Monitoring of Mixed Radiation Fields and Dosimetry with Pixel Detectors

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Outline

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Introduction

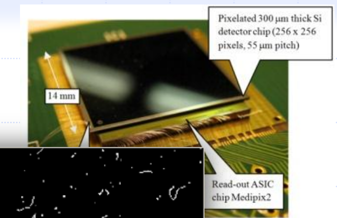
- Particle tracking with Timepix
- MIPs, Ions
- Charge sharing effect can be very benefitial

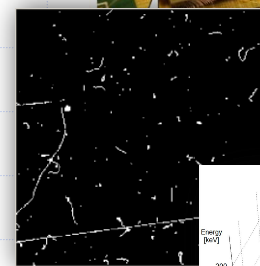
From 2D to 3D: Voxel detector

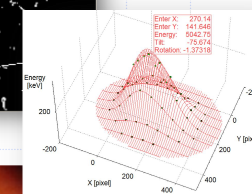
Applications

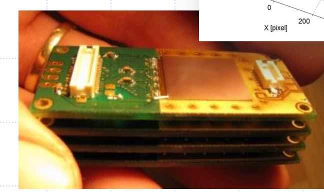
- Imaging based on particle tracking for hadron therapy
- Space dosimetry: Dosimeter for ISS
- ATLAS radiation monitor

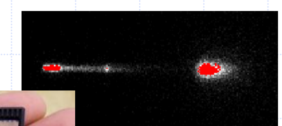
Work performed in frame of Medipix collaboration.

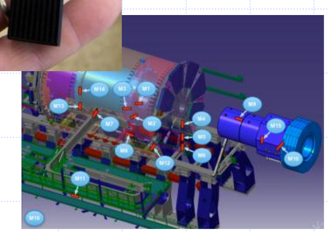












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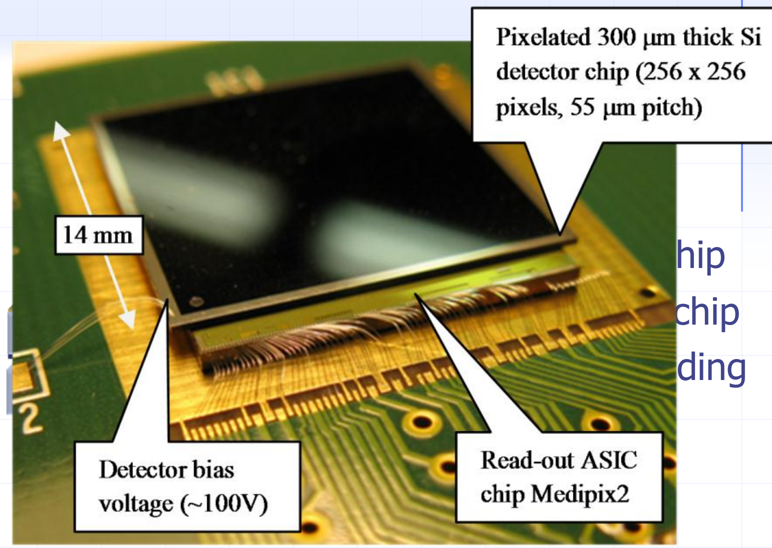
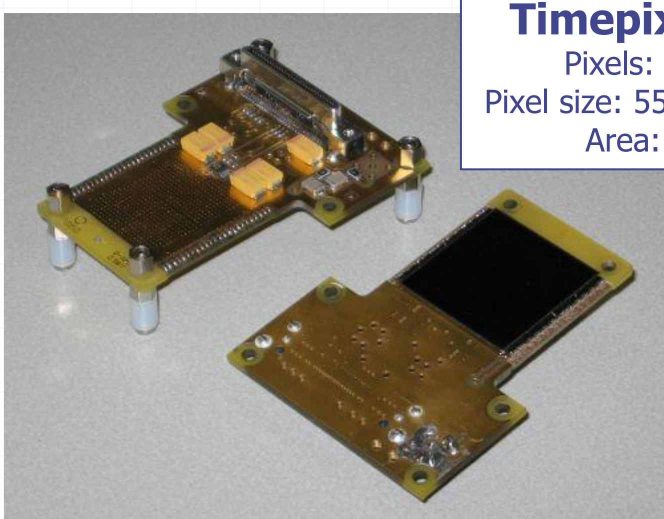
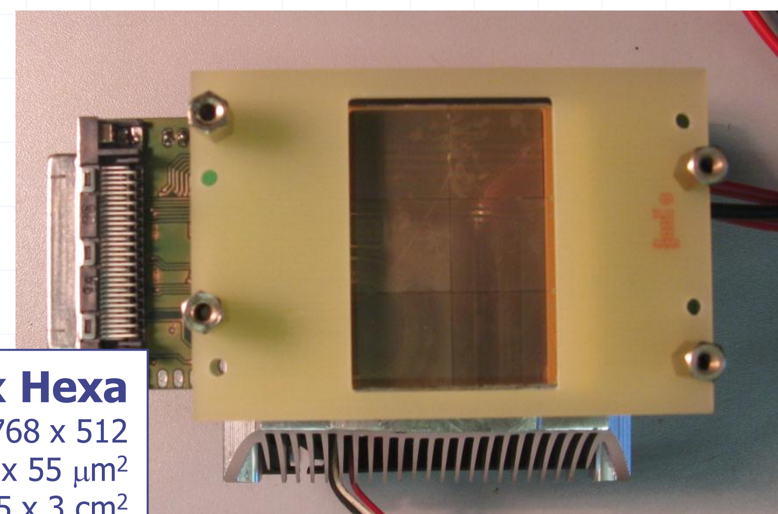
Timepix pixel device
single particle counting pixel detector

- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or **ADC** or Timer
- Multichip assemblies with no blind area: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)





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



Timepix Hexa
Pixels: 768 x 512
Pixel size: 55 x 55 μm^2
Area: 4.5 x 3 cm^2

Particle tracking With pixel detectors Timepix

Tracking with planar pixel detectors

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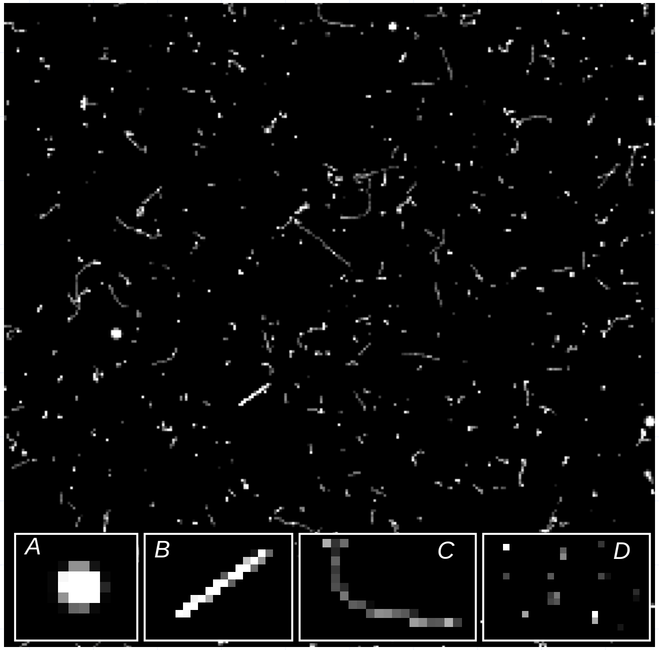
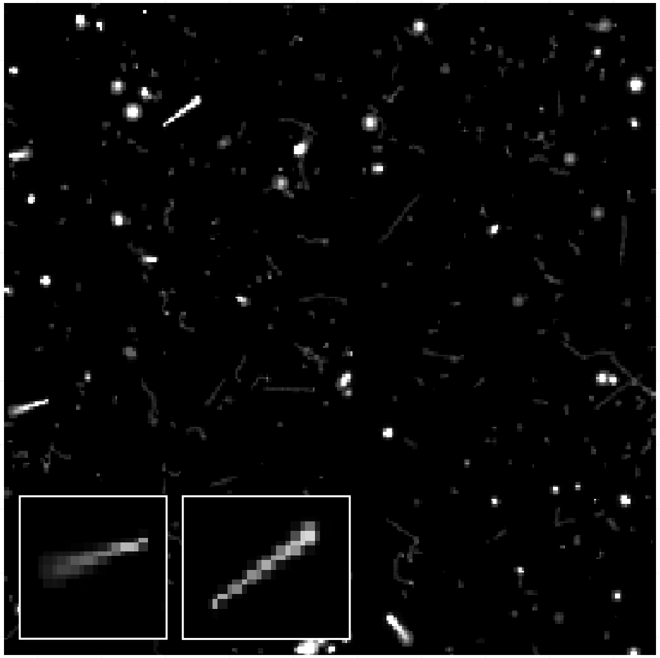
Radiation background

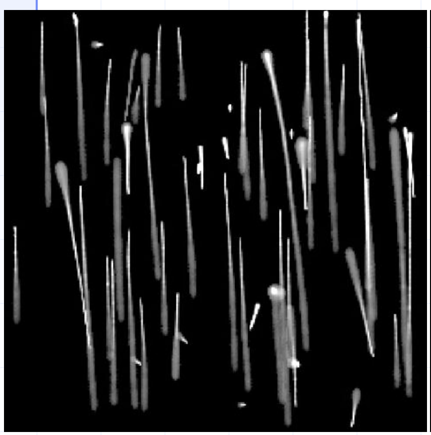


Radiation field with fast neutrons



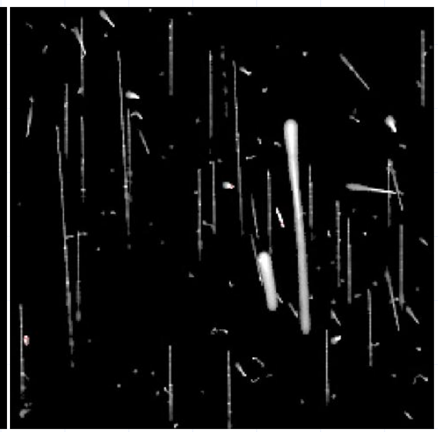
Typical observed images in hadron therapy beam

Protons 48 MeV



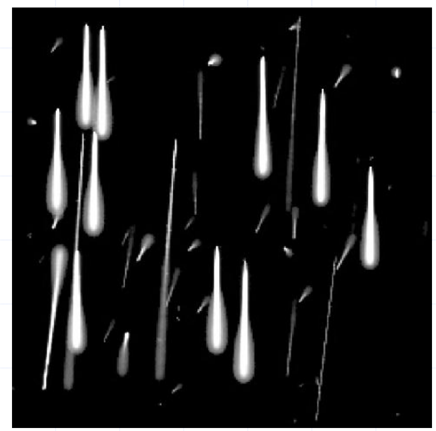
Only protons and their scattering, no secondaries.

Protons 221 MeV



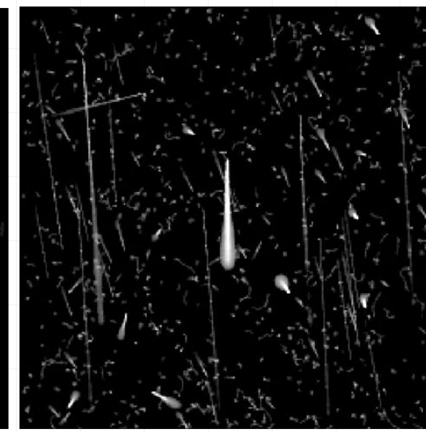
Many secondaries, (delta electrons fragments).

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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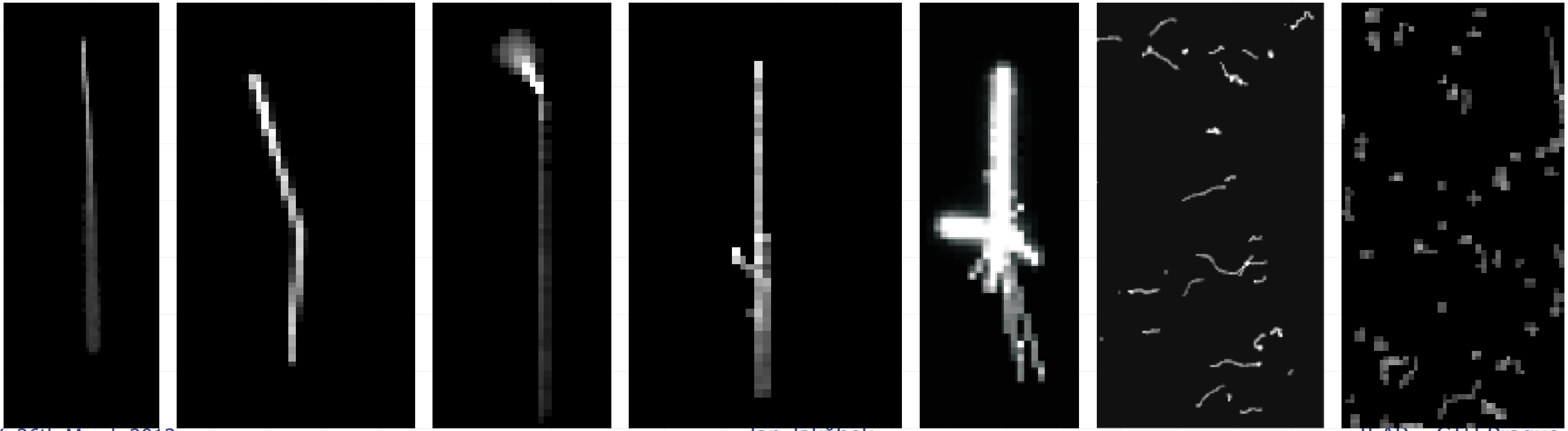
Several basic track types identified:

- 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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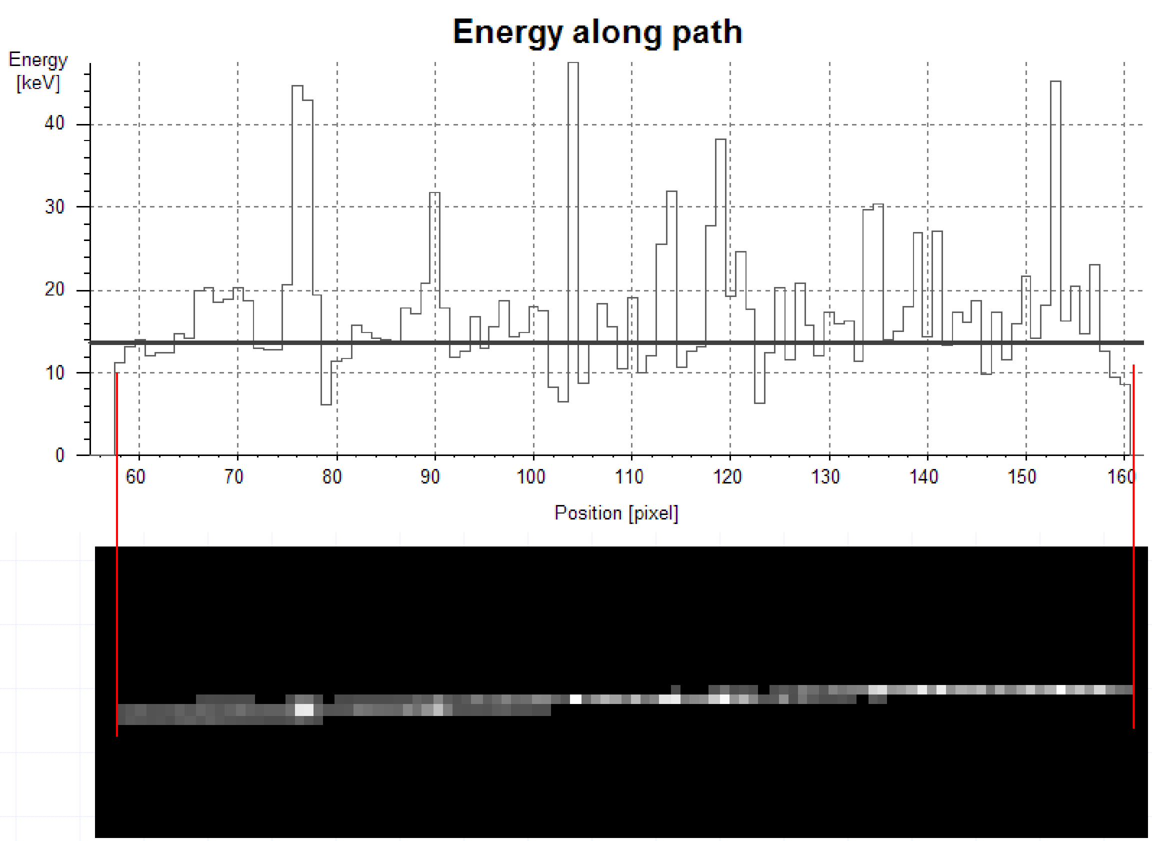
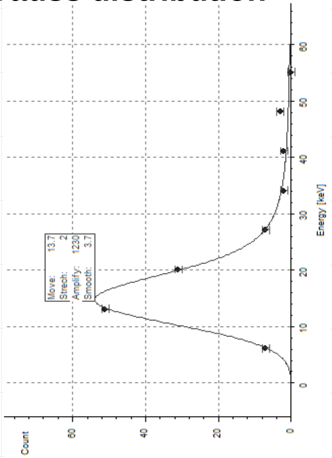
Charge sharing effect:

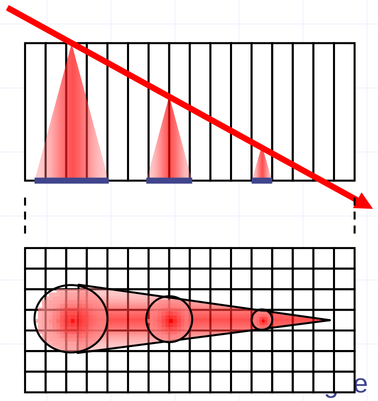
Tracks of MIP particles – Cosmics



Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





Energy mode calibration:

Heavy charged particles?

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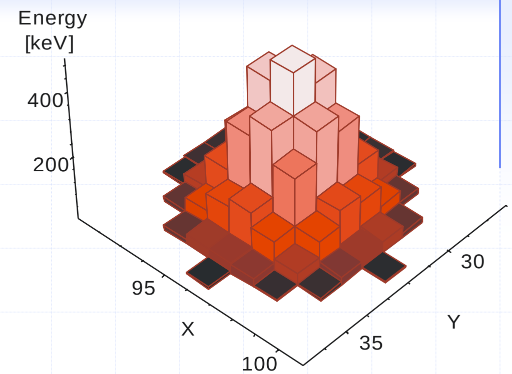
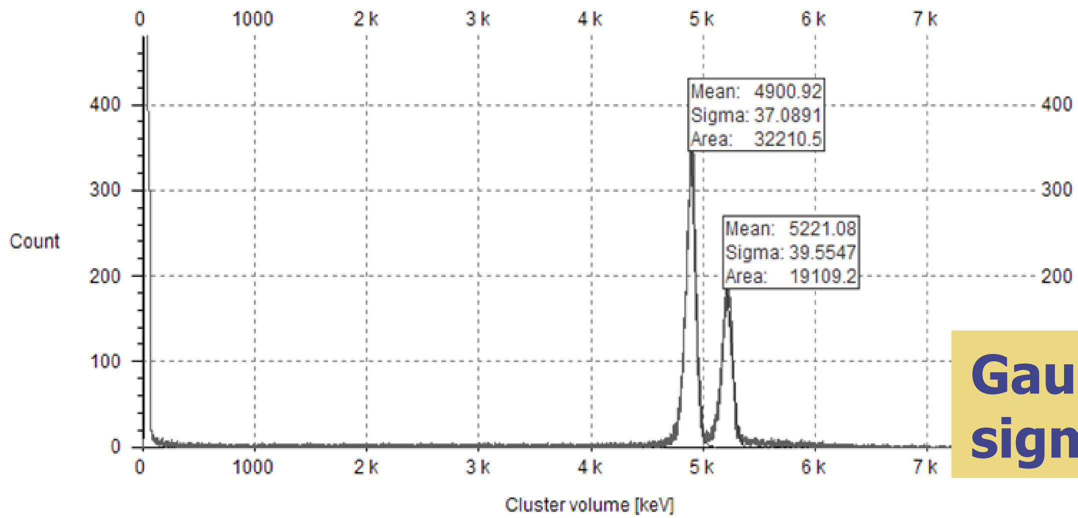
- Test: Am241+ Pu239 combined source
- 5.2 and 5.5 MeV alphas
- Really large clusters
- "Heavy" extrapolation of calibration obtained with X-rays



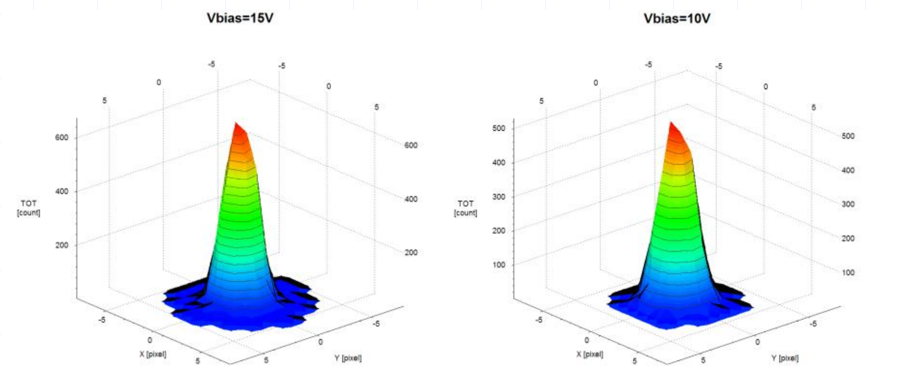
Cluster volume (energy) spectrum (measured in air)

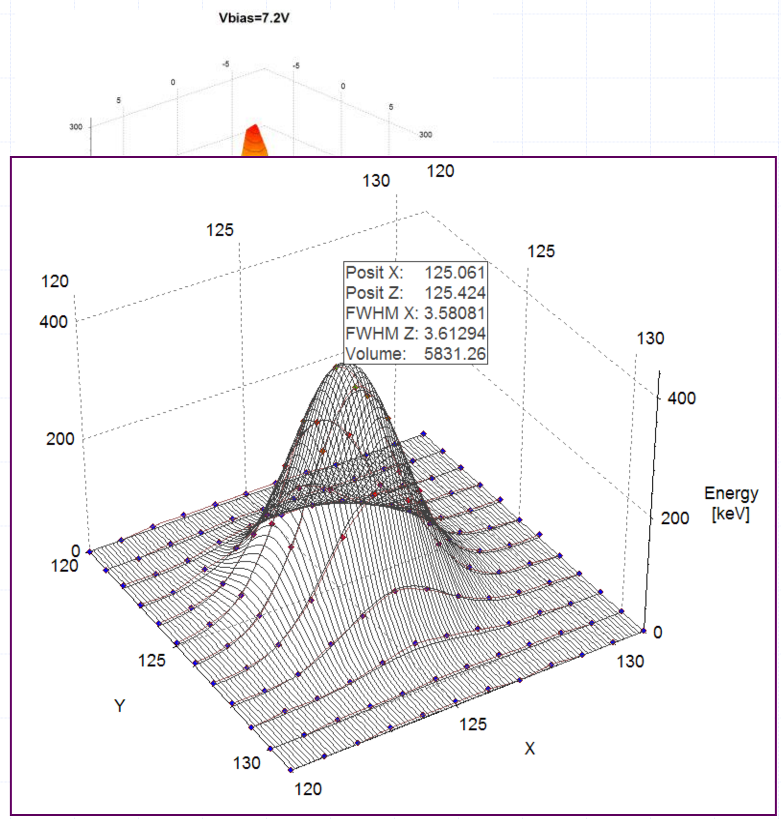


Gaussian fit
sigma = 37 keV

Heavy charged particles:
Subpixel resolution

- Charge sharing and cluster shape depends on detector bias voltage. For low bias a diffusion dominates => **Gaussian cluster shape**





⇒ Subpixel resolution is be reached by Gaussian fit.

⇒ Spatial resolution for 10 MeV alphas is **320 nm** !!

Tracks of ions stopped in Silicon

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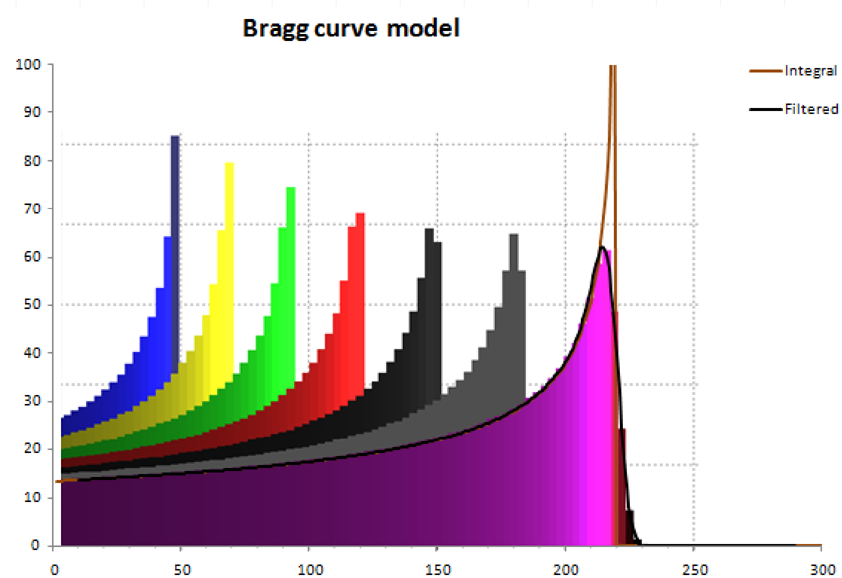
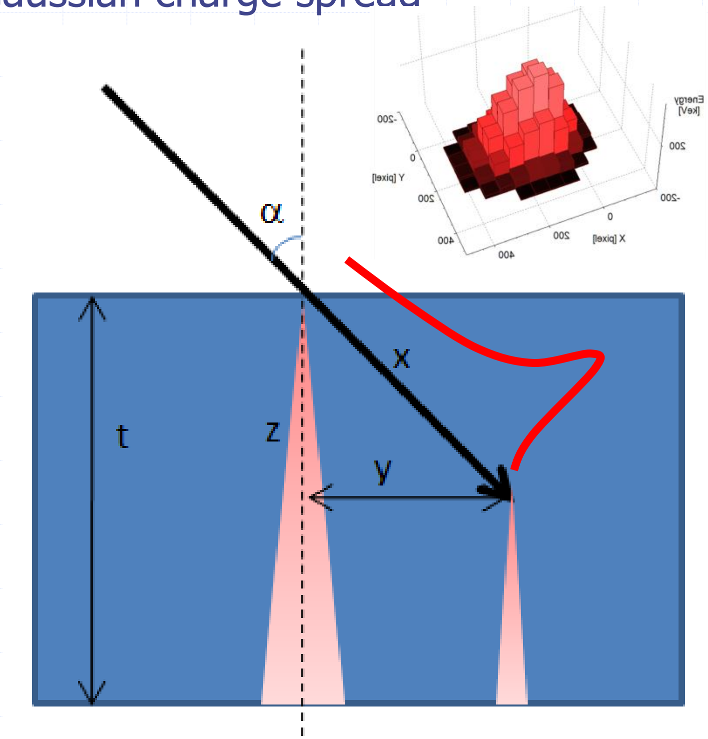
Protons:

- Energy losses defined by Bragg curve
- The charge is collected from different depths
- Low bias voltage => diffusion dominates => Gaussian charge spread





Clusters and fits

1. Brag curve
2. Depth dependence
3. Charge diffusion

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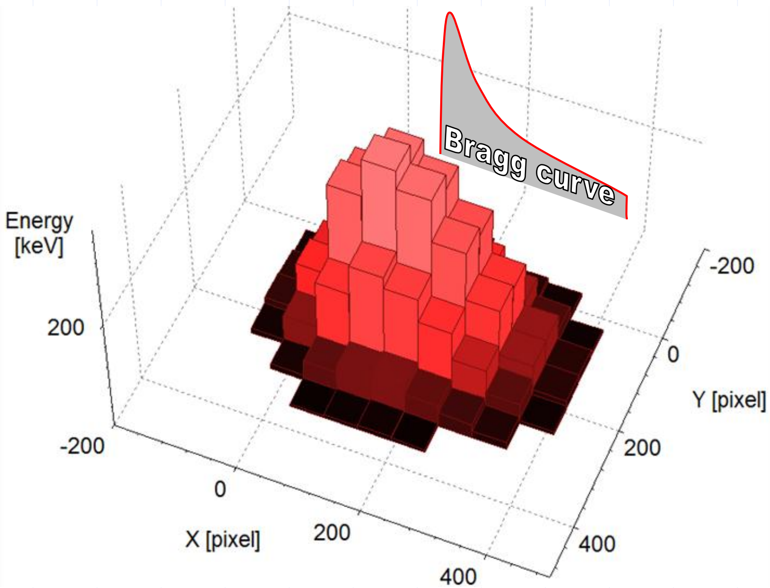

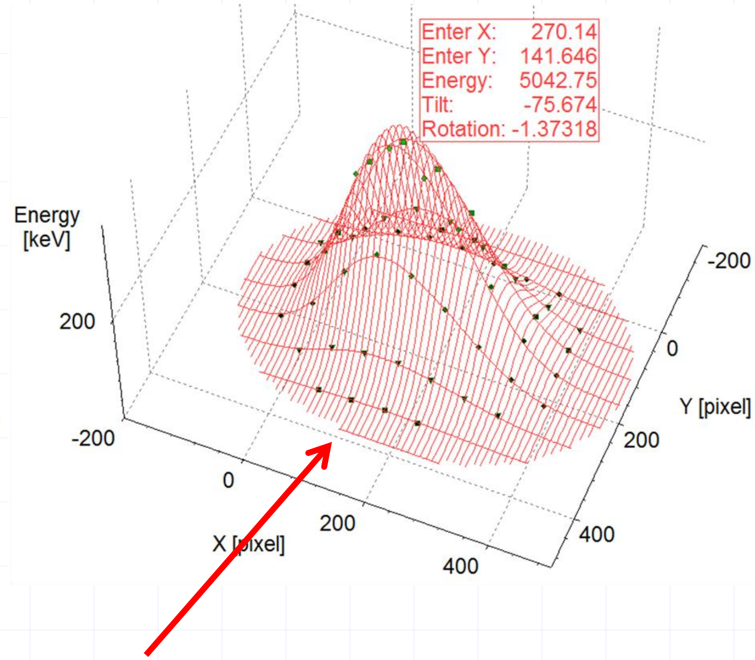

$$q(y_1,y_2)=\frac{m_{Si}c}{2\pi\sigma^2}\int_0^r e^{-\frac{t^2}{2\sigma^2}\left(\frac{y_1-Y_1-x\sin(\alpha)\cos(\beta)}{t-x\cos(\alpha)}\right)^2} e^{-\frac{t^2}{2\sigma^2}\left(\frac{y_2-Y_2-x\sin(\alpha)\sin(\beta)}{t-x\cos(\alpha)}\right)^2}\left((E_0-a)^{1-s}-c(1-e)x\right)^{\frac{s}{1-s}}dx$$

Simplified

Proton track: LET and Bragg curve

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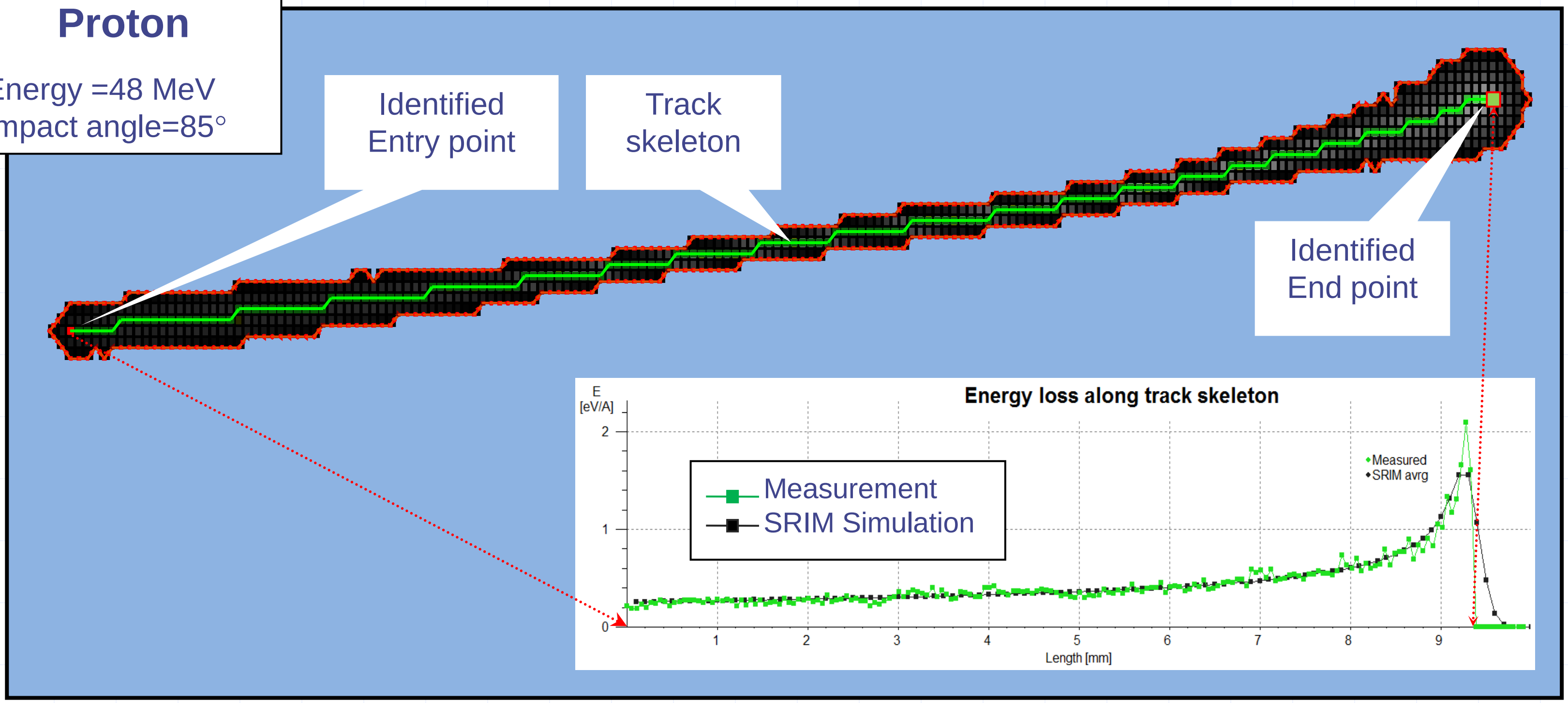
Proton

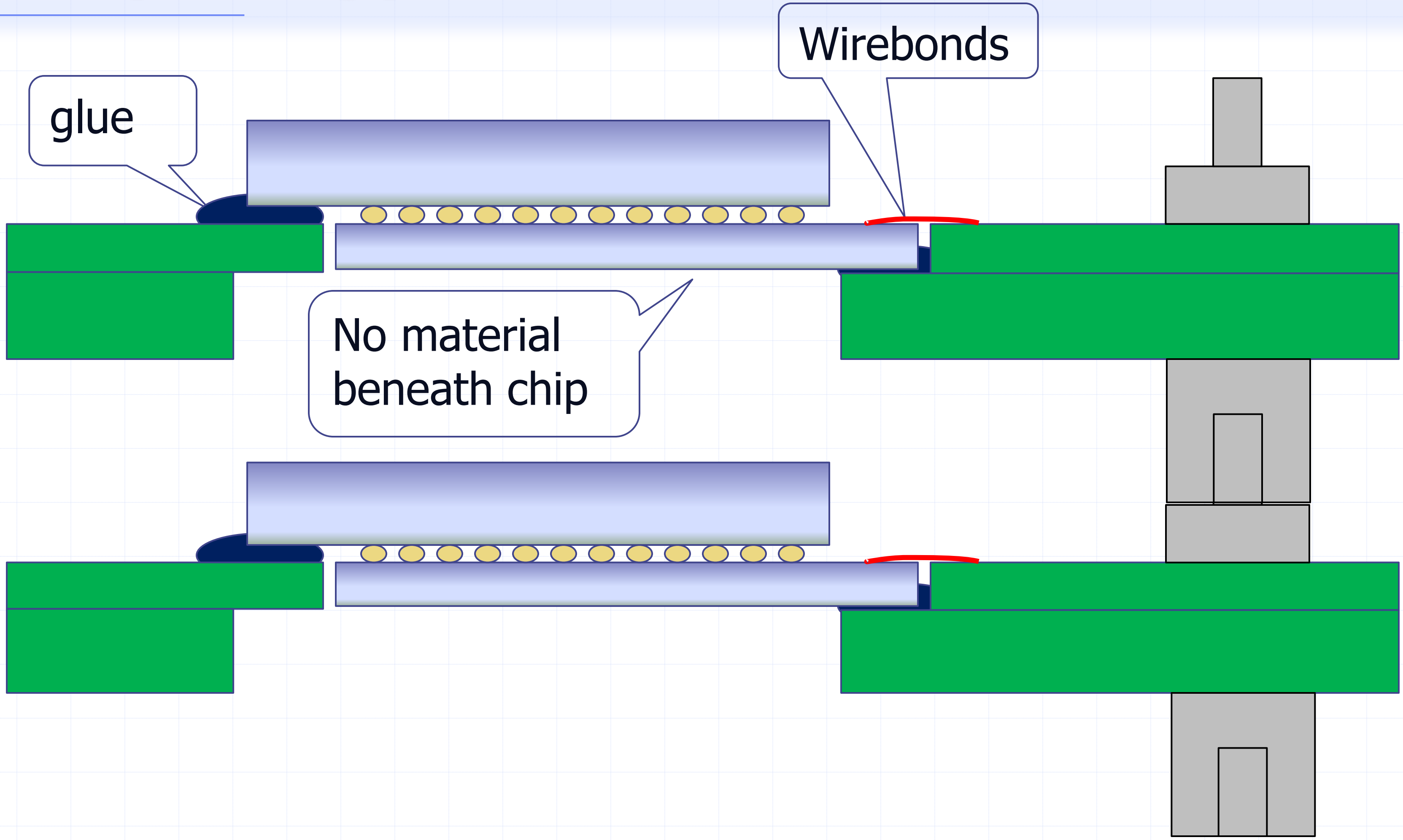
Energy =48 MeV
Impact angle=85°



Voxel detector

composed of Timepix devices

Chip assembling, PCB with 3D morphology and micro connectors



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Chip assembling, PCB with 3D morphology and flexible connectors

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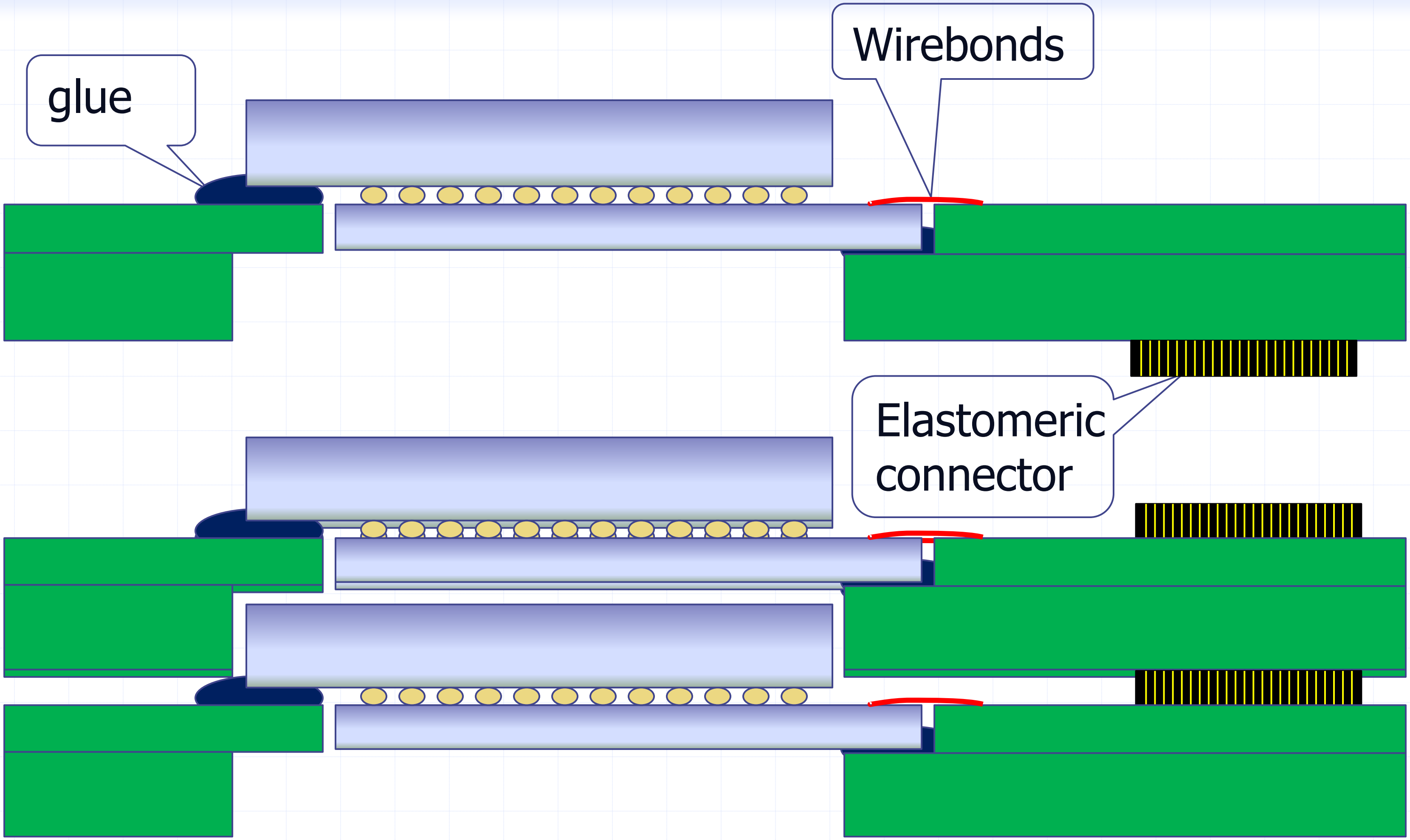

Variable setup:
Any number of chips can be stacked

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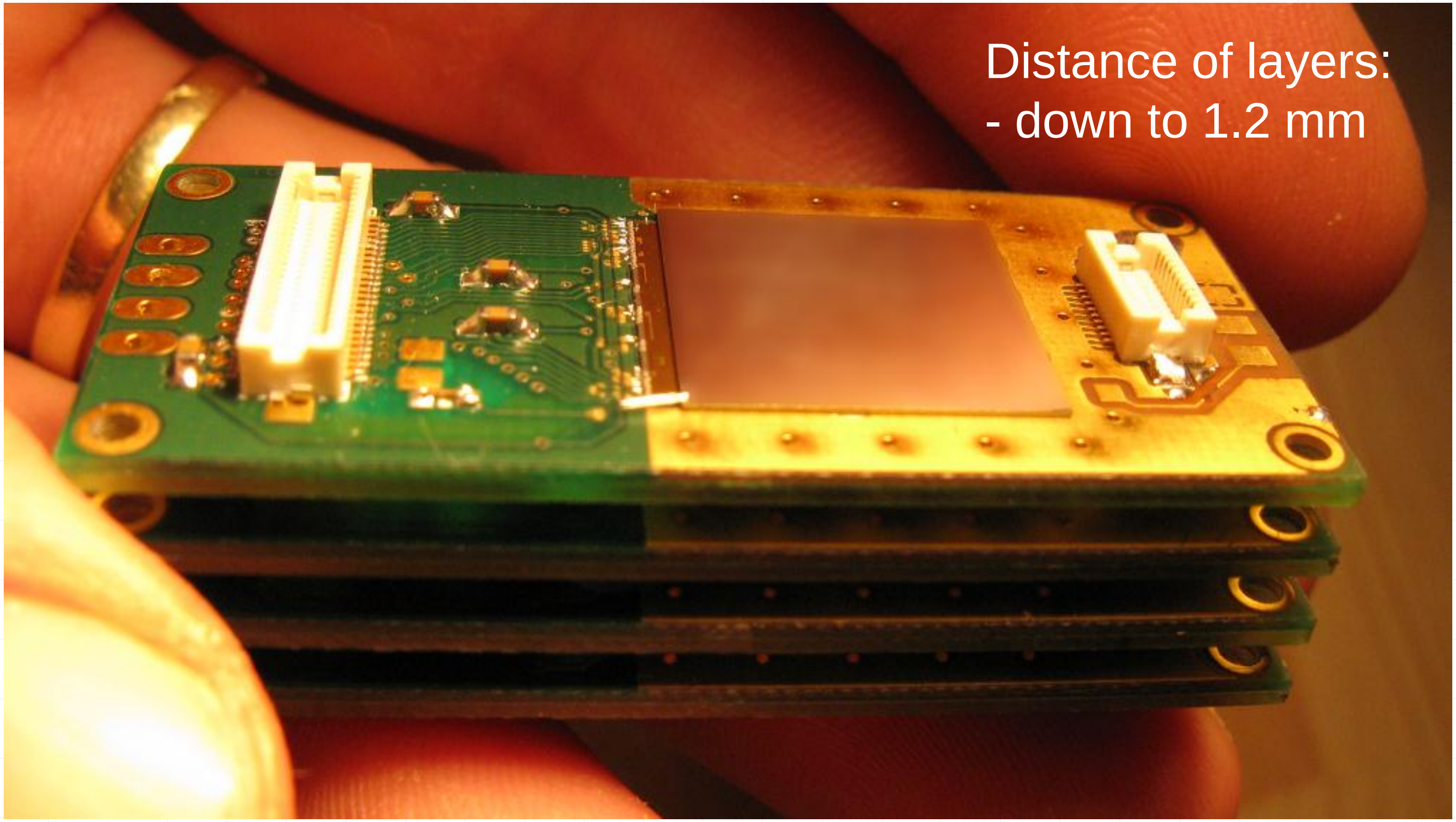

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Experimental results in Hadron Therapy Beam

Monitoring of patient treatment

Imaging principle: Tracking of secondary particles

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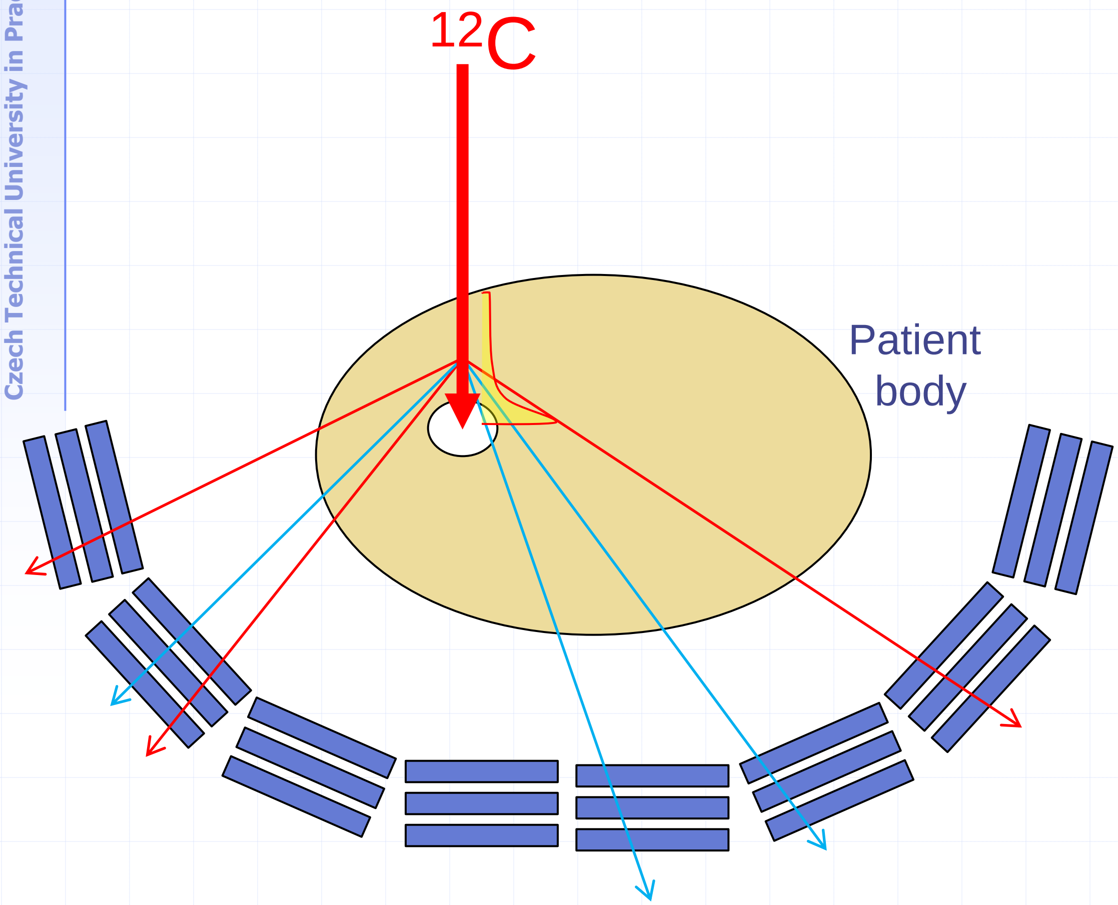
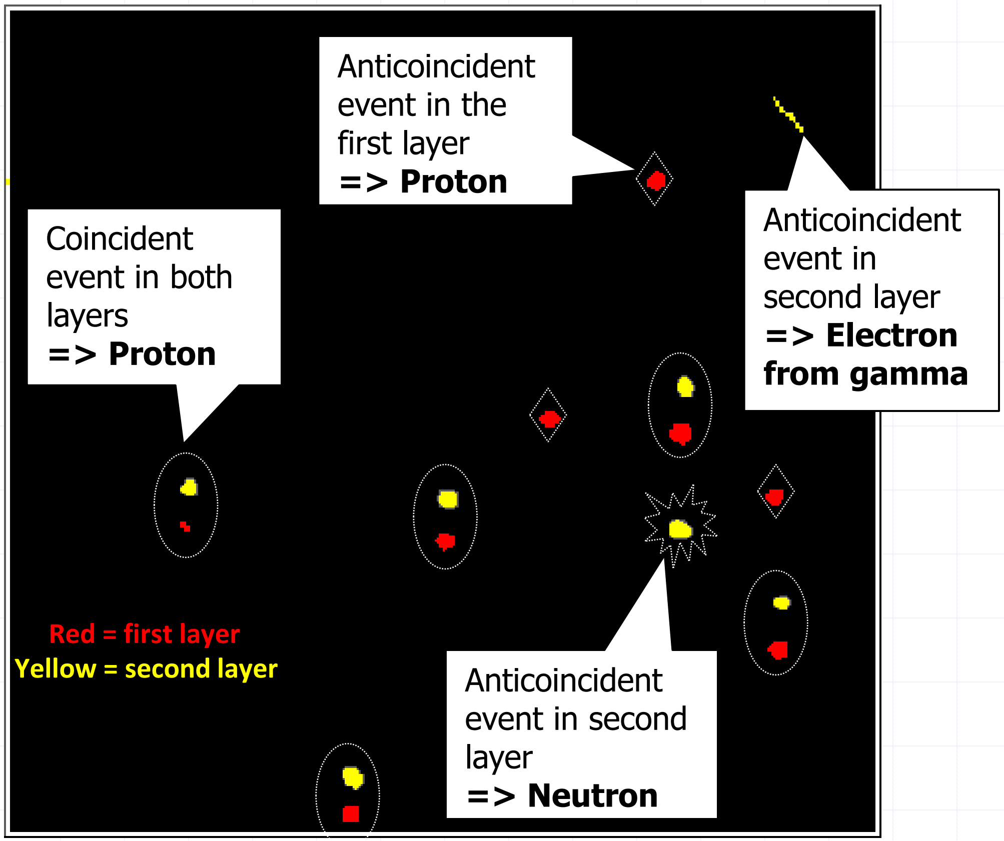


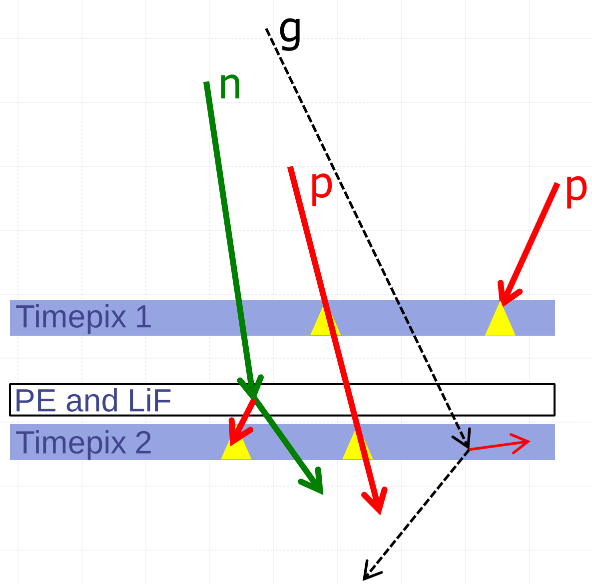
- The tracker would optimally surround the irradiated body.
- Tracker data can be back-projected to form an image of the beam path.
- Possibility to select particles with higher penetration power would improve quality.

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



Coincidences = ions

Anticoincidences in 2nd = neutrons



Observation of complete scene:
Experimental setup

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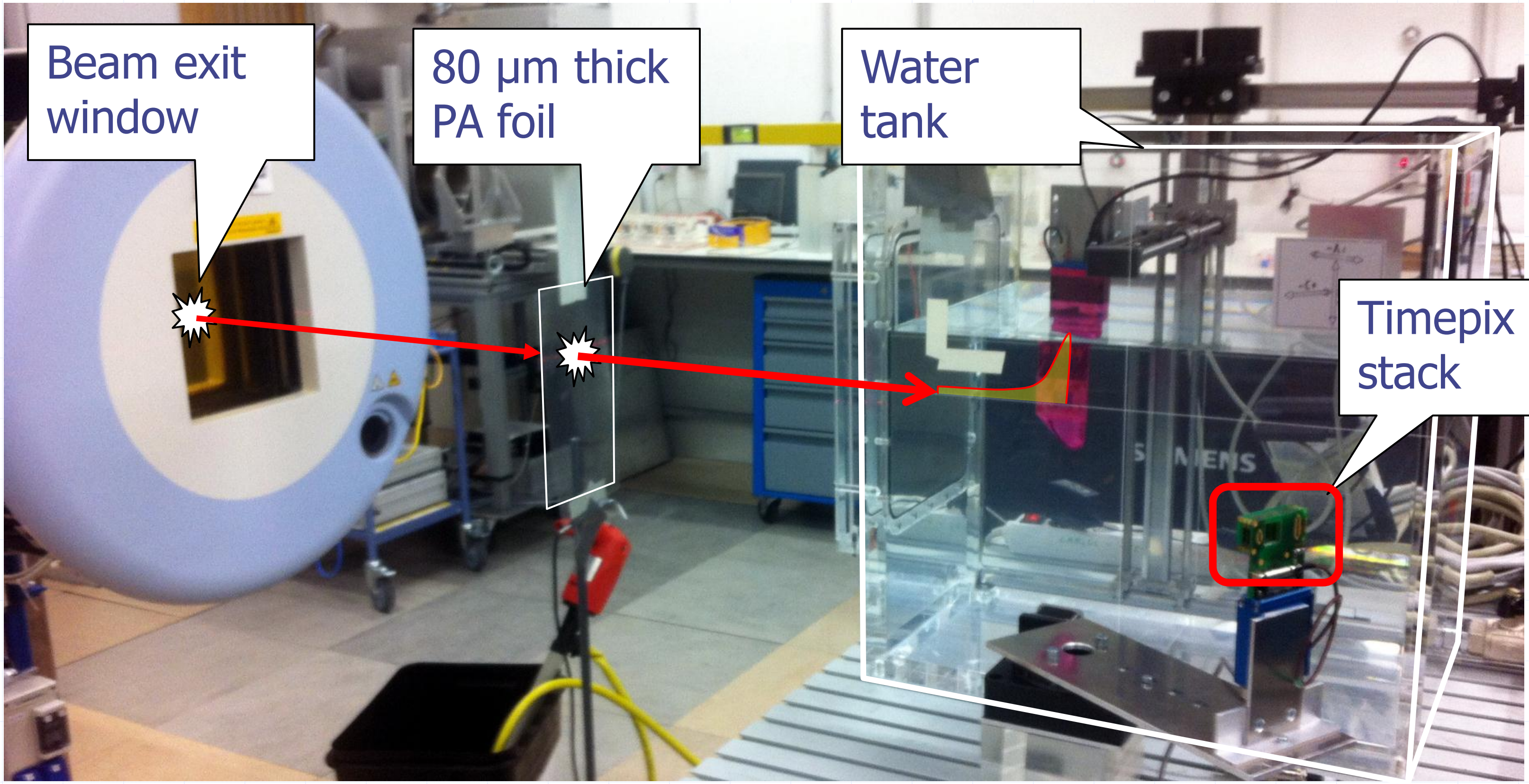
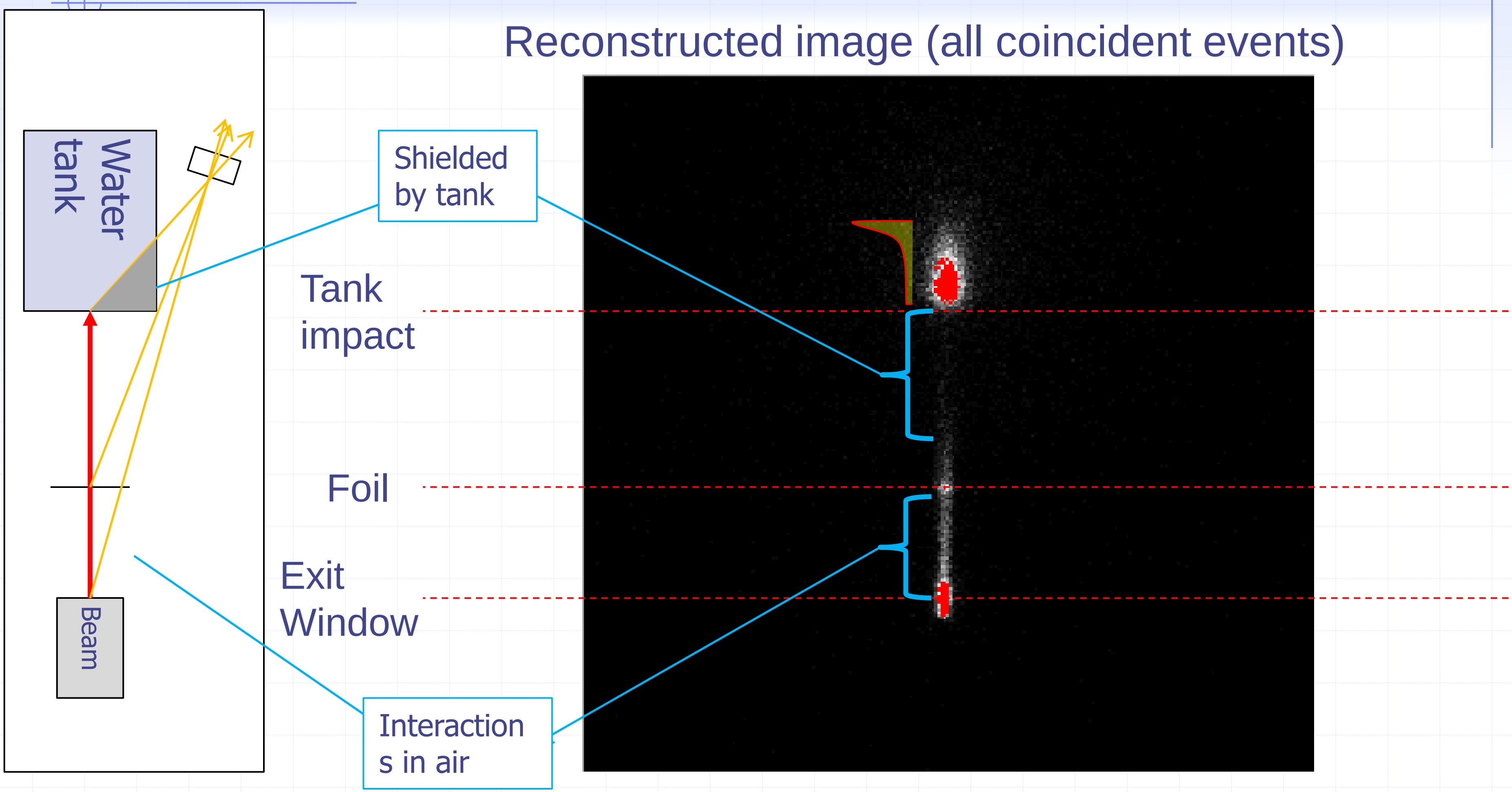


Observation of complete scene:
Beam line can be imaged

Reconstructed image (all coincident events)



Geometrical efficiency = 10^{-5} (Sensor=2 cm^2, distance=140 cm), **time = 8 min**

Summary and Current status

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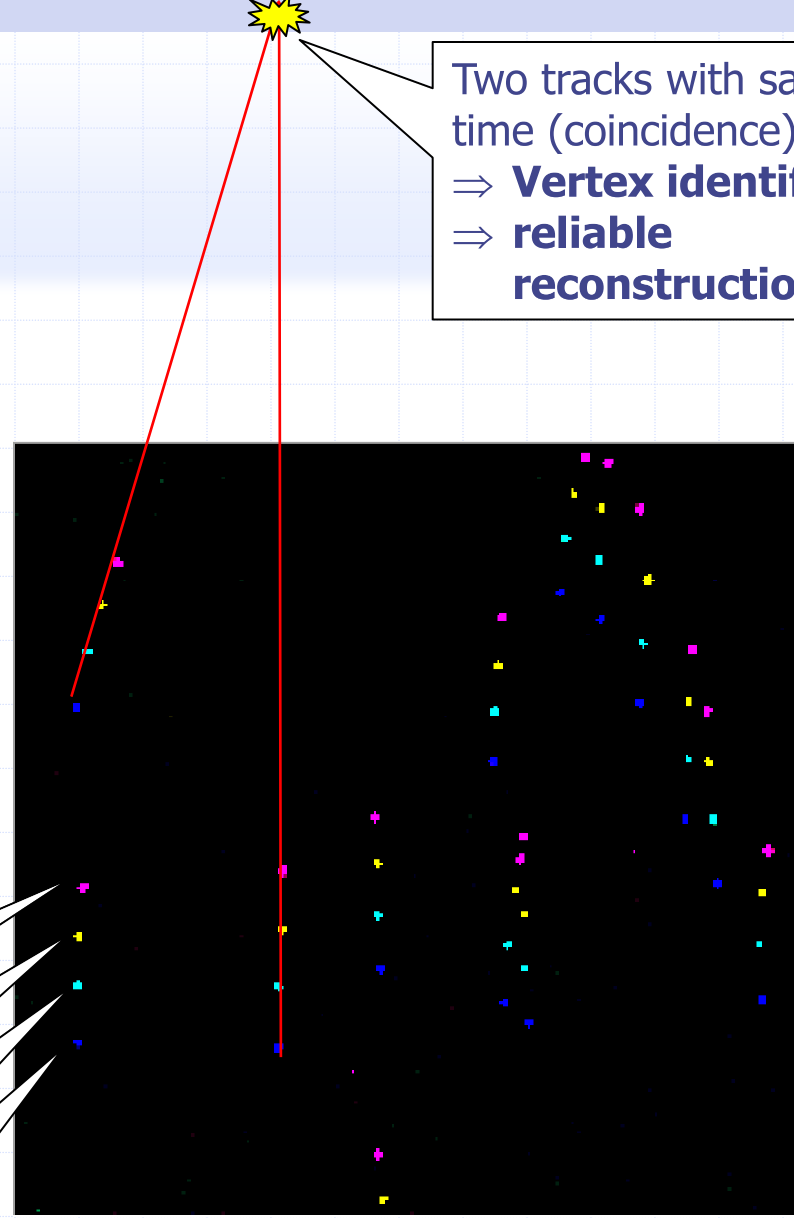
- Particle tracking is very promising technique for monitoring during hadron therapy.
- The Timepix based system allows particle discrimination resolving light particles, ions and neutrons.
- Larger system with four layers was tested recently.

Two tracks with same time (coincidence):
⇒ **Vertex identified**
⇒ **reliable reconstruction**



Sample image taken with 4 layers

First layer: ΔE_1

Second layer: ΔE_2

Third layer: time

Forth layer: ΔE_3

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Small Dosimeter based on Timepix device for International Space Station

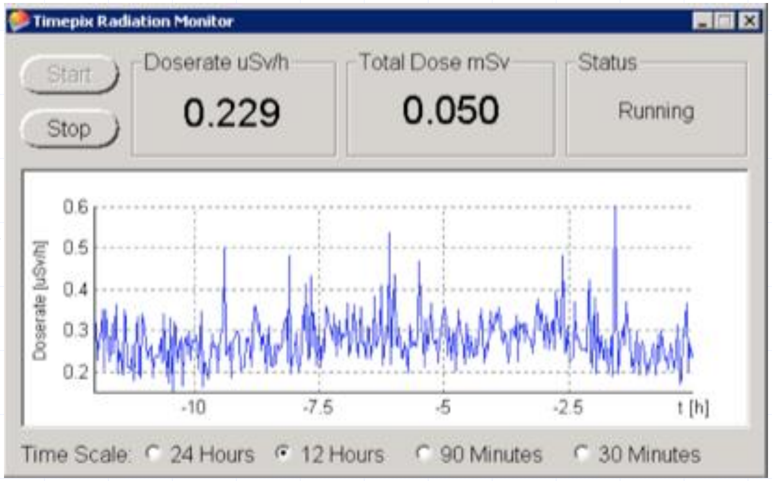
Timepix dosimeter for ISS:
Motivation and Goals

Common project of

- IEAP CTU in Prague
- University of Houston
- NASA

Motivation and goals:

- **Space:** Complex radiation field
- Most of the dose comes from interaction of **heavy ions, protons**
- Standard detection methods fail
- Important to distinguish different particle types:
  - Measuring tracks of particles
  - Measuring their deposited energy



Timepix dosimeter for ISS:
HW and SW features

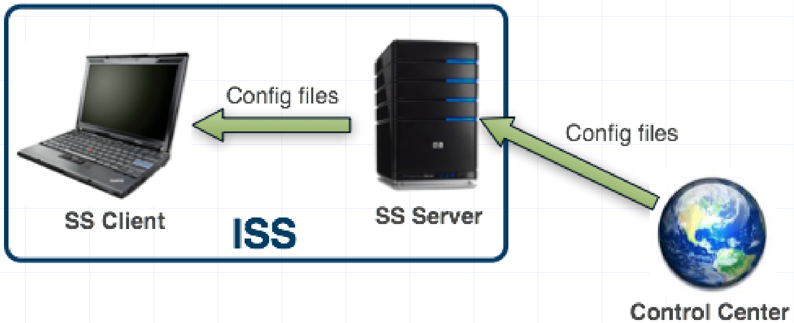
Features:

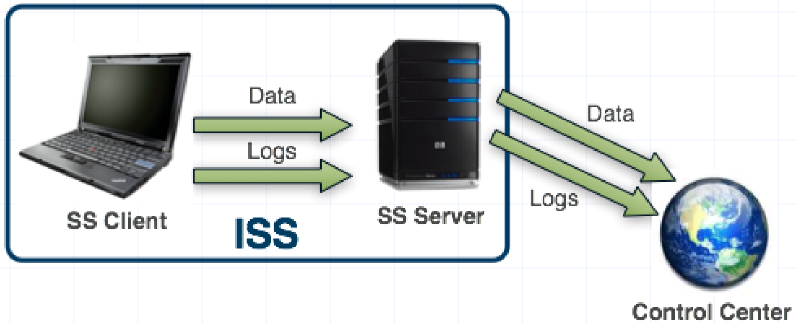
- Special version of miniaturized interface => to be directly plugged to PC (like USB flash disk)
- Special version of software based on Pixelman with Dosimetric plugin

- Fully automatic control of acquisition. Automatic adjustment of meas. parameters (e.g. exposure time). Automatic error recovery (e.g. due to Single- Event- Effect).

- Online data analysis (Frame analysis, cluster analysis, particle type identification)
- **Simple GUI (no interaction from crew required – just press start)**

- Configuration can be changed remotely (from Earth). The software downloads automatically configuration files from server and applies new configuration.
- All data are automatically sent to earth





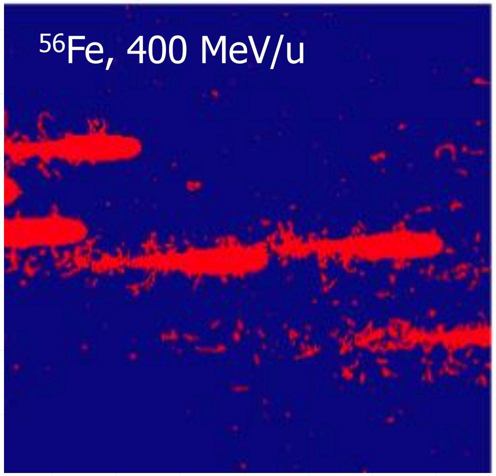
Timepix dosimeter for ISS:
Dose determination

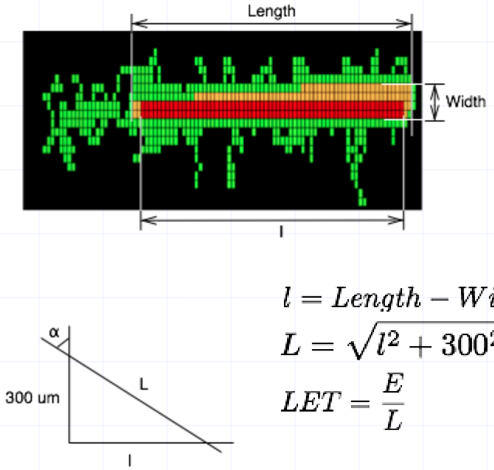
Software analyzes acquired frames to get:

- Equivalent dose rate [µS/h]
- Total cumulated equivalent dose [mSv]

How it is done:

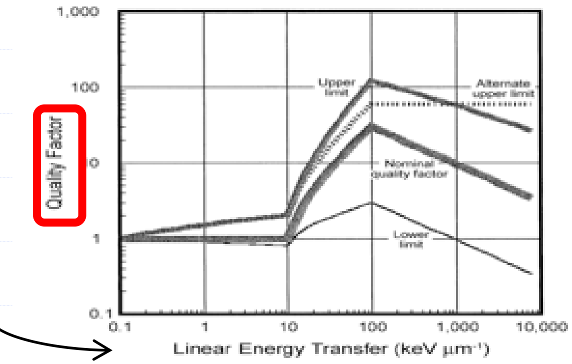
- Particle traces are recognized and sorted to categories.
- Each type of incident radiation is assigned with “quality factor” (Relative biological effectiveness).
- For tracks of **heavy ions**, the quality factor depends on LET (Linear Energy Transfer)





$$l = Length - Width$$
$$L = \sqrt{l^2 + 300^2}$$
$$LET = \frac{E}{L}$$

Quality Factor as a function of LET as proposed in National Council on Radiation Protection and Measurements (NCRP) 153 (2008). Values based on long-term risks (e.g. cancer)



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Timepix dosimeter for ISS:

Device and software testing

Frame analysis software tested using:

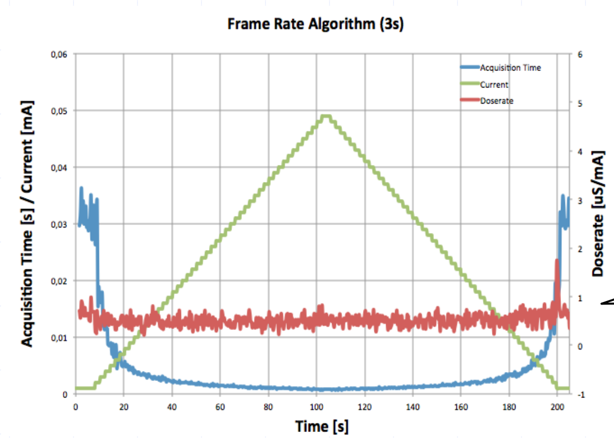
- Data from HIMAC, Japan - measured for various: ions, energies, impact angles
- NASA space Radiation Laboratory at Brookhaven, USA

Incident angle	30º	60º	75º	85º
Determined angle	28.5º	57.9º	75.1º	84.3º
Std. dev. LET	0.07 %	0.02 %	0.02 %	0.79 %

Example for ^{56}Fe 400 MeV/u

Automatic exposure time tested:

- Using X-ray tube (varying current) and radioactive sources (varying distance)



Exposure time was automatically adapted to keep constant dose per frame

Timepix dosimeter for ISS:
Waiting to be lifted to ISS

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Current status:

- Hardware and Software passed all security tests
- Device now waits for lift to ISS
- All measured data will be saved and sent to earth for further analysis …

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Measurement of complex radiation field in ATLAS:

ATLAS-MPX network

ATLAS-MPX device description

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Neutron conversion structures:

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

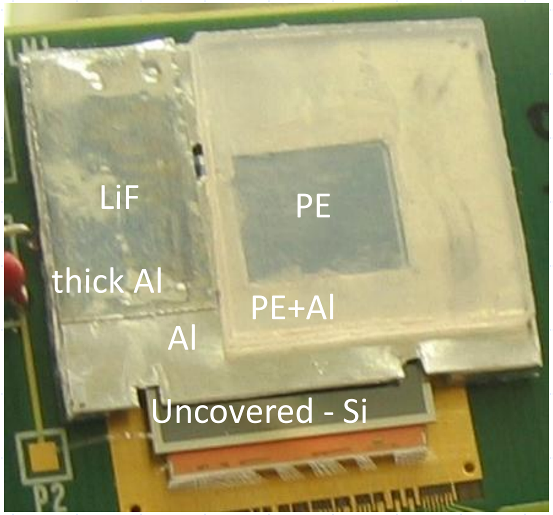
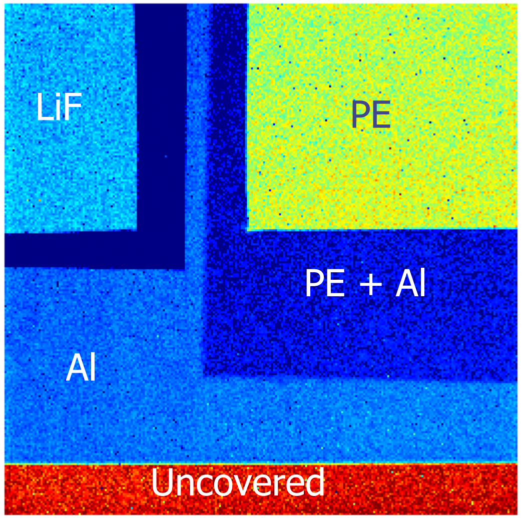


Image of the detector



Arrangement of conversion layers

Medipix2 ASIC with 300μm Si sensor + USB interface:

1) 256 x 256 square pixels of 55 μm in size
2) Sensitive area of ~2 cm² (87% of the chip)
3) Maximum countrate: ~100 kHz per pixel
4) Amplifier, two discriminators and a 13-bit counter in each pixel cell. It is possible to select a window in energy. Upper and lower threshold can be adjusted pixelwise with 3 bits
5) Only radiation hard electronics installed in UX15
6) Framerate 0.15fps
7) All devices were calibrated for X-rays, gamma rays, slow and fast neutrons. Measured overall device tolerance is 30%.

Neutron efficiency calibration

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Calibrated efficiency:

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

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

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

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

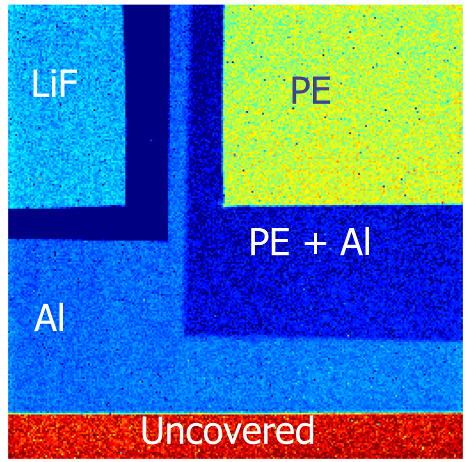
PE / PE+Al cluster count ratio:

^{252}Cf: 10.70 ± 0.04

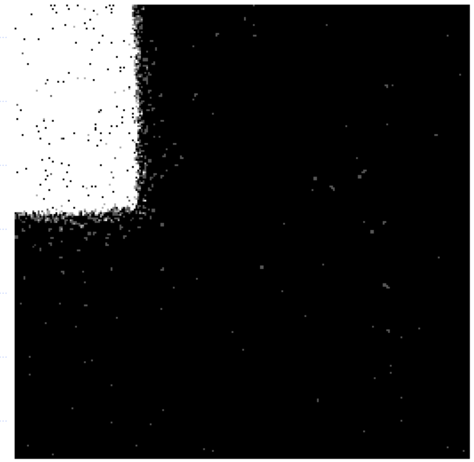
^{241}AmBe: 5.18 ± 0.03

VDG: 2.51 ± 0.03

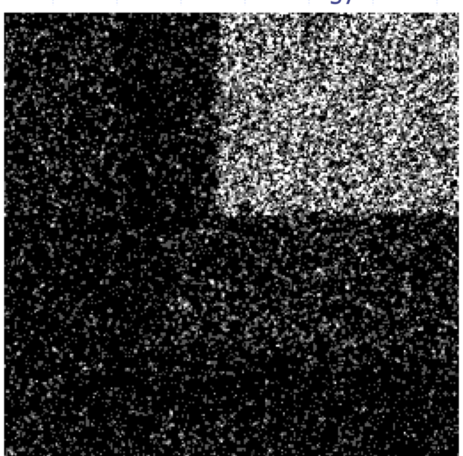
X-ray image of conversion layers



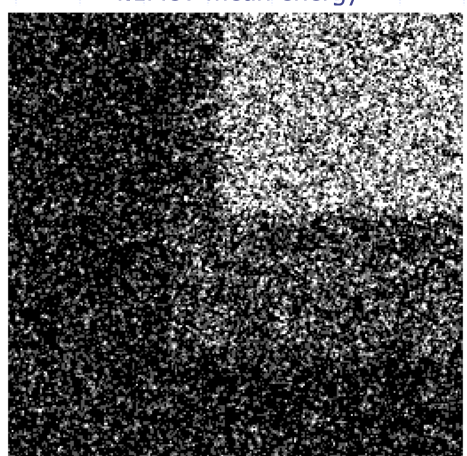
Thermal – 500s, 2.5E6 neutrons,
25meV energy



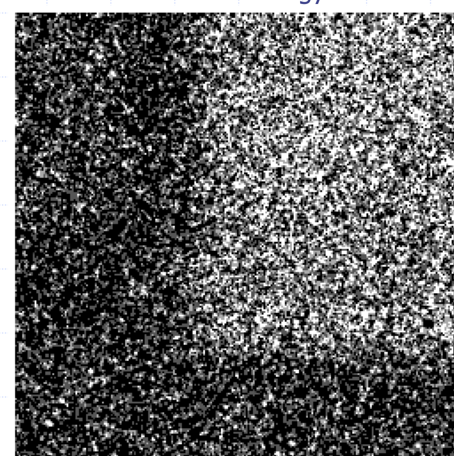
252Cf – 2000s, 1E8 neutrons,
2.3MeV mean energy



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



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



ATLAS-MPX position overview

(16 devices installed within ATLAS)

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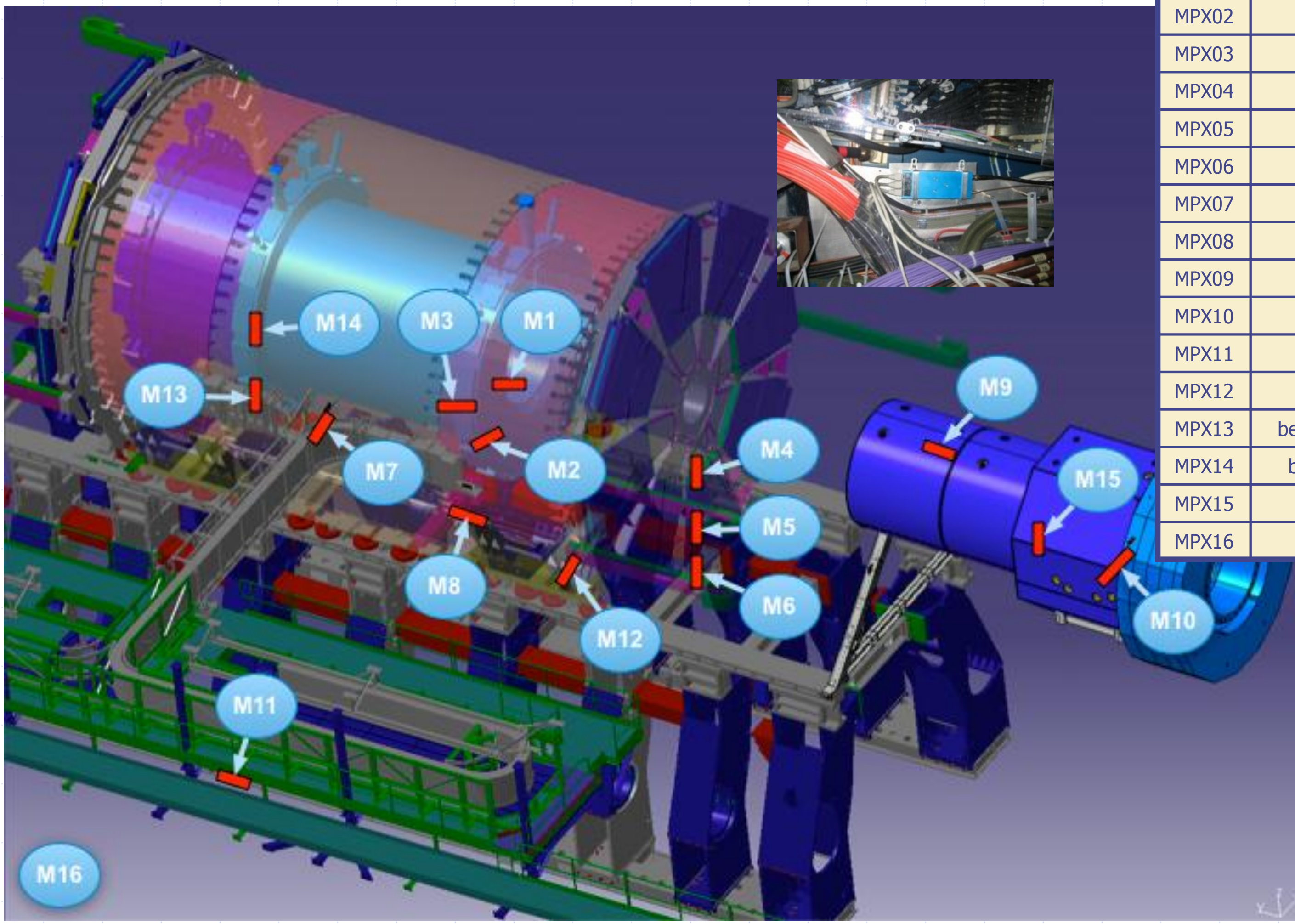
MPX01	between ID and JM plug
MPX02	between TILE and TILE EB
MPX03	between TILE and TILE EB
MPX04	on the Small Wheel
MPX05	on the Small Wheel
MPX06	on the Small Wheel
MPX07	top of TILECAL barrel
MPX08	top of TILECAL EB
MPX09	on the JF cylinder
MPX10	cavern wall HO
MPX11	cavern wall USA side
MPX12	on the EIL 4
MPX13	between TILE and TILE EB, side C
MPX14	between ID and JM plug, side C
MPX15	at the back of LUCID
MPX16	in the USA15 cavern



ATLAS-MPX operation

Detail from 13.8 – 17.8.2010

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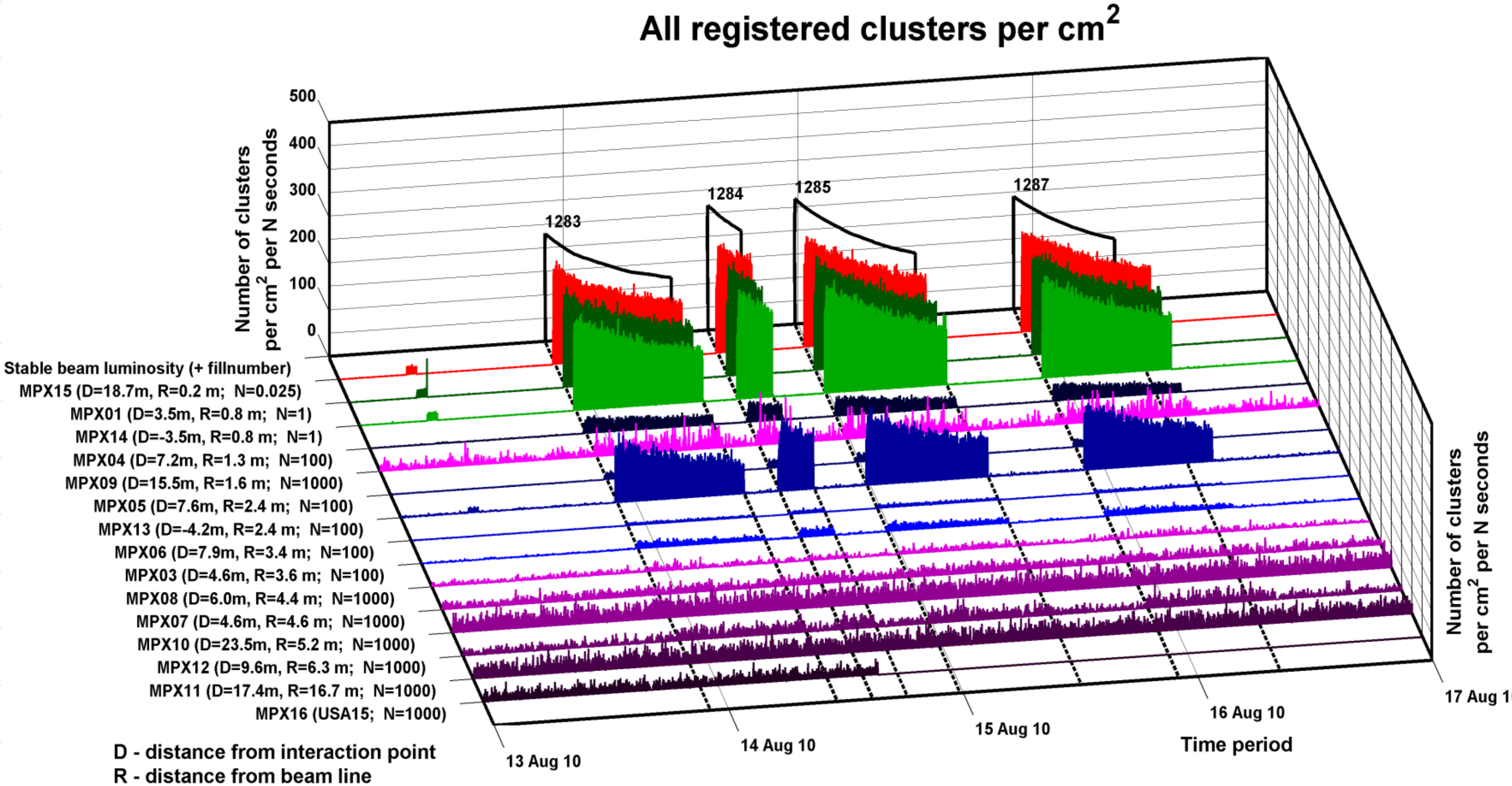
Plots of stable beam luminosity with corresponding fill numbers. There is a obvious correlation between signal from all devices. Beam decay is clearly visible.



ATLAS-MPX signal distribution in the ATLAS cavern

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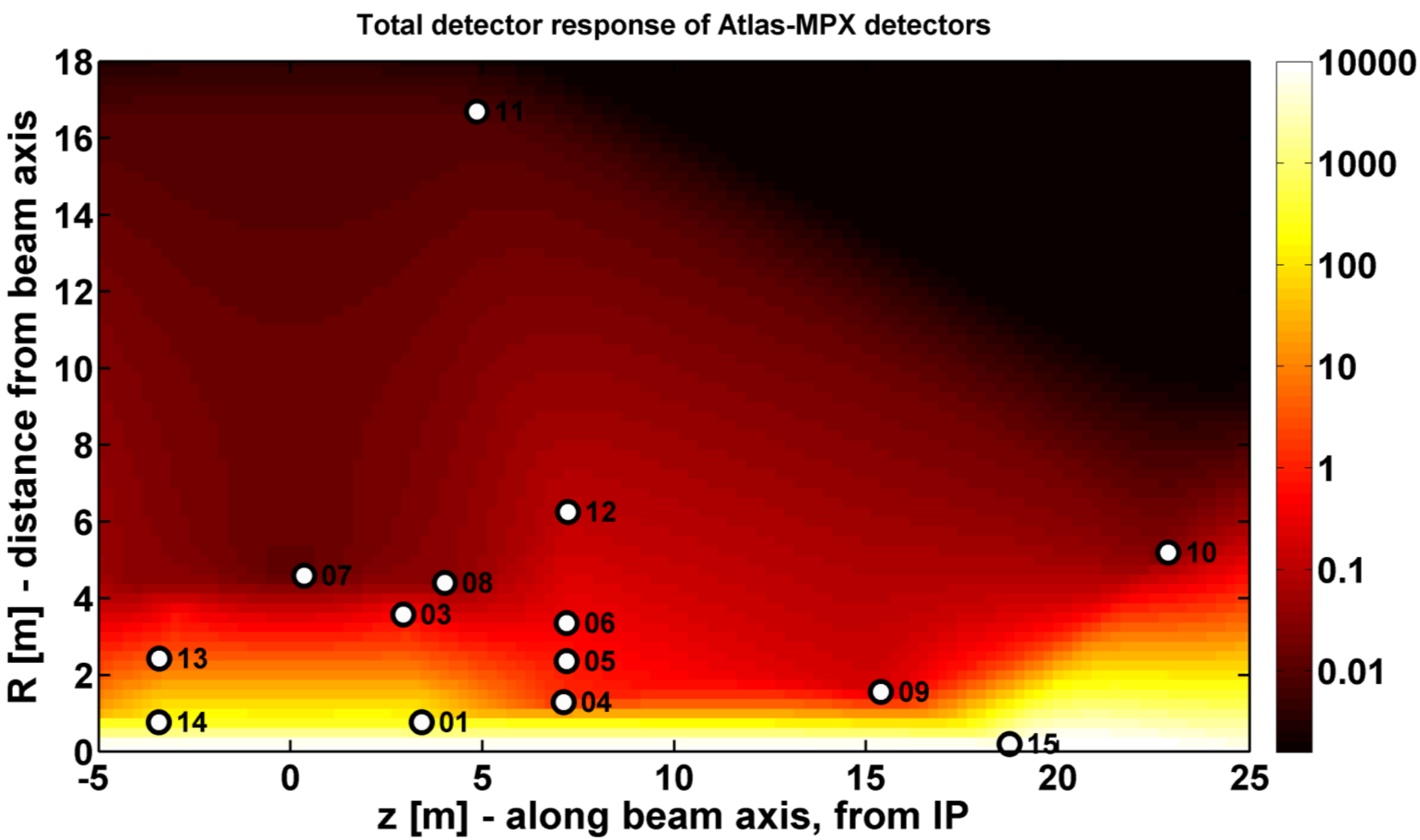
Image shows the mean cluster countrate [clusters/cm²s] for given time period
- Linear interpolation between individual devices (we suppose axial symmetry here)
- Extrapolation to the displayed plain



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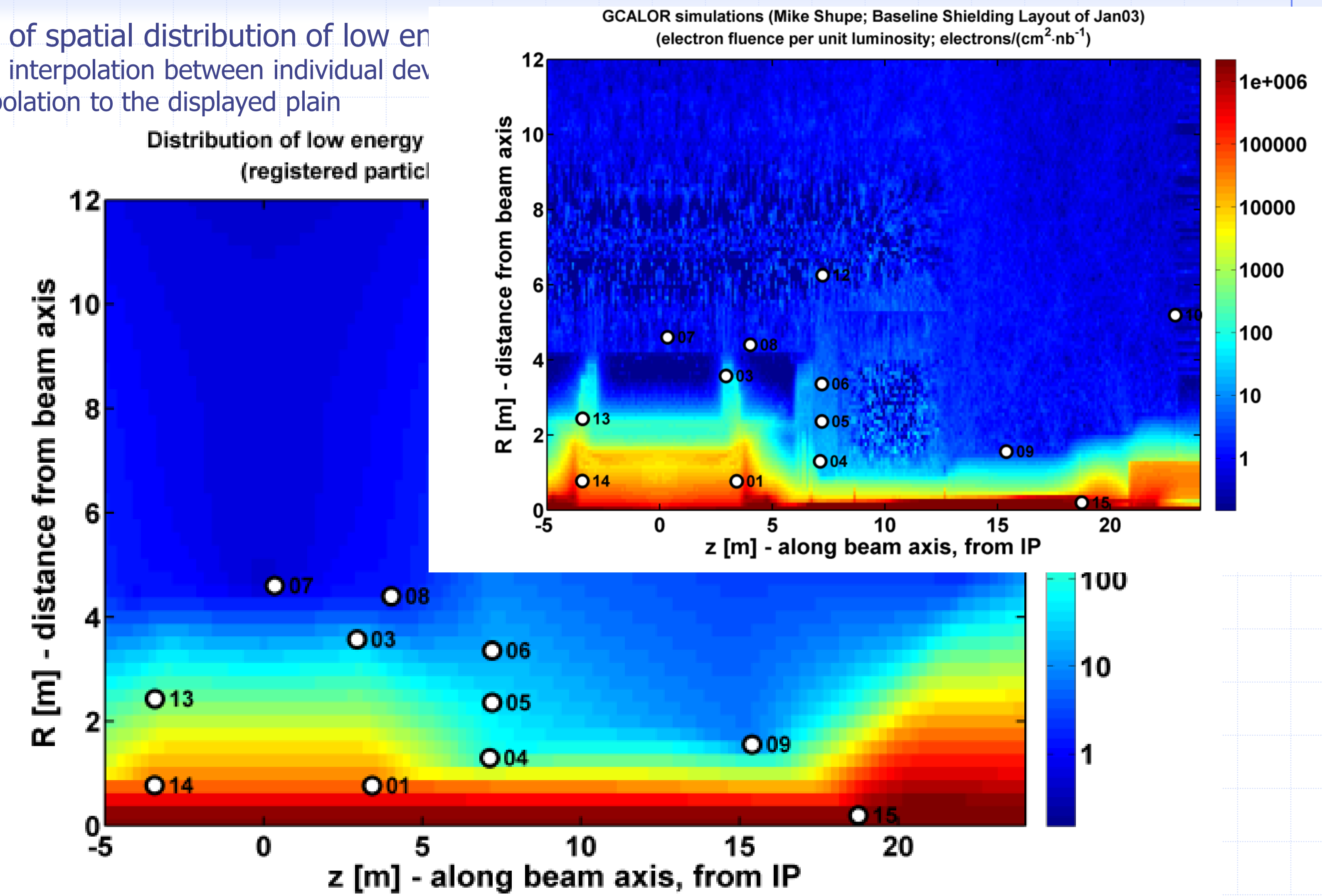
Low energy transfer particles (excluding MIPs) distribution in ATLAS cavern

2D maps of spatial distribution of low en
- Linear interpolation between individual dev
- Extrapolation to the displayed plain



Thermal neutron f
distribution in ATL

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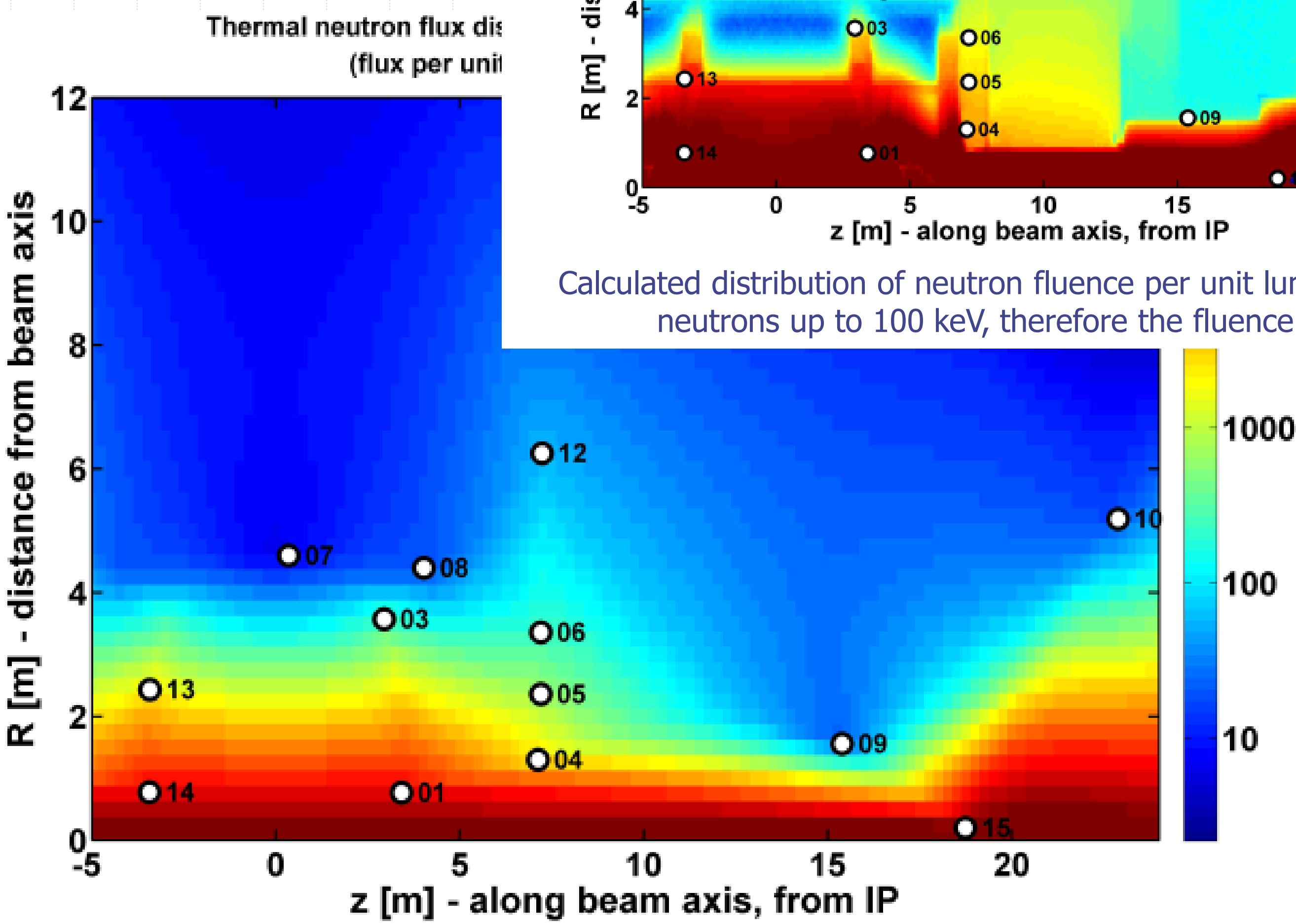
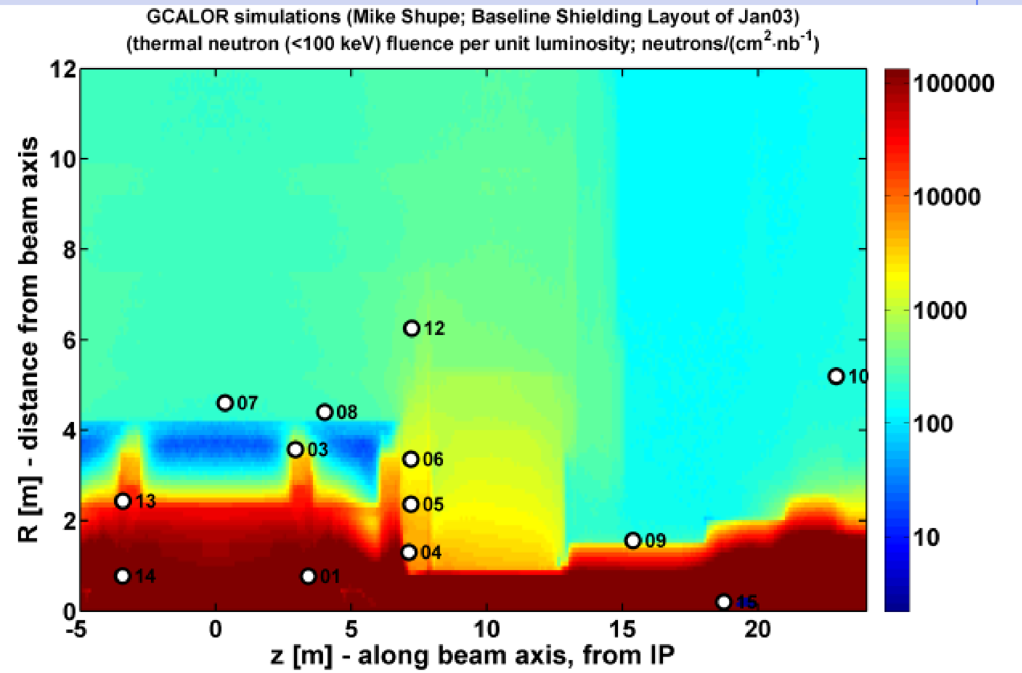
2D maps of thermal neutron fluence spa
- Linear interpolation between individual dev
- Extrapolation to the displayed plain

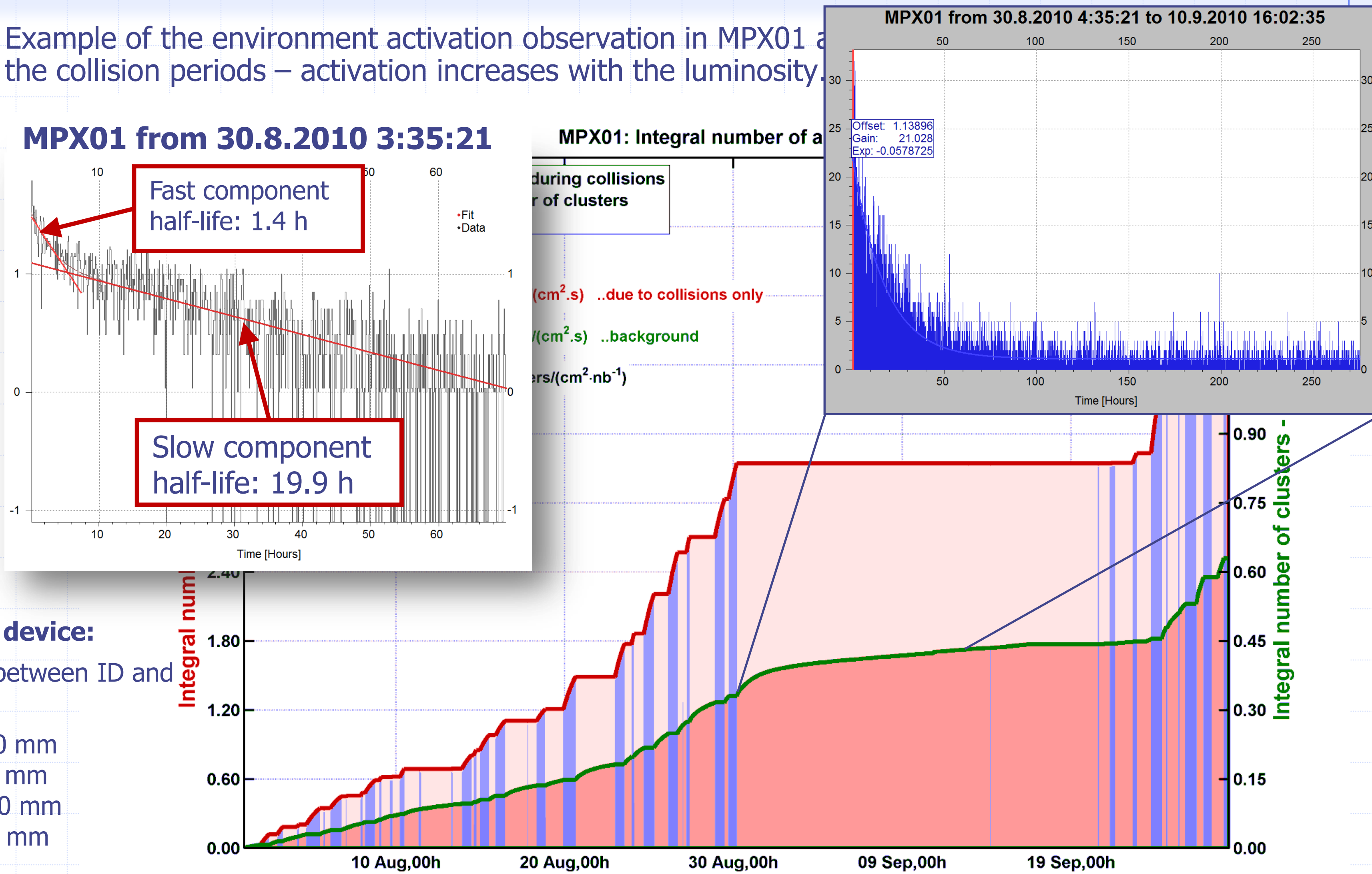




Calculated distribution of neutron fluence per unit luminosity includes neutrons up to 100 keV, therefore the fluence is higher.

Activation of the environment

Example of the environment activation observation in MPX01 a… the collision periods – activation increases with the luminosity.



MPX01 device:

Side A, between ID and JM plug.

X = -710 mm
Y = 290 mm
Z = 3420 mm
R = 770 mm

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Conclusions and Summary

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- Charge sharing effect in pixel detectors can be very useful – allows to get more information about each particle (type, angle, LET, …)

- Visualization of particle traces is very powerful tool allowing **identification of particle types**.

- Particle identification allows assignment of correct quality factor => **more reliable dose estimation.**

- Dosimeter based on pixel technology can provide good results in very unusual radiation environment => **Device can be used during unexpected events (accidents)**.

- Usage of Medipix technology for dosimetry is protected by our patent.

Deep subpixel spatial resolution with energetic ions

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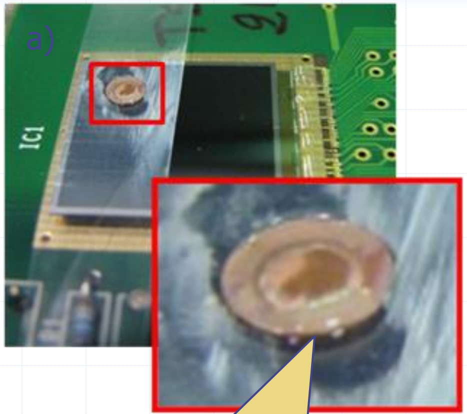
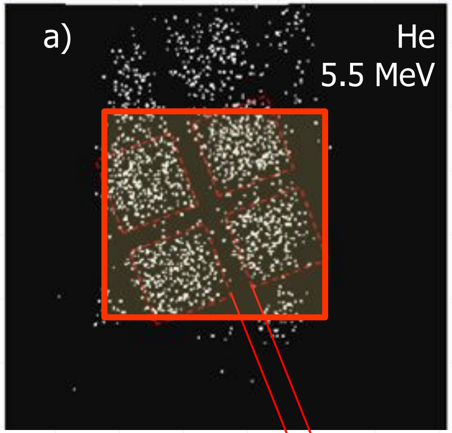
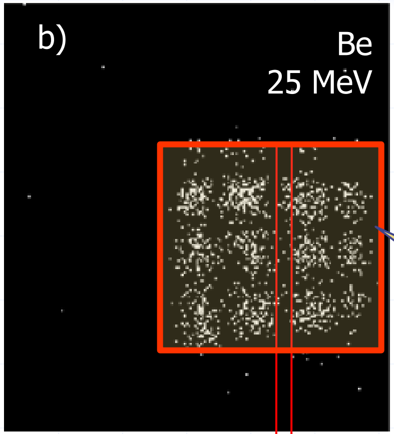


Copper grid for electron microscopy
a) 25 μm
b) 12.5 μm

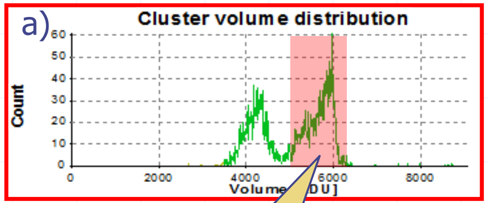


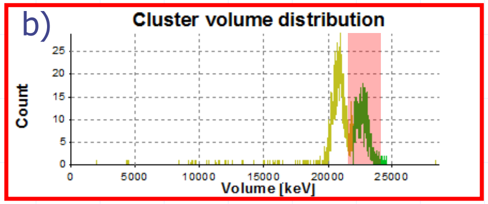
5 μm



2.5 μm

Pixel size





Energy used for image