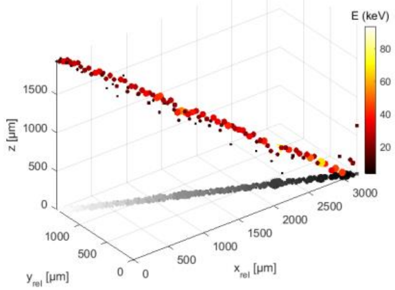
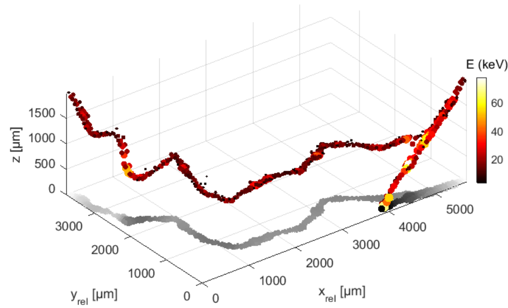
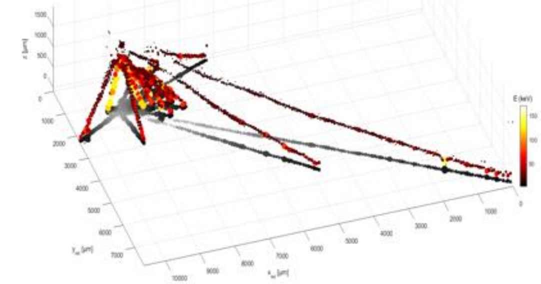
Muon



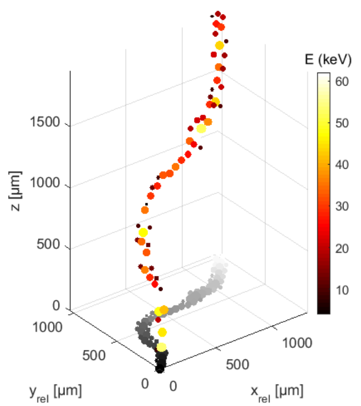
Pion + delta electron



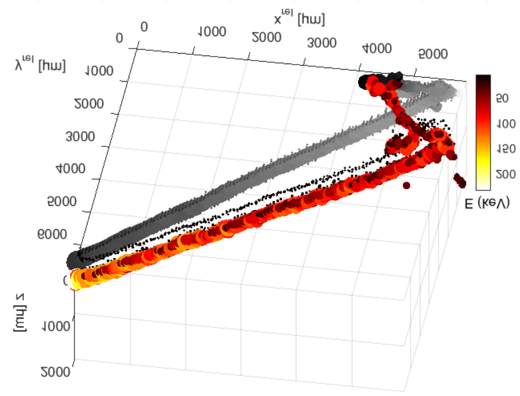
Fragmentation



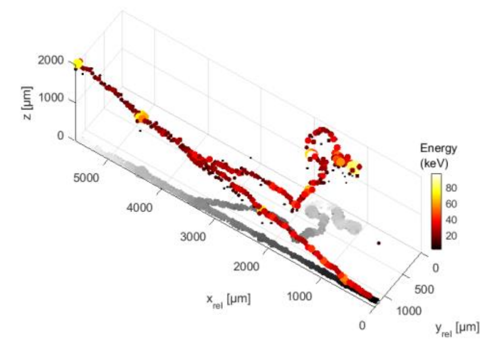
Electron



Heavy track



Pion + delta electron



ATLAS-TPX devices in the ATLAS experiment

Timepix3 in ATLAS is synchronized with LHC clock

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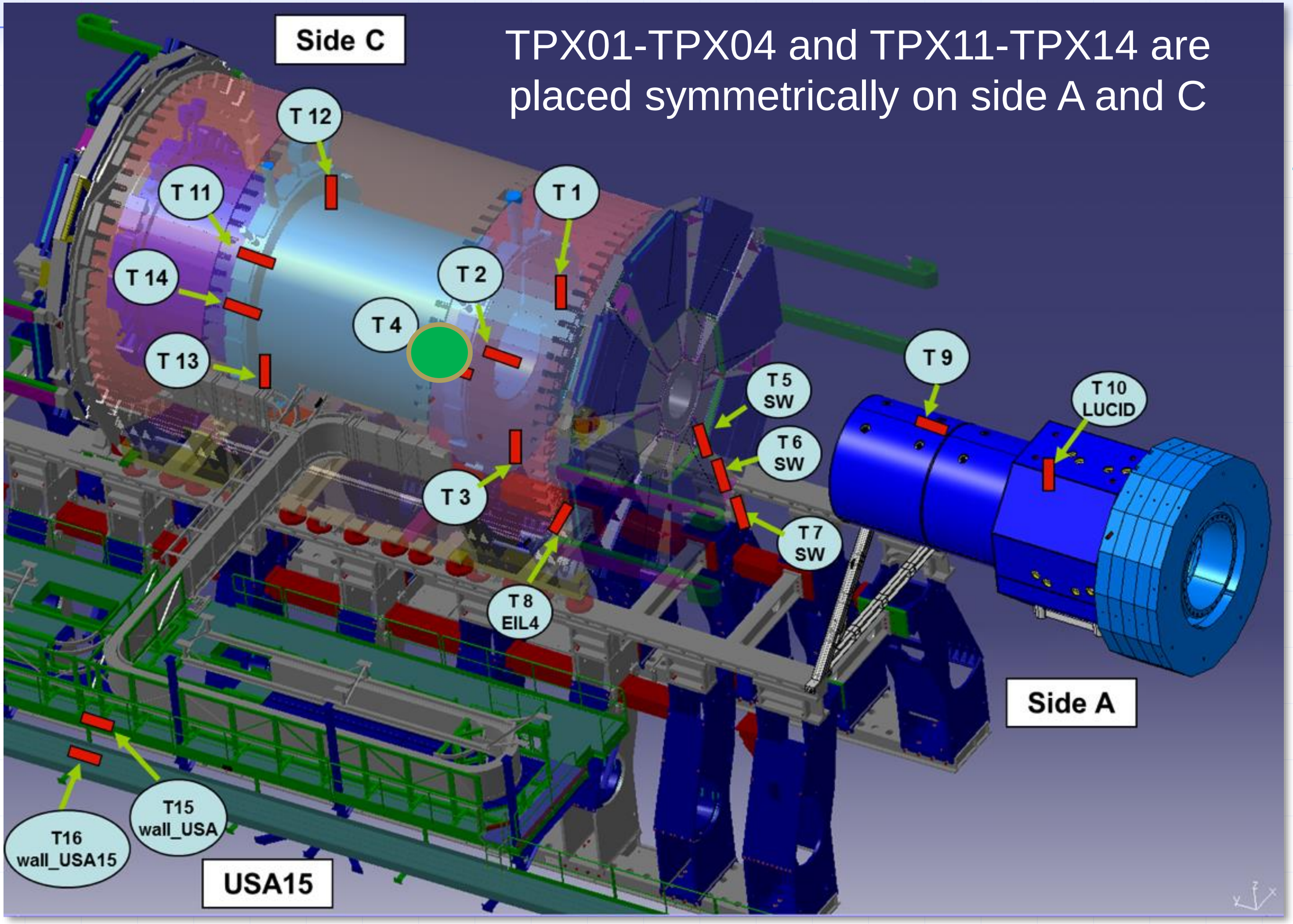
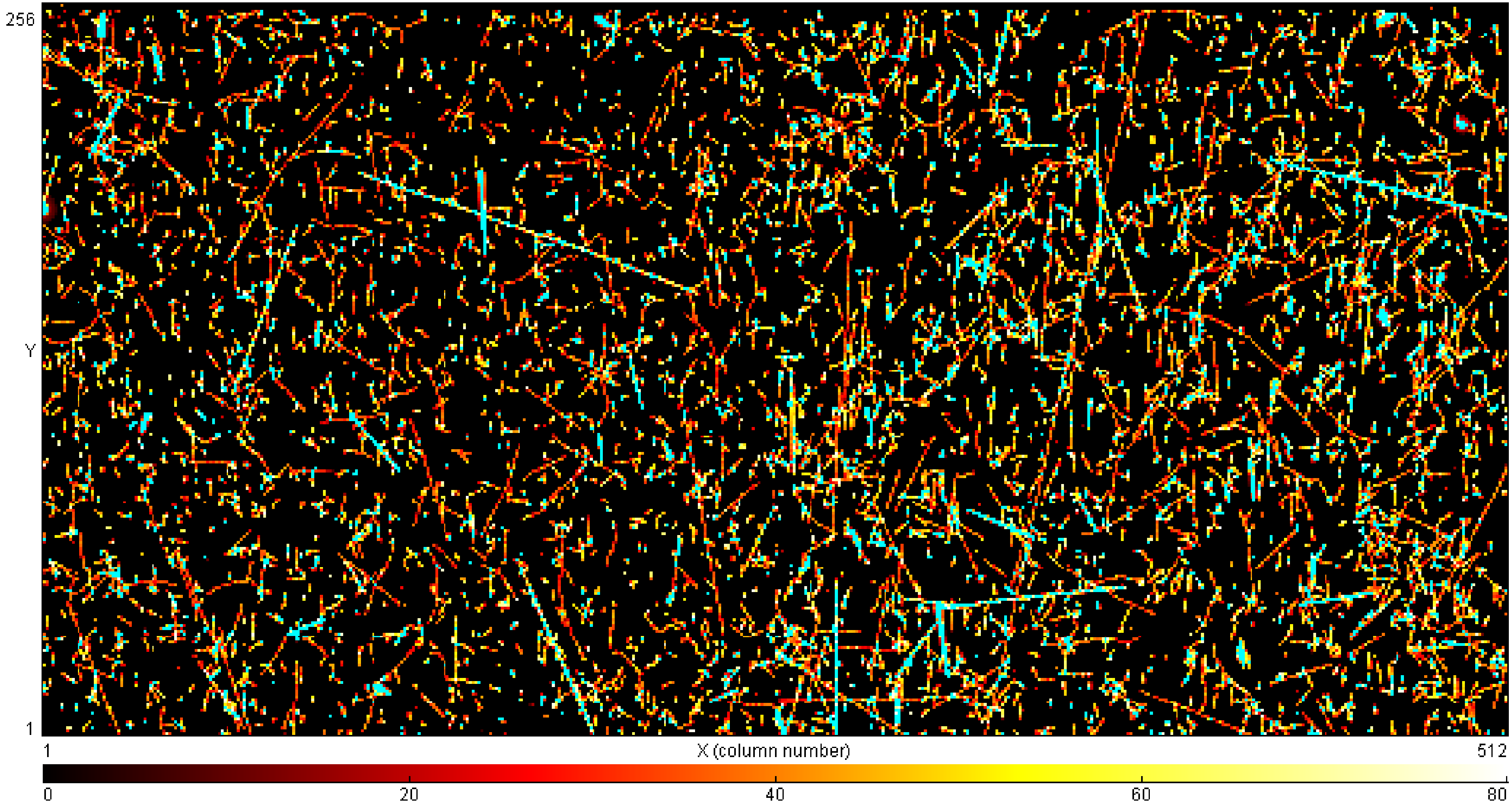


TPX-2013

TPX3-2018

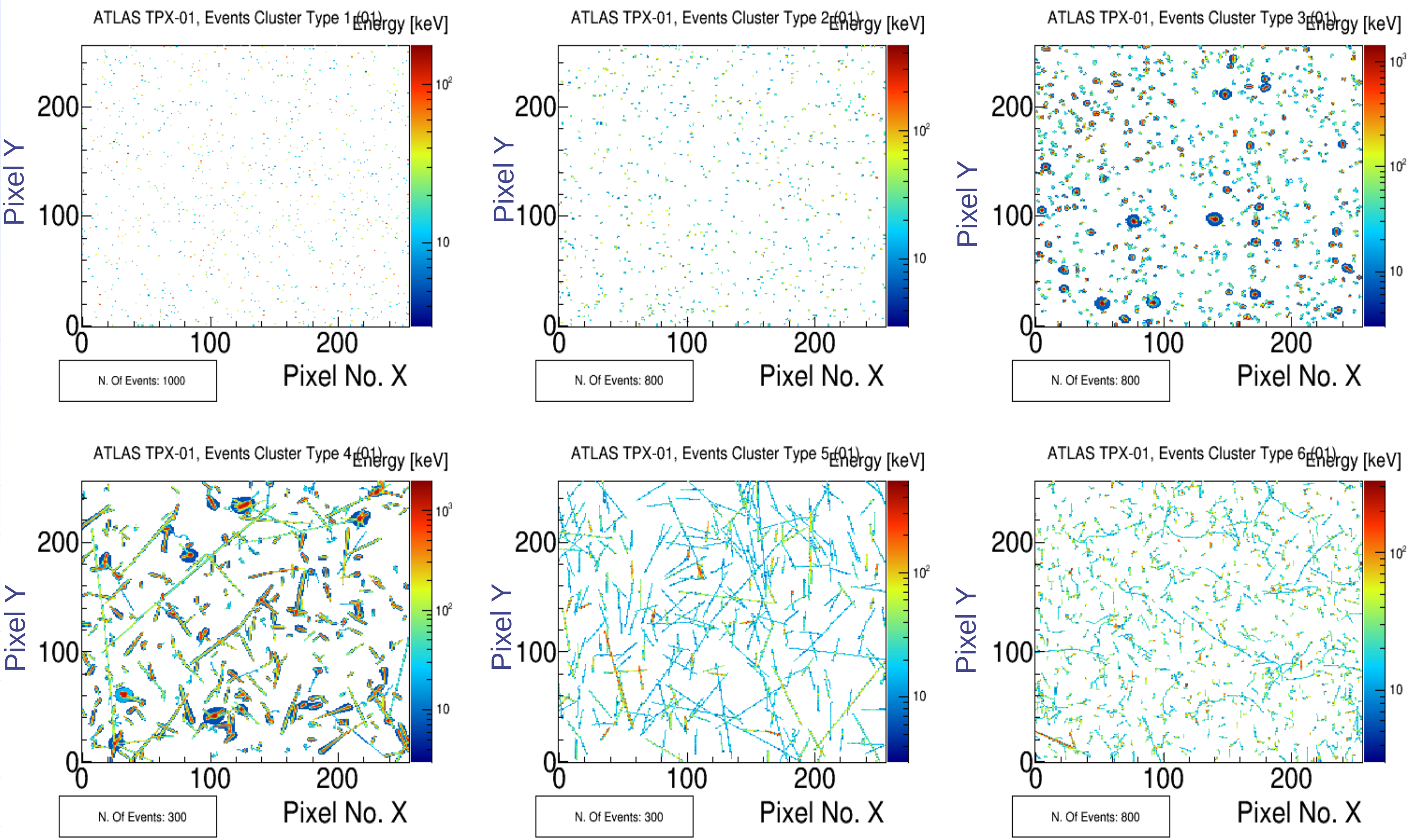
Response of the ATLAS-TPX device to isotropic? mixed radiation field

sandwich of 2 detectors, left 300μm, right 500μm



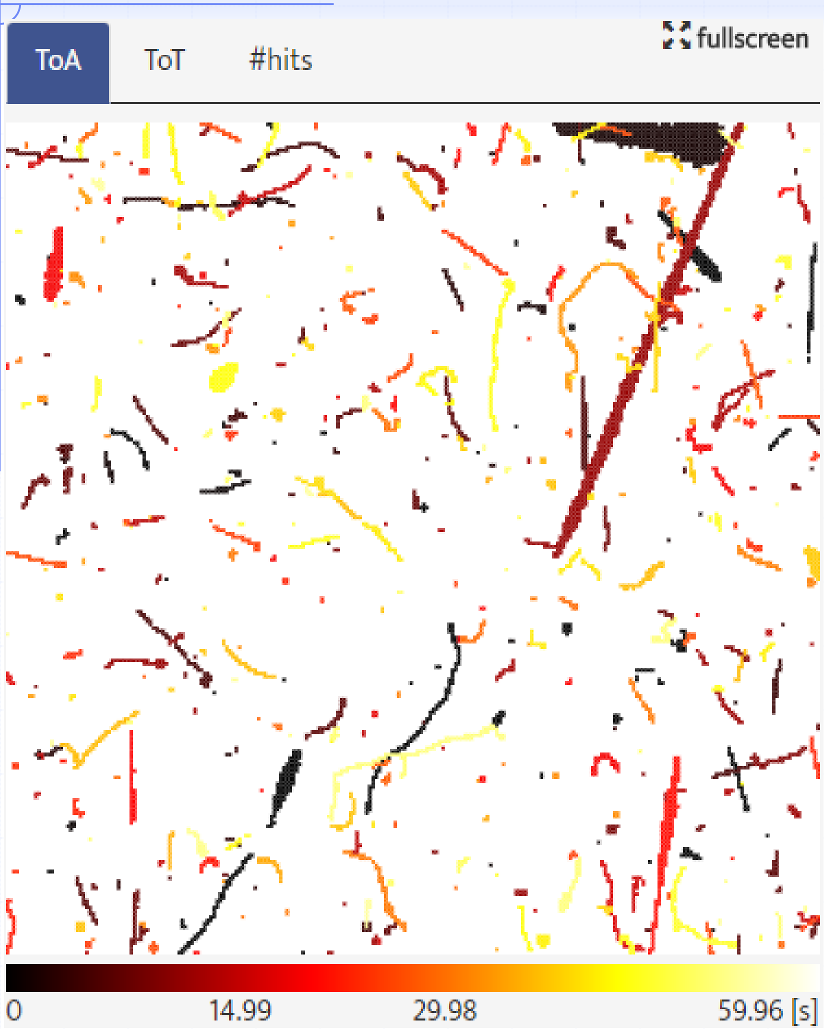
Sample of clusters measured during the collision period by ATLAS-TPX 01 (500 μm sensor)

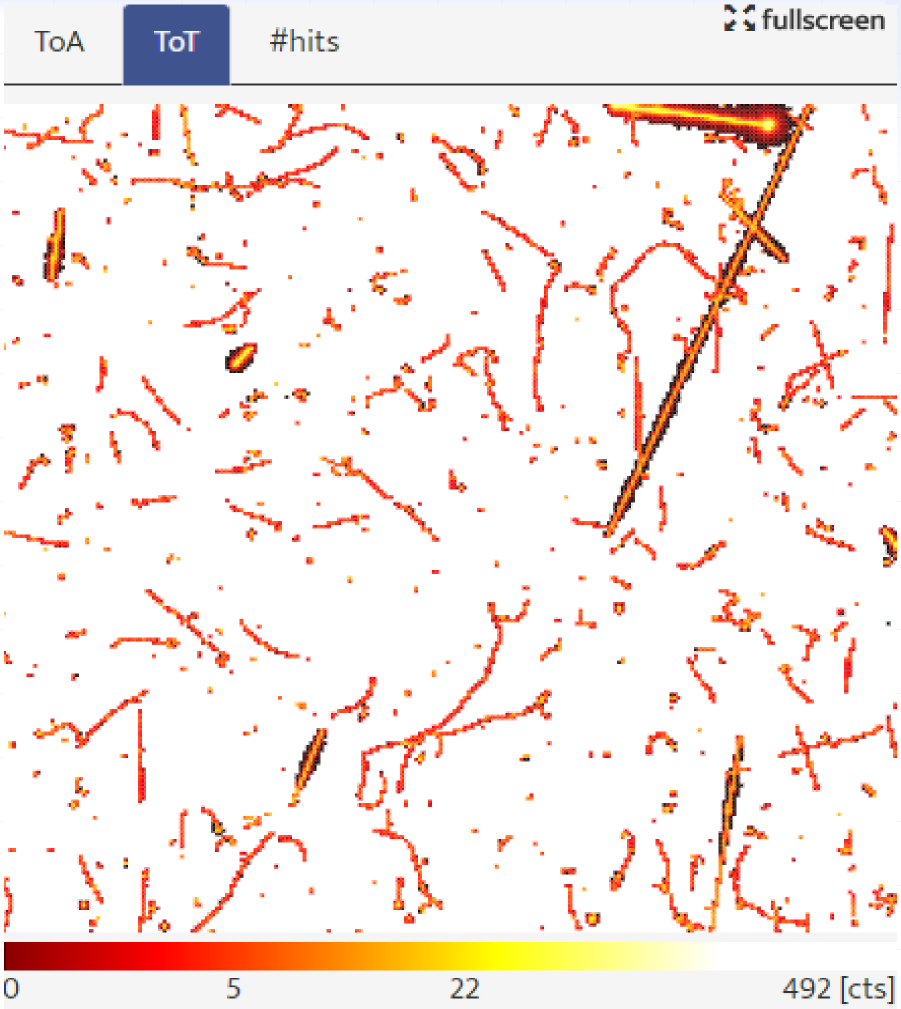
selected by means of developed pattern recognition procedure



Composition of radiation environment in Central barrel region of ATLAS experiment

60s „frame measured during the LHC beam-beam collisions





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Detail view on bunch-bunch collisions recorded by ATLAS-TPX3 device synchronized with LHC

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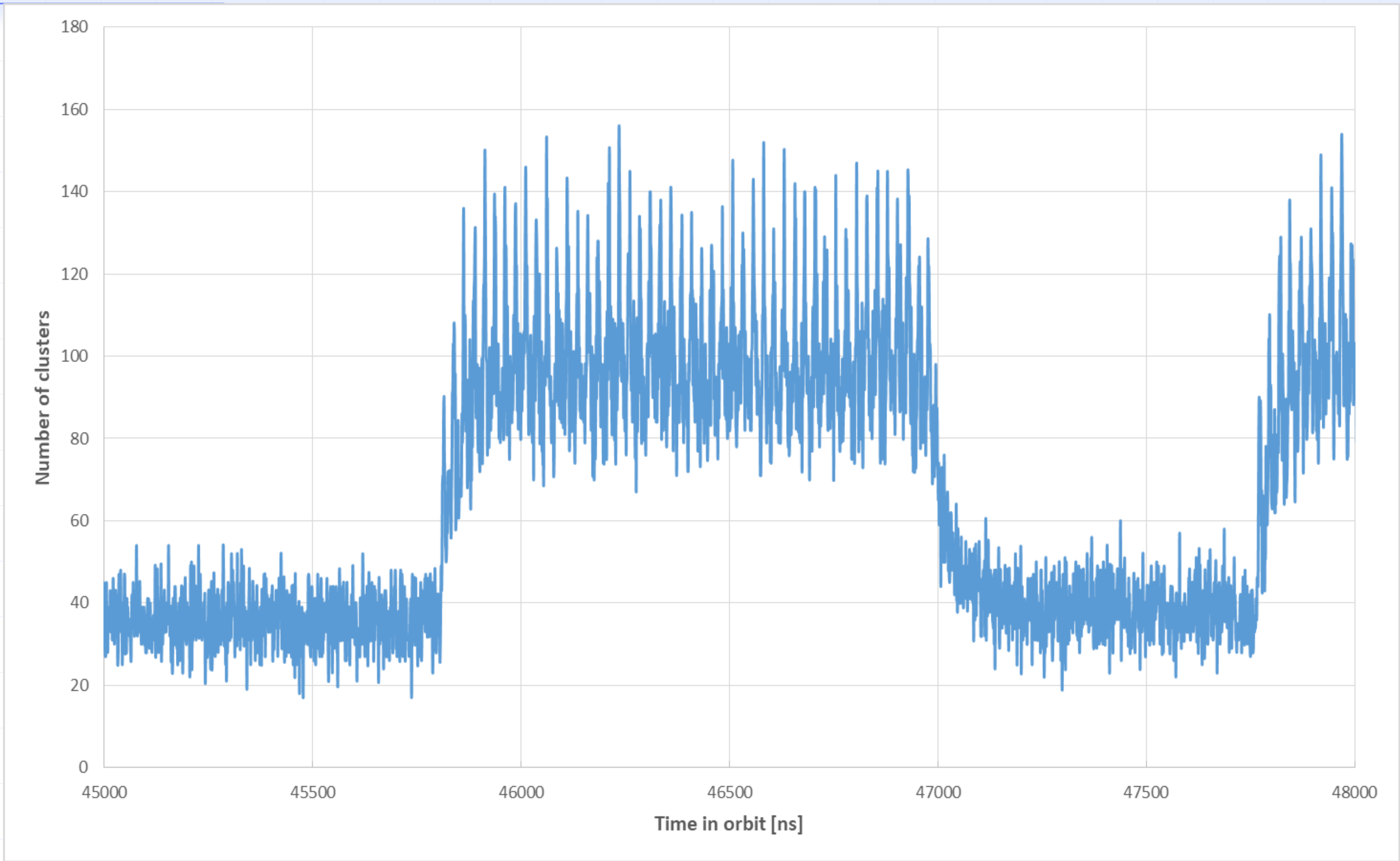

Composition of recorded cluster during individual bunch-bunch colissions including operational radiation background

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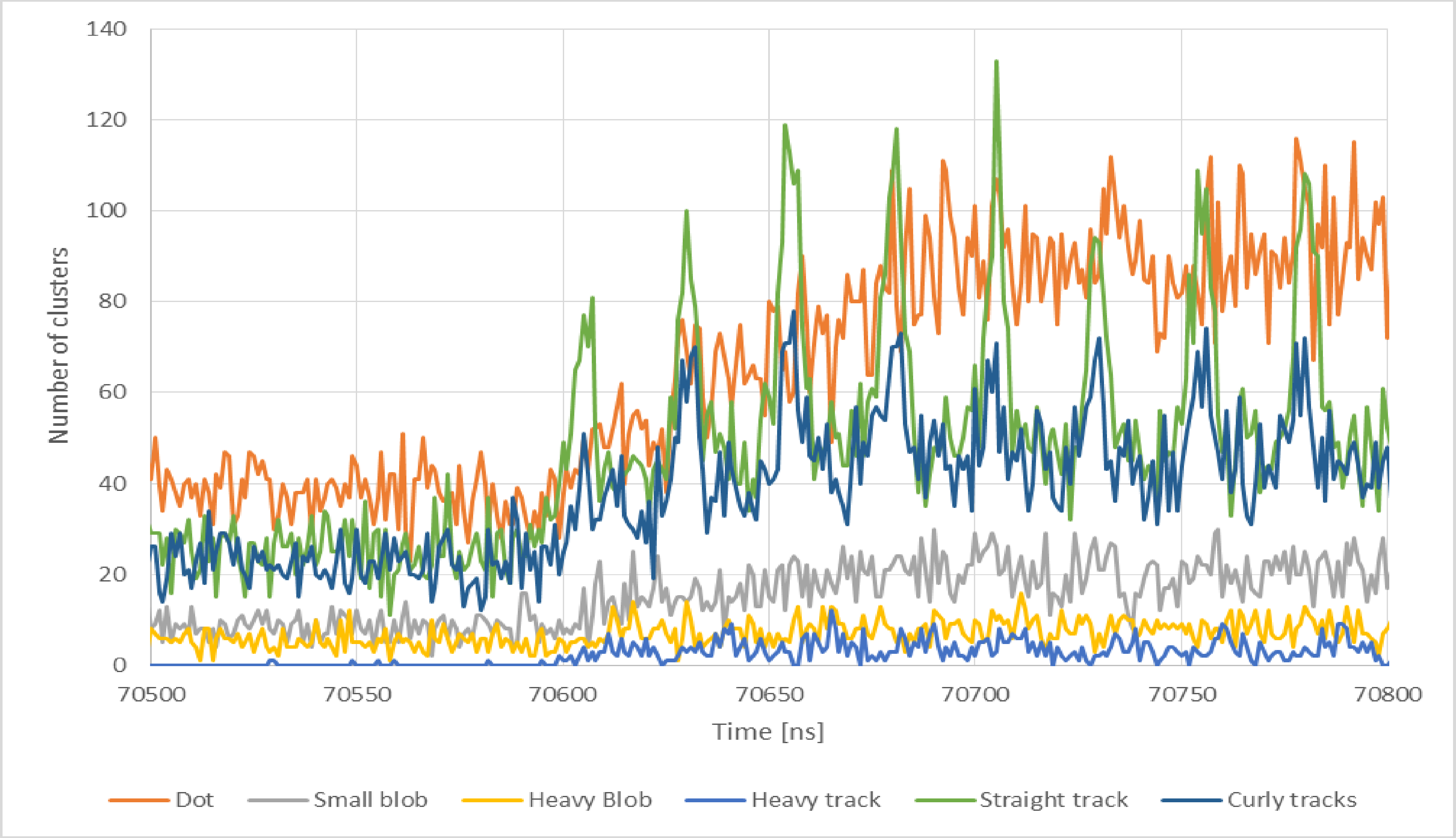

Straight tracks (MIPS) and curly tracks dominating periodically within 2.5 ns bunch-bunch collisions

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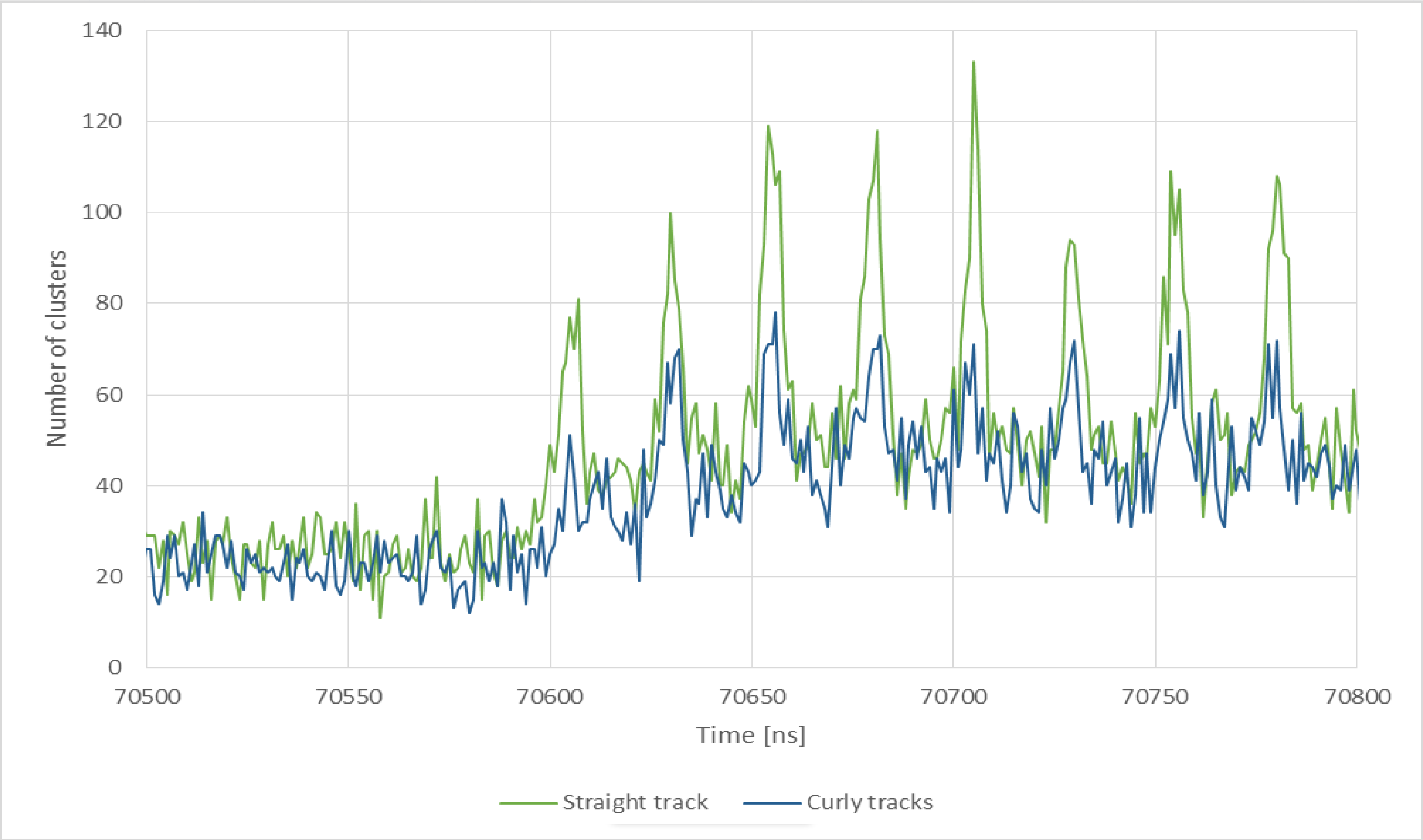

Recorded tracks of particles generated during an individual bunch-bunch collision of the LHC beam supperposed on radiation background in ATLAS

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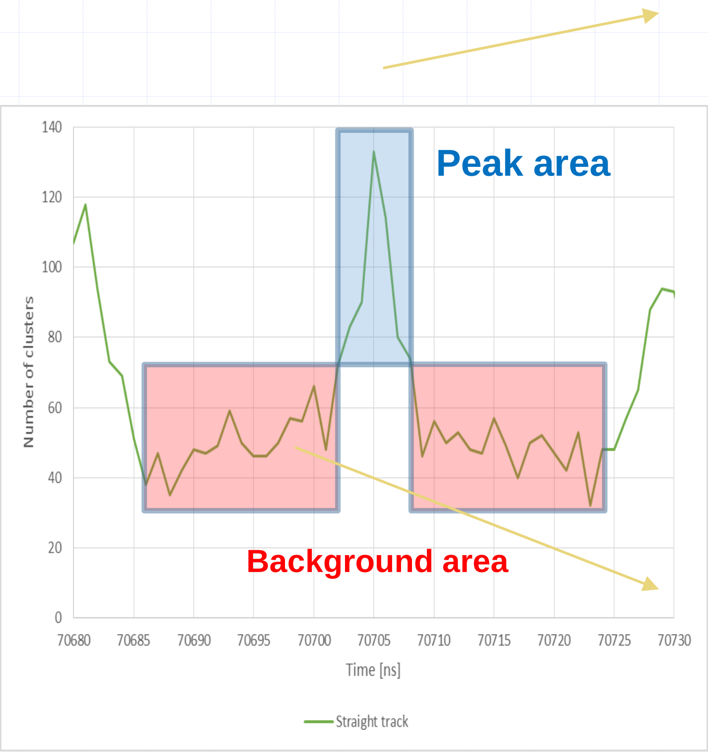
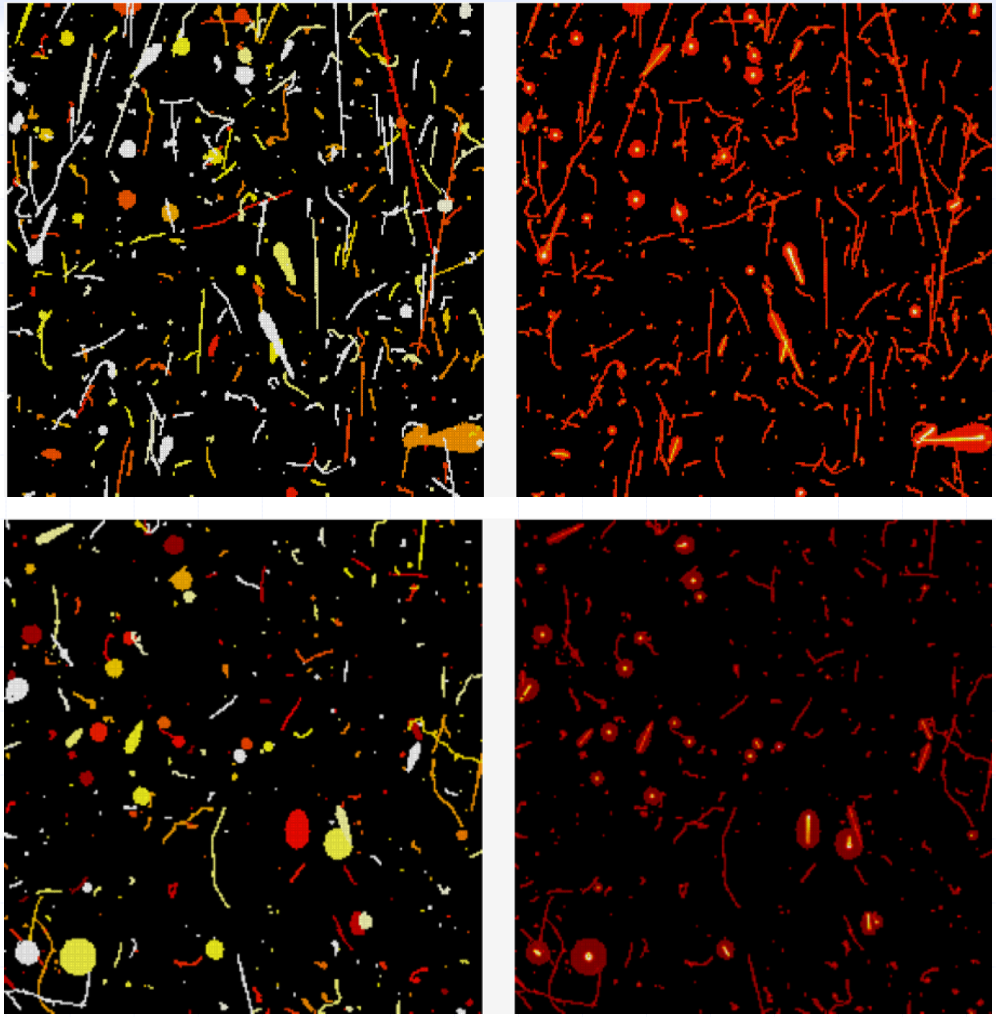
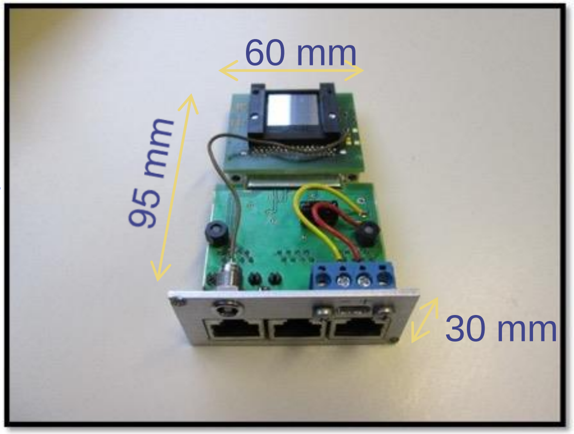


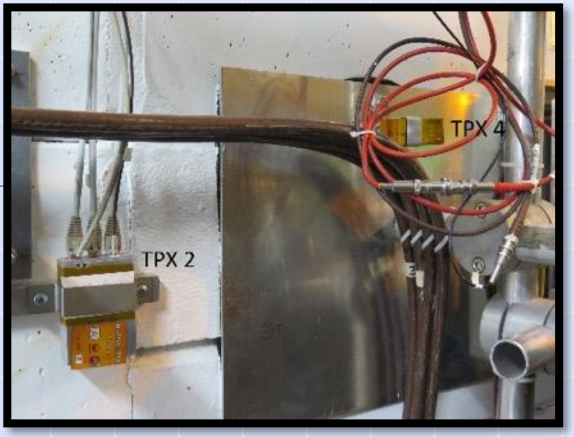


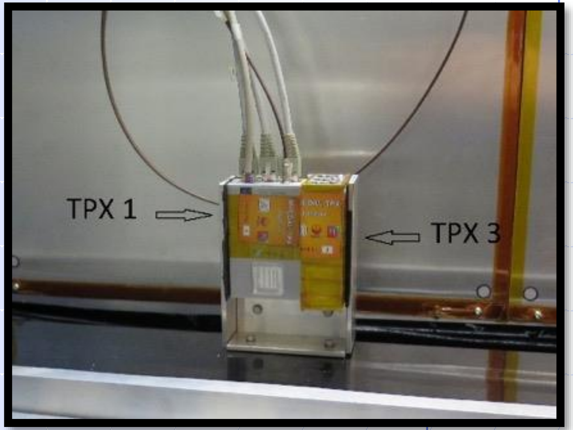
The TPX devices in the MoEDAL network

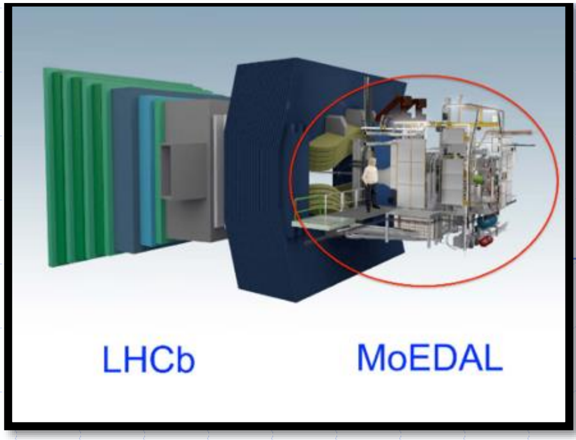
5 Timepix detectors of different thicknesses (300 µm and 1000 µm, 1 of them equipped with neutron converters) placed in chipboards with radiation tolerant electronics installed in the MoEDAL at LHC

2013







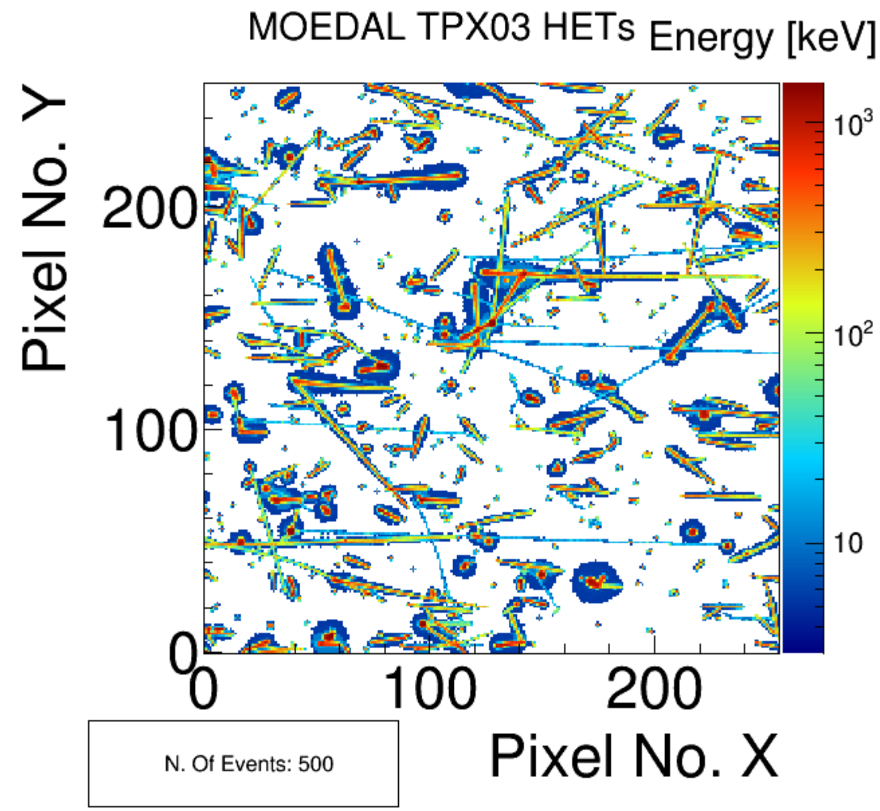


Timepix devices in the MoEDAL experiment

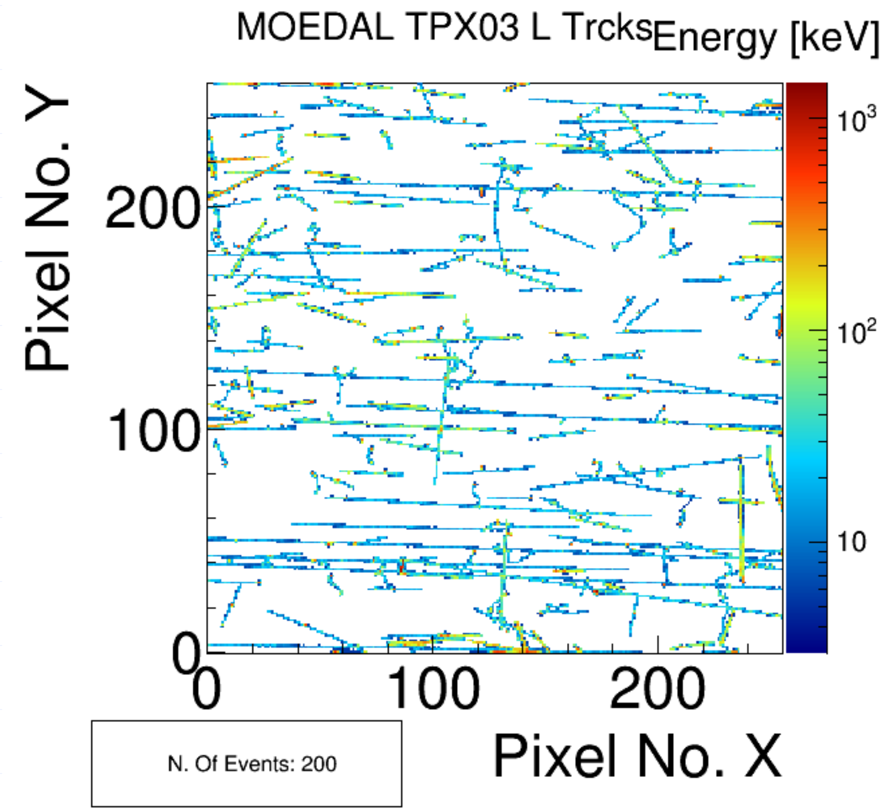
Selected tracks observed with MOEDAL TPX03

12/09/2015

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



Long Tracks
(Min Clstr Height: 300 keV)



Directionality of the particles recorded in MoEDAL experiment at LHC in proximilty of the IP
(25th November Angle Plots E05-W0036)

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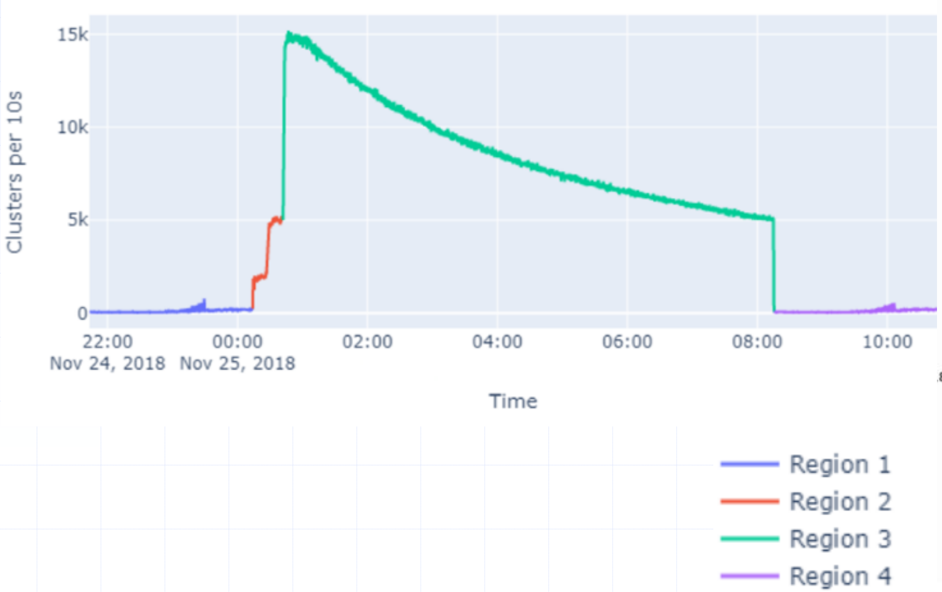
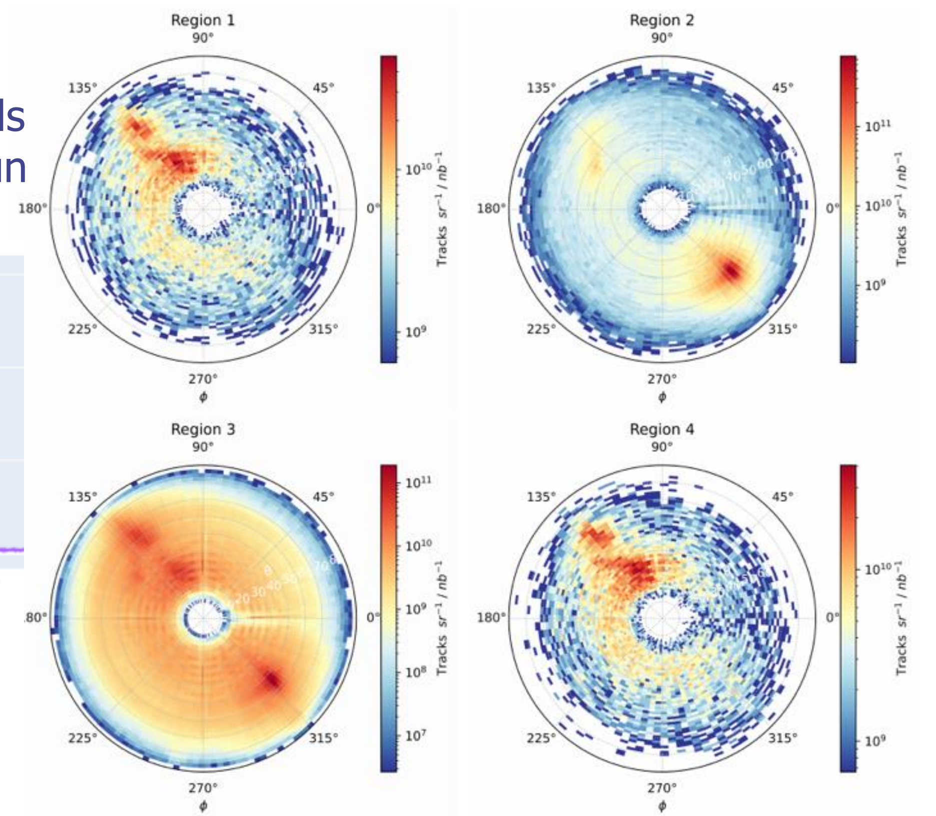
- Polar plot shows phi going round anti-clockwise, theta going radially outwards
- Timeline shows regions analysed on run





Directionality of the particles recorded in MoEDAL experiment at LHC in proximilty of the IP
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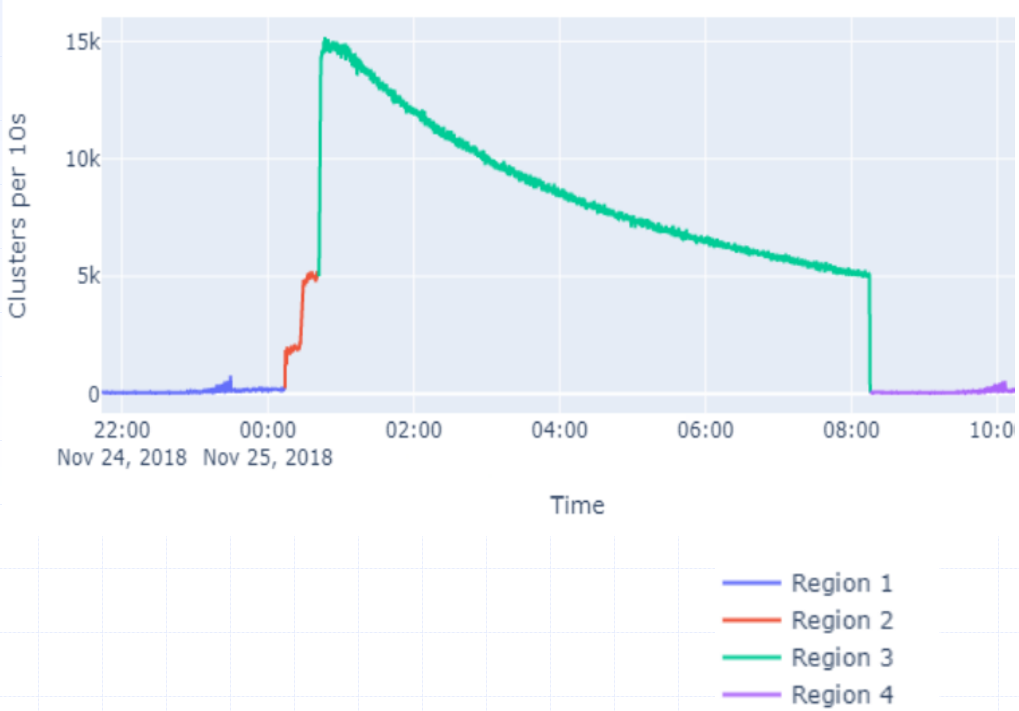

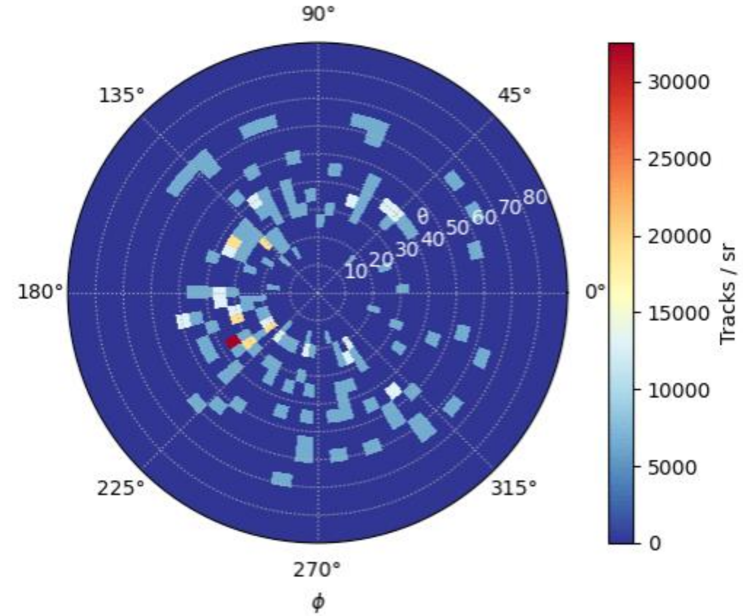

The IEAP CTU Timepix device in ISS cupola plugged in laptop of Chris Cassidy, NASA astronaut

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Courtesy of L-Pinsky, UoH)

Typical frame recorded on ISS with exotic track

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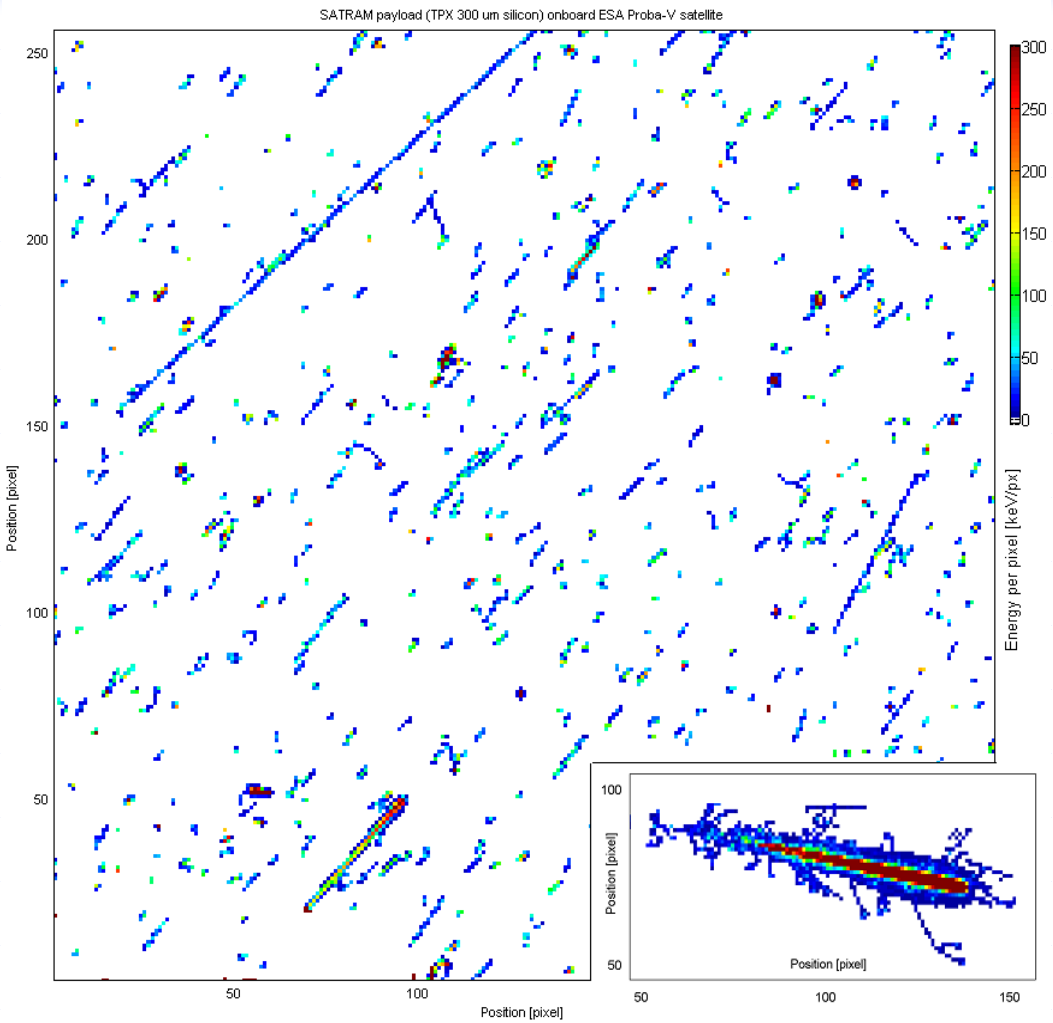


ESA Vega-2 rocket – May 2013

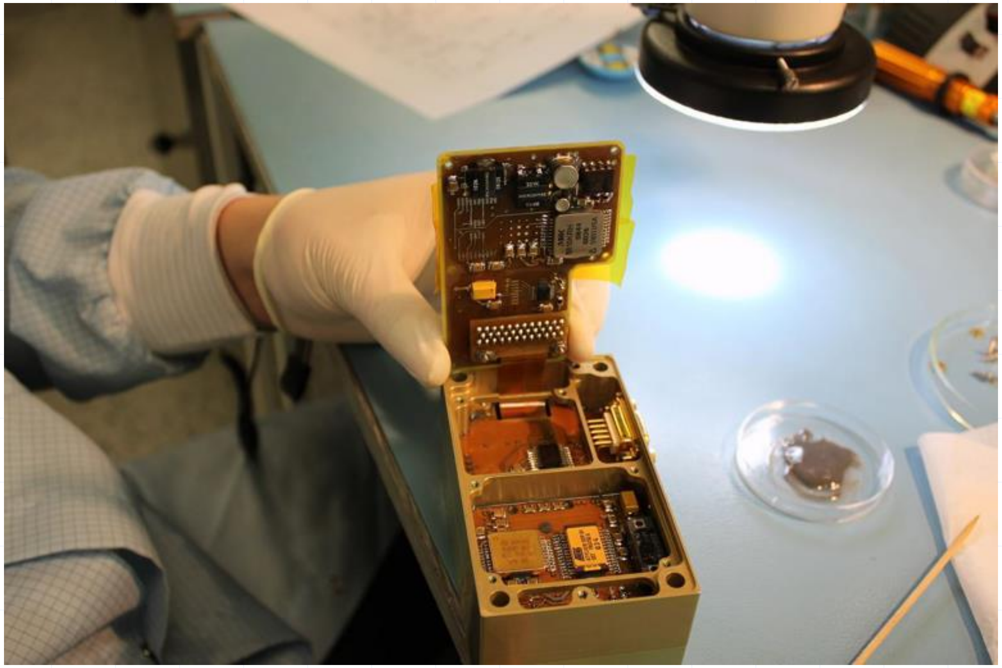
- SATRAM payload (arrow) onboard ESA Proba-V satellite.
- ESA Vega-2 launcher rocket upper stage

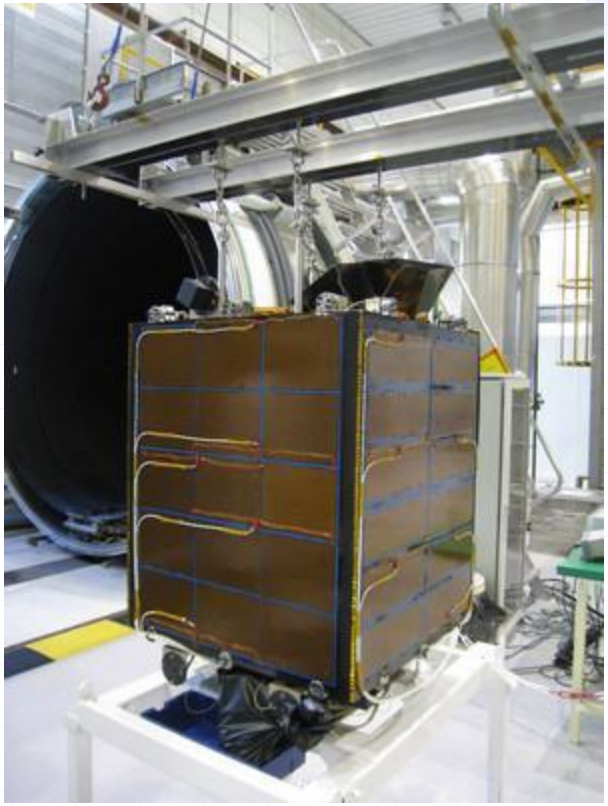
Dosimetry in space:
SATRAM – ESA Proba-V satellite

2013

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

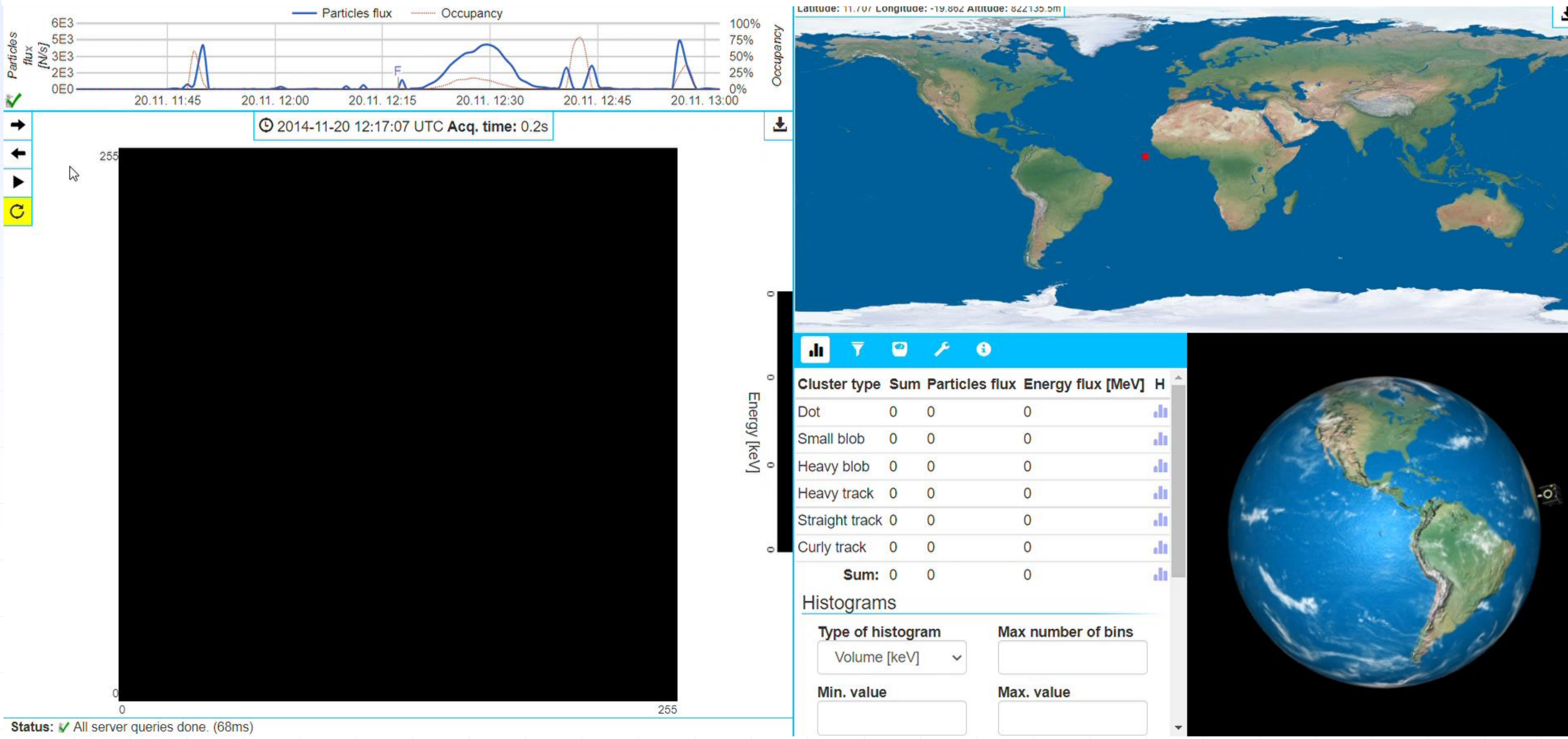




proba VEGETATION

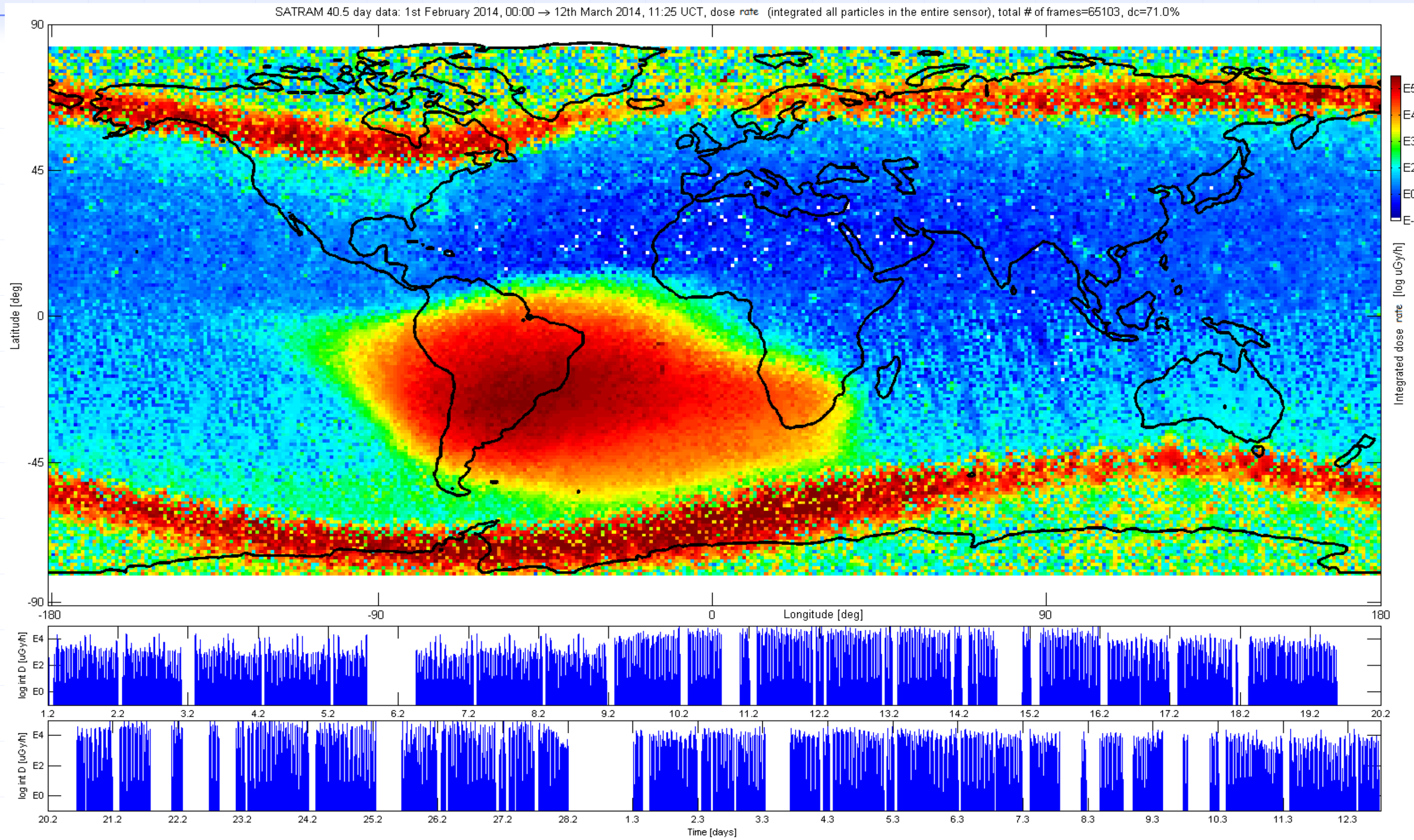
SATRAM has been primarily dedicated to measurement of so called Sun weather

(on-line acces to https://satram.utef.cvut.cz/)



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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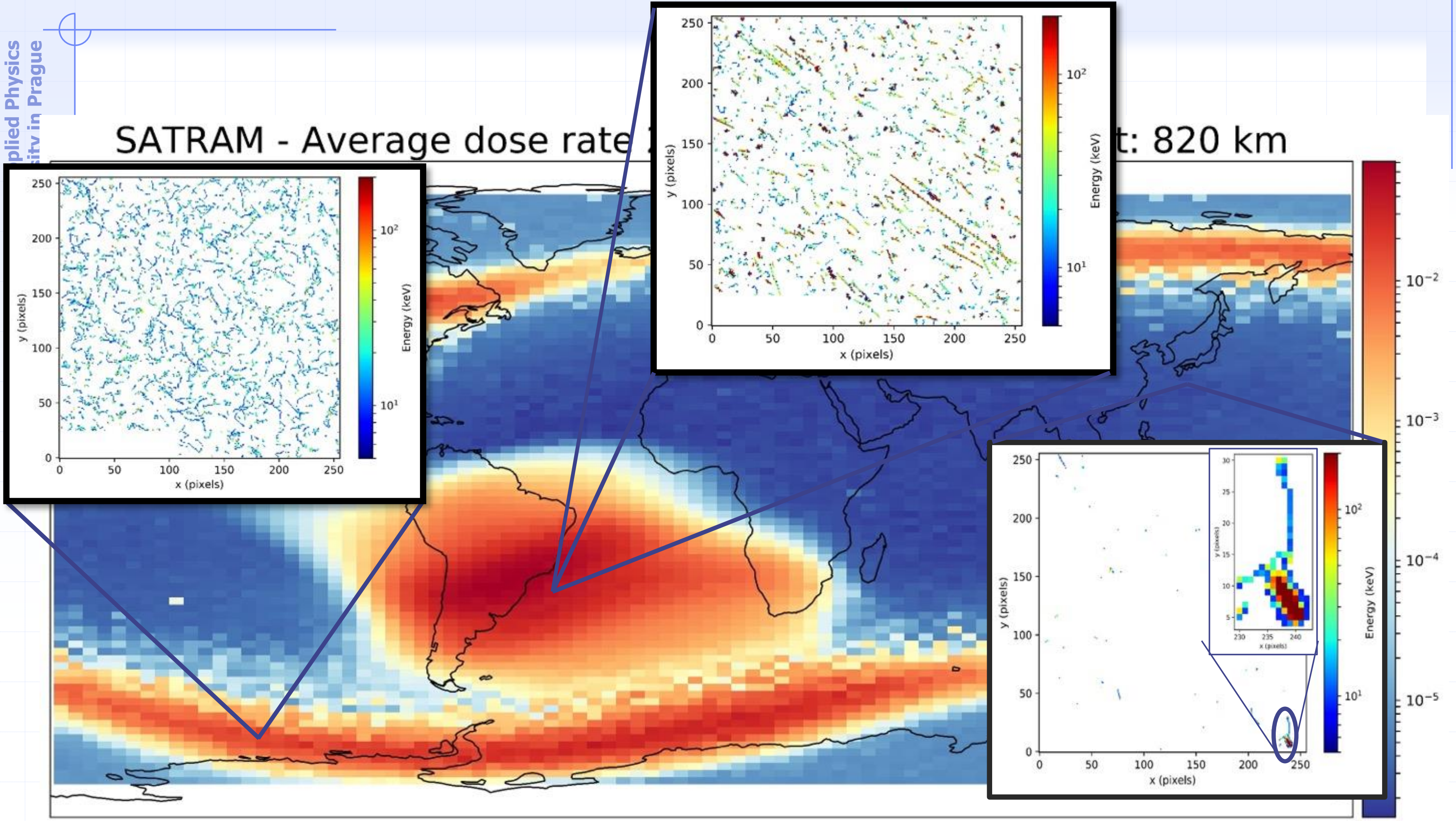
SATRAM

Average dose rate 2015-2018 in Mgy/h on orbit 820 km



Timepix/ESA Proba-V:

LEO space radiation @ 820 km

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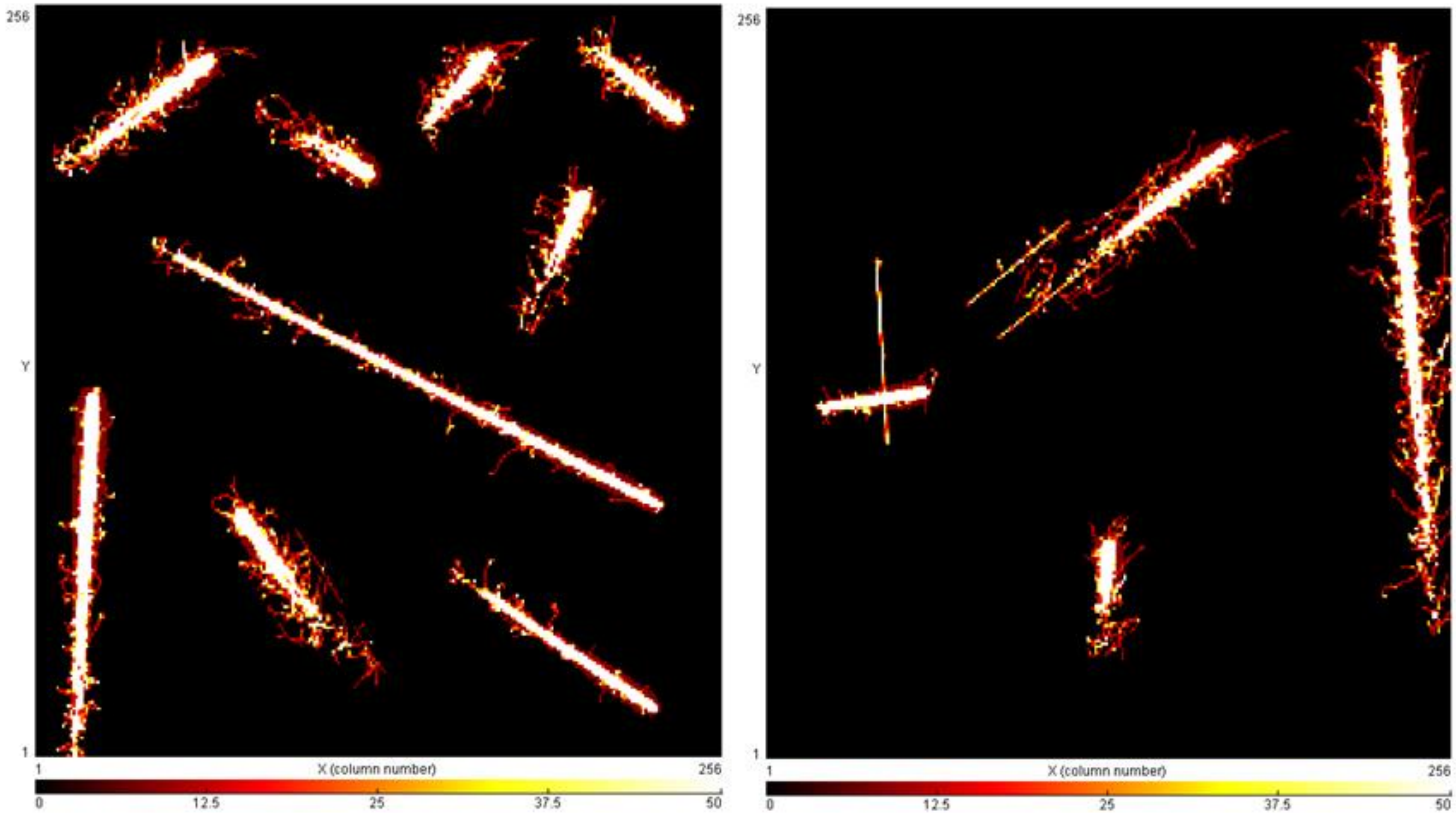
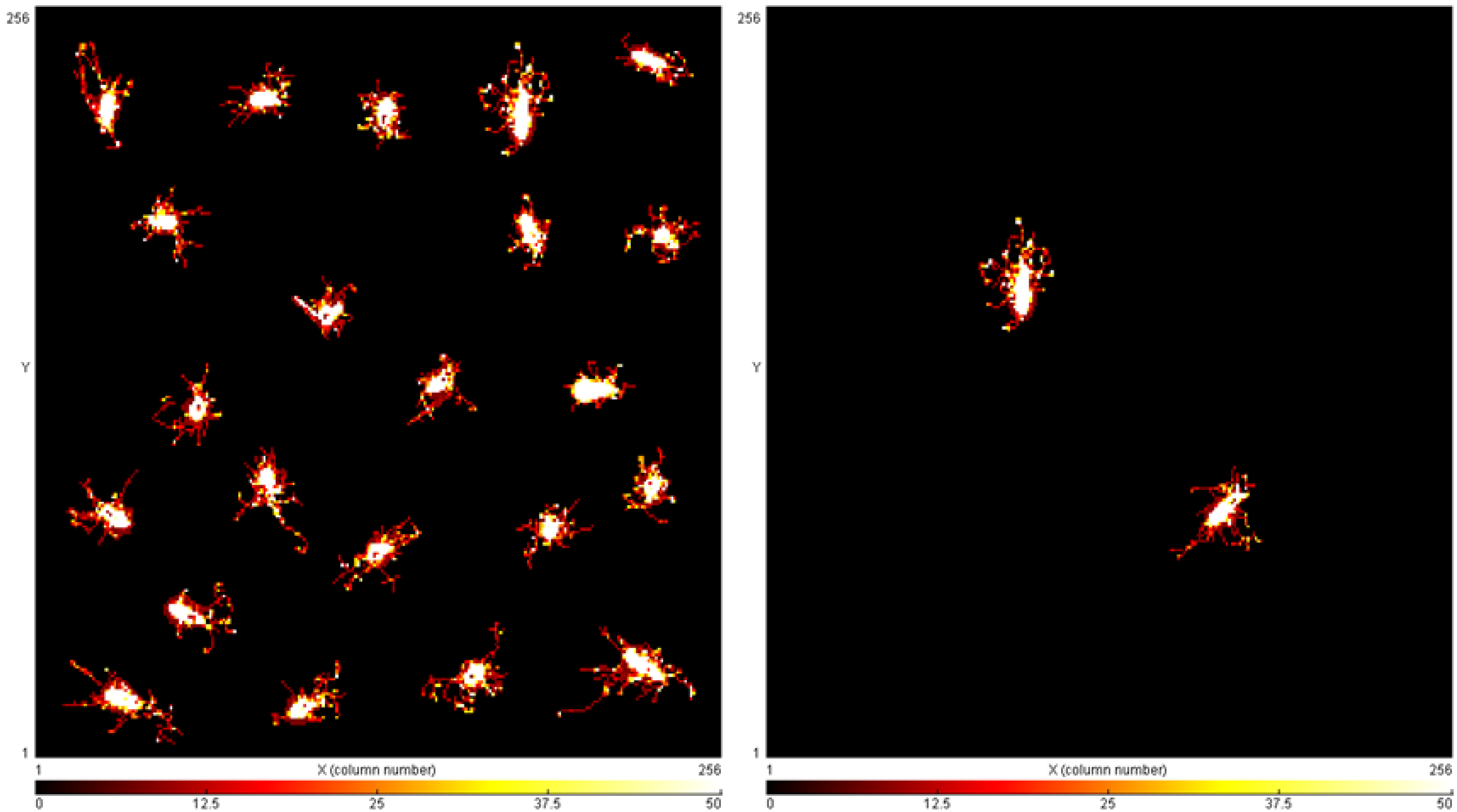
HETPs: Highly energetic heavy charged particles (ions) → HZE's



Timepix/ESA Proba-V:

LEO space radiation @ 820 km

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



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

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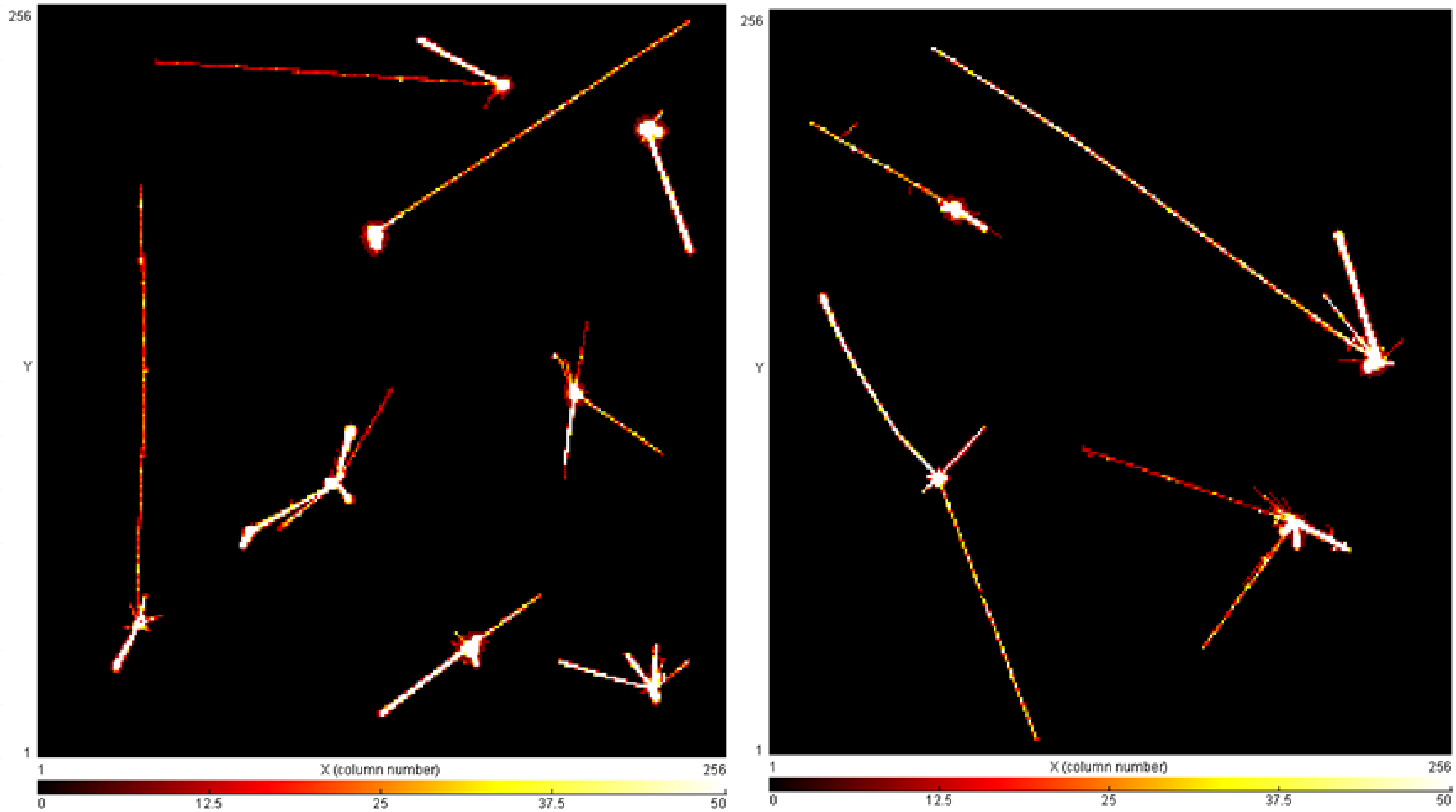
LETPs: Energetic light charged particles (I) + nuclear interactions



Horizon 2020
European Union Funding
for Research & Innovation

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I E A P

X.Wu et al., Penetrating Particle ANalyzer (PAN), Adv. Space Res. 63, 8, 2672-2682 (2019) https://doi.org/10.1016/j.asr.2019.01.012

http://www.pan-space.eu/

Development of a demonstrator penetrating particle analyzer (**mini.PAN**) for deep space missions

Penetrating Particle Analyzer

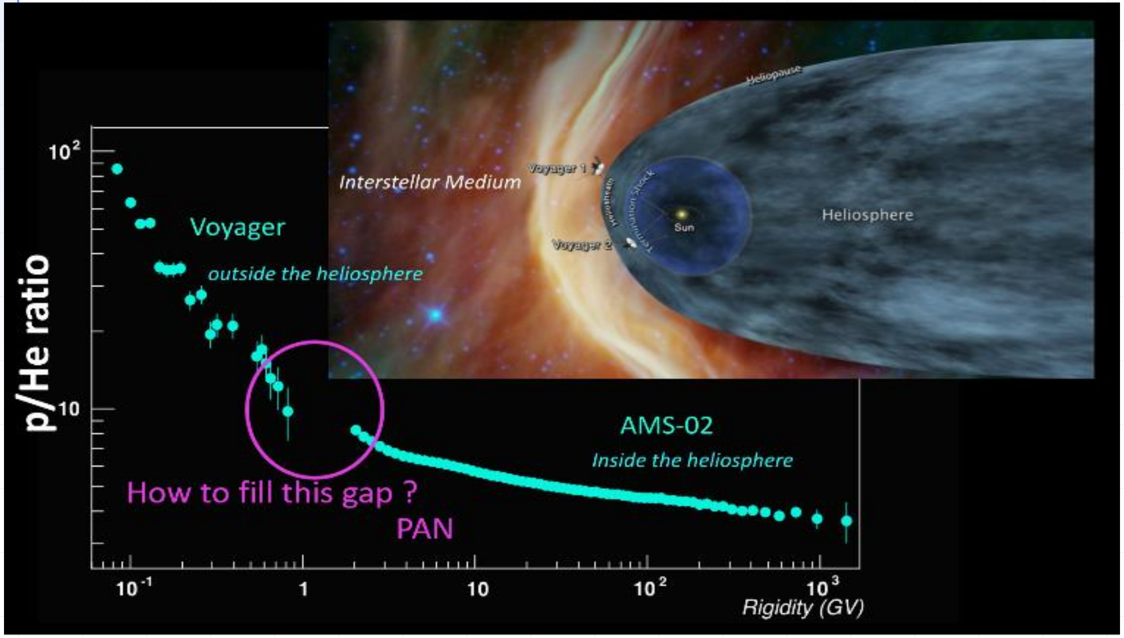
INSTITUTE OF EXPERIMENTAL AND APPLIED PHYSICS CTU IN PRAGUE

UNIVERSITÉ DE GENÈVE

INFN PERUGIA

Scientific objectives of mini.PAN

Precisely measure and monitor flux, composition, and direction of penetrating particles (up to ~20 GeV/nucleon)



Galactic cosmic ray (GCR) physics:

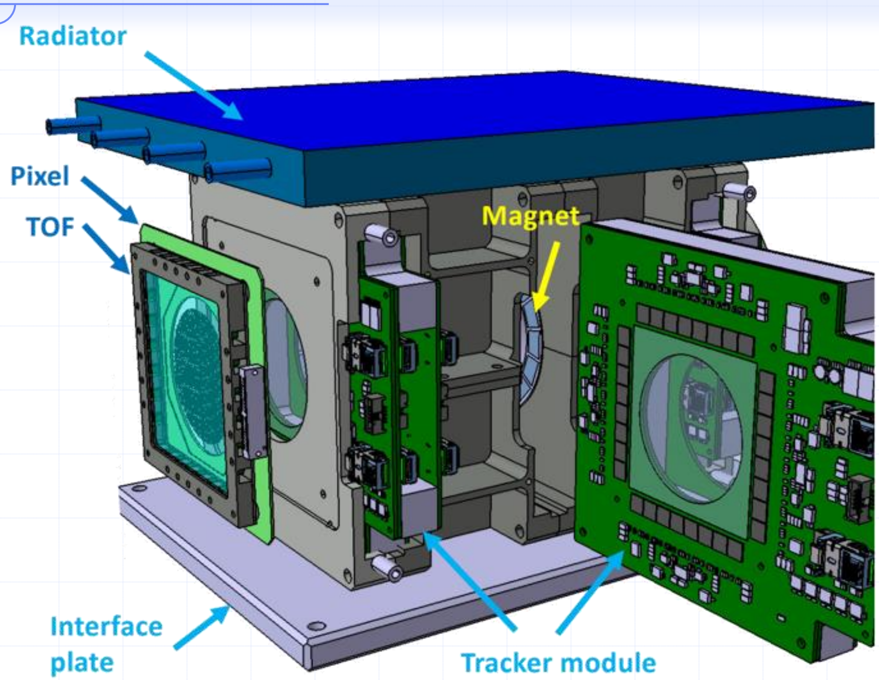
- Understand origin, acceleration mechanisms and propagation properties
- Antimatter content

Dosimetric aspect:

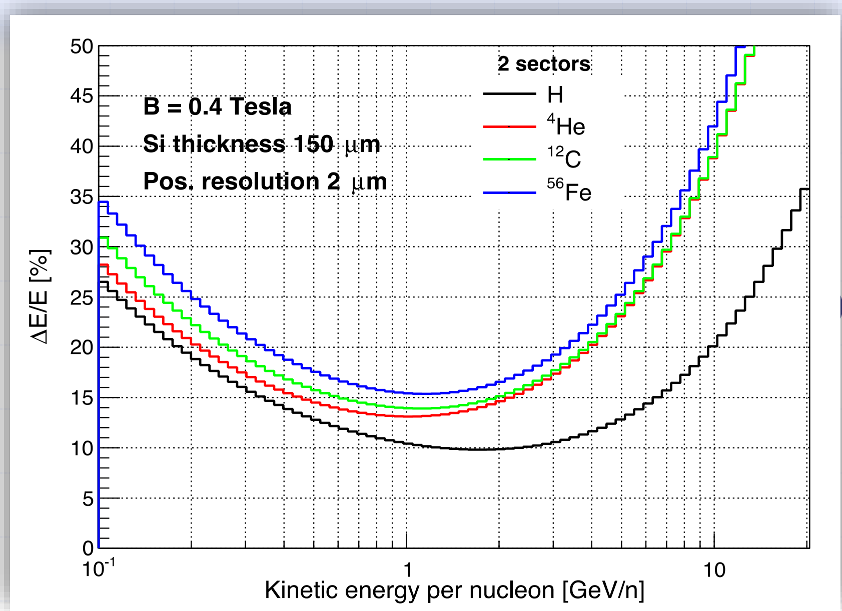
- GCR major source of dose for astronauts on (interplanetary) missions

Conceptual design

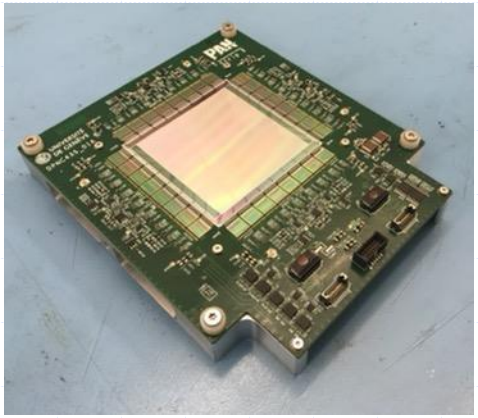
Mini.PAN ~10 kg, ~20-30 W



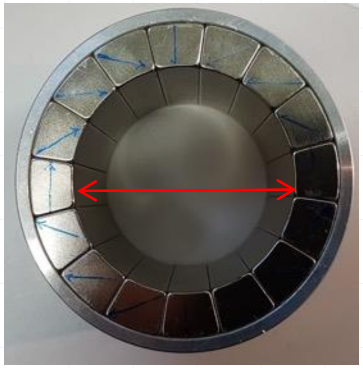
Expected performance:



Pixel module



Permanent magnet block
NdFeB, B = 0.4 Tesla
- outer Al-ring dia. 120 mm
- inner diam.



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Performance consideration on Pix.PAN project based on Timepix4 technology

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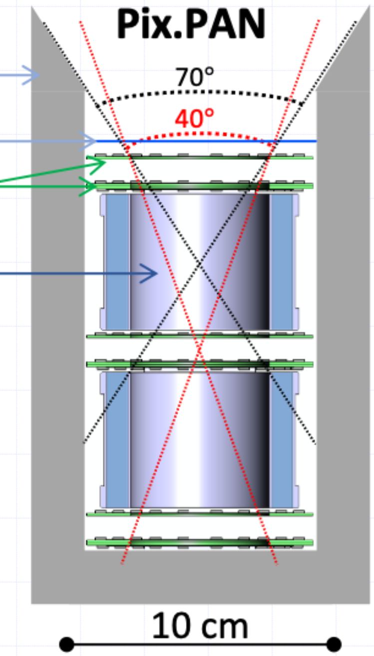
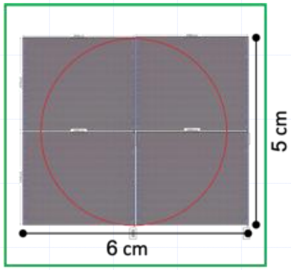
Mini.PAN with 3 tracking station consisting of 2 Timepix4 quads as sensing element

→ Significant simplification of mini.PAN
→ Add high-rate capability
→ Self-triggered operation in data-driven mode
→ 5D vector $(\vec{x}, t, \frac{dE}{dX})$ with $\Delta t < 200$ ps in each station





Requirements/challenges:

- Thin sensor and ASIC (total thicknesss < 400 µm)
- Synchronization of 24 Timepix4 with low jitter
- Desired power consumption < 20 W (vs 60 W)
- Bending direction spatial resolution needed is < 5µm (vs current Timepix4 baseline design 16 µm)

Outlook:

- The Timepix detector's capability of single-layer particle tracking and particle recognition represents radiation monitors with one order of reduction in mass lower

- Latest generation of Timepix detectors could be the **baseline for particle spectrometers for astroparticle physics**

Acknowledgement

The presented results have been achieved within research activities cultivated at IEAP CTU in Prague. They result from extensive partnerships in frame of the Medipix2/3/4 collaboration with significant contributions of the following colleagues:

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[14] ONERA/DPHY, Universitè de Toulouse, France
[15] University of Geneva, Switzerland