Probe and Scanning System for

3D Response Mapping of Pixelated Semiconductor Detector

with X-rays and the Timepix Read-out

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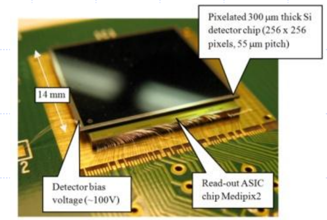
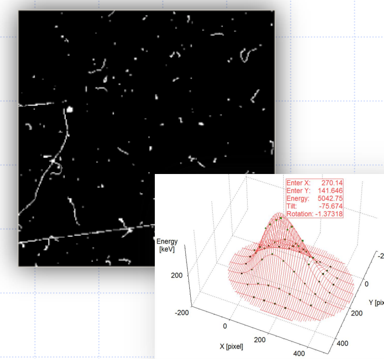
Outline

Introduction

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

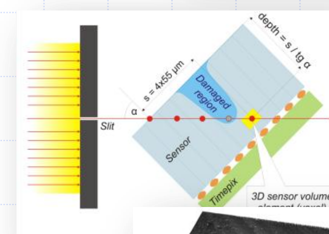


3D scanning of sensor using ions



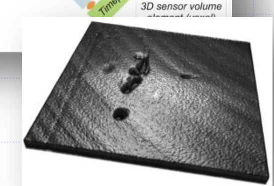
3D scanning of sensor properties with X-rays

- Fresh silicon detector
- Radiation damaged detector
- Other sensor types: CdTe, GaAs



Applications

- Imaging based on particle tracking for hadron therapy



Work performed in frame of Medipix collaboration.

www.cern.ch/medipix

Timepix pixel device
single particle counting pixel detector

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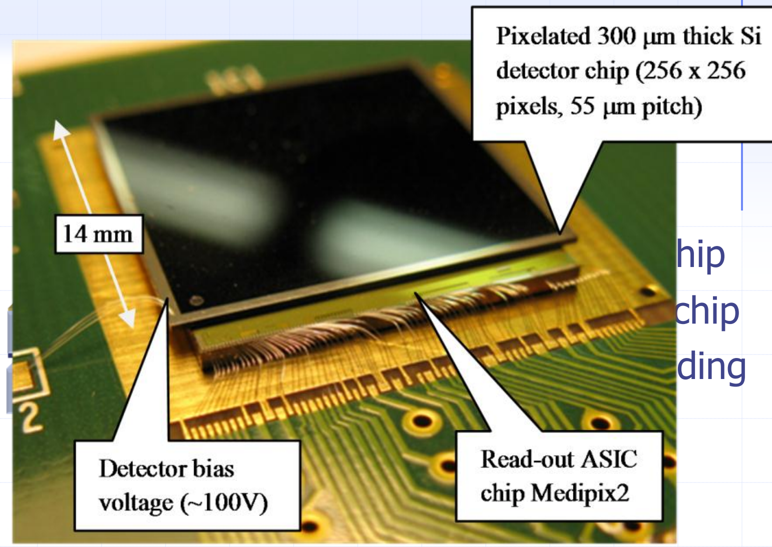
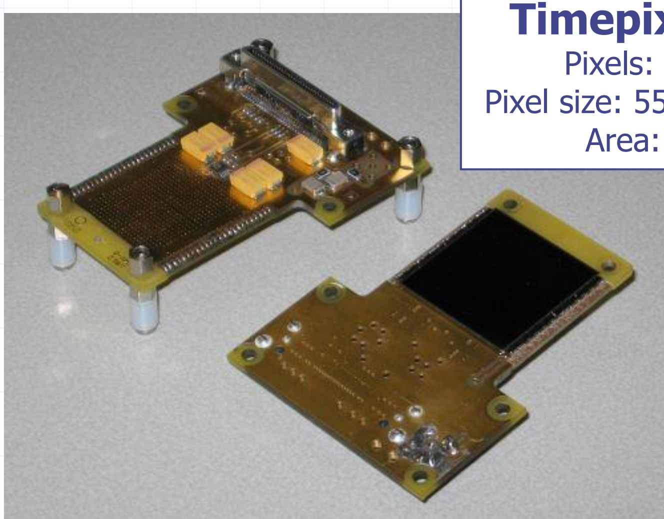
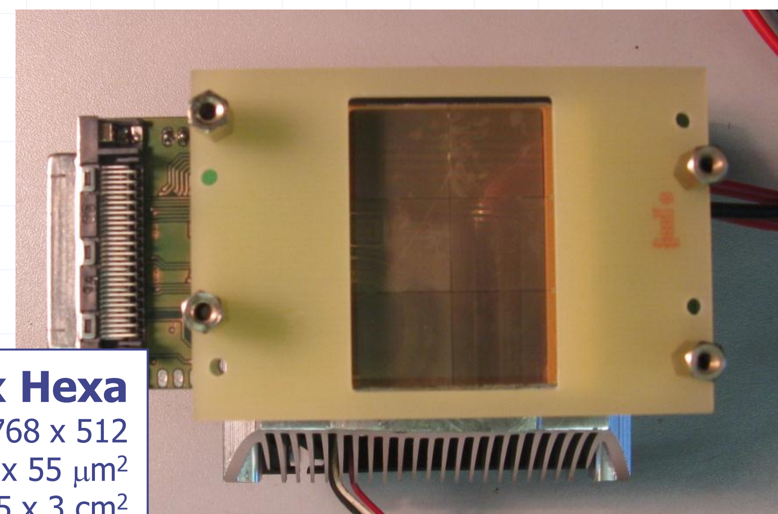
- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or **ADC** or Timer
- Multichip assemblies with no blind area: **Quad** (30 x 30 mm), **Hexa** (45 x 30 mm)

hip
chip
ding





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

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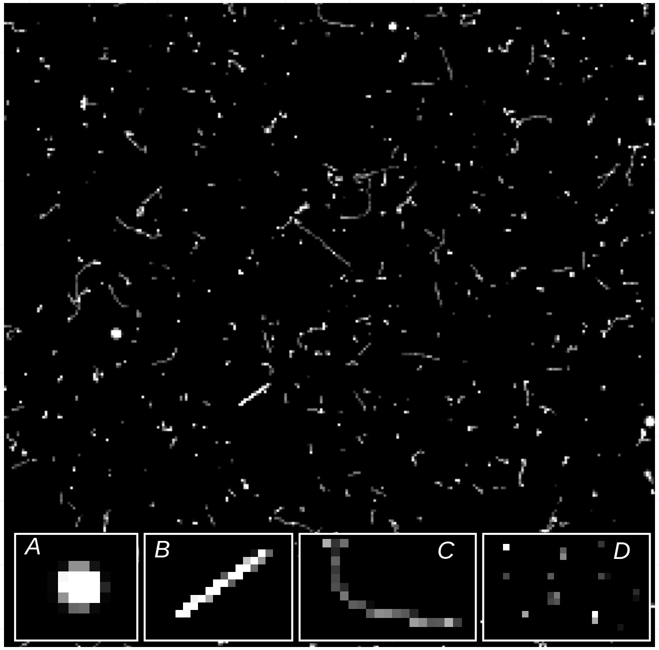
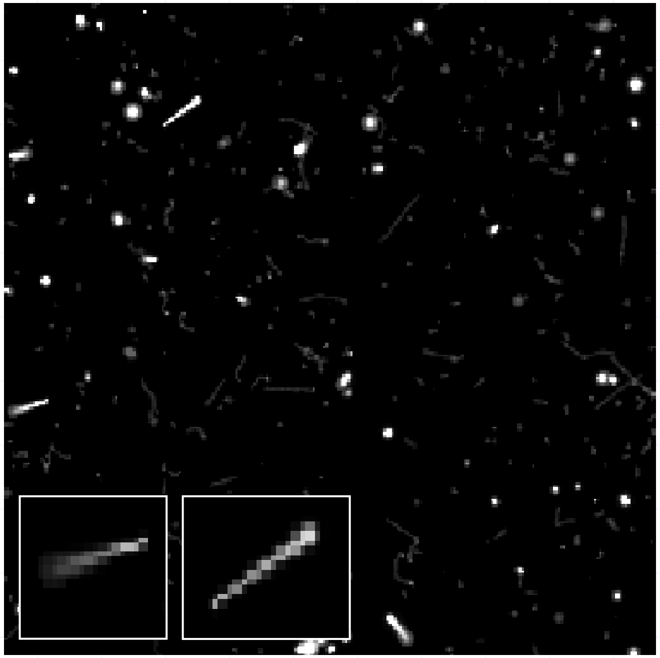
Particle tracking
With pixel detectors
Timepix

Tracking with planar pixel detectors

Radiation background



Protons recoiled by fast neutrons



Typical observed images in hadron therapy beam

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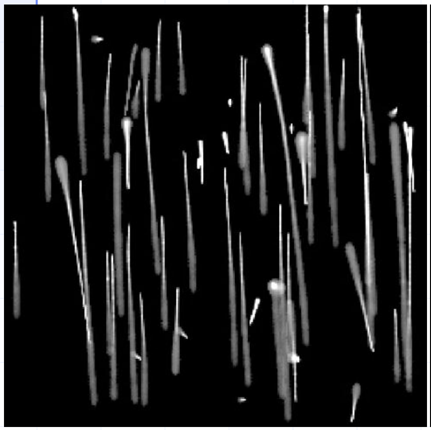
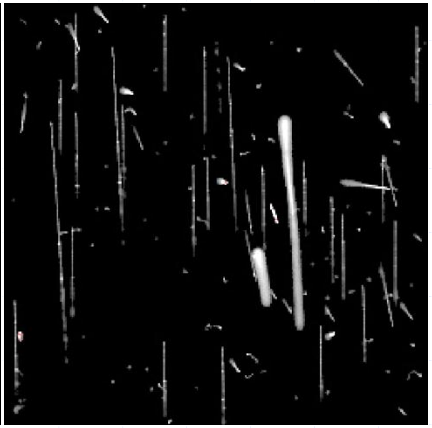
Protons 48 MeV



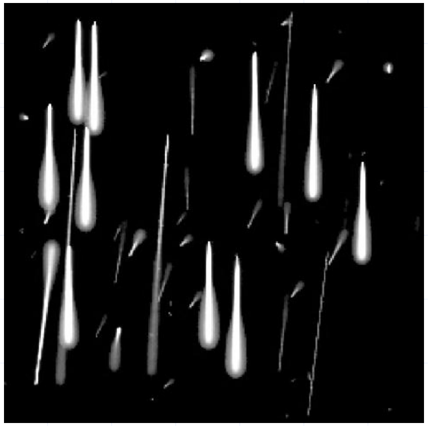
Only protons and their scattering, no secondaries.

Protons 221 MeV



Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u



Carbons and protons and their scattering, no secondaries.

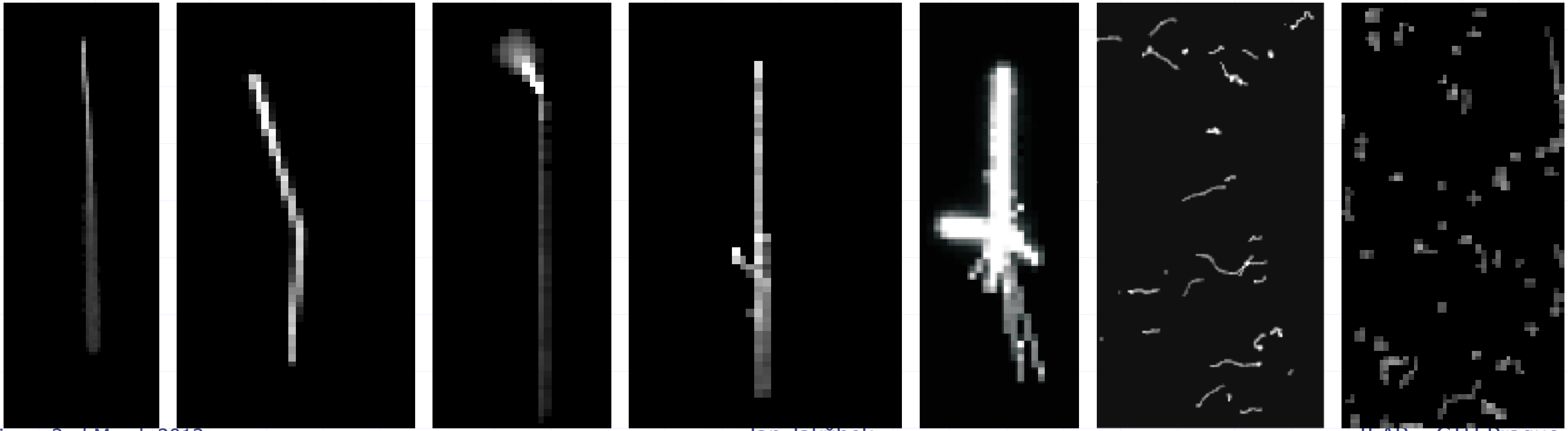
Carbons 430 MeV/u

Carbons and many secondaries.

Hadron therapy:
Recorded track types

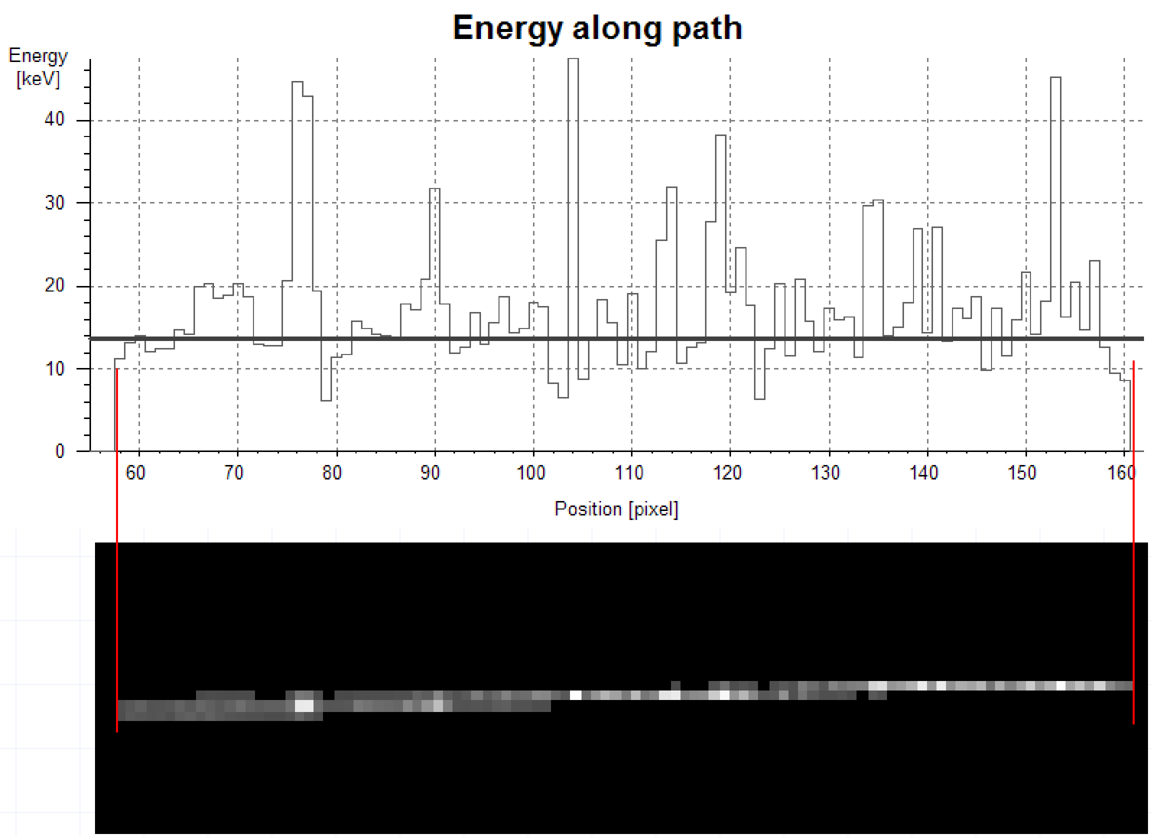
Several basic track types identified:

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



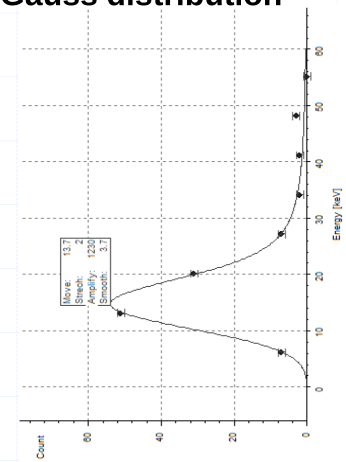
Charge sharing effect:

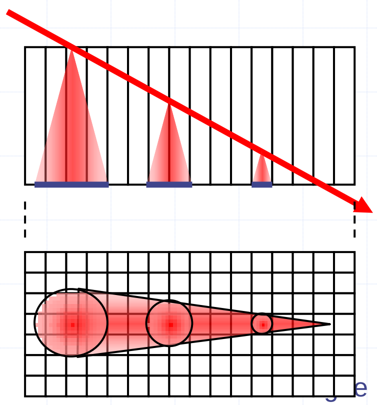
Tracks of MIP particles – Cosmics



Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





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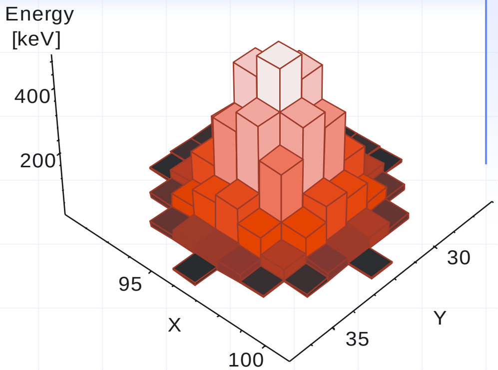
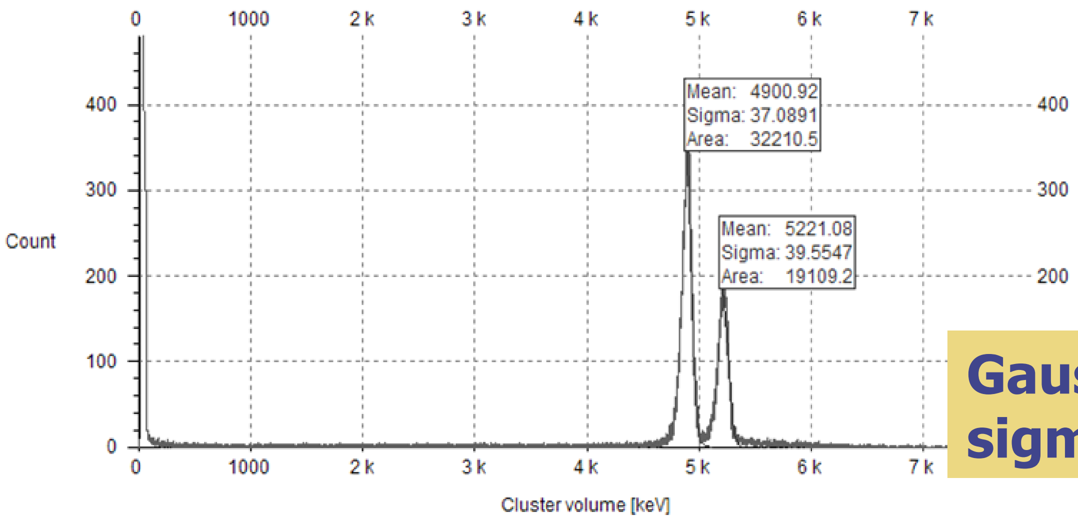
Energy mode calibration:

Heavy charged particles?

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



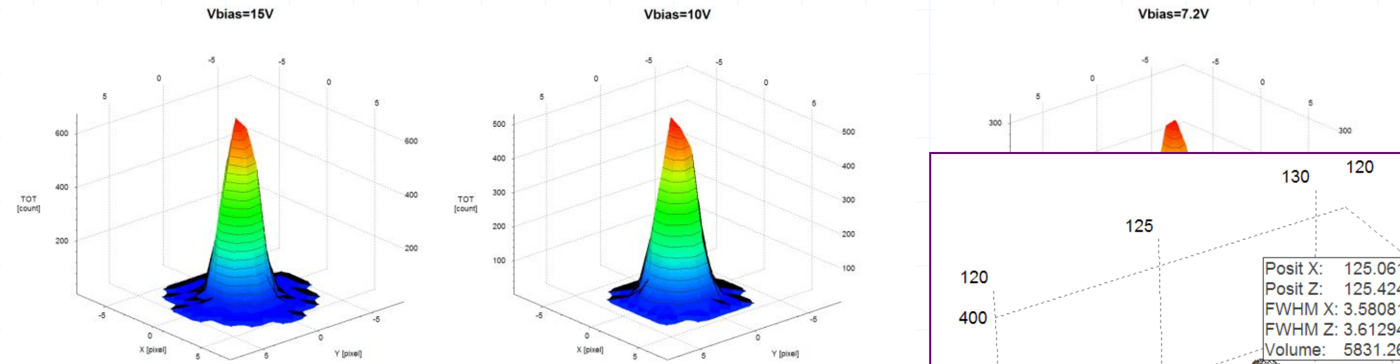
Cluster volume (energy) spectrum (measured in air)

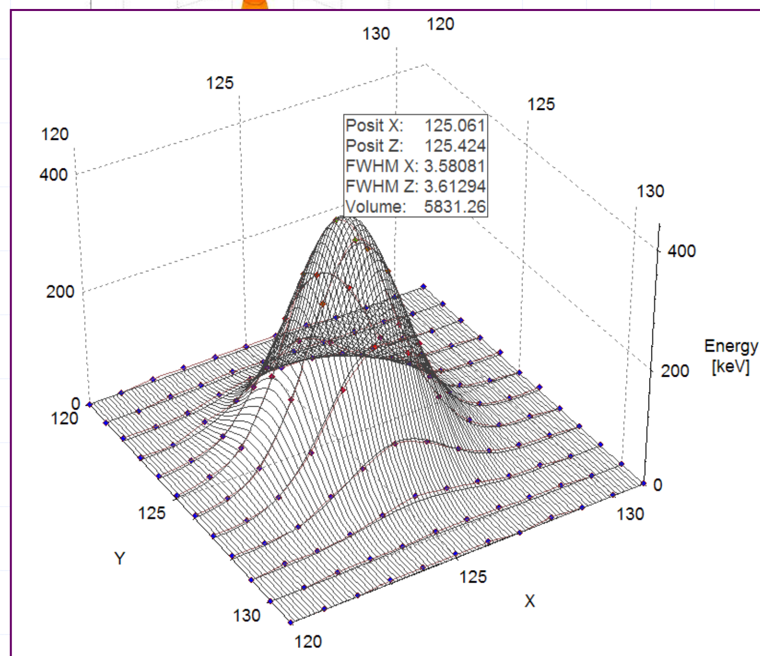


Gaussian fit
sigma = 37 keV

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** !!

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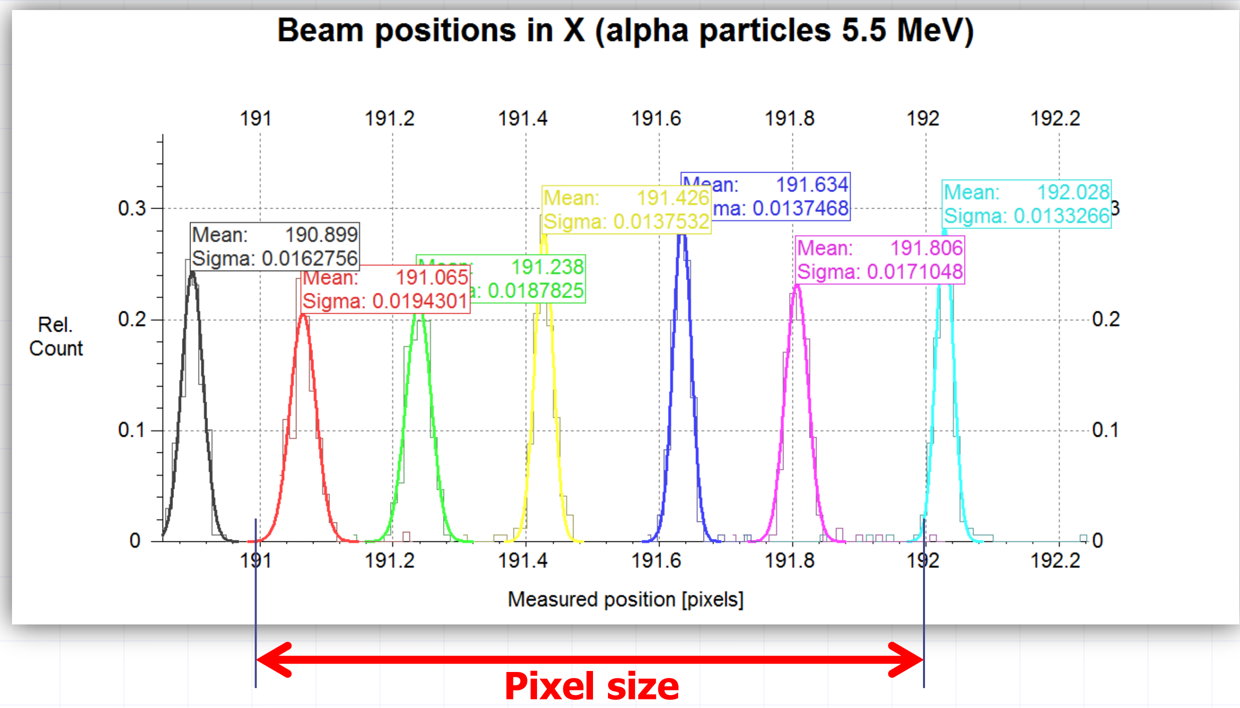
Spatial resolution with ions:
Ion Microbeam on accelerator in IBIC ANSTO

5.5 MeV alphas:



Reached spatial resolution: **880 nm** (the limit of microbeam).

=> The intrinsic resolution of detector is better

Deep subpixel spatial resolution with energetic ions

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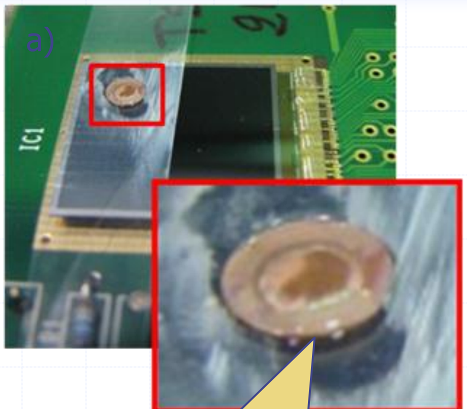
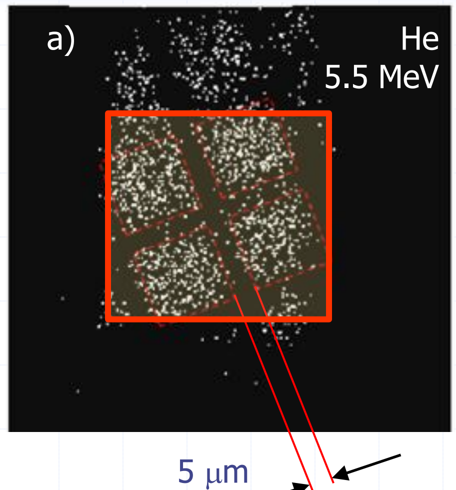
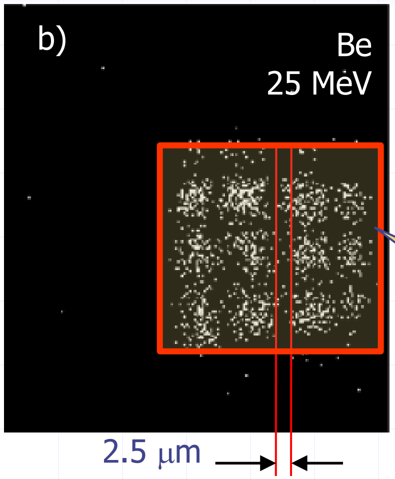
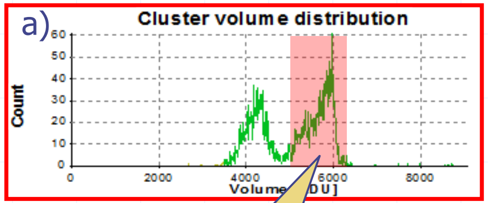


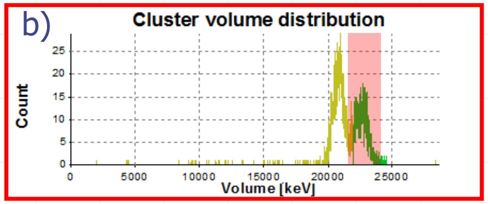
Copper grid for electron microscopy
a) 25 μm
b) 12.5 μm





Pixel size



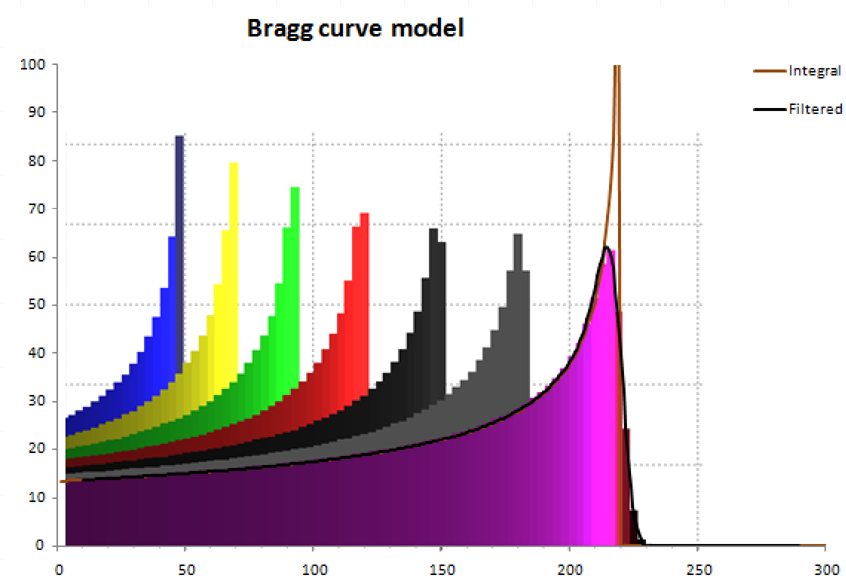


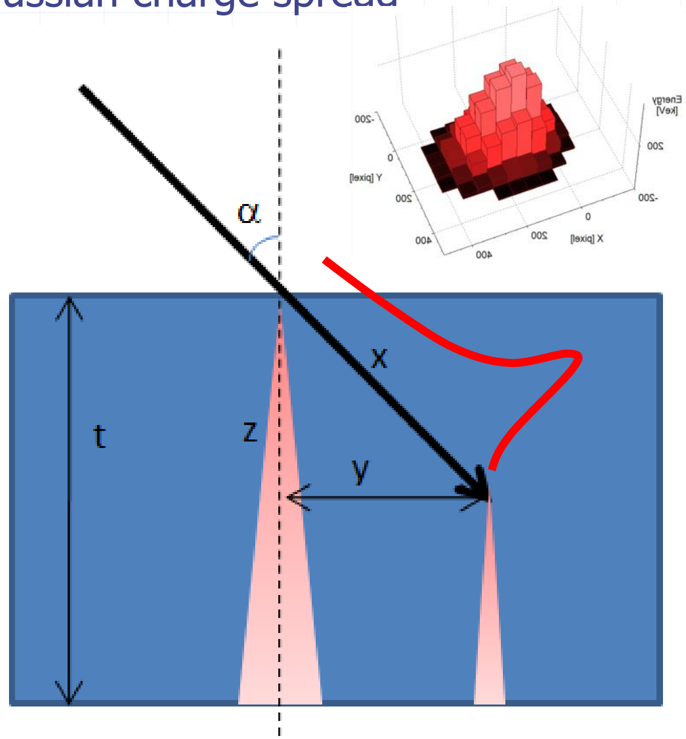
Energy used for image

Tracks of ions stopped in Silicon

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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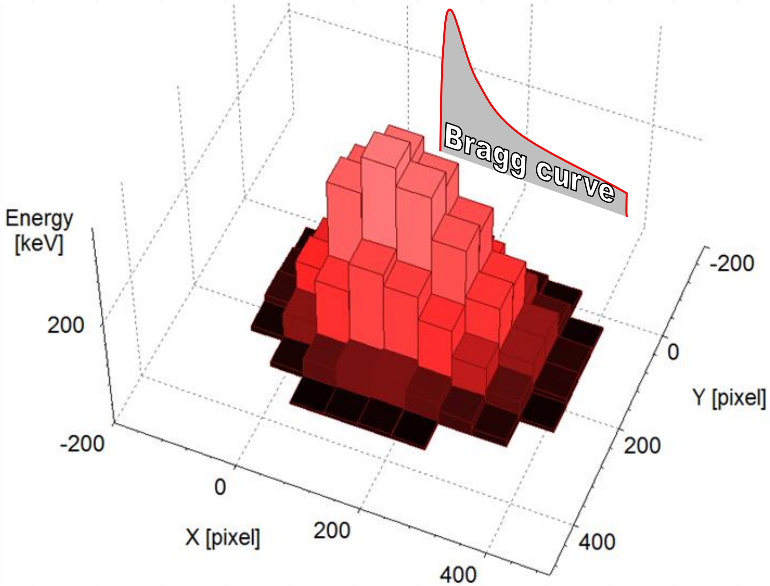

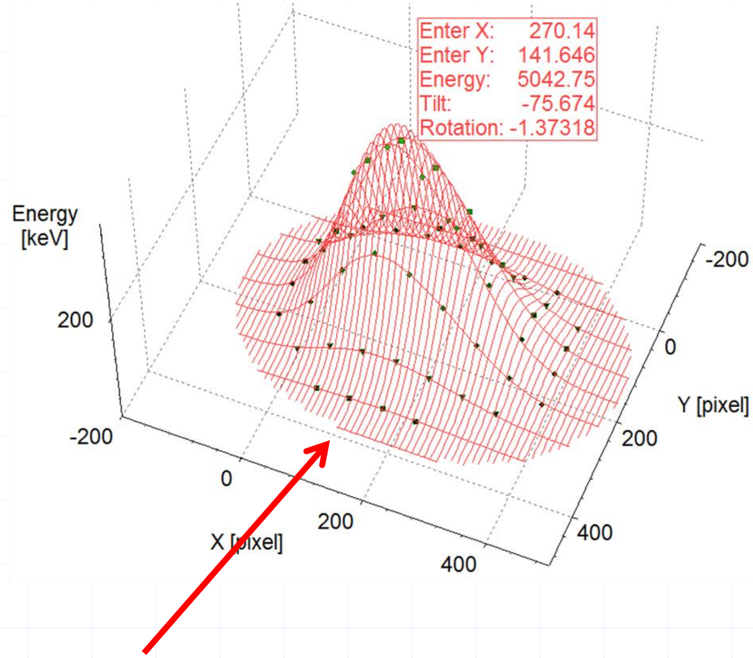

$$q(y_1,y_2)=\frac{m_{Si}c}{2\pi\sigma^2}\int_0^r e^{-\frac{t^2}{2\sigma^2}\left(\frac{y_1-Y_1-x\sin(\alpha)\cos(\beta)}{t-x\cos(\alpha)}\right)^2} e^{-\frac{t^2}{2\sigma^2}\left(\frac{y_2-Y_2-x\sin(\alpha)\sin(\beta)}{t-x\cos(\alpha)}\right)^2}\left((E_0-a)^{1-s}-c(1-e)x\right)^{\frac{s}{1-s}}dx$$

Simplified

Proton track: LET and Bragg curve

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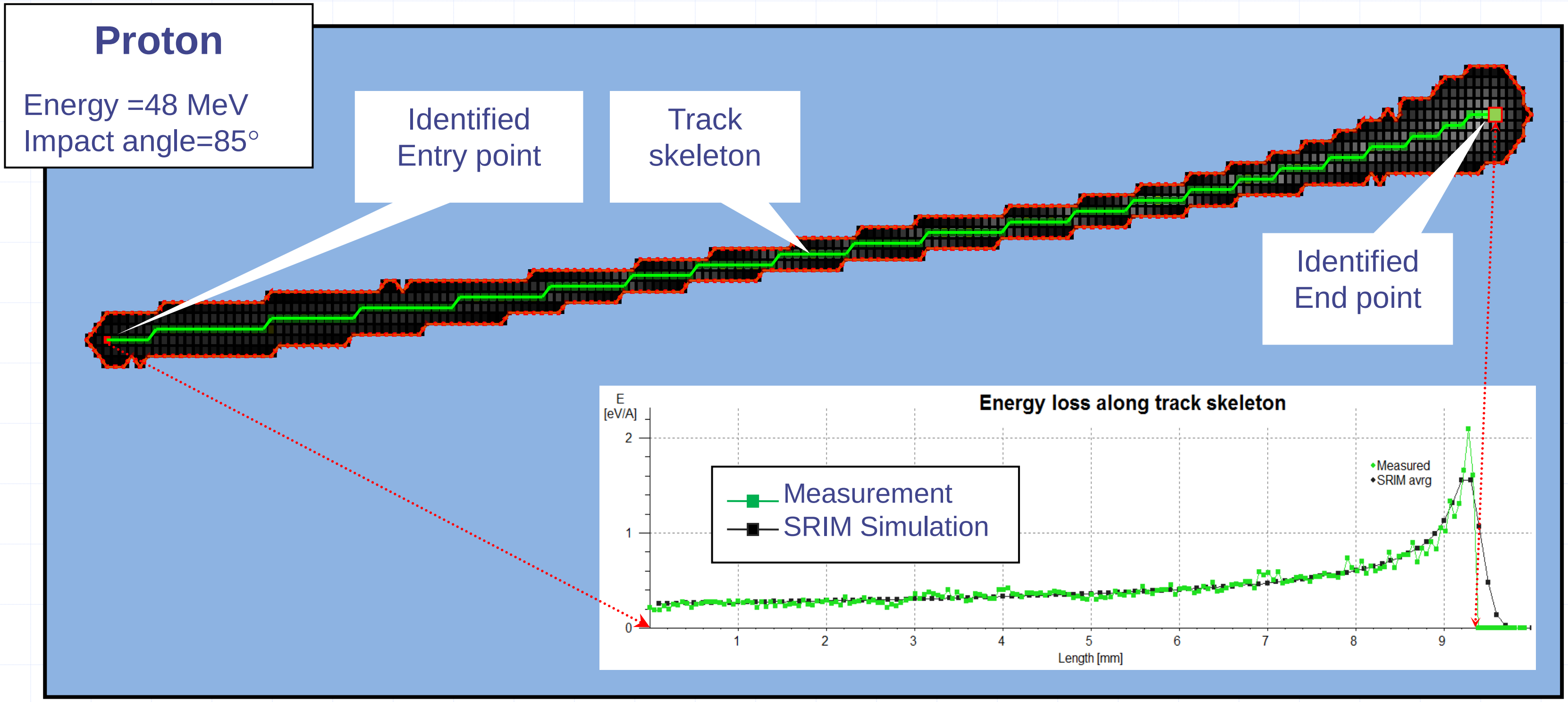

Everything is nice?

- Good level of charge sharing improves tracking precision a lot.

- But it has to be well described, predictable, homogenous and stable in time

Is it?

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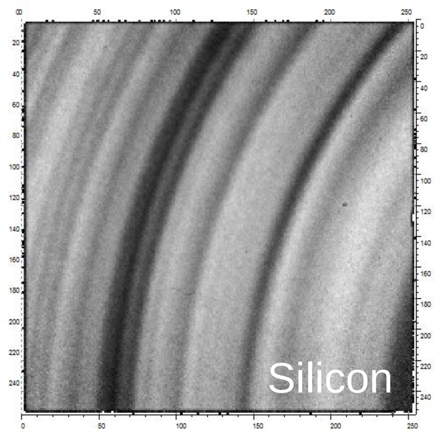
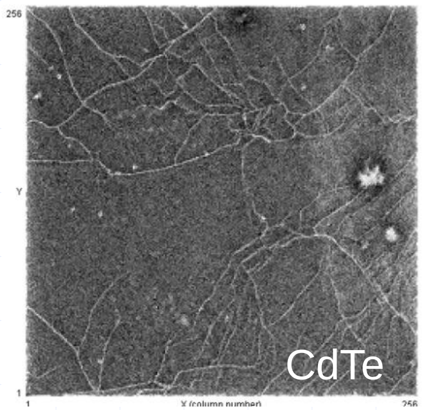
Known issues

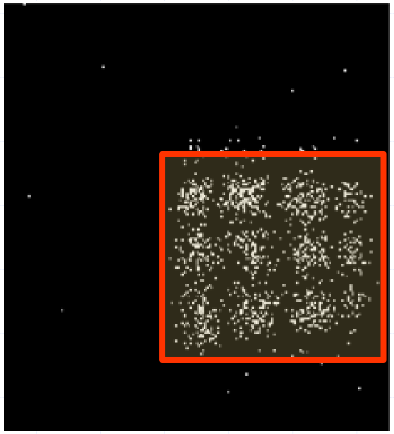
Inhomogeneity of the sensors bump-bonded to timepix device was observed in dependence on material type, bias voltage, temperature, radiation damage …

Local cluster size (alphas 5.5 MeV)





Reconstruction deformed



Idea: Use Timepix as the multichannel microprobe to measure local performance of sensor in 2D preferably in 3D.

Target: Si (planar, 3D), CdTe, GaAs, Radiation damaged …

3D scanning of pixelated sensor with ions

(and Timepix)

Ions used as microprobe

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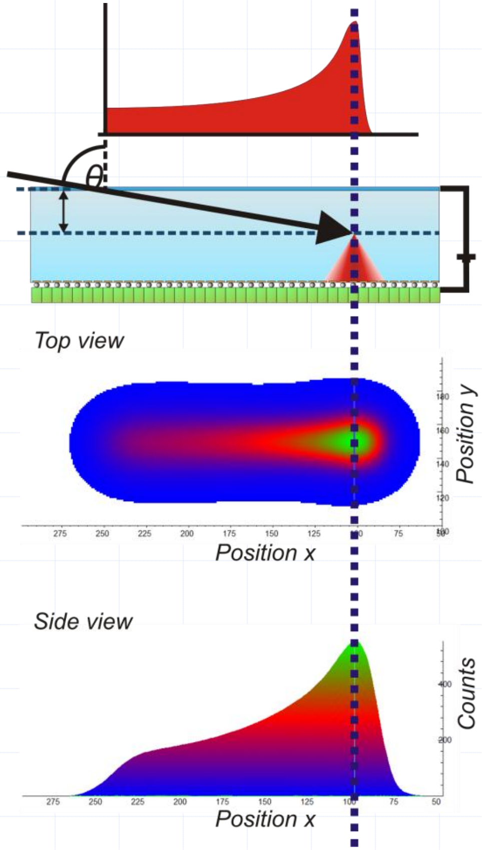
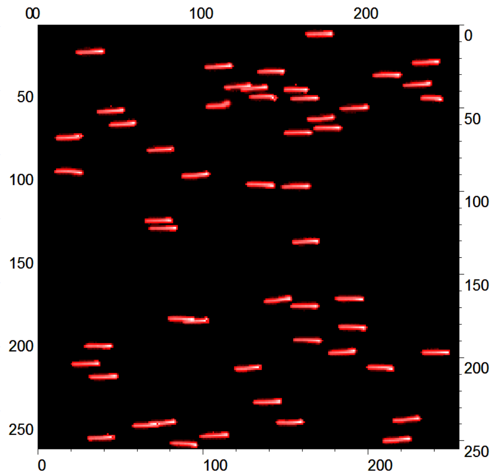
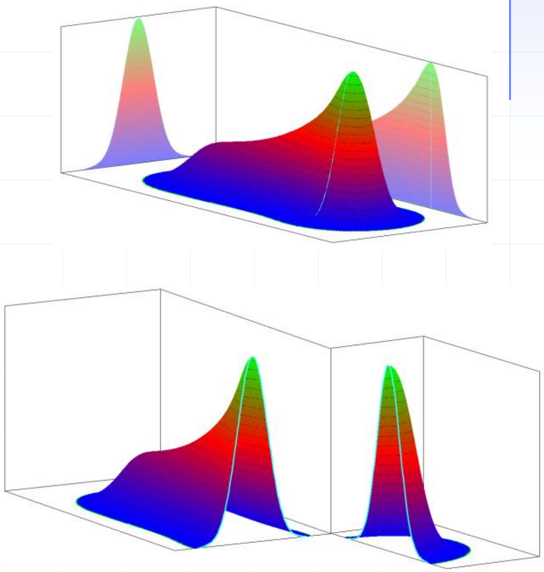
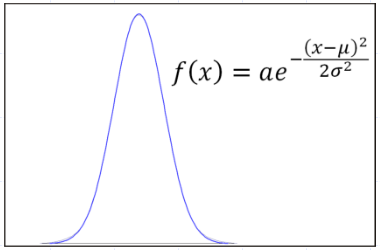


Protons 11 MeV at 85°

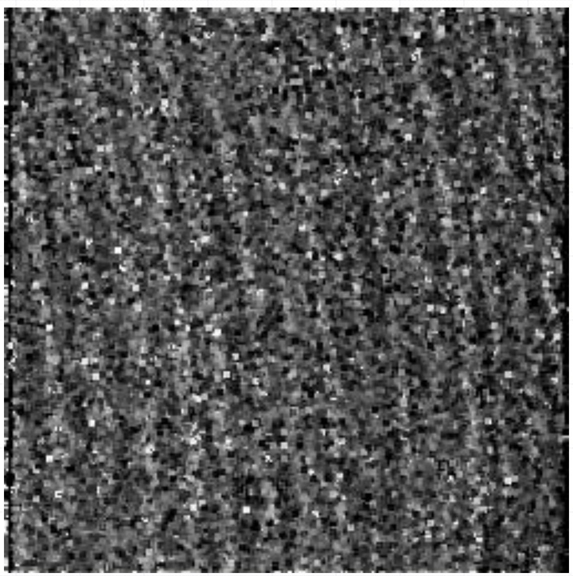




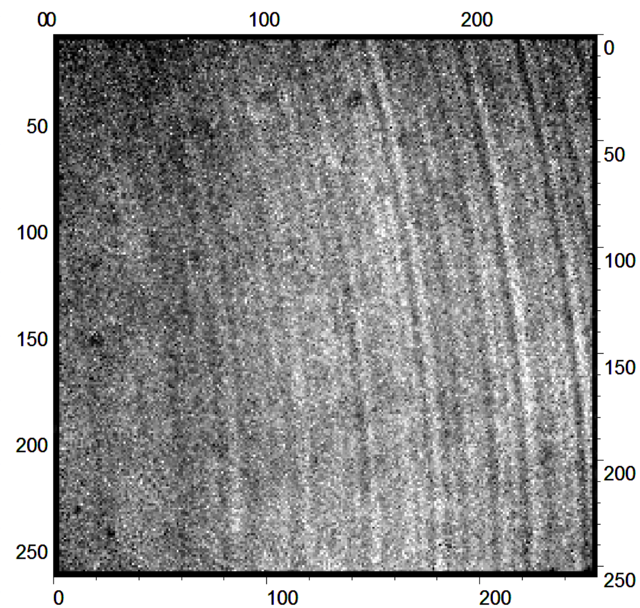


Results with ions

- Silicon sensor 300um, bias=7.5V



Protons: Energy = 3.5 MeV, Incident angle 85°; Penetration depth d=10 μm; Number of events = 40 000



Alphas: Energy = 5.5 MeV, Incident angle 0°; Penetration depth d=28 μm, Number of events = 400 000

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3D scanning of pixelated sensor with X-rays

(and Timepix)

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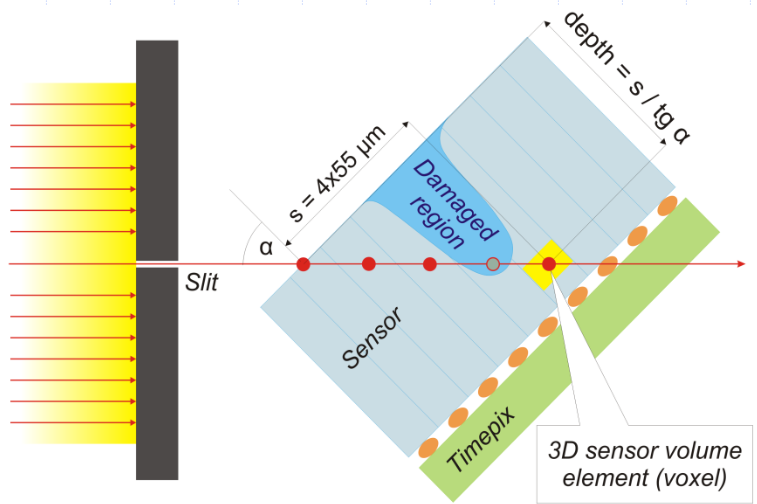
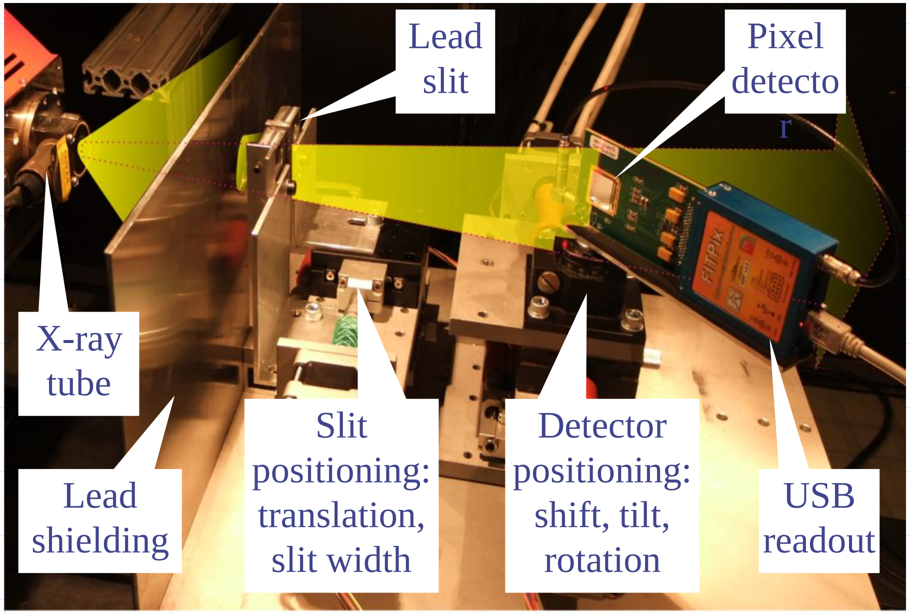
Principle of 3D Scanning of Pixelated Sensor

- System use narrow collimated X-ray beam (min 3 μm)
- The beam can be sent on to detector at a shallow angle
- The depth of interaction can be determined for each pixel along the beam path
- Shifting the detector along the axis perpendicular to the plane of the beam (hitting other columns) we can obtain a 3D map of the sensor response



(a)



(b)

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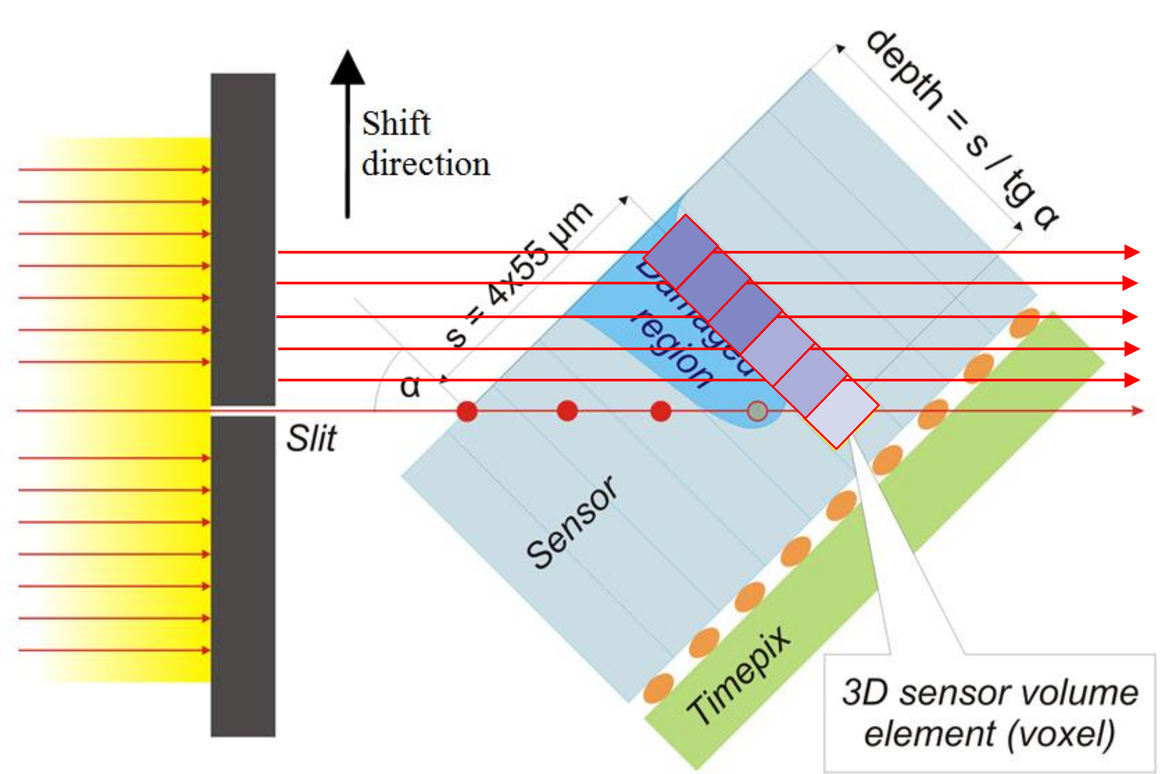
How to measure 3D response?



Why X-rays:

Each photon deposits all the energy in single point (photoefect)

No deconvolution needed

Negligible radiation damage

For each X-ray photon we record:

- 3D Position
- Energy => Local charge collection efficiency
- Charge sharing => local charge diffusion => collection time

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Test of the New Silicon Sensor

Bias voltage 60 V

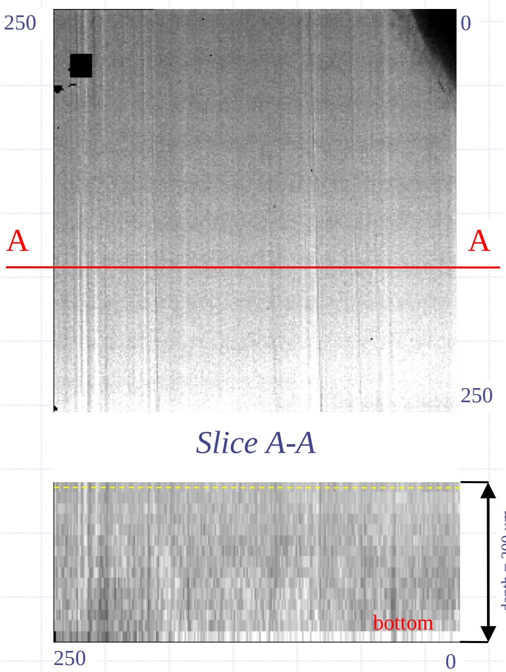
- detector is fully depleted
- nicely homogeneous response
- the response is shown in depth of 8 µm

Bias voltage 12 V

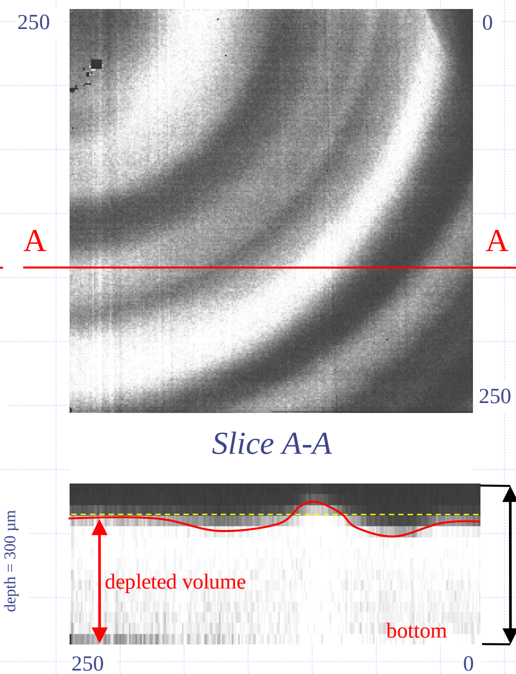
- depleted volume is 220 µm thick with variations caused by local variations of E field
- the response is shown in depth of 60 µm

Bias voltage 6 V

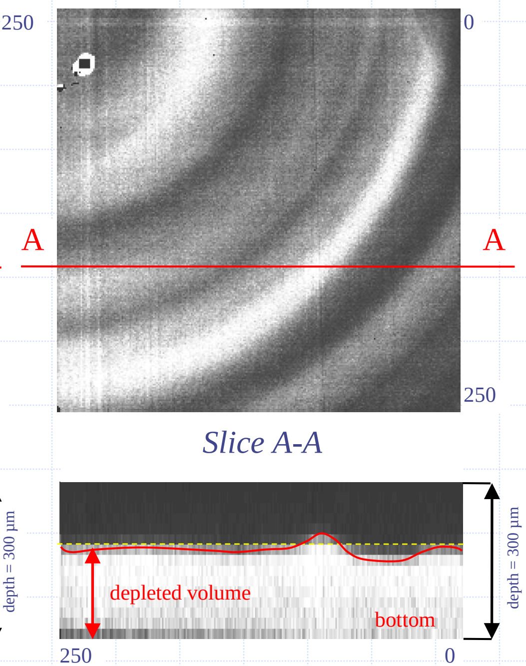
- depleted volume is 170 µm thick.
- the response is shown in depth of 120 µm



(a)



(b)



(c)

Test of Sensor Damaged by Proton Beam

Energy of 3 resp. 4.9 MeV (range 93 resp. 210 μm)

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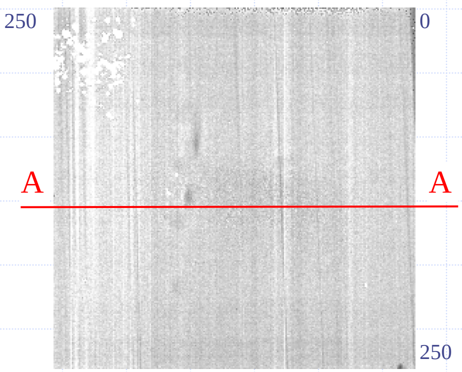
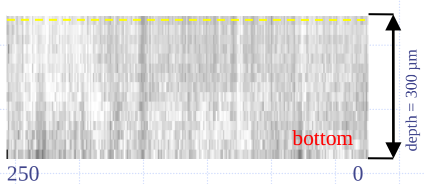
Bias voltage 60 V

- detector is fully depleted
- Well homogeneous response
- the response is shown in depth of 8 μm

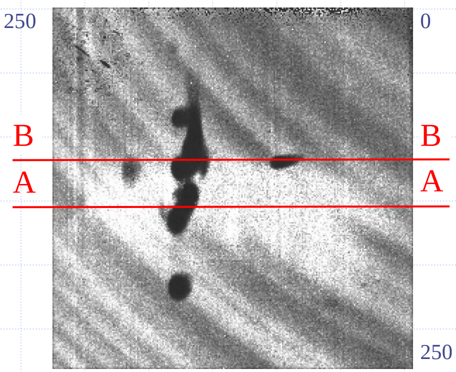


Slice A-A

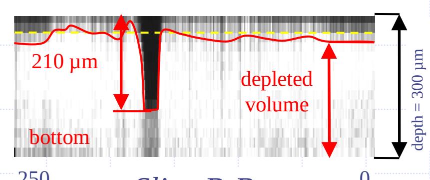


Bias voltage 12 V

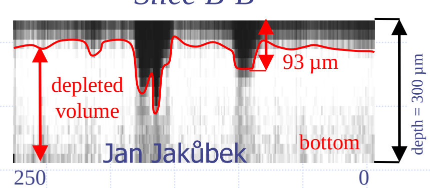
- depleted volume is 240 μm
- the damaged regions appeared
- response layer is shown in depth of 20 μm



Slice A-A

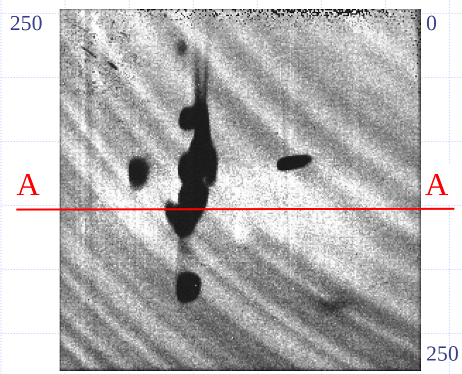


Slice B-B

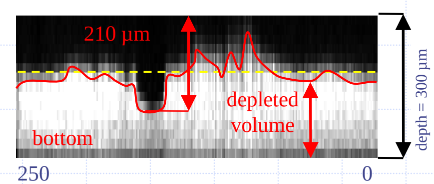


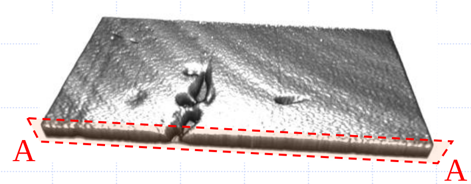
Bias voltage 6 V

- depleted volume is 160 μm.
- the response layer is shown in depth of 120 μm



Slice A-A





Surface of depleted volume rendered in 3D

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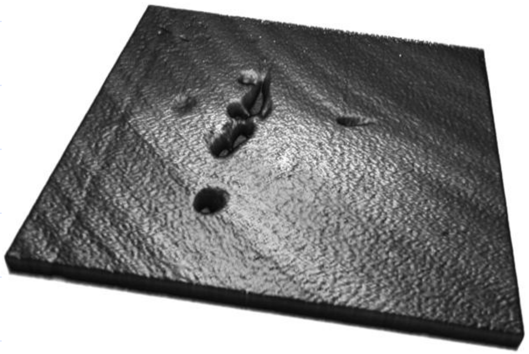
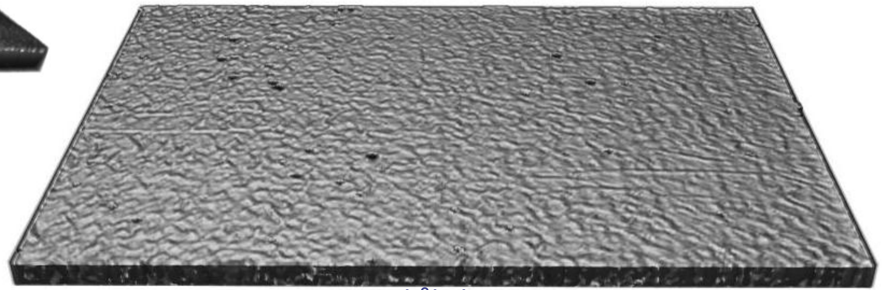
Si (G09-W0015) Radiation damaged

- bias +6 V (partially depleted)
- 300 µm thick
- 256x256 pixels
- 55 µm pitch



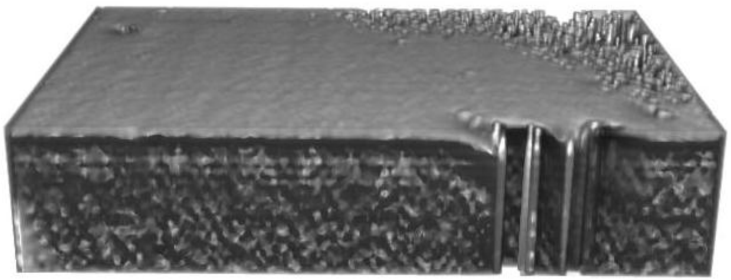
GaAs (H11-W0087)

- bias -200 V (fully depleted)
- 300 µm thick
- 256x256 pixels
- 55 µm pitch



CdTe (C04-W0083)

- bias -200 V (fully depleted)
- 1000 µm thick
- 128x128 pixels
- 110 µm pitch



Conclusions:

- Described method allows to generate a 3D map of charge collection efficiency in dependence on various detector parameters such as: **bias voltage, detector temperature and radiation damage.**
- The spatial resolution of 3D mapping is determined by pixel size (lateral) and width of the slit (depth). Results were demonstrated for 55x55x10 µm. The minimal slit width is 3 µm.
- The energy of X-rays can be chosen combining X-ray tube target material and filter – it is only semi-monochromatic. Standardly we use W target and W filter => 59 keV. Other options are Cu (8 keV), and Mo (17 keV).

Voxel detector
composed of Timepix devices

Chip assembling, PCB with 3D morphology and micro connectors

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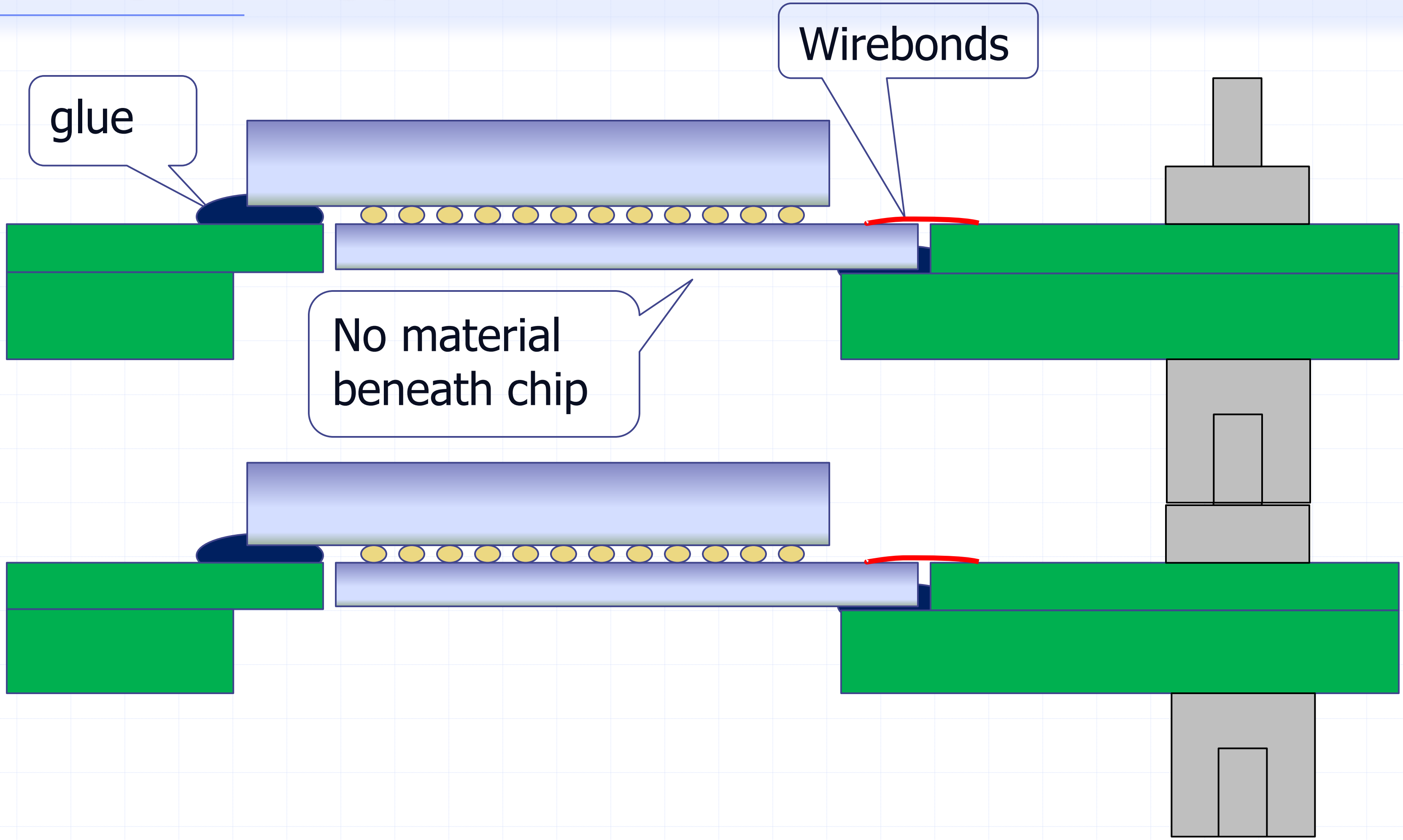

Chip assembling, PCB with 3D morphology and flexible connectors

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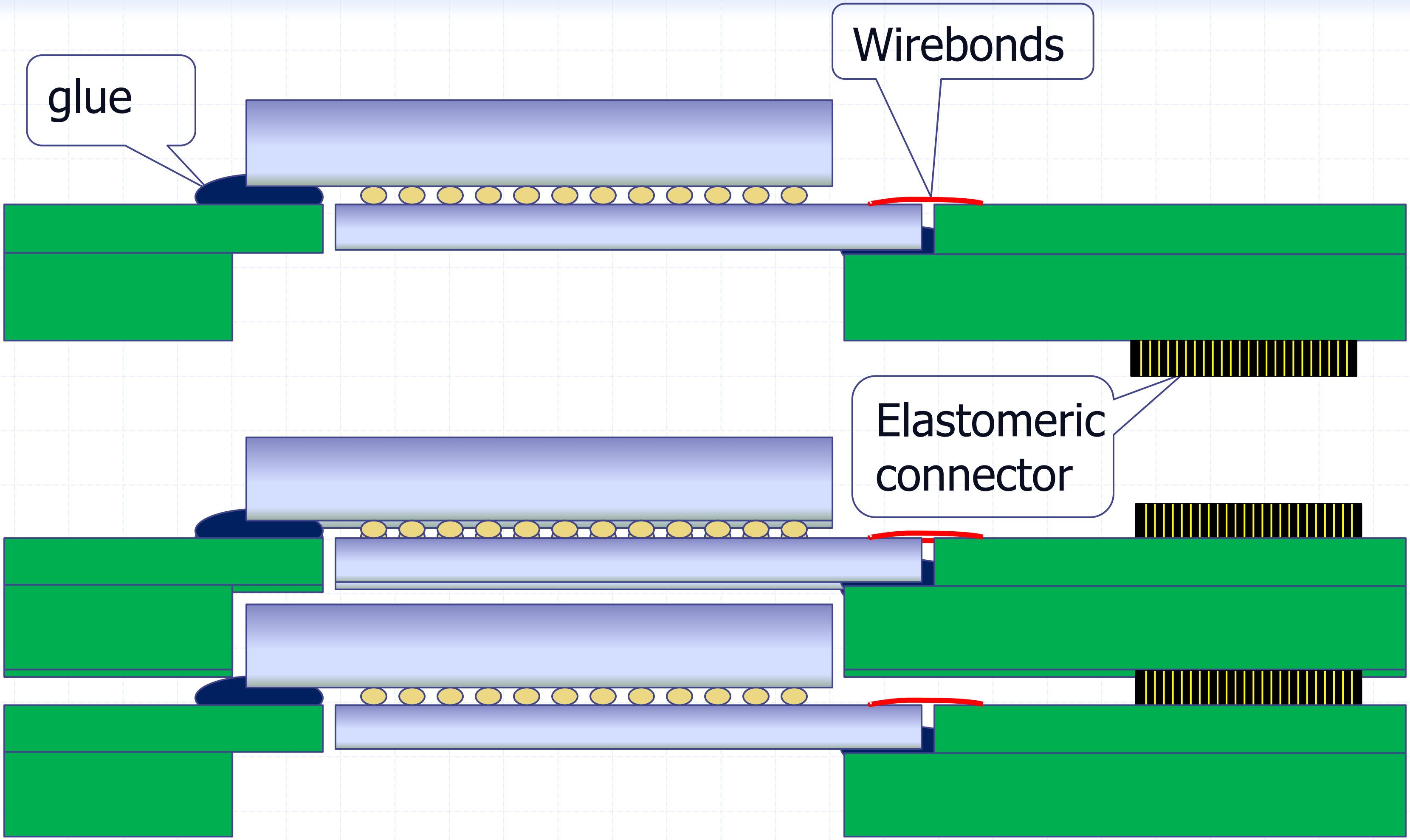

Variable setup:
Any number of chips can be stacked

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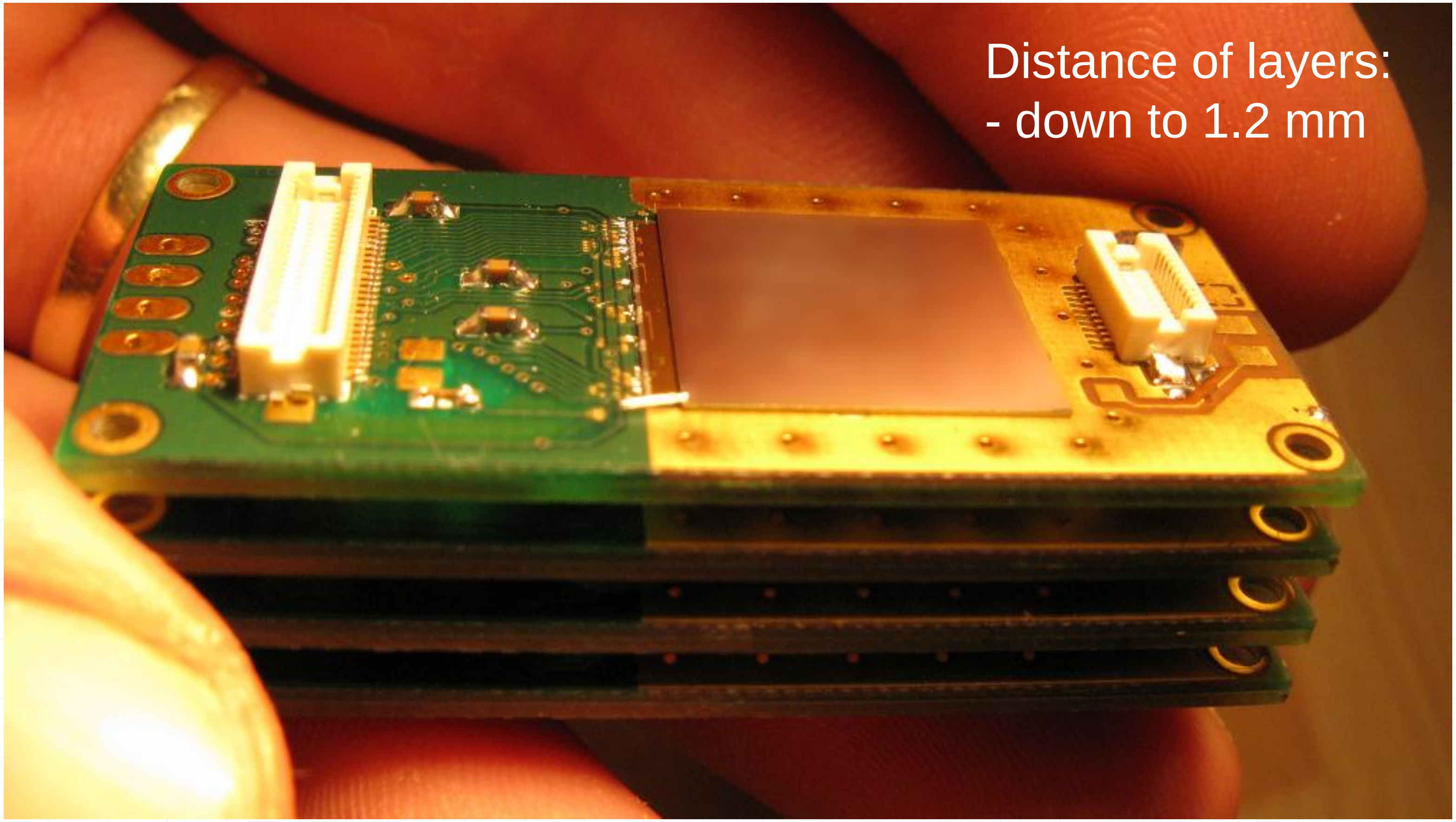

Experimental results in Hadron Therapy Beam

Monitoring of “patient” treatment

Imaging principle: Tracking of secondary particles

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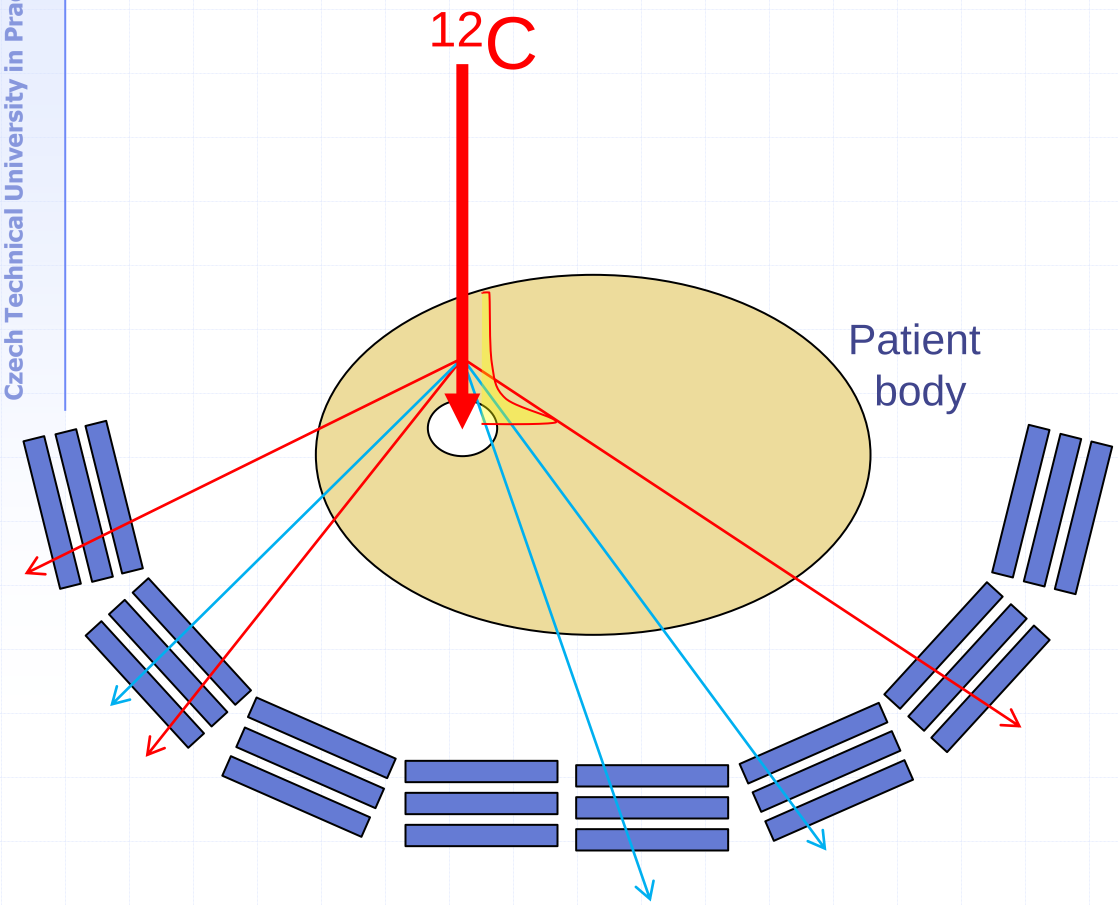

- The tracker would optimally surround the irradiated body.
- Tracker data can be back-projected to form an image of the beam path.
- Possibility to select particles with higher penetration power would improve quality.

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

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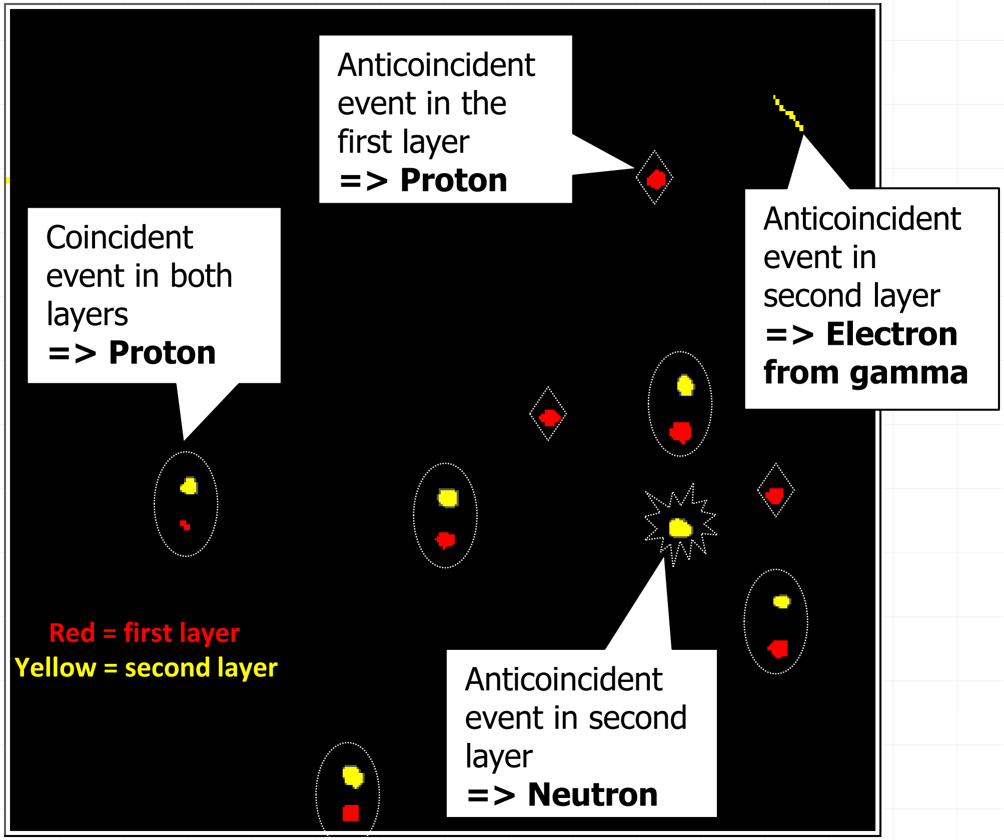
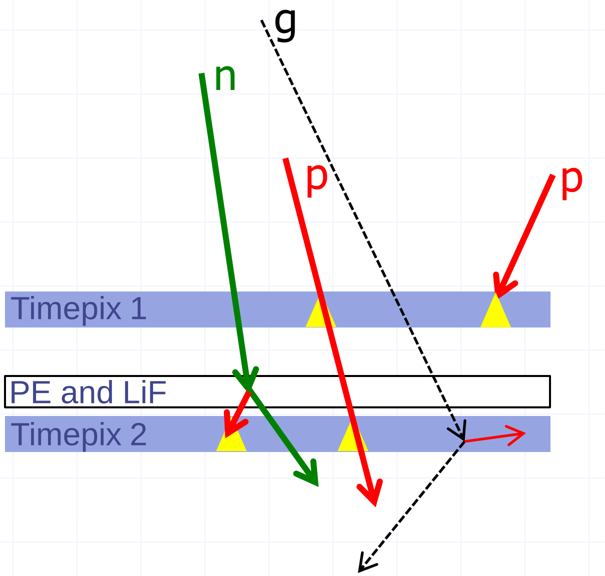


Coincidences = ions

Anticoincidences in 2nd = neutrons



Observation of complete scene:
Experimental setup

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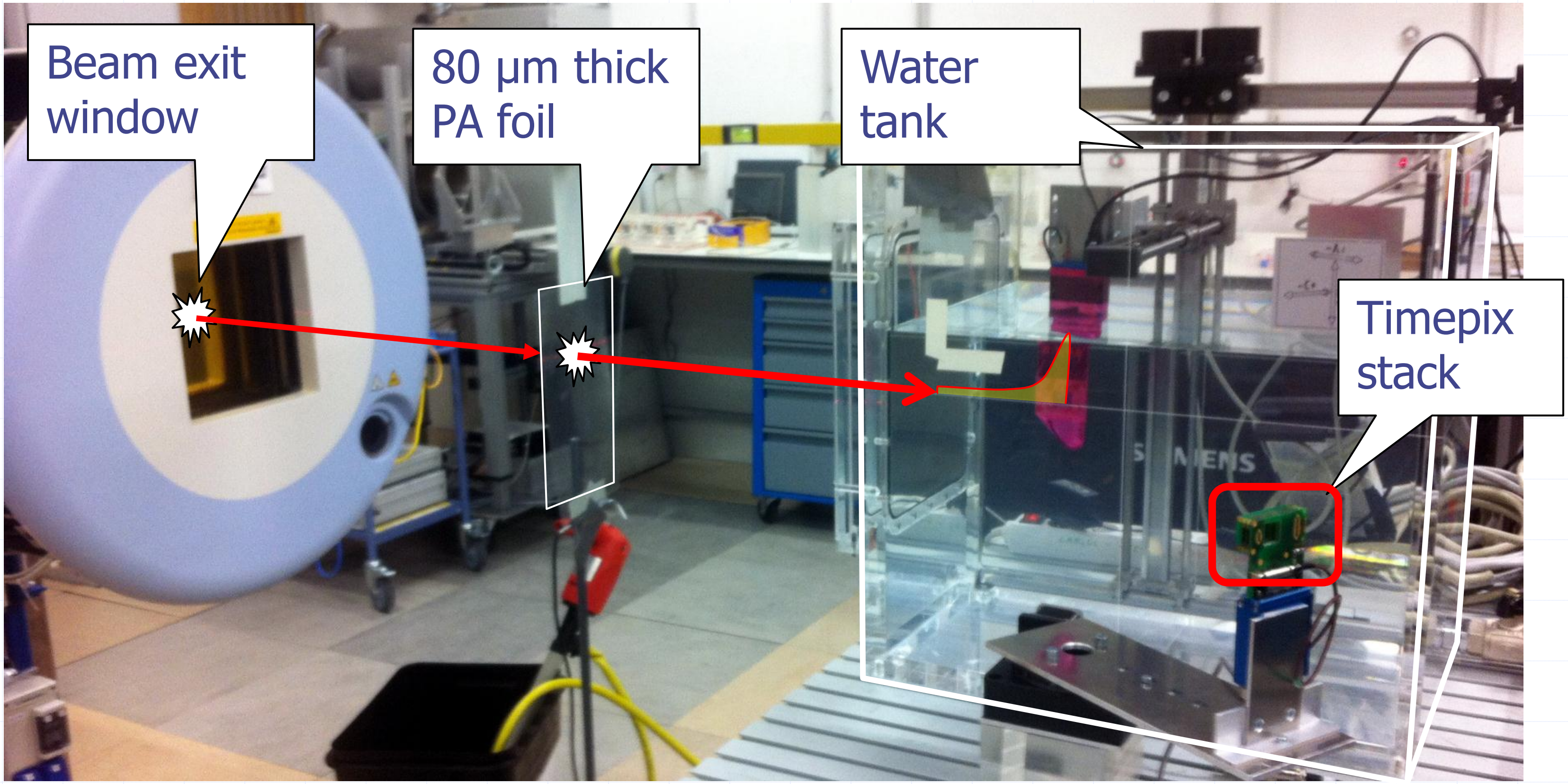
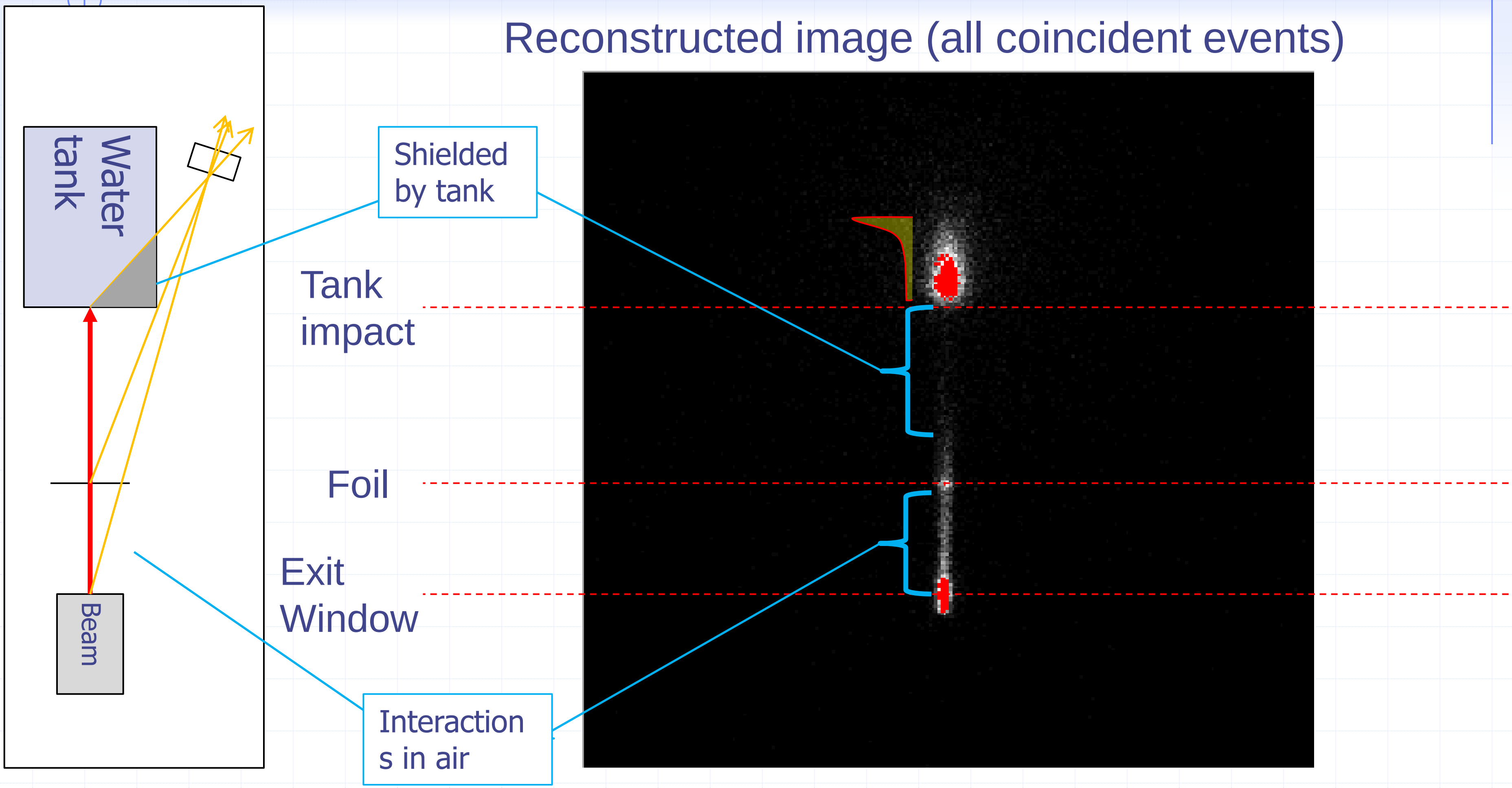


Observation of complete scene: Beam line can be imaged

Reconstructed image (all coincident events)



Conclusions and next steps

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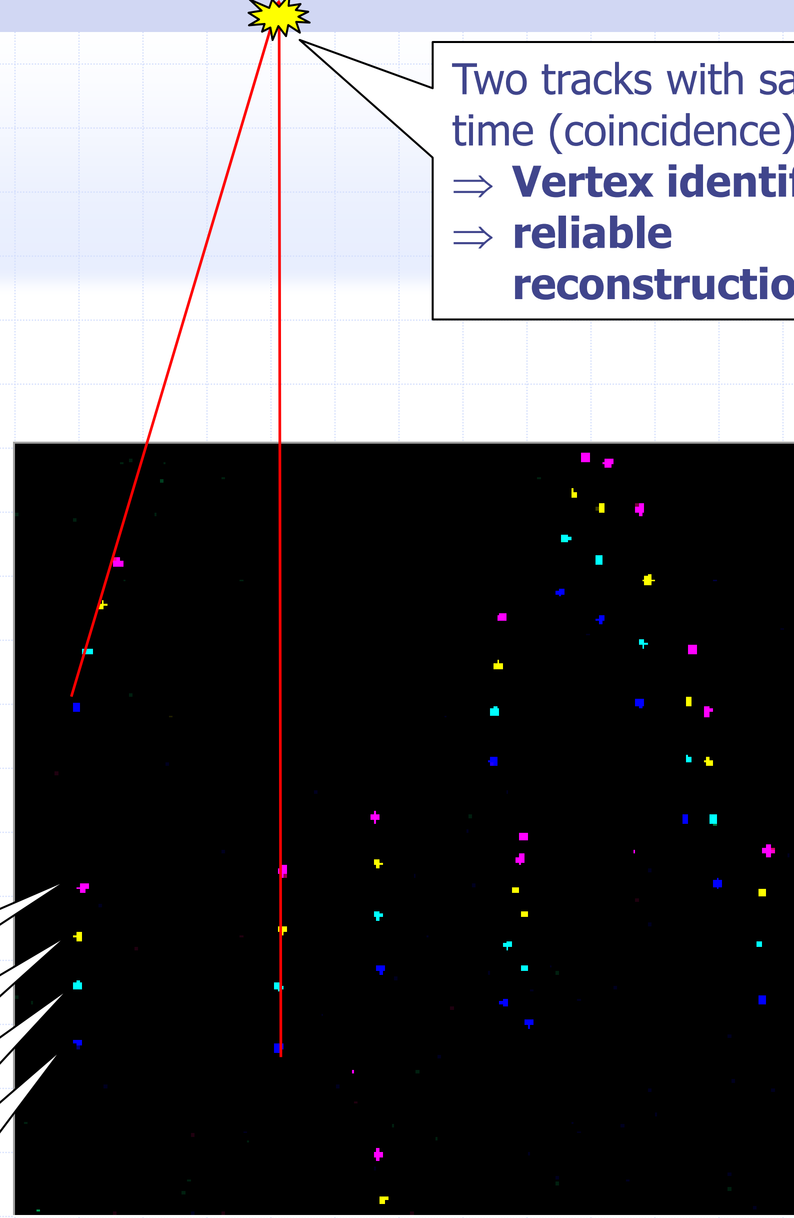
- Particle tracking is very promising technique for monitoring during hadron therapy.
- The Timepix based system allows particle discrimination resolving light particles, ions and neutrons.
- Larger system with more layers will be tested in near future (done during last weekend).

Two tracks with same time (coincidence):
$\Rightarrow$ **Vertex identified**
$\Rightarrow$ **reliable reconstruction**



First layer: ΔE_1

Second layer: ΔE_2

Third layer: time

Forth layer: ΔE_3

Sample image taken with with 4 layers