Miniaturized Tracking System Based on Timepix Detector

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Timepix pixel device
single particle counting pixel detector

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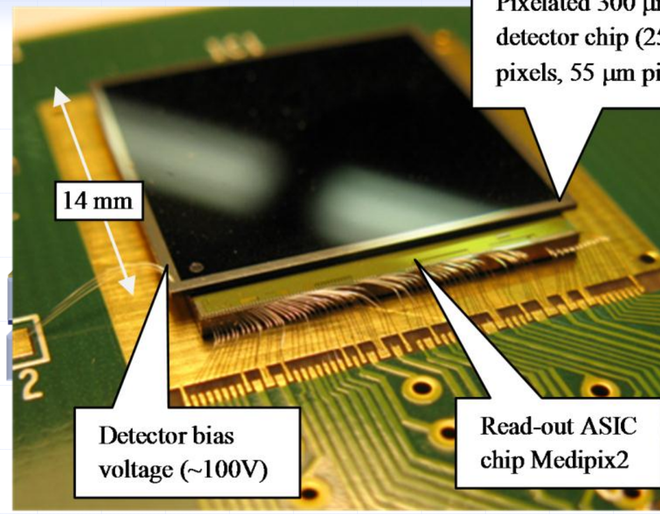
- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or ADC or **Timer**
- Multichip assemblies with no blind area: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)



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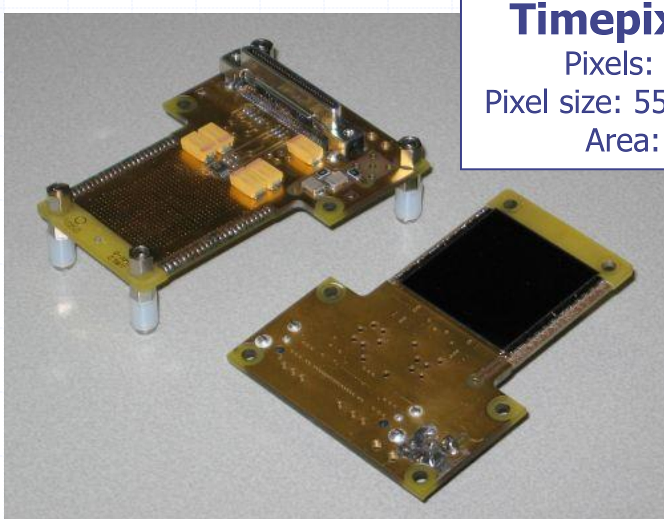
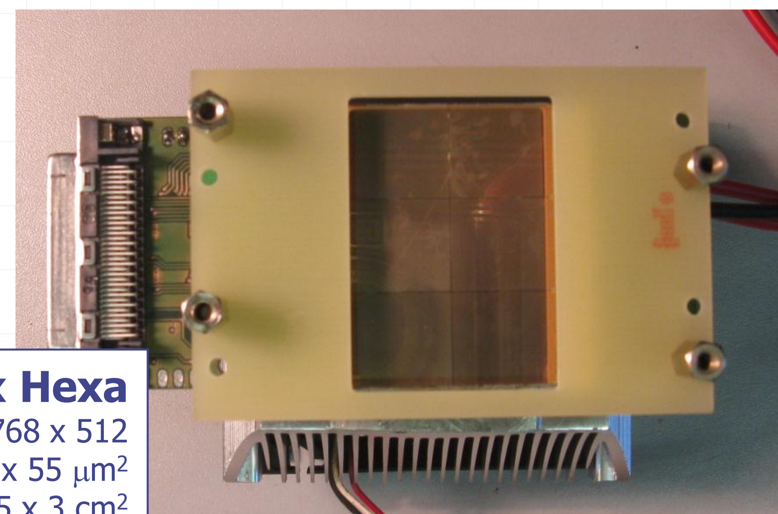
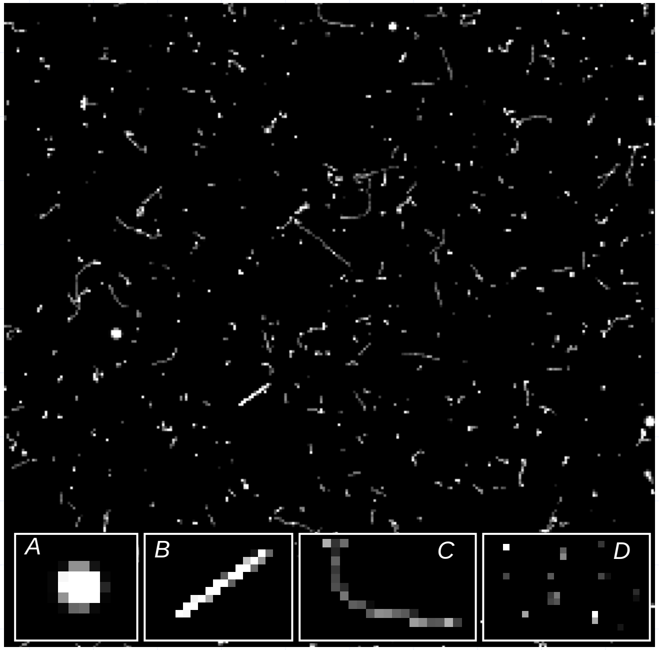


Timepix Quad
Pixels: 512 x 512
Pixel size: 55 x 55 μm^2
Area: 3 x 3 cm^2

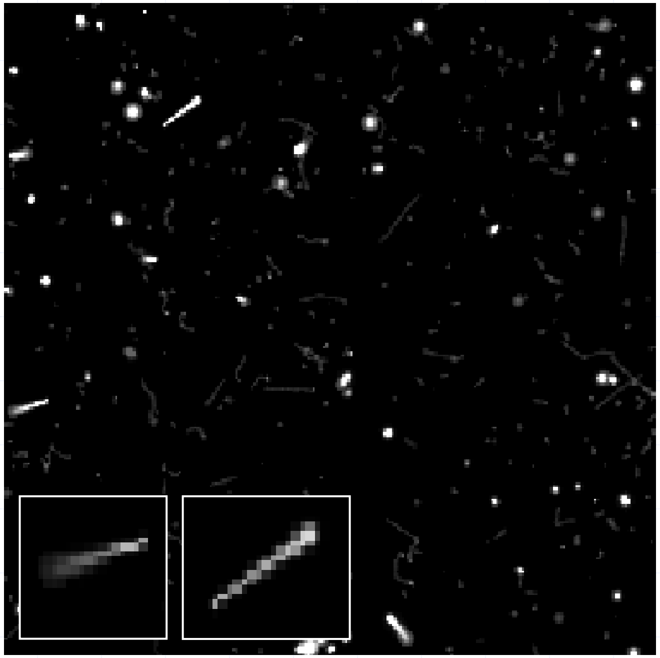


Timepix Hexa
Pixels: 768 x 512
Pixel size: 55 x 55 μm^2
Area: 4.5 x 3 cm^2

Particle tracking with pixel detectors



Radiation background



Protons recoiled by fast neutrons

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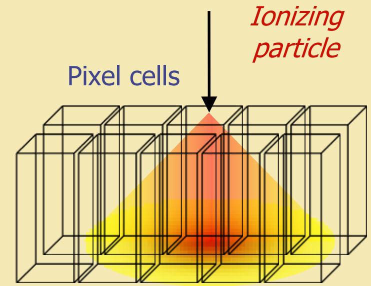
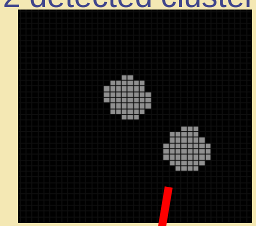
Heavy charged particles:
Charge sharing effect

- Particle creates a huge charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- The charge cloud expands (diffusion, repulsion, …)
- The charge cloud overlaps several adjacent pixels => **CLUSTER**
- Pixels overlapped by the charge cloud detect the charge if it is higher then threshold.

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

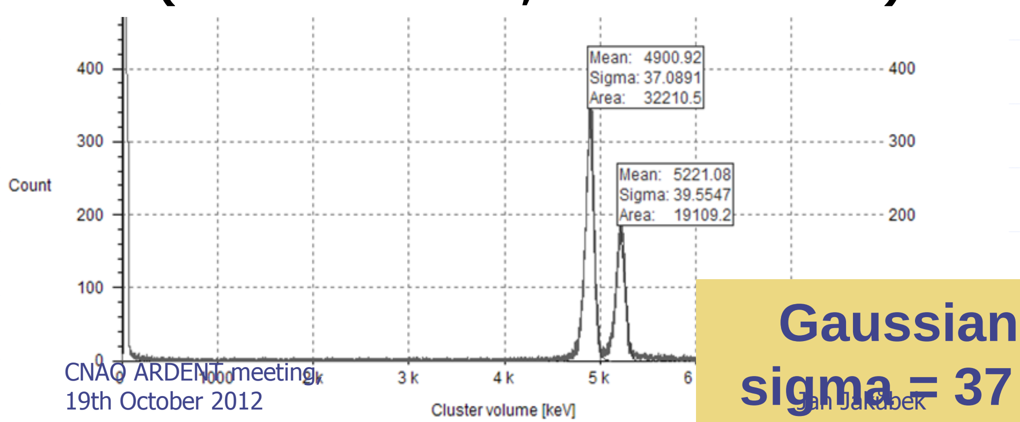


2 detected clusters



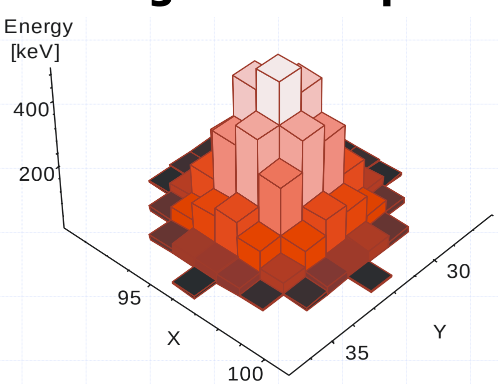
Cluster size can be >100

Am241+ Pu239 combined alpha source (5.2 and 5.5 MeV, measured in air)



Gaussian fit sigma = 37 keV

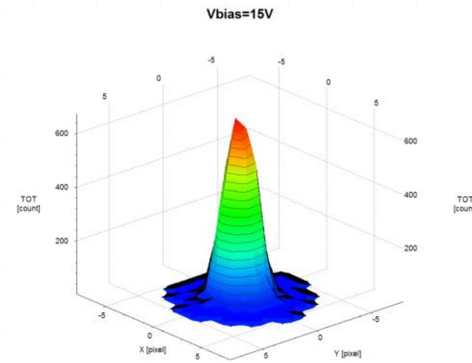
Timepix measures charge in each pixel

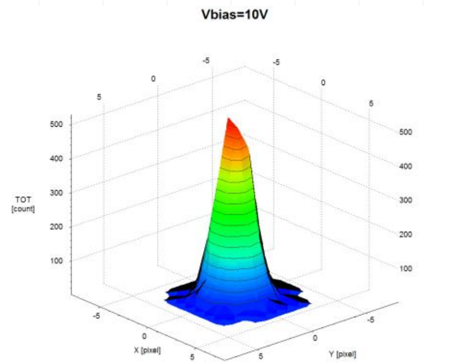


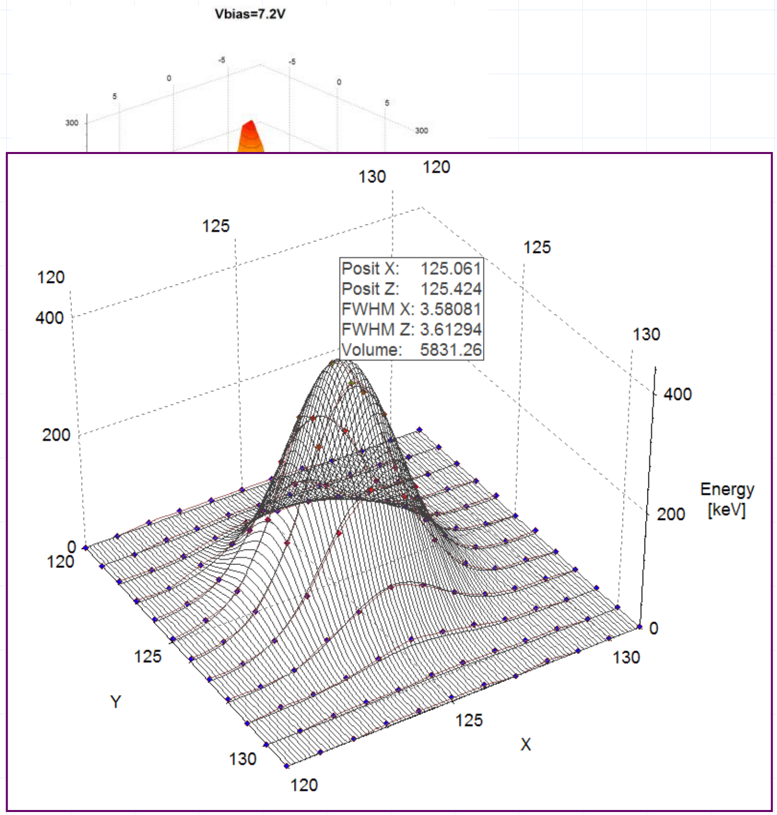
Heavy charged particles:

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** !!

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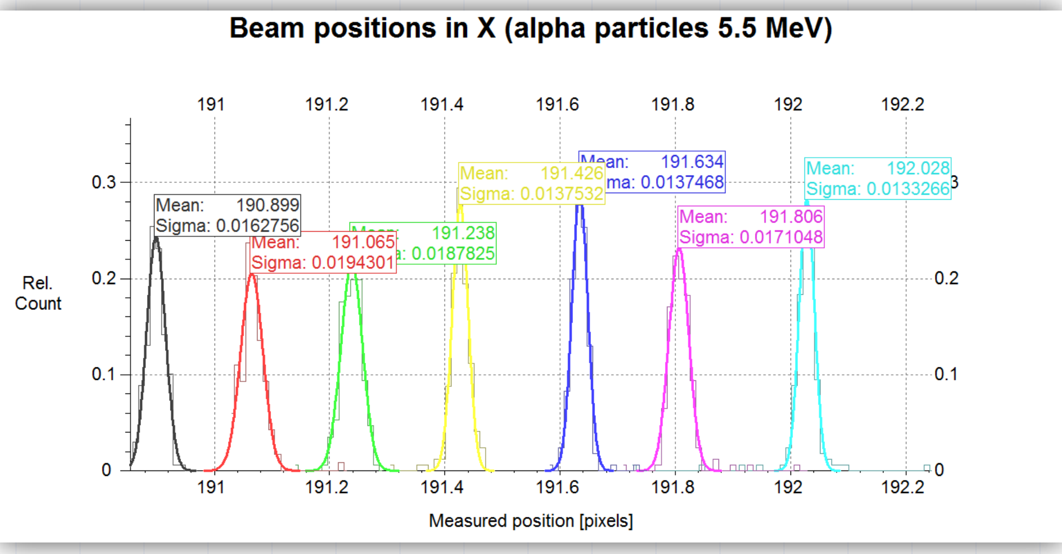
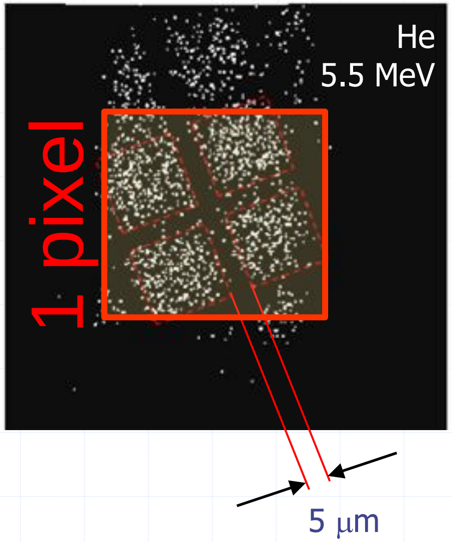
Deeply subpixel spatial resolution with ions:
Ion Microbeam (IBIC ANSTO)

Microbeam spots (5.5 MeV alphas):



Imaging of Cu grid (pitch of 25 µm)



Resolution: 880 nm (the limit of microbeam)

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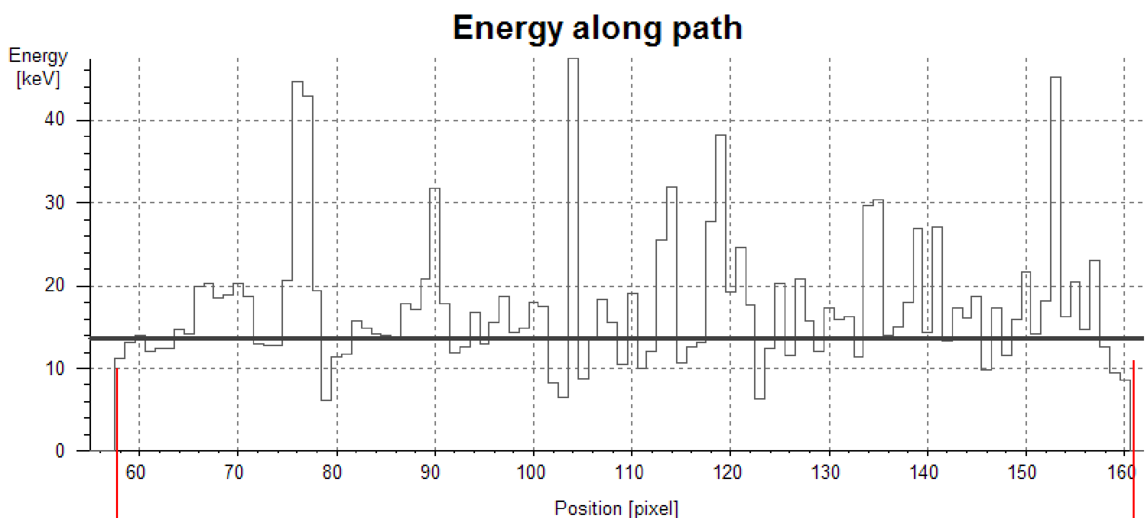
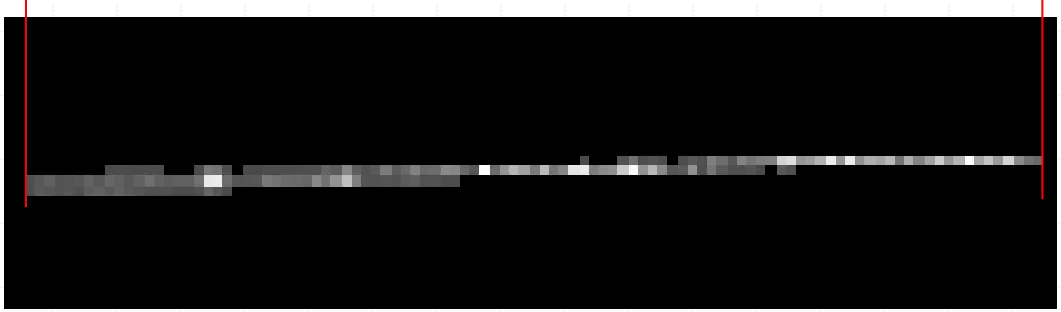
Charge sharing effect:

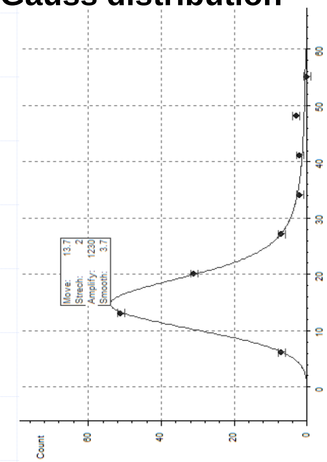
Tracks of MIP particles – Cosmics

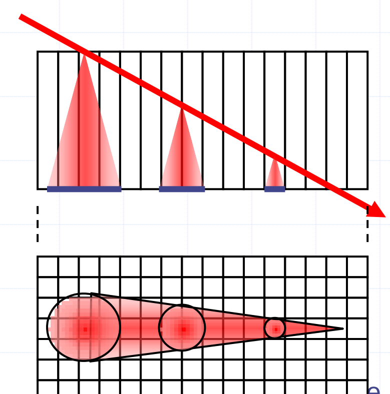




Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





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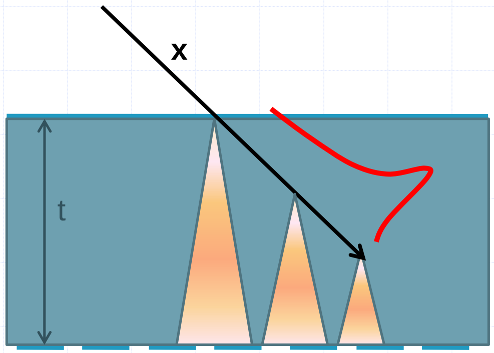
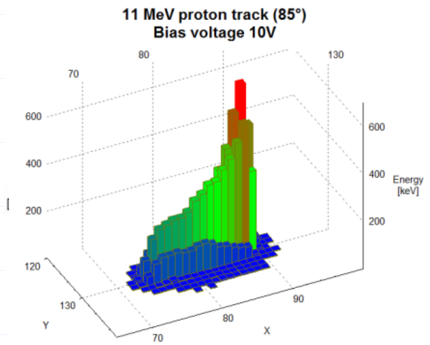
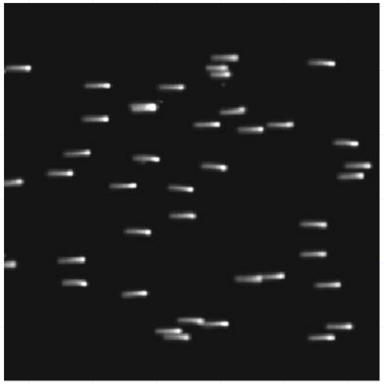
Proton tracking:
Can we determine 3D direction from measured data?



=>

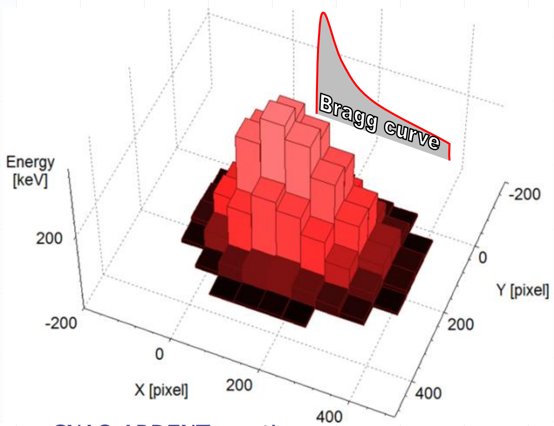
Asymetric clusters

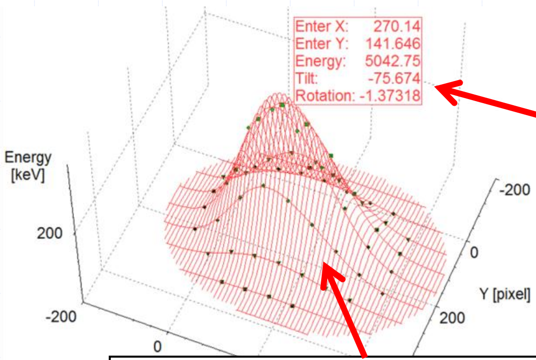




11 MeV protons at 85 deg

- Energy losses defined by Bragg curve, charge spreads according to gauss distribution (low bias voltage) => model can be assembled





The 3D direction was determined by fit

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

Typical images observed with ion beam at grazing impact angle

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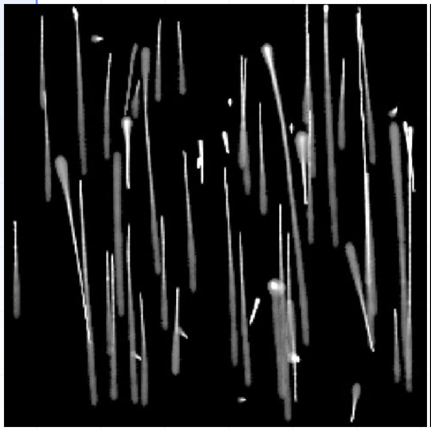
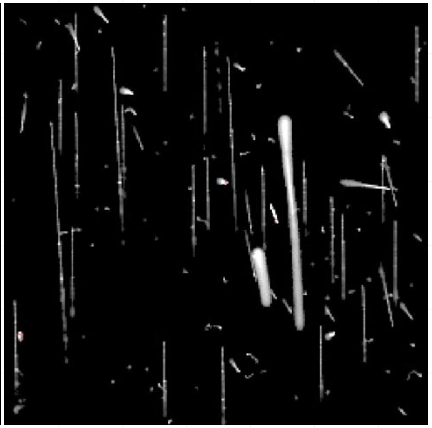
Protons 48 MeV



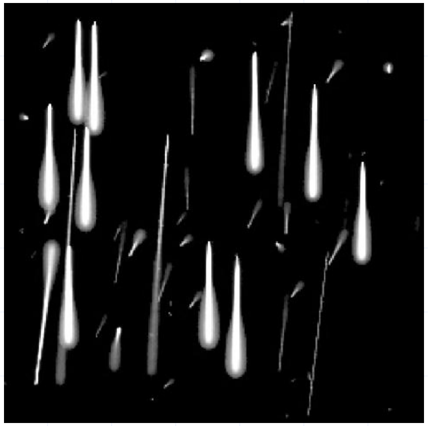
Only protons and their scattering, no secondaries.

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.

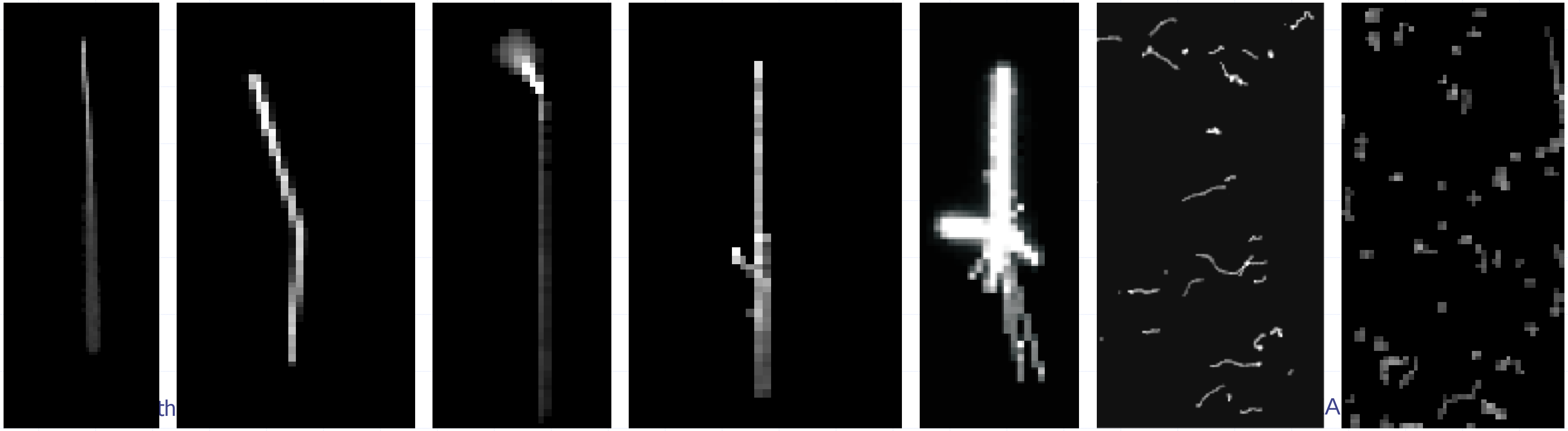
Can we do the reconstruction of directions?

And can we do it on-line?

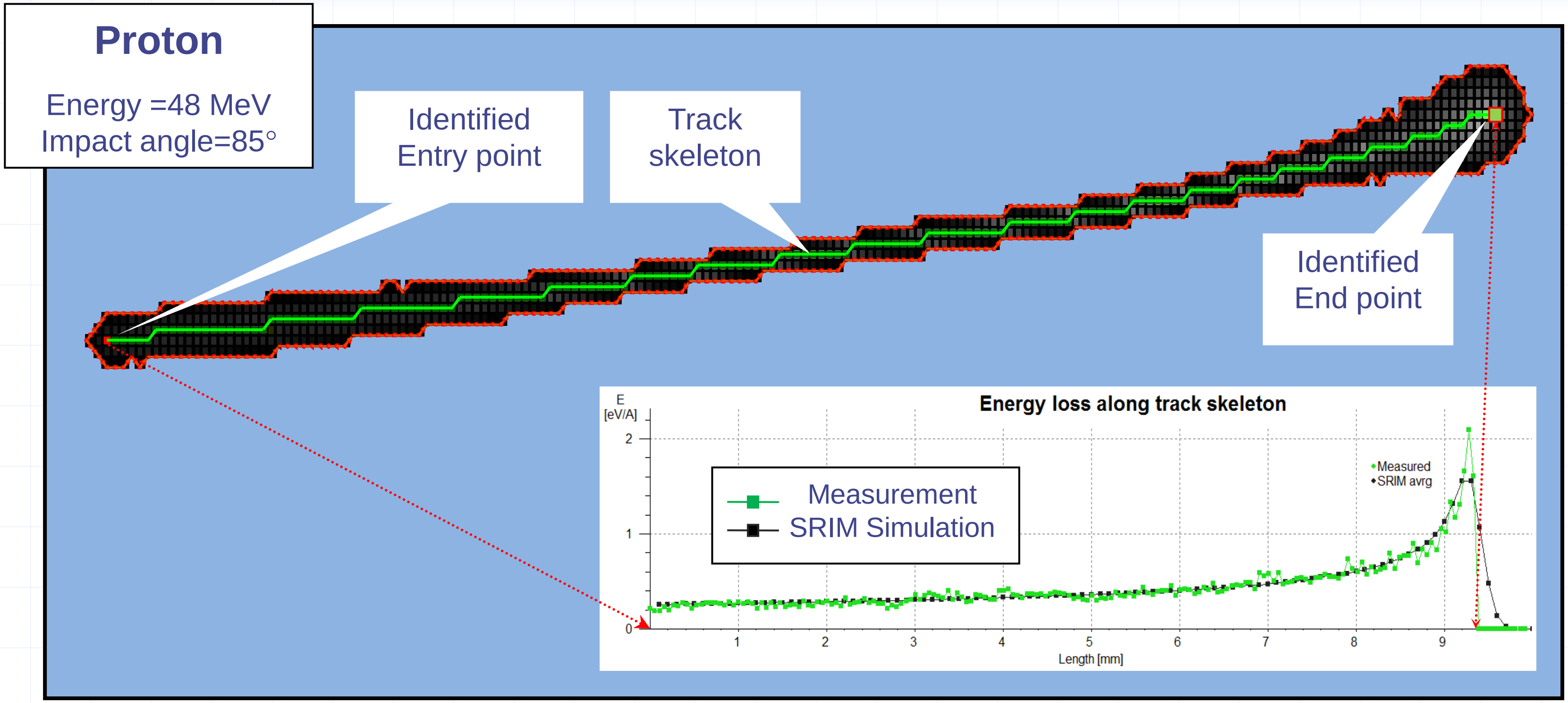
Hadron therapy:
Recorded track types

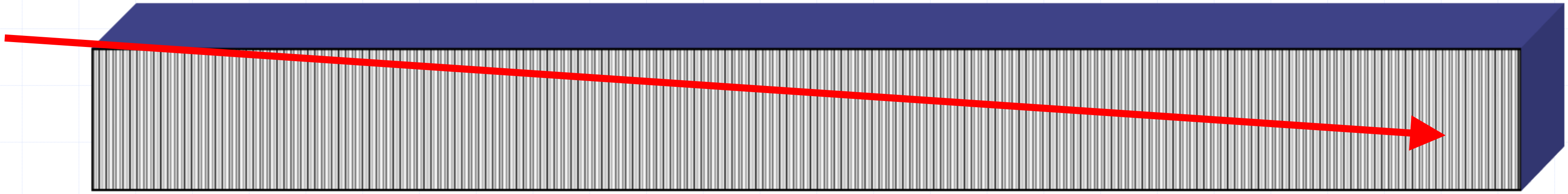
Several basic track types identified:

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



Proton track: LET and Bragg curve





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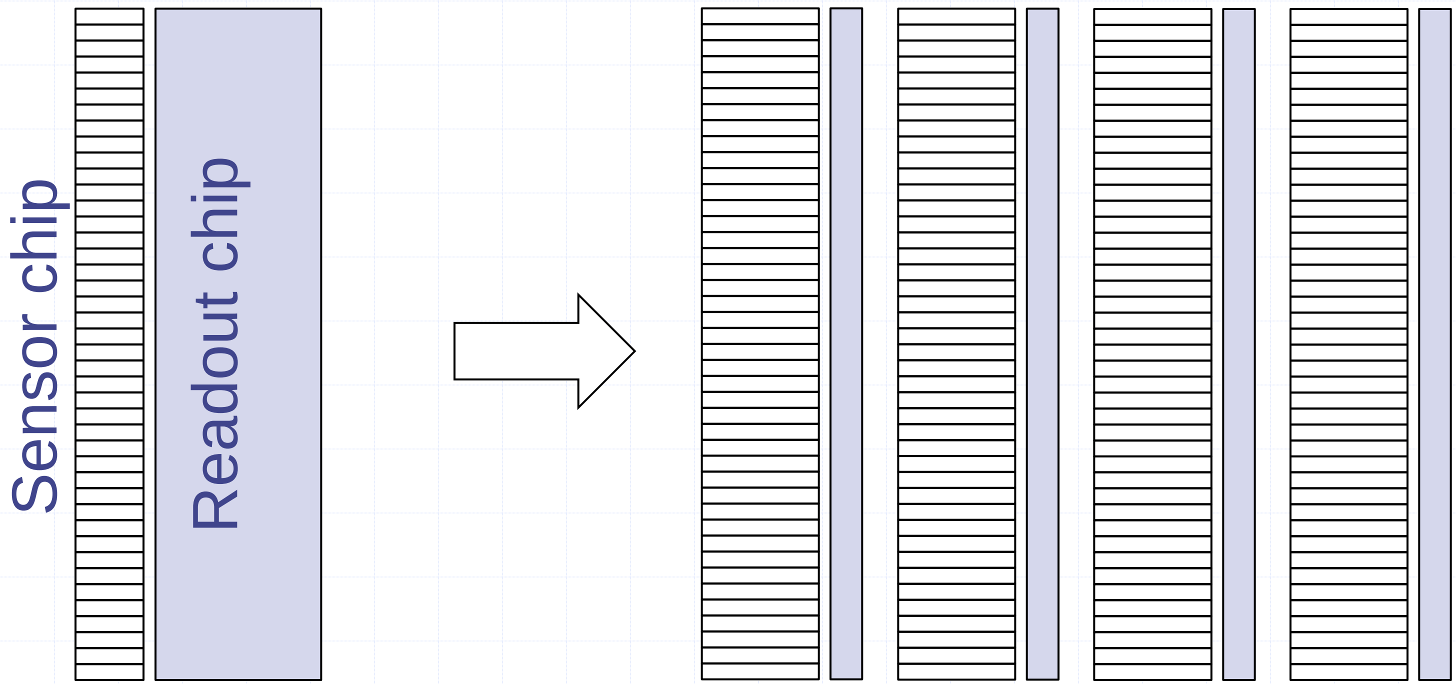
Voxel detector
Composed of several Timepix layers

Voxel detector concept

- Transition from 2D position sensitive detector to 3D => **Voxel detector**



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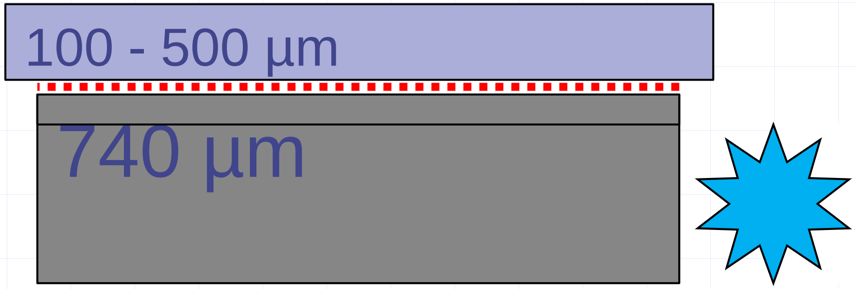
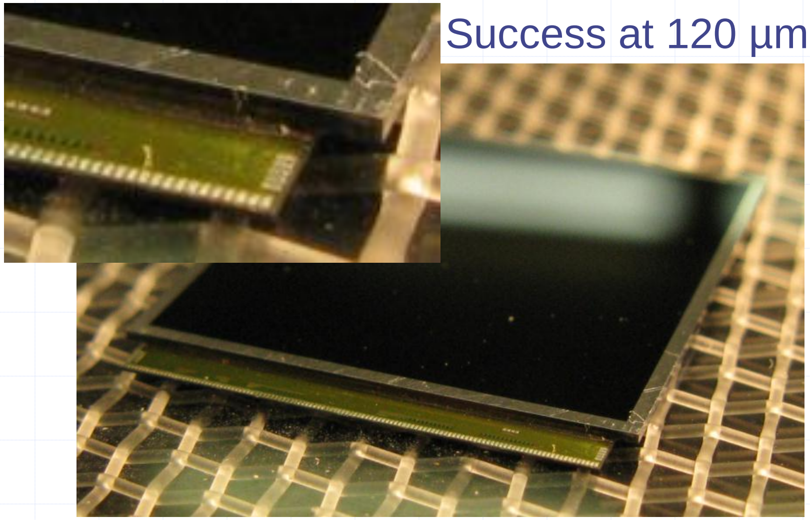
Task 1:

Readout chip thinning

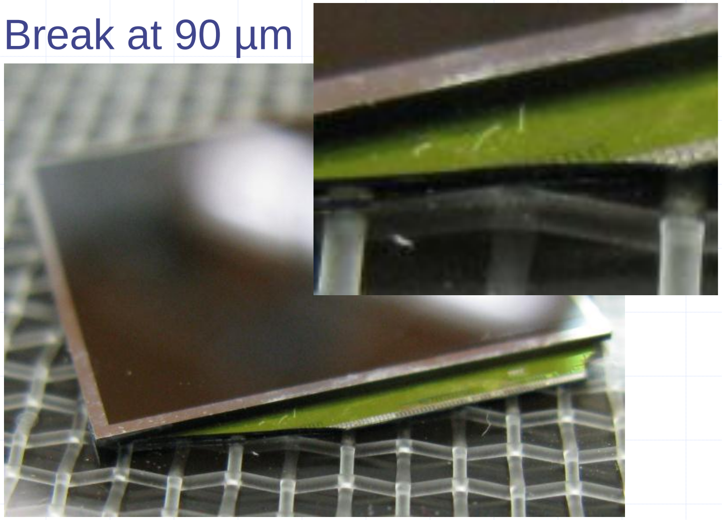
- For gamma camera and light particles the readout chip is too thick (~740 µm).
- It should be as thin as possible
- We have tested the method of polishing out the unwanted material





Success at 120 µm

Break at 90 µm



Current status: 50 µm reached

Variable setup:
Any number of chips can be stacked

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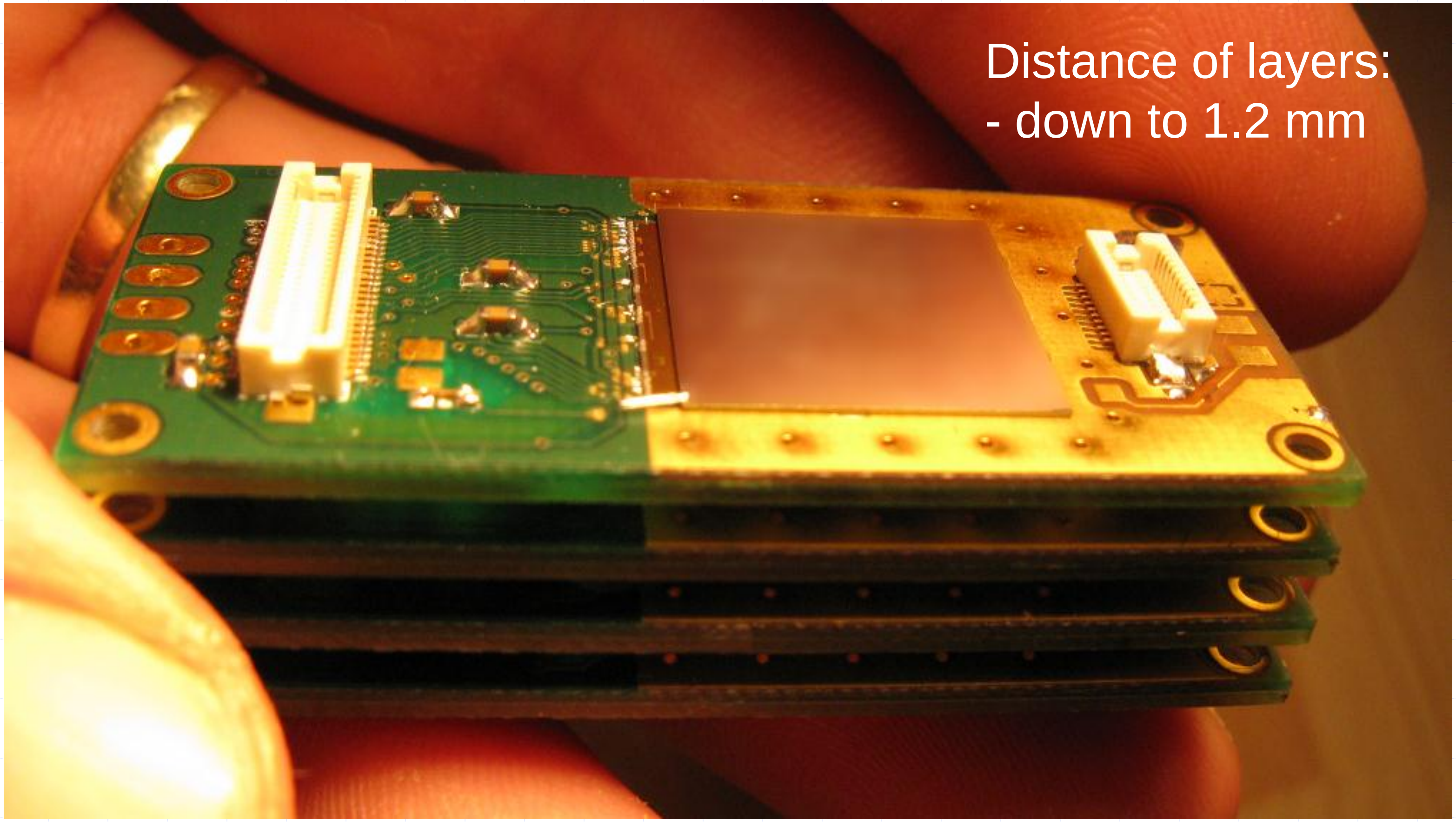

Sample image taken with 48 MeV protons

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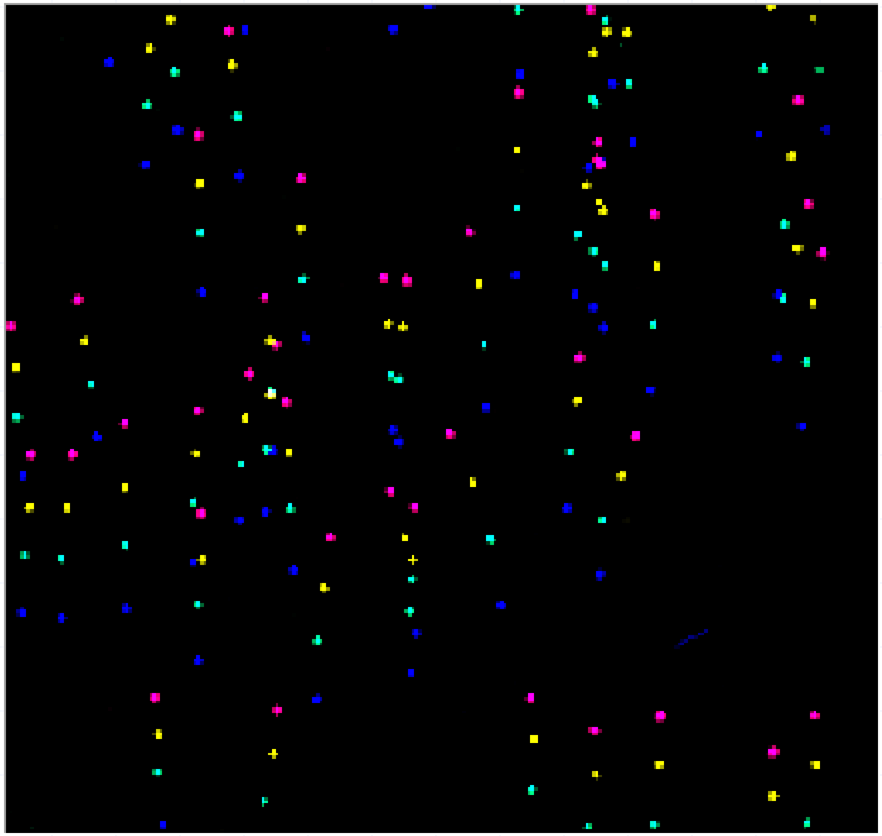

How to identify tracks?

a) **Time mode** (select clusters with same timestamp)

b) **Use geometry** (track clusters should lie on straight line)

Dose delivery imaging for hadron therapy: Tracking of secondary particles

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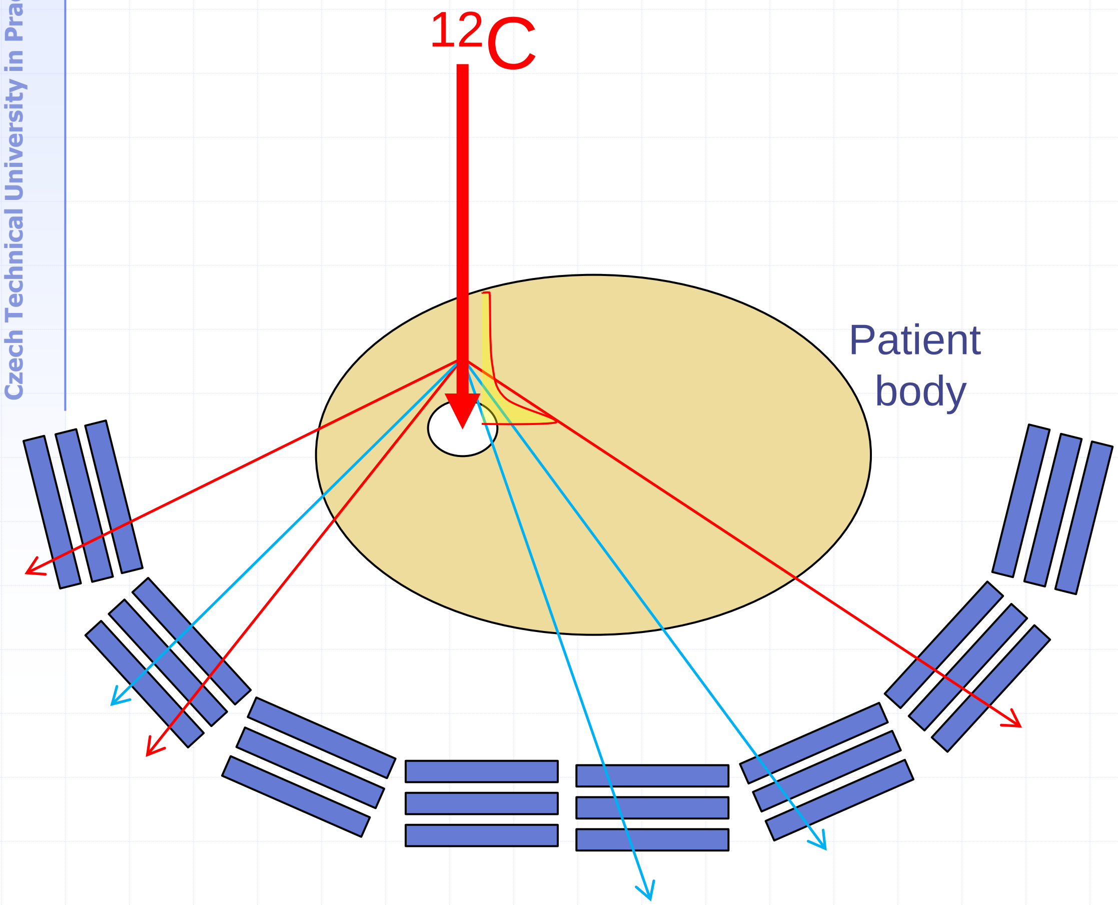

- The tracker would optimally surround the irradiated body.
- Tracker data can be back-projected to form an image of the beam path.
- Possibility to select particles with higher penetration power would improve quality.

Voxel detector in Time mode:
Experimental setup

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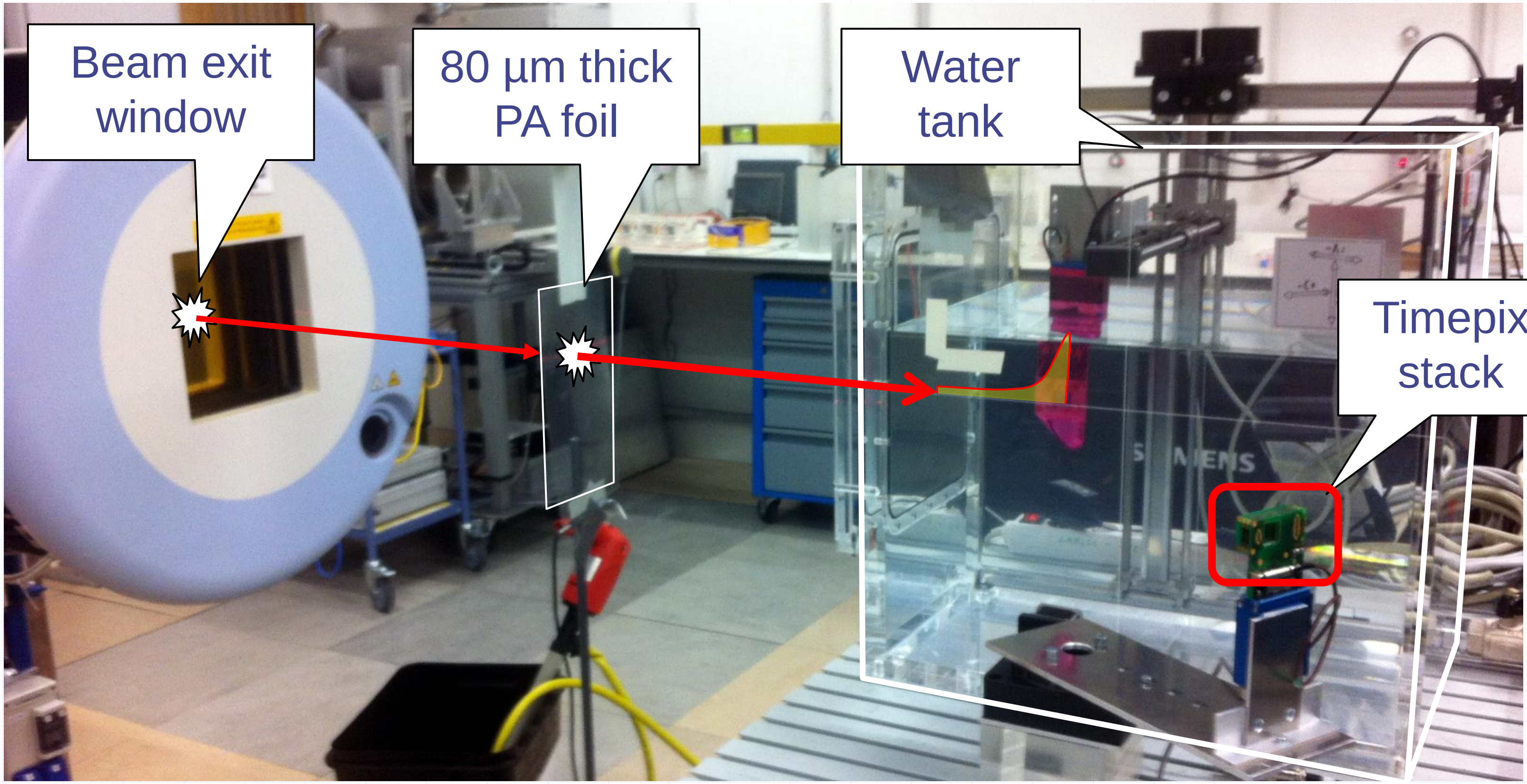
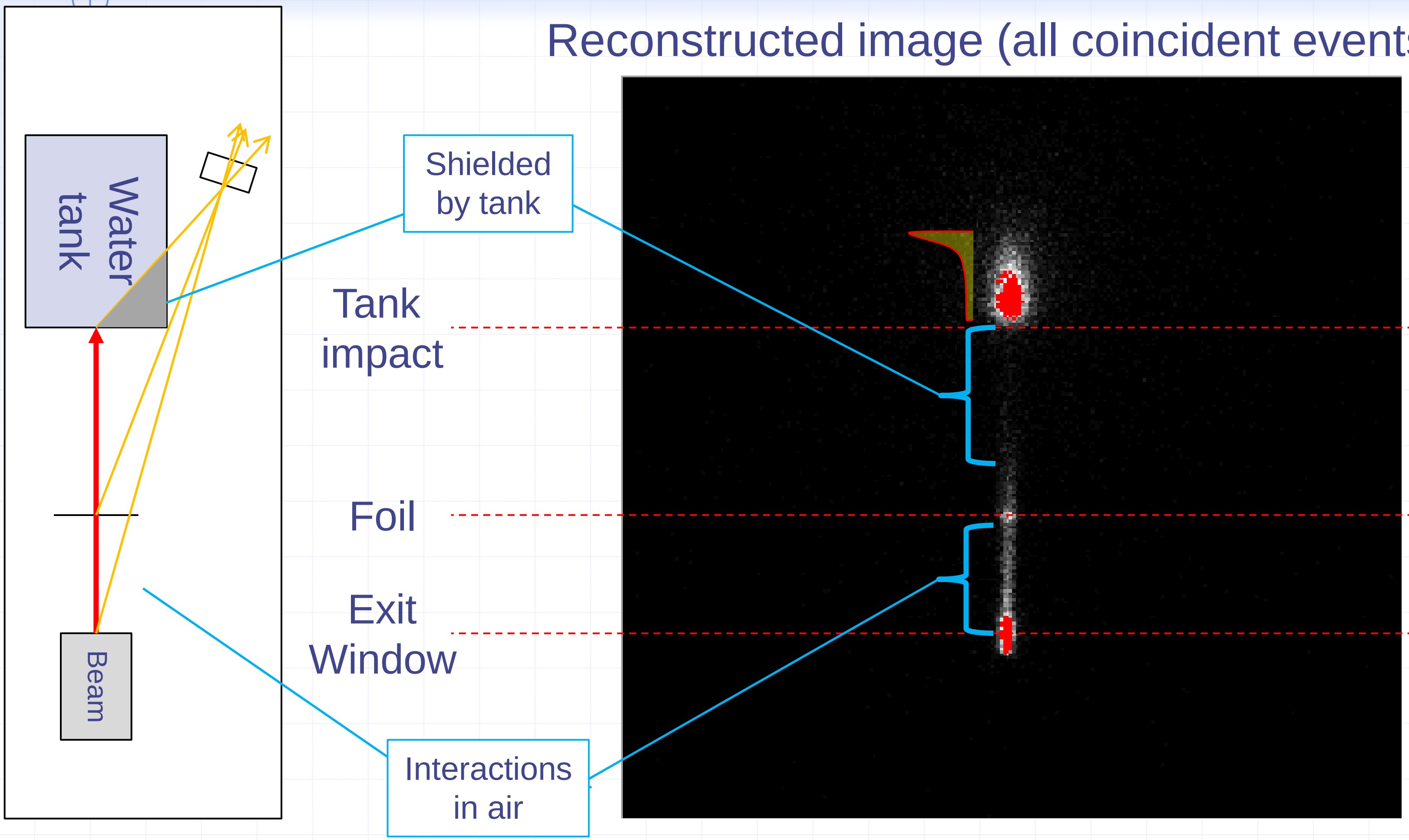
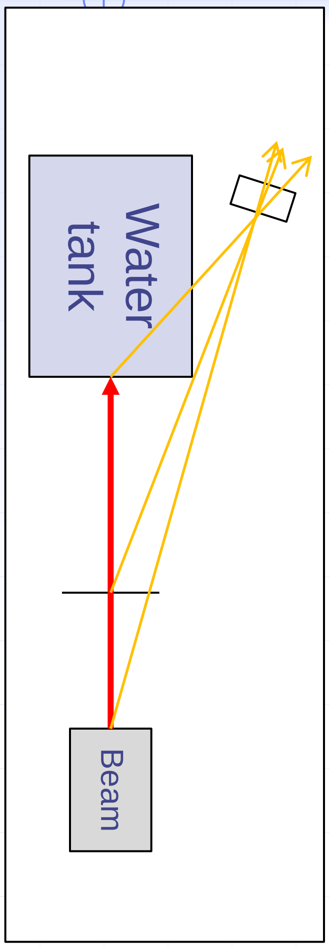


Observation of complete scene:
Beam line can be imaged

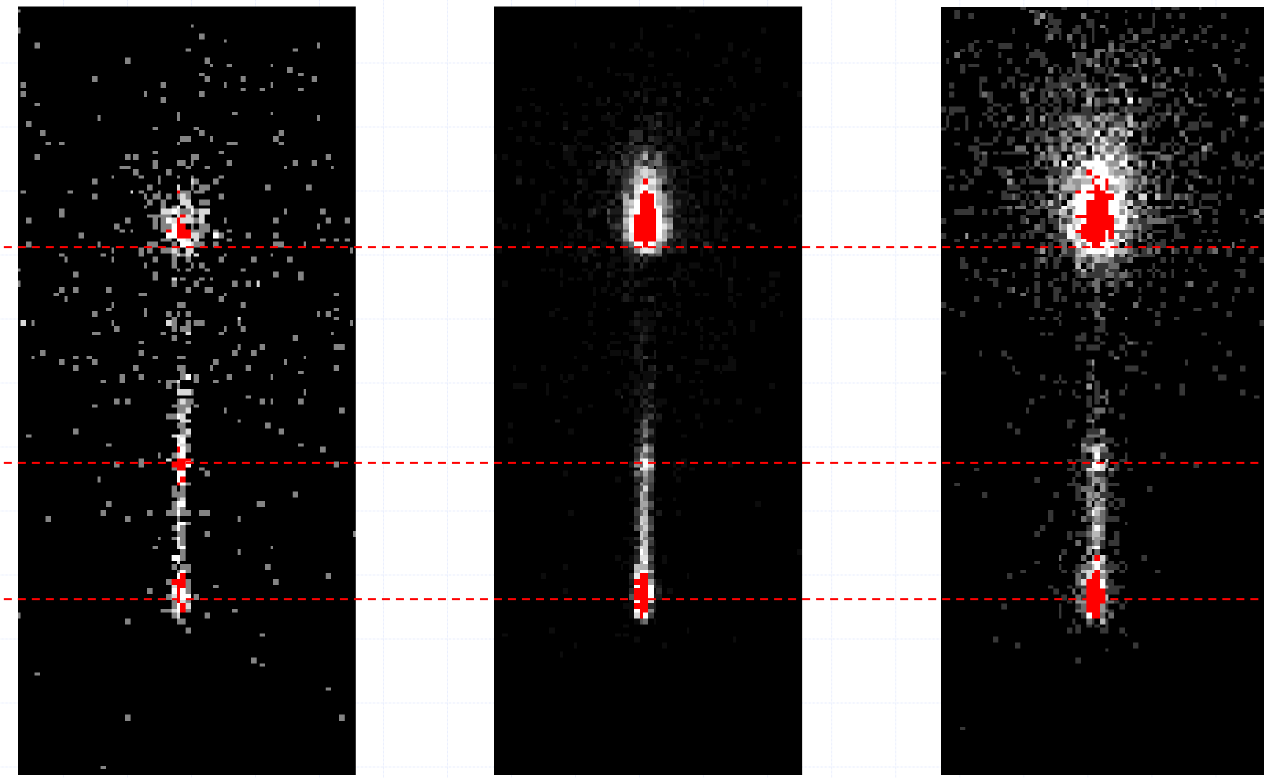
Reconstructed image (all coincident events)



Observation of complete scene:
Beam line can be imaged



Small clusters (high E protons, muons) | Middle clusters (protons) | Large clusters (low E protons, ions)



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

Other techniques:
Imaging based on scattering

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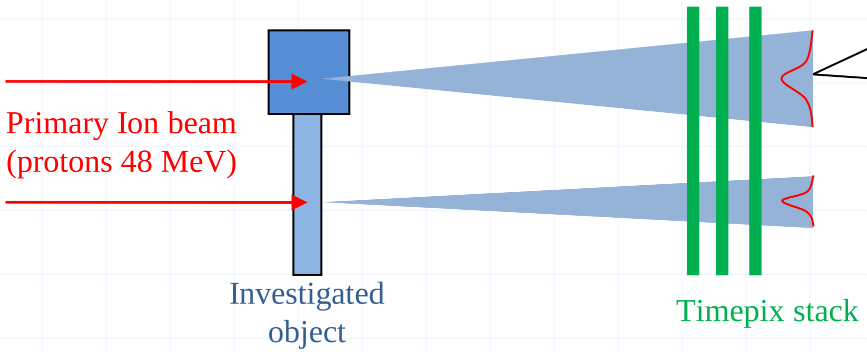


Spread of scattered ions corresponds to material properties along beam line.

Four PMMA plates with thickness from 2-9 mm

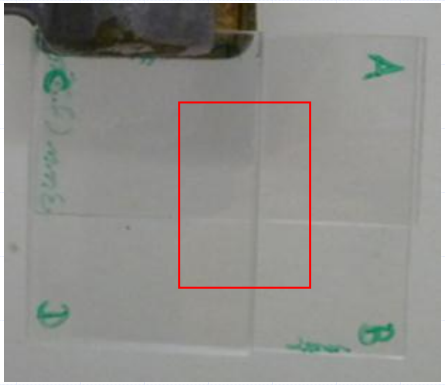
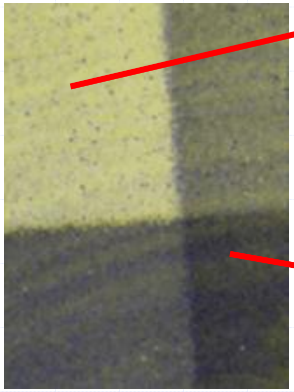
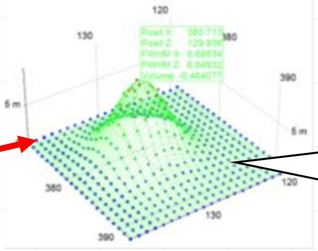
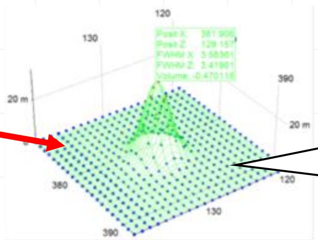


Image reconstructed from scattering data in each point





Wider distribution behind of thicker part of object



Narrower distribution behind of narrower part of object

What to be improved?

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- **Energy information is missing in Timepix mode (measuring time)**

⇒ We cannot sort particle types according to ΔE:

- Cannot precisely evaluate biological effects of particles (if used in dosimetry)
- Cannot select just certain particle types (if used for imaging)

Energy sensitivity

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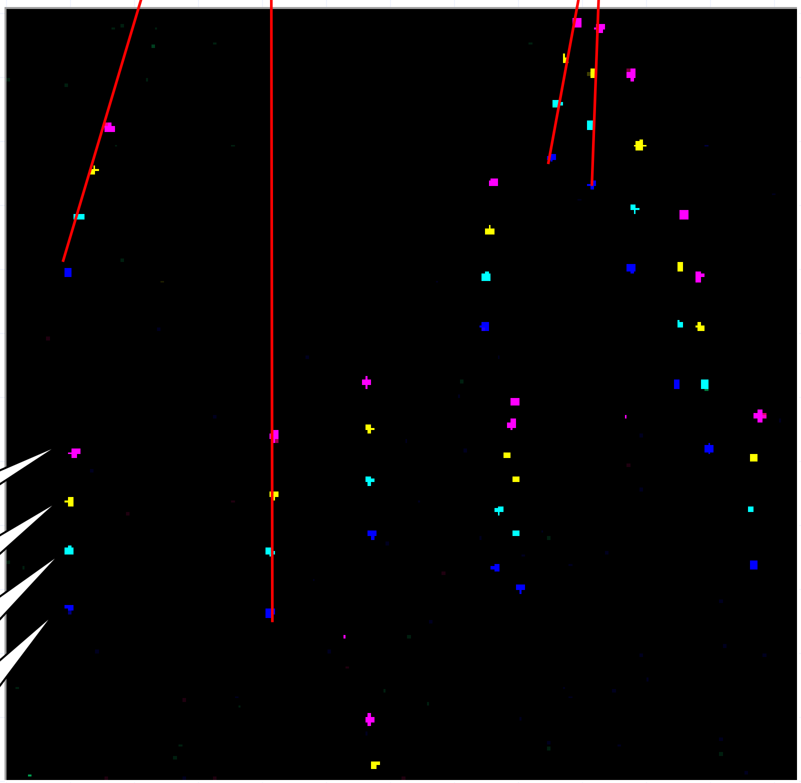
- Combination of Energy and Time modes in different layers allows identification of coincident tracks and vertex.
- ΔE allows particle sorting
- But: Highly complex data processing

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



First layer: ΔE_1

Second layer: ΔE_2

Third layer: time

Forth layer: ΔE_3

Sample image taken with 4 layers

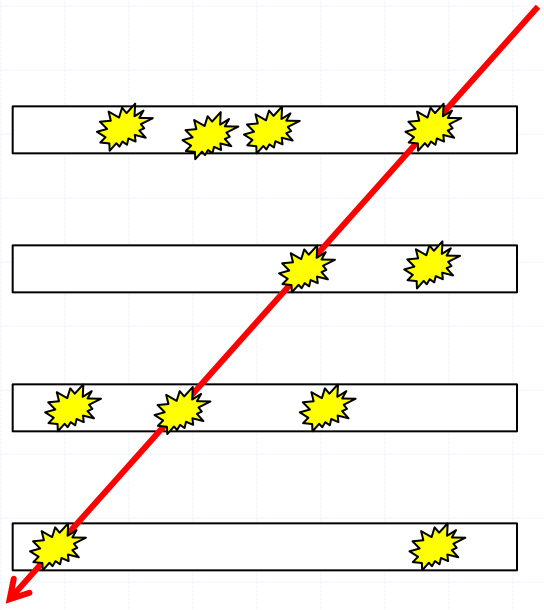
Geometrical track identification

Assumption:

- Straight tracks (for ions and MIPs).

Problems:

- Impossible to check all combinations - too high complexity even with low occupancy (single frame from 4 layers with 100 tracks give 10^8 combinations)
- The option would be to select candidates in the first layers and check them in remaining layers => complexity is still very high due to searching for candidates (10^4) followed by seeking of their continuations.



Can we use estimation of the track direction based on single layer data to reduce the problem complexity?

Particle direction determination

Assumption:

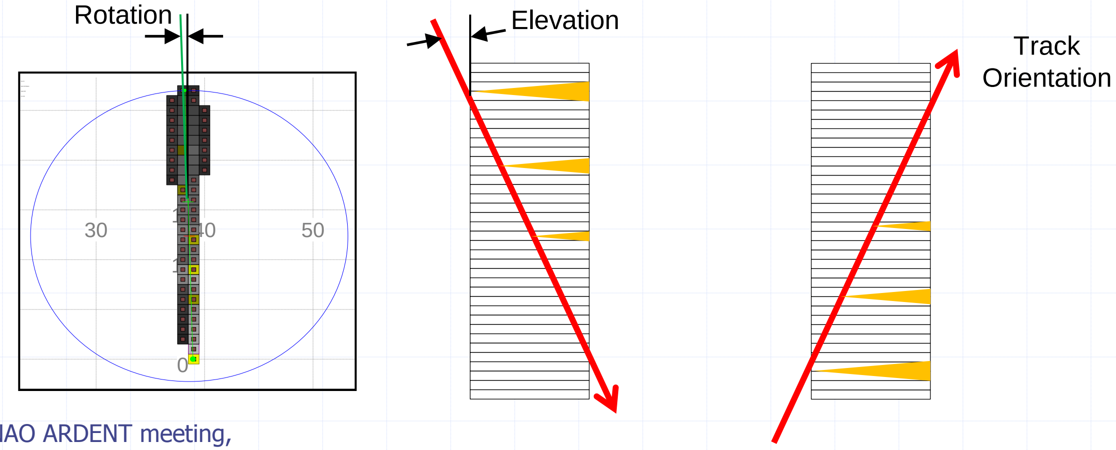
- Ions are able to fully penetrate the sensor (they are not absorbed)

Requested algorithm properties:

- Distinguishing of badly shaped clusters (not caused by ions)
- Better is to loose some good clusters than to positively qualify bad ones
- Algorithm should be simple and fast (no fitting of any complex model)

The task has three parts:

- Finding axis of the cluster in detector plane => Rotation angle
- Finding length of the cluster to determine the impact angle => Elevation angle
- Determine track orientation



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Methods

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Rotation is calculated using least-square fit:

- Axis goes through center of gravity
- Angle is determined minimizing perpendicular distance of pixels from axis using energy as weighting factor (version of linear regression)

Cluster length determination methods:

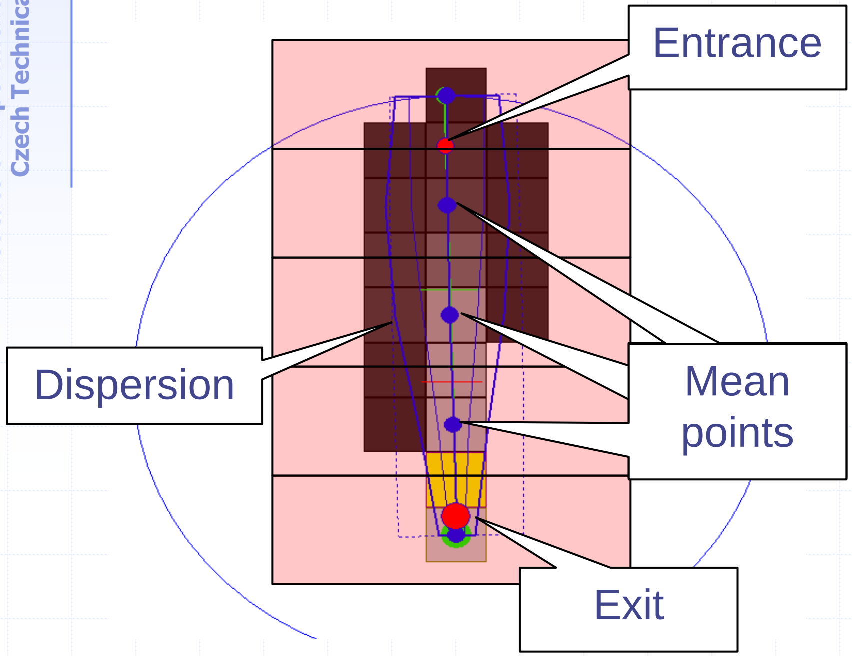
- Linear Length: The distance of the two most distant pixels along cluster axis – doesn't take into account charge sharing effect.
- Linear length shortened by:
  a) width of the cluster (Used in pixelman for dose calculation in space - ISS)
  b) width of gaussian distribution (at some threshold) of distances of pixels from cluster axis

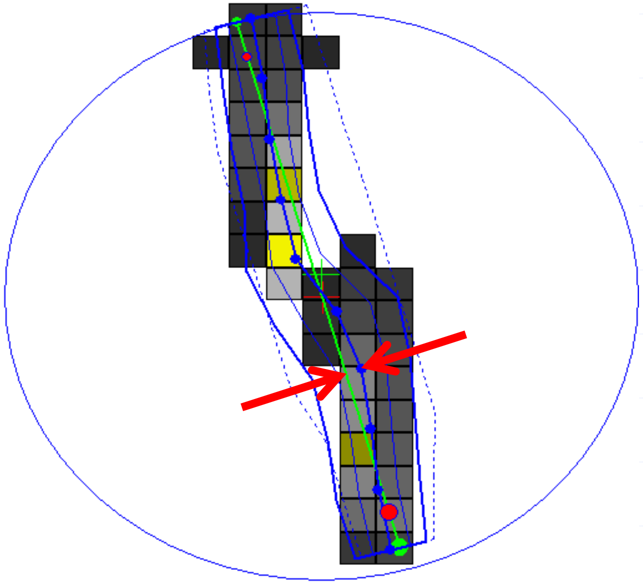
- Linear profile:
  - Cluster is divided to many sections along the axis
  - Distribution of pixel distance from the axis is calculated in each section evaluating mean point and sigma
  - Dispersion (sigma) at the beginning and end are used for calculation of the length

Impact direction determination

Profile along clustr axis

- Cluster is divided to many sections along the axis
- Distribution of pixel distance from the axis is calculated in each section evaluating mean point and sigma
- Dispersion (sigma) at the beginning and end are used for calculation of the length

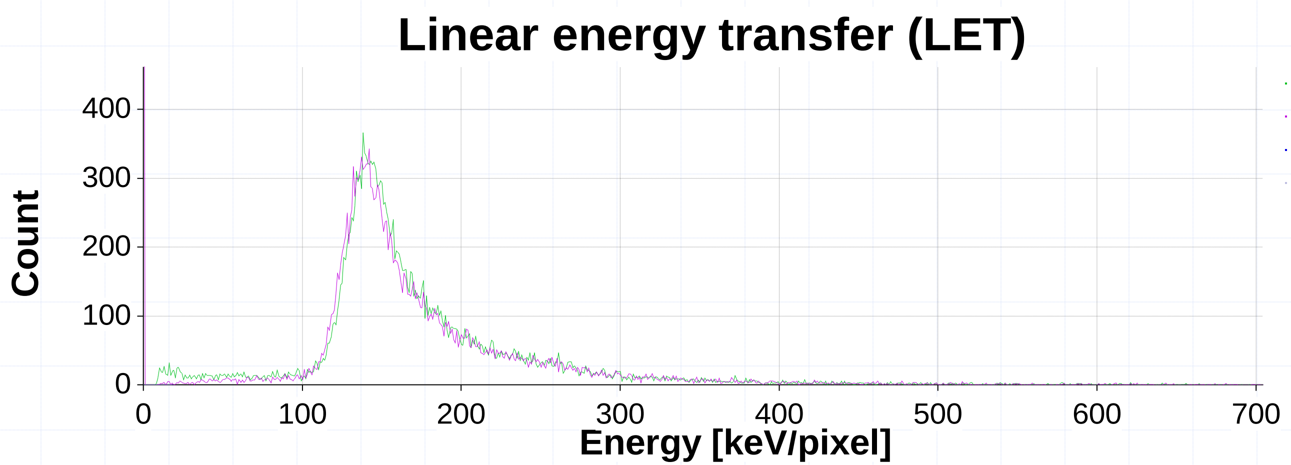




Bad cluster can be easily identified checking distance of mean points from axis

Profile along cluster axis

Sample results for 48 MeV protons



Efficient cluster search

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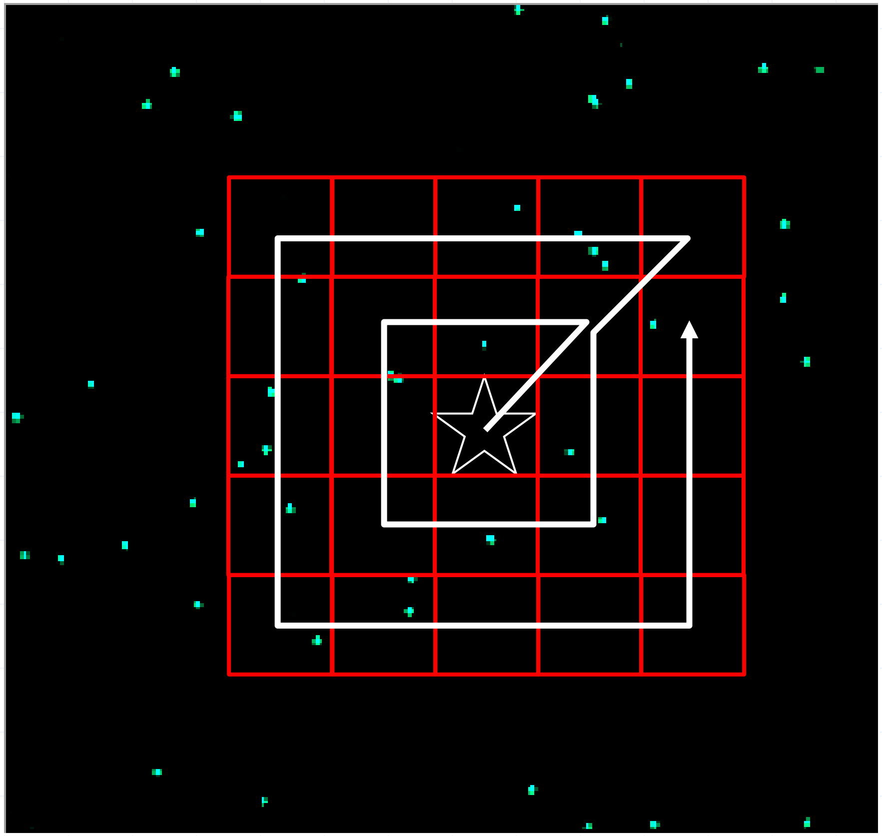

Goal:

- To find cluster closest to certain point

=> Searching in spirals

Reduction of complexity by factor of 10000.

Using particle direction calculated in the first layer

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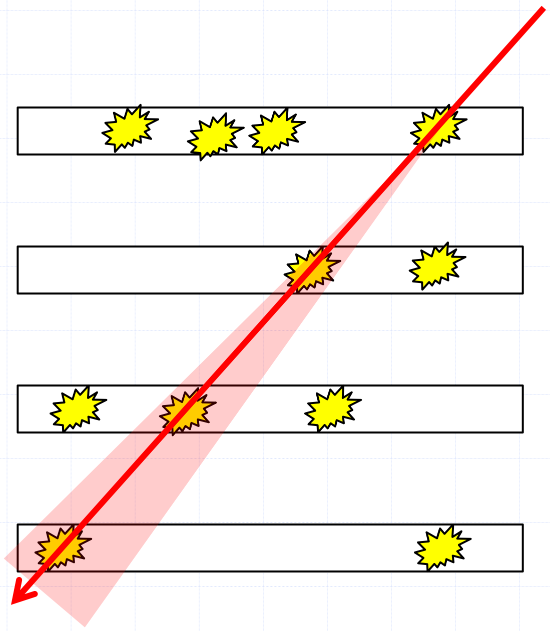

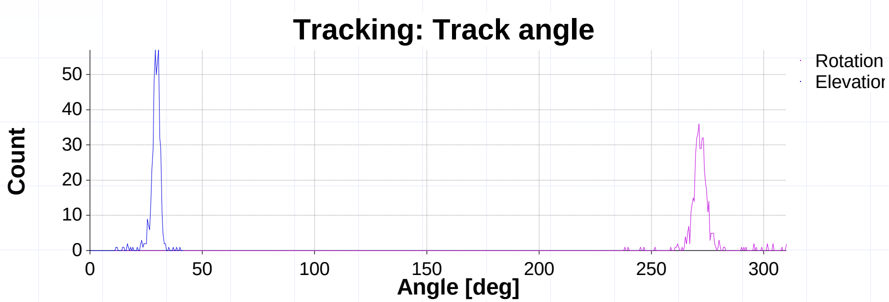

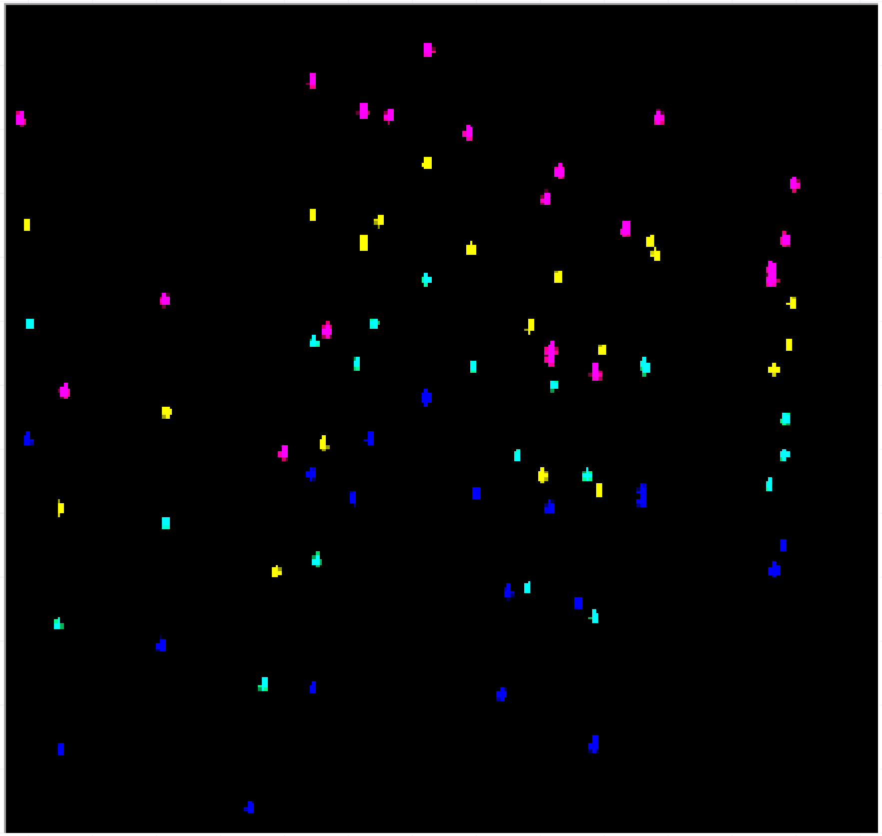

The principle works.

Can we use it for two layers only?

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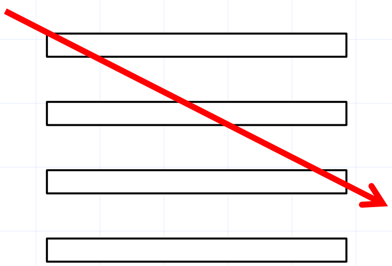
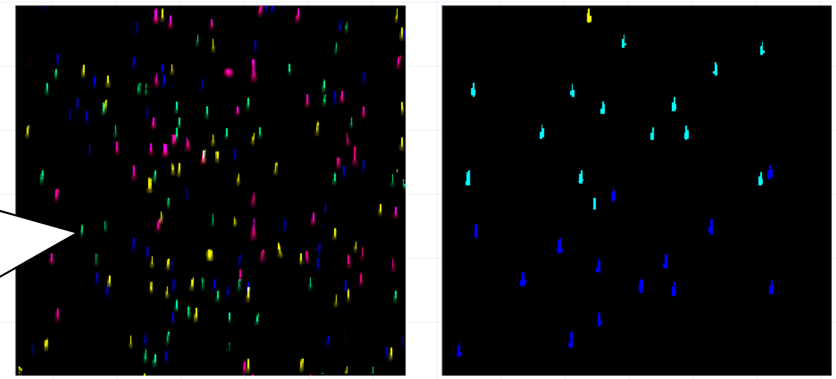
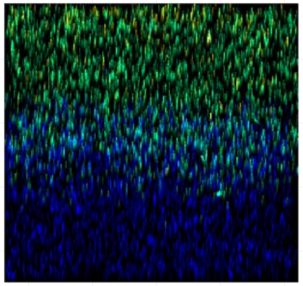
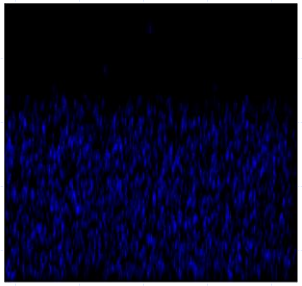
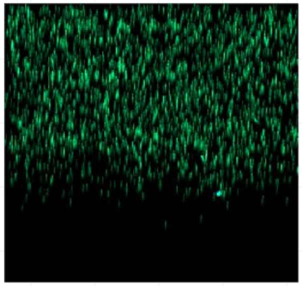
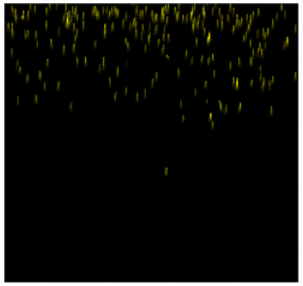
- Detector with 4 layers was irradiated at angle of 60 degrees => **two layers are hit by each particle in most cases**
- Try to localize tracks intteracting in the first layer.



Processing of such frame would take **6 million** of line calculations and wouldn't end with any result.



50 tracks per layer

All events	Identified tracks In all layers	1st layer	2nd layer	3rd layer	4th layer
					

Neutron detection
By Timepix telescope

Detection of slow/fast neutrons with very high selectivity and background rejection

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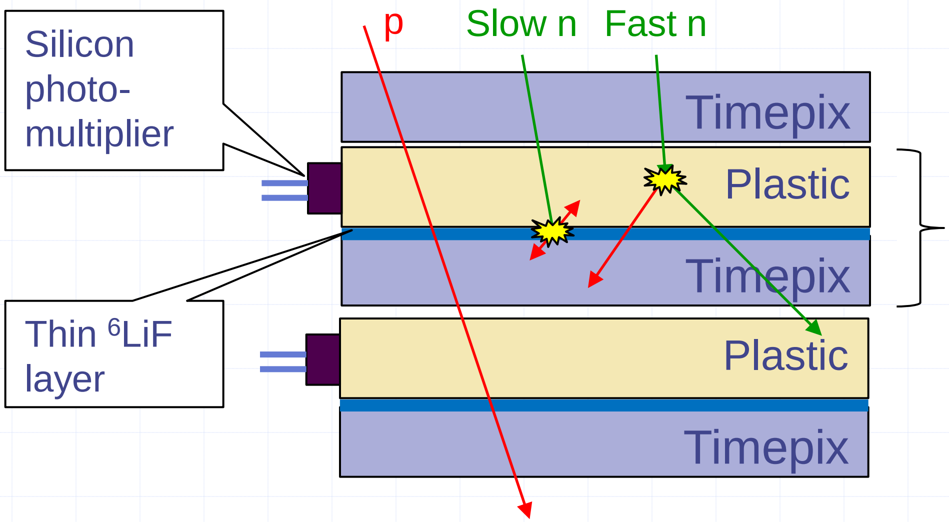
Multilayer detecting structure:



Strong selection criteria:

1. Coincidence/anticoincidence technique (trigger sources: all Timepixes, SiPMs)
2. Total energy has to correspond to n capture by ^{6}Li
3. Cluster shape has to be correct

⇒ **Extremely high selectivity for thermal and fast neutrons.**

⇒ **Primary Ions and MIPs are identified very well too.**

⇒ **The detection efficiency is increased using many layers.**

⇒ **Can work as Compton camera as well.**

Experimental verification in HIT Heidelberg

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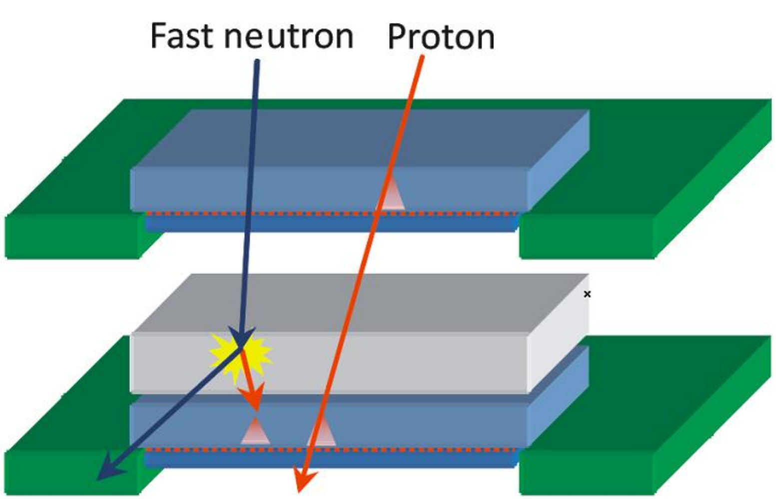
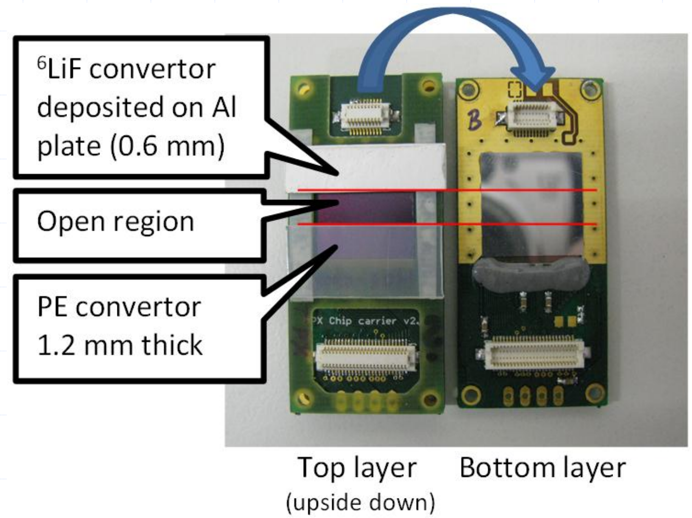
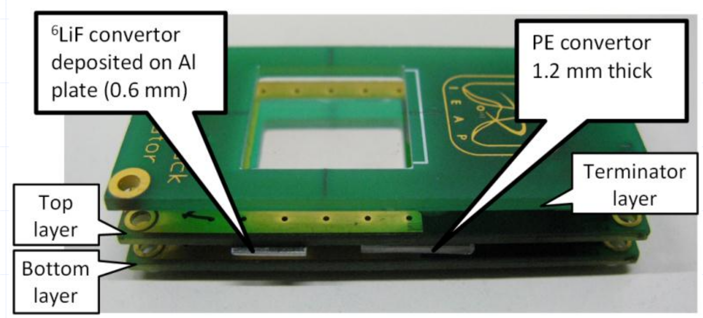
- Interlacing neutron convertors in the stack we can resolve neutrons
- **Anticoincidence mode to reject ions**
- With different convertors such as PE and ^{6}LiF we can discriminate fast and slow neutrons



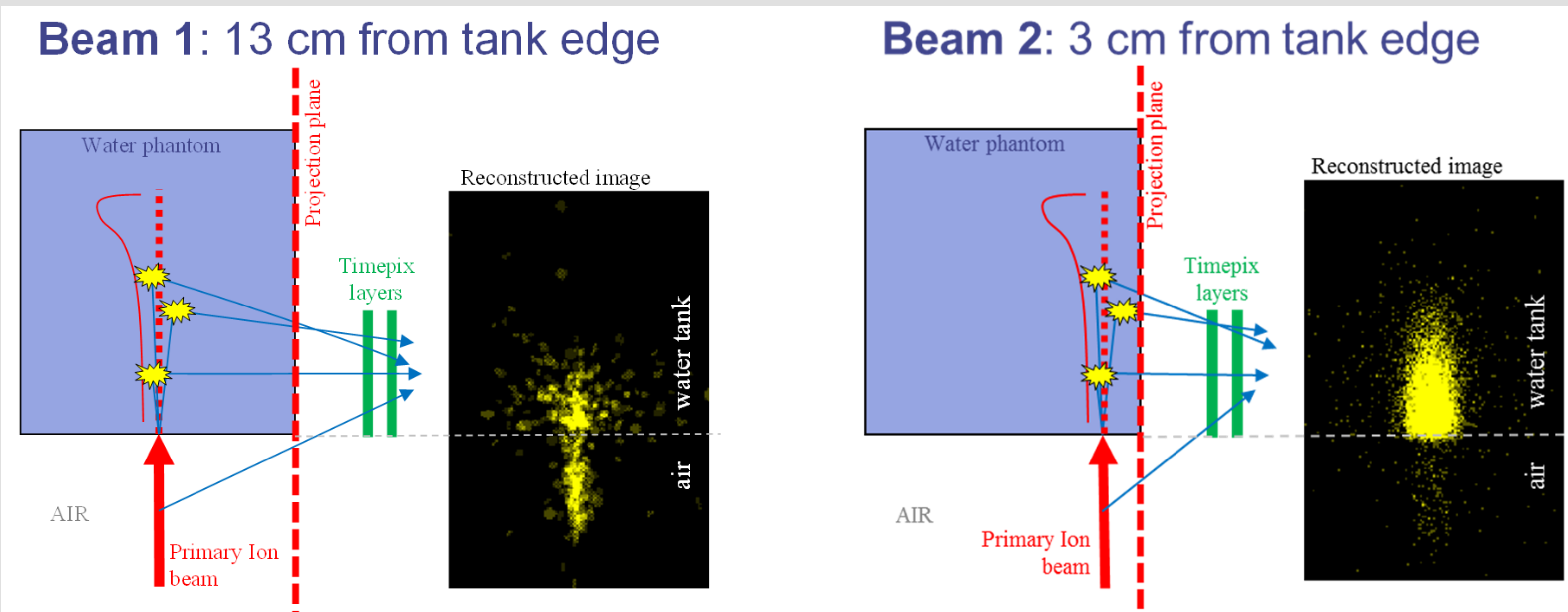




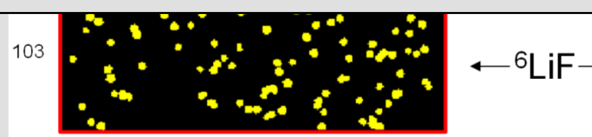
Water tank results:

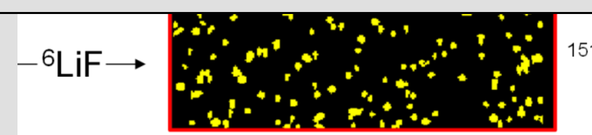
(^{12}C at 250 MeV/u)

Coincidences



Anticoi





Fast/Slow = **0.45**

Fast/Slow = **6.70**

Position sensitive scintillator + Timepix => new hybrid detector

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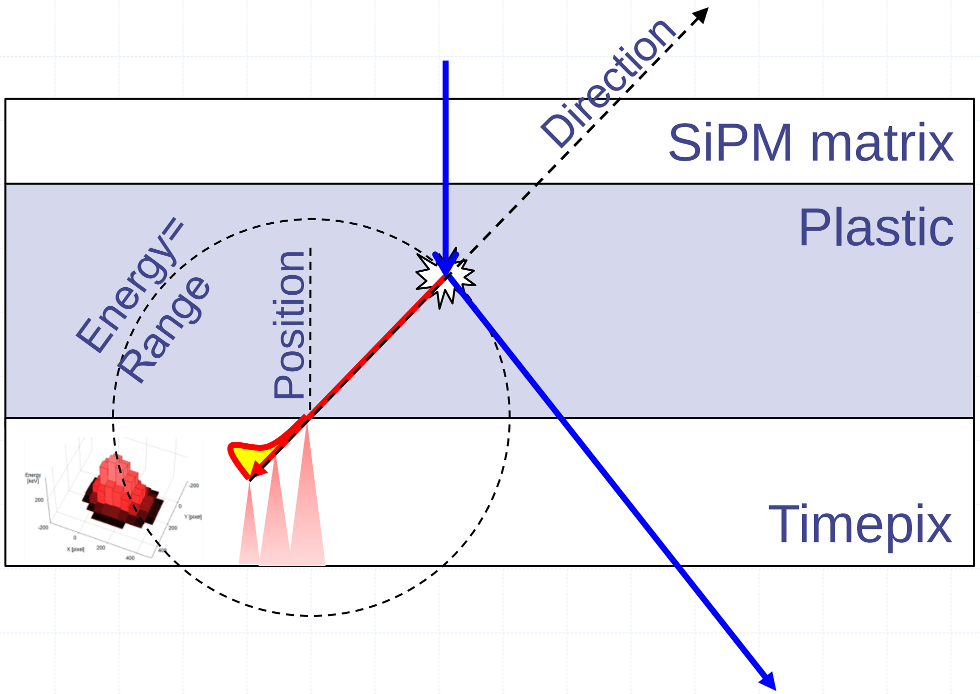
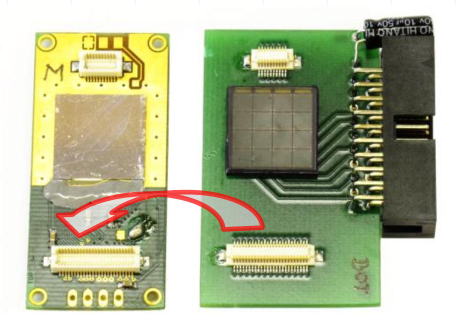
- More information can be acquired
- Both directional and energy sensitivity can be achieved



Photomultiplier 4x4 array produced by SensL company. Devices can be tiled for larger areas.

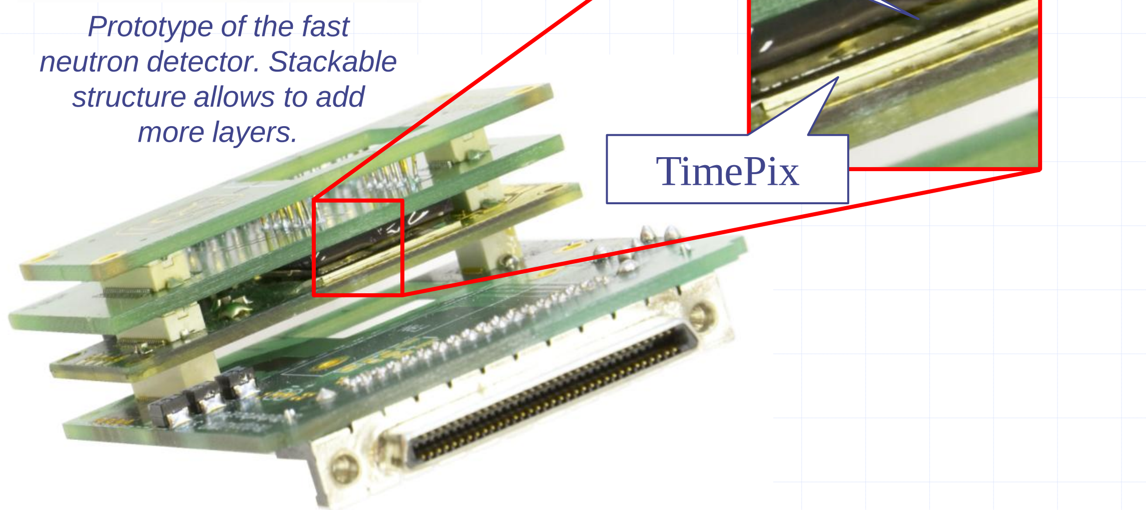
Prototype of hybrid detector

- Layer carrying SiPM matrix and plastic scintillator was built. The layer is compatible with Timepix stack. Many layers can be combined.



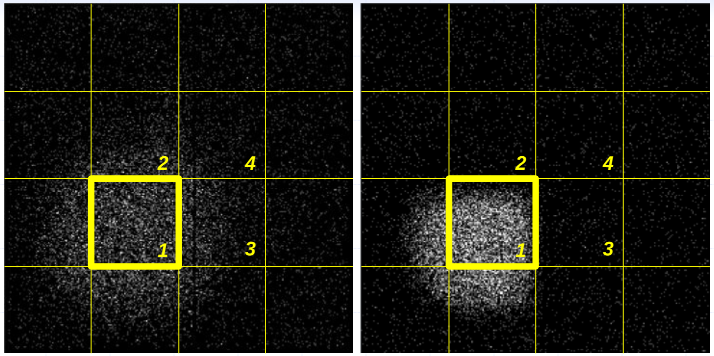
Two parts of the detecting structure: TimePix detector (left) and silicon photomultiplier array (right) are assembled face to face.

Prototype of the fast neutron detector. Stackable structure allows to add more layers.

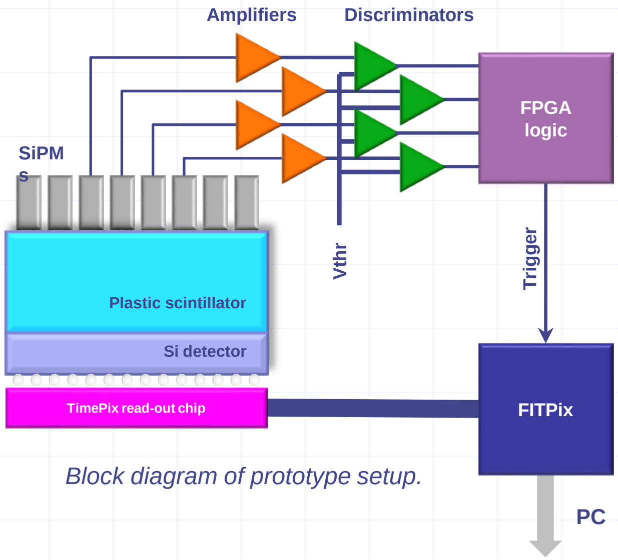


First experimental results

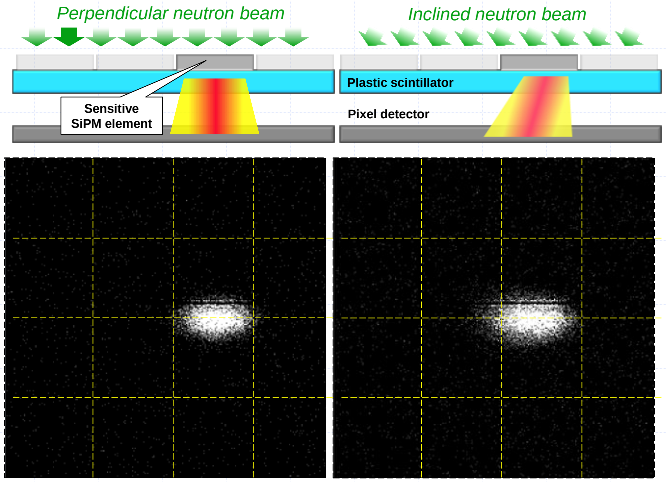
- 14 MeV neutrons from D-T generator used
- Complex coincidence logic used for triggering

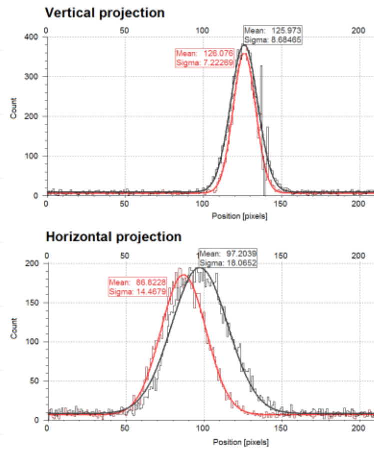


Only one sensitive SiPM element can be chosen without officiating of the other elements (left). But the condition can be more strict, e.g. valid for element 1 while invalid for 2, 3, 4 (right). The cloud become asymmetrical.



Block diagram of prototype setup.





The response of the intersection of two neighboring elements in perpendicular neutron field creates centric cloud. Rotation of the filed moves the midpoint of the cloud. The angle of rotation can be estimated from change of the position.

Conclusions

- Handheld particle tracking system exists.
- The Timepix based system allows particle discrimination resolving light particles, ions and neutrons.
- Combination of Energy and Time modes in different layers allows identification of coincident tracks and vertexes.

Current technological challenges:

- Fast sparse readout, smaller pixels, larger area …
- New interface FITPix 3.0 allows 870 fps (0.5 M tracks/s)
- New chips are coming: Timepix3, SmallPix
- Large area: Edgeless sensors allow seamless tiling (6x6 cm^2 1 Mpix prototype exist, 14x14 cm^2 6.5 Mpix is coming)

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Thanks for your attention