Imaging Based on Tracking of Individual Particles with the Timepix Pixel Detector

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Outline

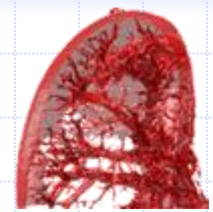
Introduction
- Radiation imaging and pixel detectors
- Primary application – X-ray transmission radiography

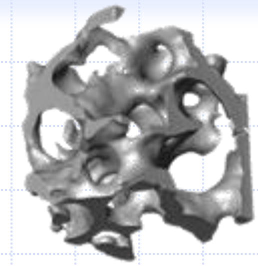
Particle tracking with single layer Timepix device
- Per pixel calibration and charge sharing
- Examples (Ions, MIPs)

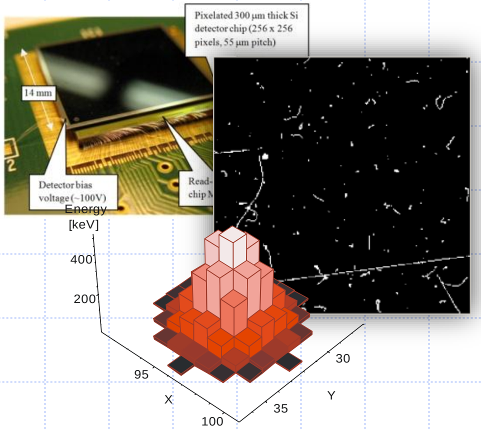
Energy sensitive imaging
- Emission (XRF)
- Material sensitive X-ray transmission imaging

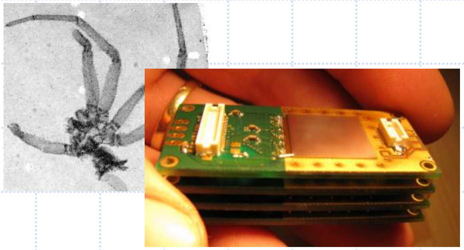
Voxel detector concept and tests

Work performed in frame of Medipix collaboration.









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Radiation imaging = Radiography

Radiography (film) or radioscopy (digital)
= Imaging of (internal) sample structure using radiation

Radiation source is placed outside of a sample:

- Absorption radiography recording intensity change
- Energy changes
- Phase contrast imaging
- Diffraction imaging, …

Radiation originates in a sample body:

- Autoradiography using isotopic marker (PET, SPECT, …)
- Autoradiography of activated sample (e.g. neutron activation)

Combination of both approaches:

- Prompt gamma imaging (excitation by neutron beam)
- X-ray fluorescence (excitation by X-rays, gammas, heavy particles, …)

Multimodal imaging

Wilhelm Conrad Roentgen showed that bones could be visualized by X-raying his wife's hand in 1895

Radiation imaging detector principles (for radiography)

Integrating devices ⟶ Event by event processing

1895 (Roentgen)	1969 (Boyle, Smith)	~ Early 90s	~ new millennium
Film emulsions change of chemical or physical properties after interaction with radiation. Needs special treatment (developing process, scanning, …).	**Charge integrating devices** Ionizing radiation creates charge which is collected and integrated in pixels (CCDs, CMOS sensors, Flat panels, …)	**Single particle (counting) pixel detectors** Ionizing radiation creates charge which is compared with threshold and registered digitally in pixels	**Imaging based on tracking of individual particles** The detector (pixel detector, CCD …) records traces of individual particles which are analyzed generating images of various features.
+ Very high resolution Low noise Cheap	+ High spatial resolution Low price	+ Good spatial resolution High read-out speed No noise, no dark current Unlimited dynamic range, Energy discrimination	+ High spatial resolution No noise, no dark current Unlimited dynamic range **Multimodality, selectivity.** (energy, mass, direction …)
- Nonlinear response Limited dynamic range Needs processing	- Dark current Noise Limited dynamic range	- Not suitable for very high Intensities (like XFEL)	- Intensity restrictions, large volume of data, complex data processing

Hybrid particle counting pixel detectors

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Pilatus - PSI

- 60 x 97 pixels, pitch of 172 um
- Counter: 20 bits, single threshold
- Module 16 chips, then tilling

Eiger - PSI

- 256 x 256 pixels, pitch of 75 um
- Counter: 12 bits, single threshold

Medipix2 – CERN

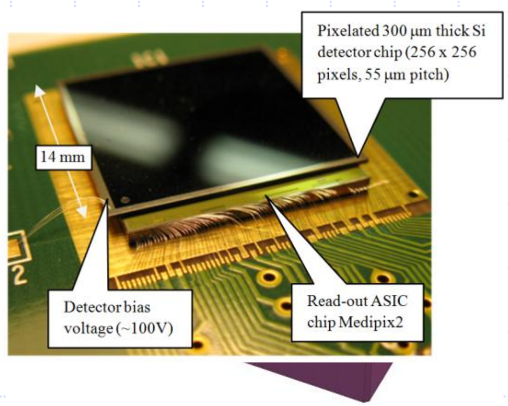
- 256 x 256 pixels, pitch of 55 um
- Two thresholds
- Module 6 chips

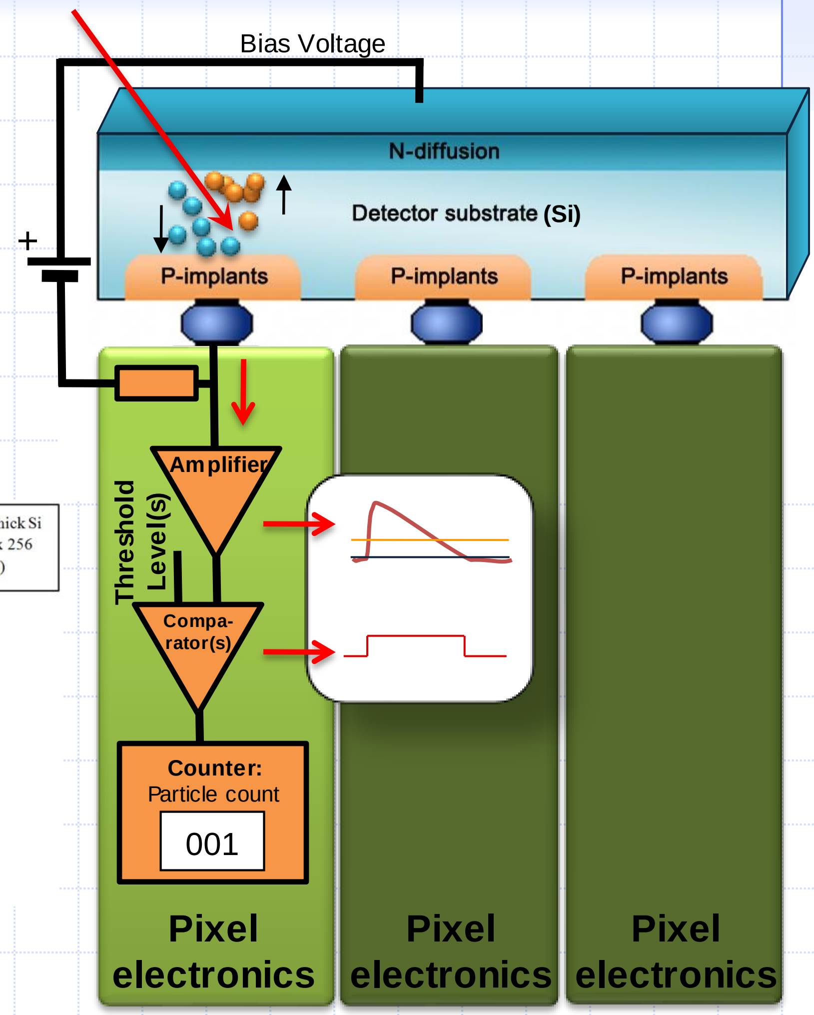
Medipix3 – CERN

- 256 x 256 pixels, pitch of 55 um
- Charge summing
- Continuous readout
- Up to 8 thresholds

Timepix - CERN

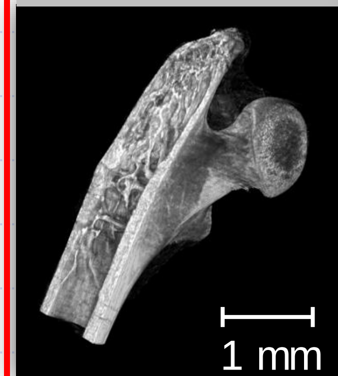
- Time stamp
- Allows Energy measurement in each pixel



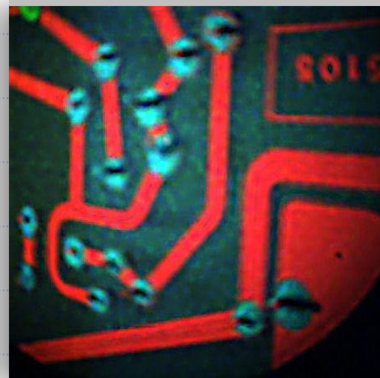


Applications:

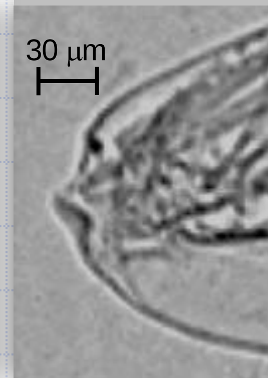
X-rays: intensity



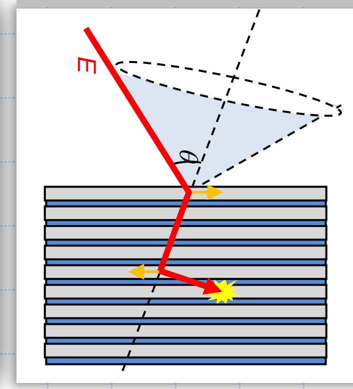
X-rays: energy



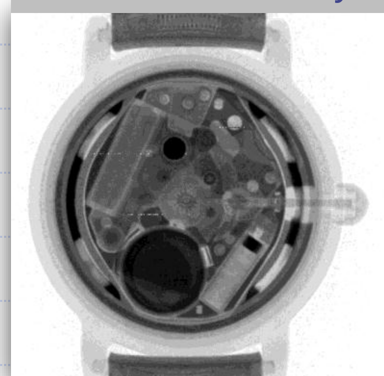
X-rays: phase



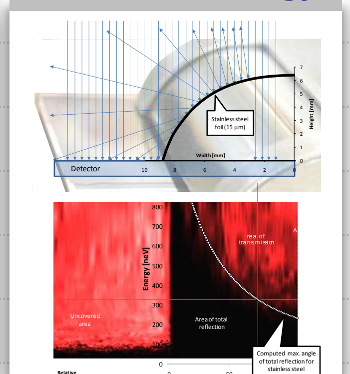
Gamma: SPECT



Neutrons: intensity

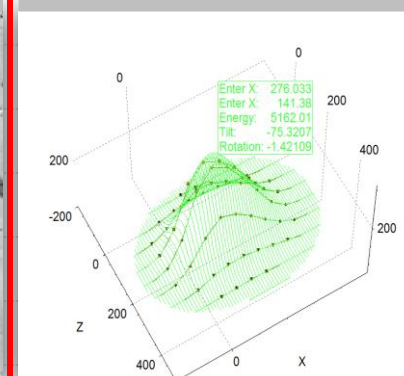


Neutrons: energy



Ions: energy

Ions: direction



Primary application:

X-ray radiography with very high contrast

Primary Application: High contrast imaging

Mouse backbone and pelvis

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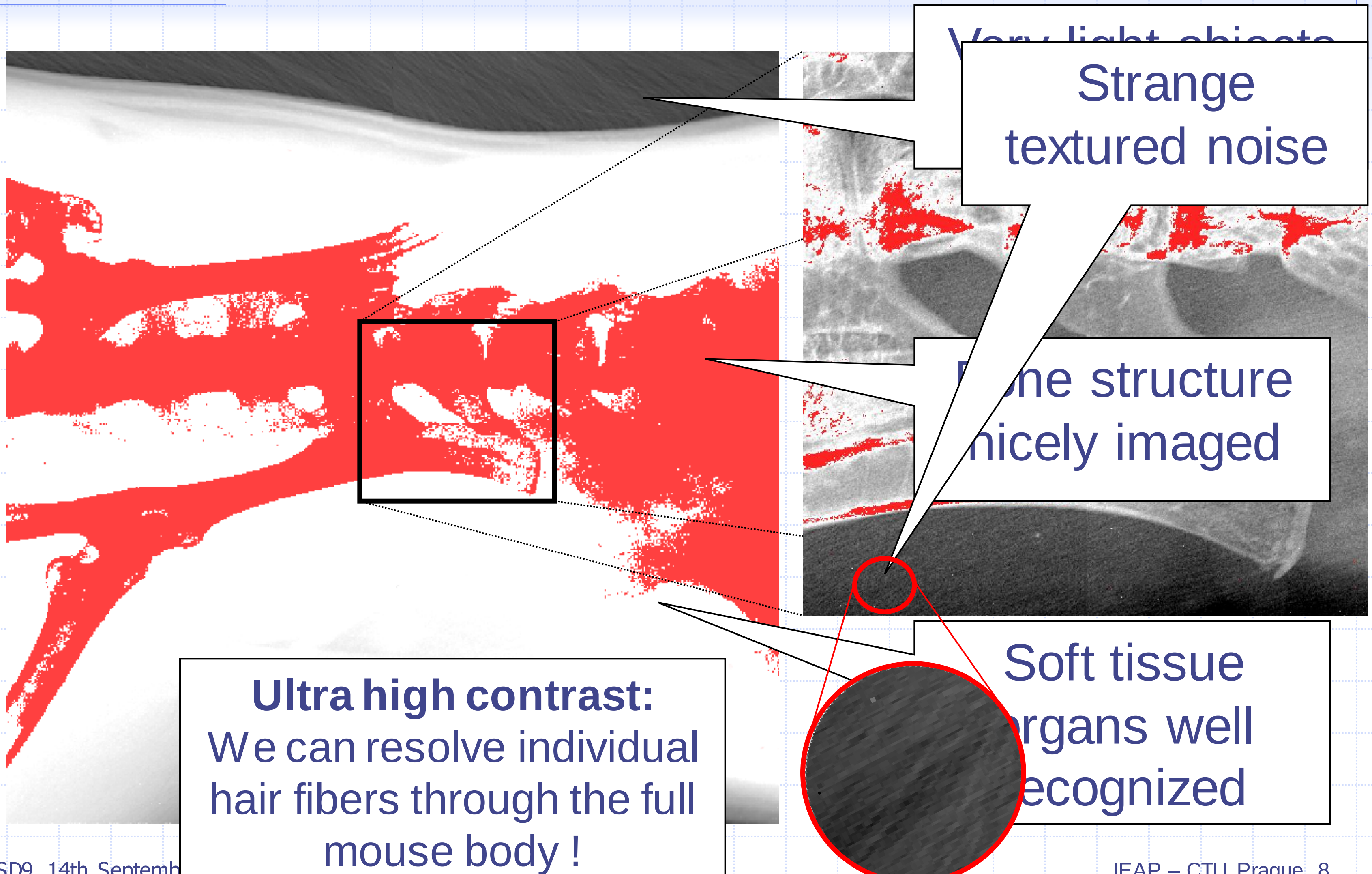
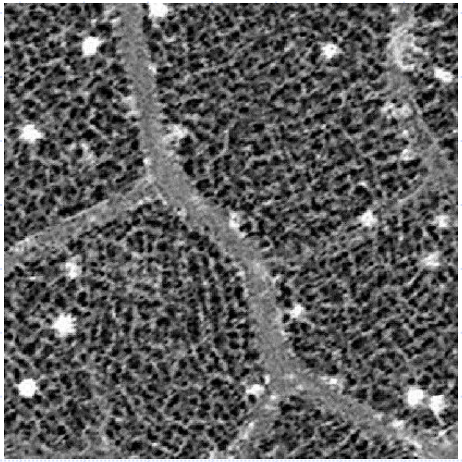


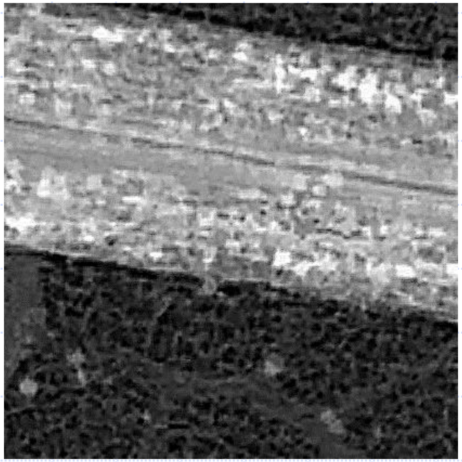
Ultra high contrast:
We can resolve individual hair fibers through the full mouse body !

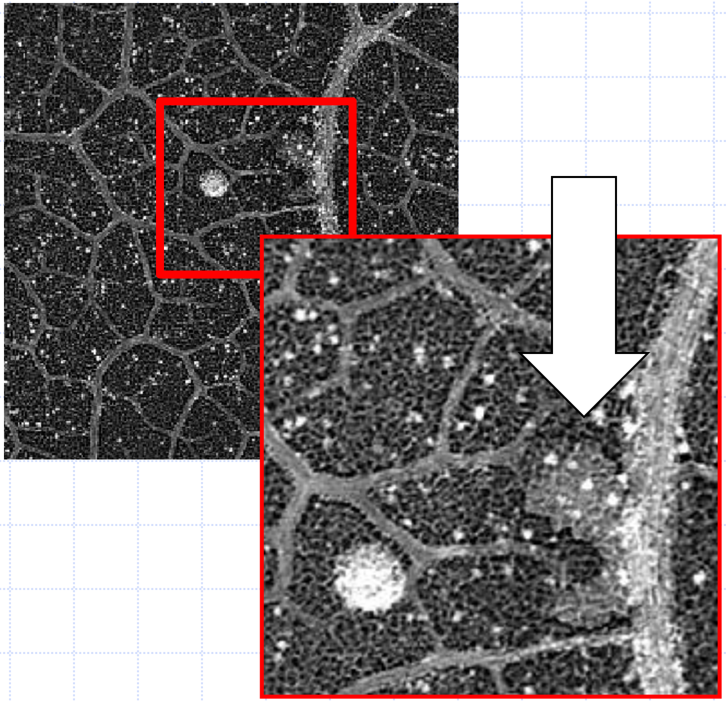
High resolution and high contrast X-ray radiography:

Example: Leaf Miner story

Leaf miner (*Cameraria ohridella*) - small moth. In larva 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 (summer).







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.

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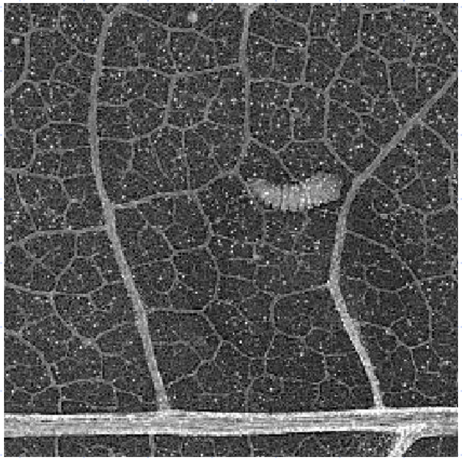
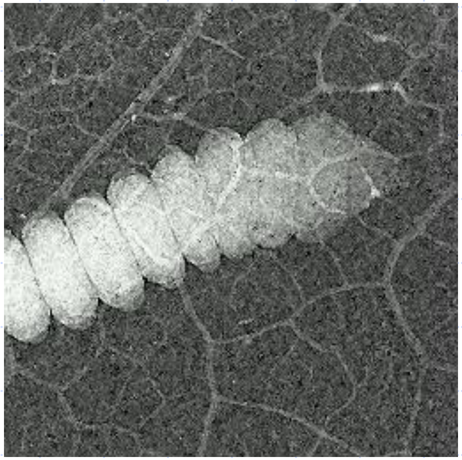
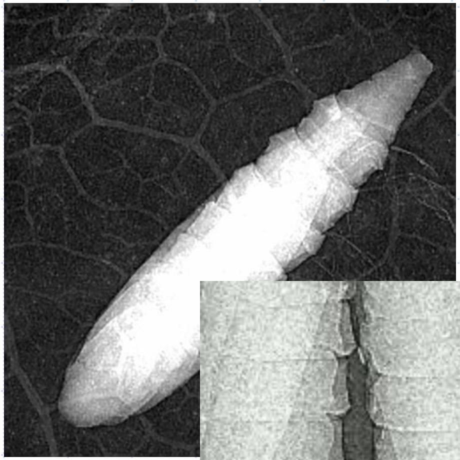
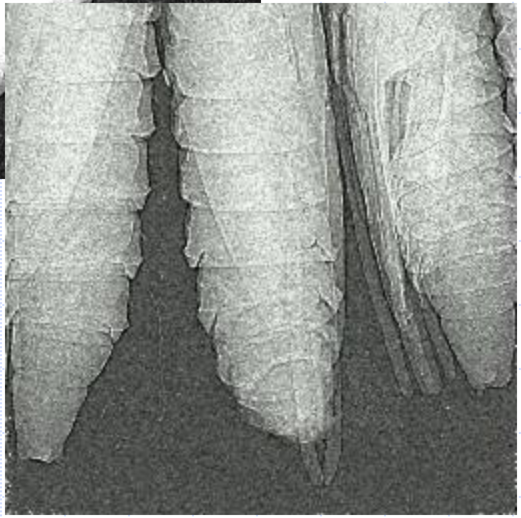
High resolution and high contrast X-ray radiography:

Example: Leaf Miner story

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

Several collected pupas

Particle tracking
With pixel detectors

Particle tracking with pixel detectors

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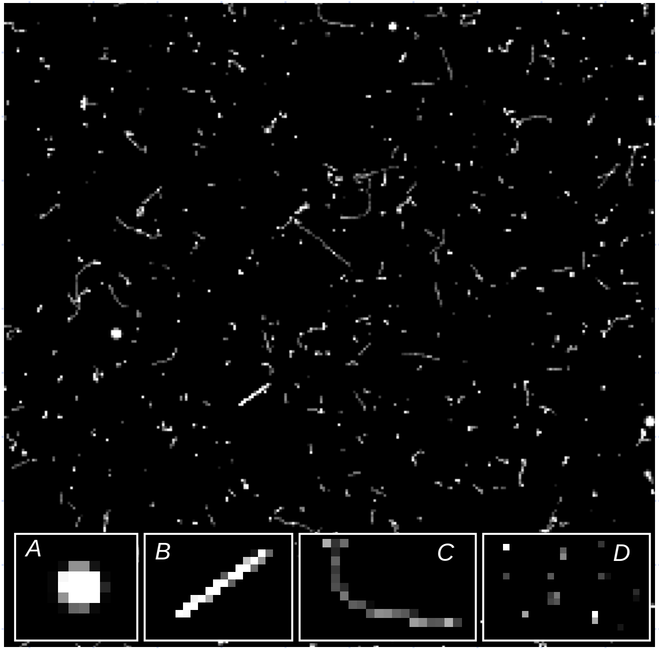
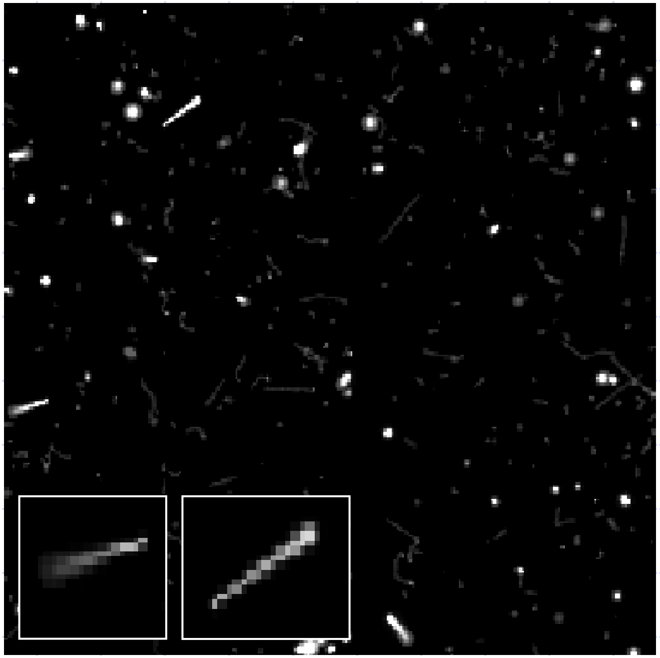


Radiation background



Protons recoiled by fast neutrons

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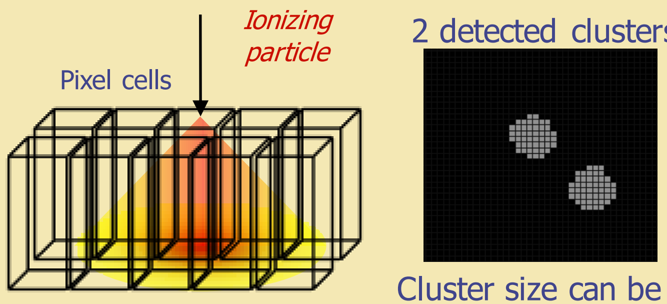
Charge sharing effect - clusters

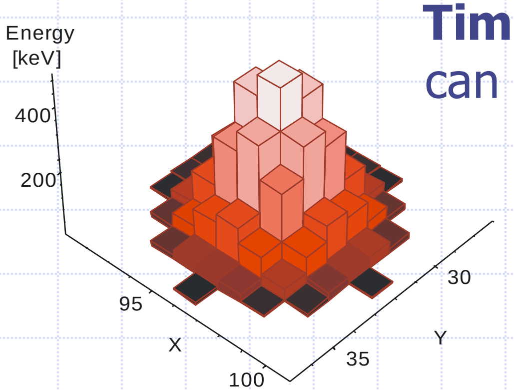
- Ionizing particle creates a charge in the sensor.
- The charge is collected by external electric field => the process takes some time
- Due to charge diffusion the charge cloud expands
- The charge cloud can overlap several adjacent pixels => **CLUSTER**
- Pixels in a cluster will detect the charge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

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



The Cluster size depends on:

- Particle Energy
- Depth of interaction
- Detector Dias Voltage



TimePix in TOT mode can measure charge in each pixel !

Need of per pixel energy measurement:
TimePix and its TOT mode

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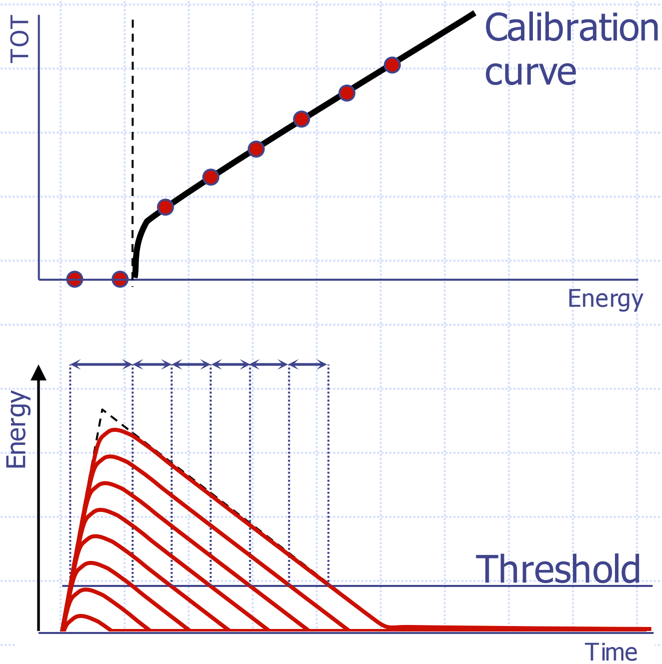
Counter in each pixel can be used as

- **Timer** to measure detection time => TOF experiments, TPC detectors, …
- Wilkinson type **ADC** to measure energy of each particle detected.



- If the pulse shape is triangular then Time over Threshold is proportional to collected charge i.e. to energy.
- Due to limited bandwidth the pulse can be NEVER perfectly triangular.
- Non-linear TOT to energy dependence

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TOT mode calibration:

Surrogate calibration function

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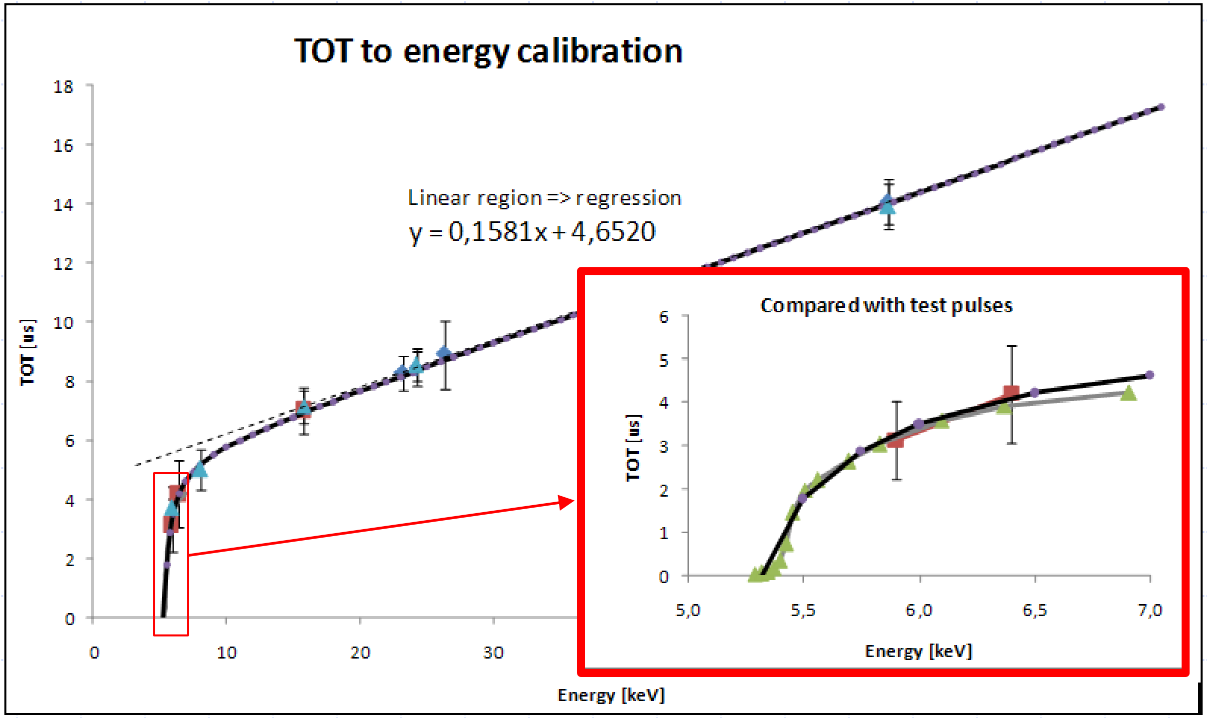
$$f(x) = ax + b - \frac{c}{x - t}$$

Meaning of parameters:

a,b – linear regression in high energy range
c – curvature extent
t – threshold



Parameters computed Using global calibration data:

a=0.158
b=4.65
c=2.4
t=4.86

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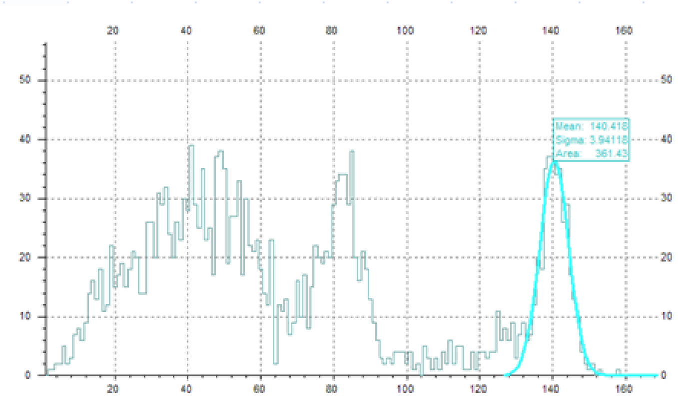
TOT mode calibration:

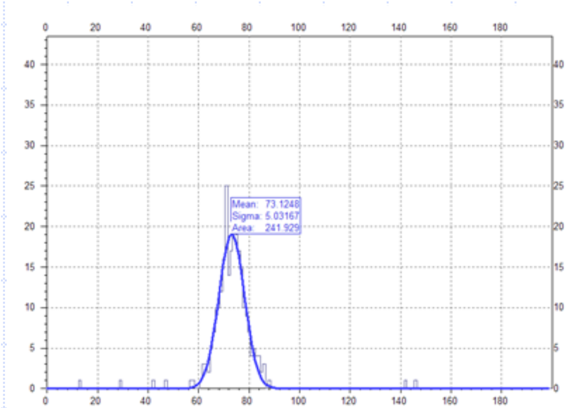
Per pixel calibration

- To improve energy resolution per pixel calibration is needed.
- Calibration done using 5.9keV (Fe55), 15.8keV (Zr) and 59.5keV (Am241) using single pixel clusters.
- Good per pixel spectra of one pixel clusters needed => **200 000 000 clusters** analyzed in case of Am241.
- Gaussian fit done for each peak and each parameter => **200 000 gaussians**
- Just three parameters determined for each pixel: ***a,b*** and ***t.***
- Parameters ***c*** and ***d*** were set constant to 2.4 and 1 respectively.

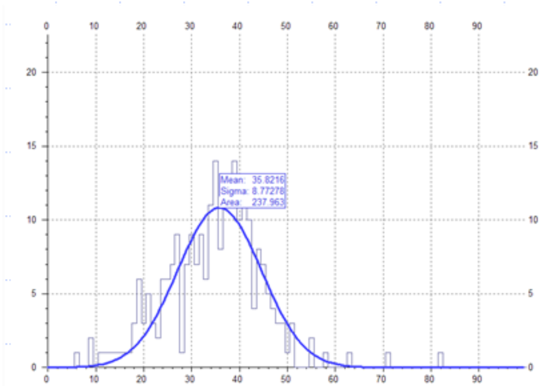
Am241 (59.5keV):



Zr (15.8keV):



Fe55 (5.9keV):



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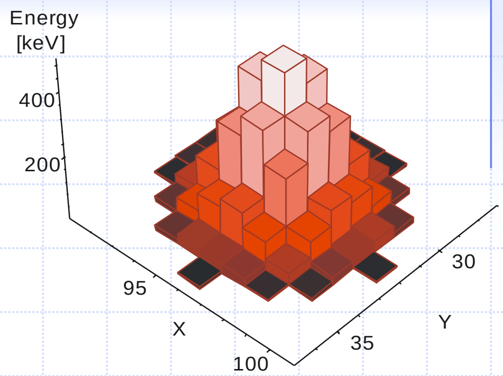
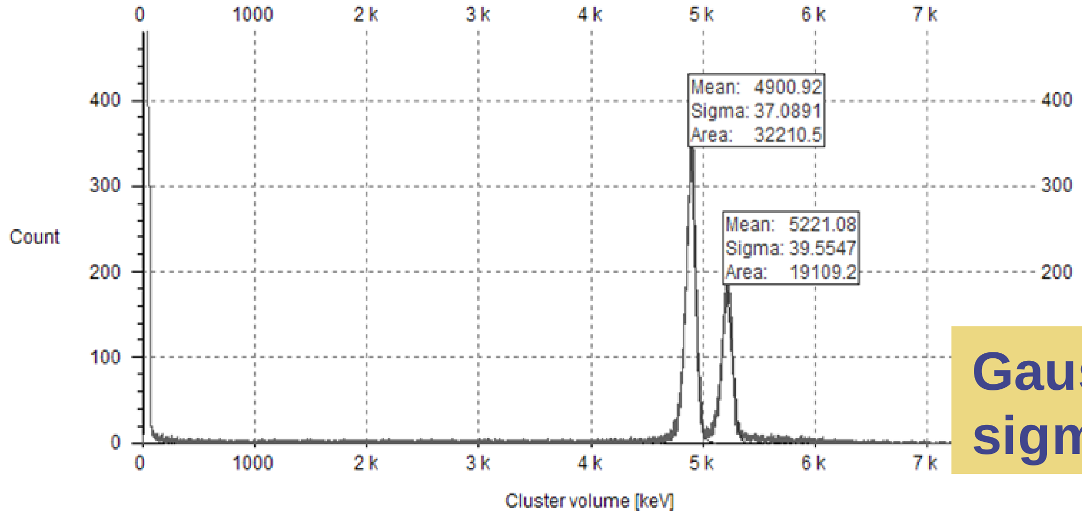
TOT mode calibration:

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

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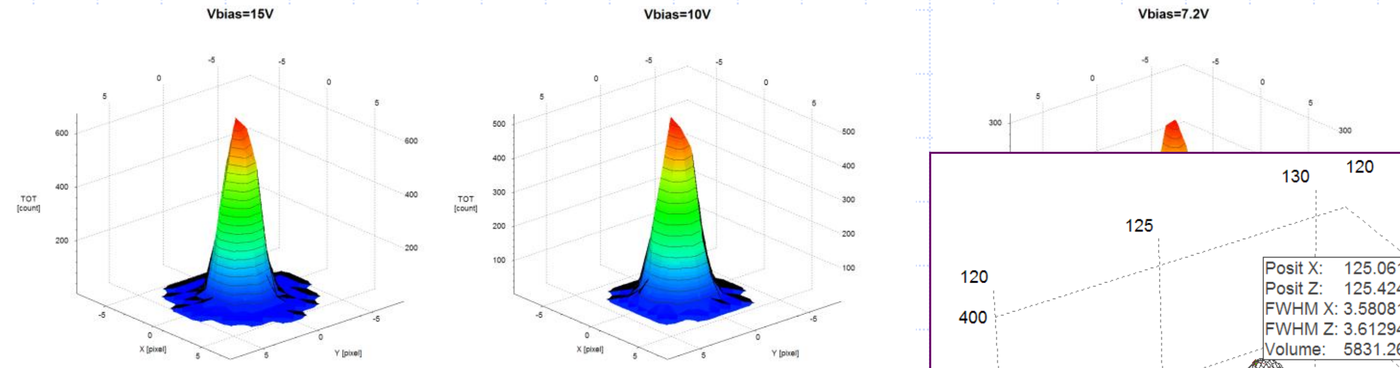
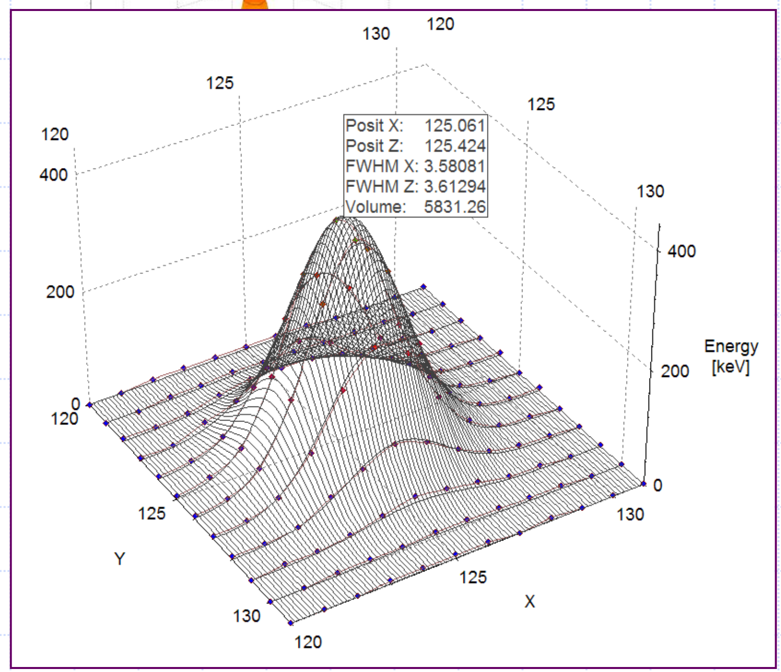
Heavy charged particles:

Subpixel resolution

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





⇒ Subpixel resolution is reached by Gaussian fit.

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

Deep subpixel spatial resolution with energetic ions

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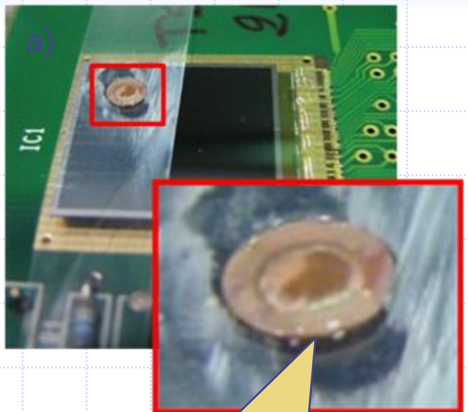
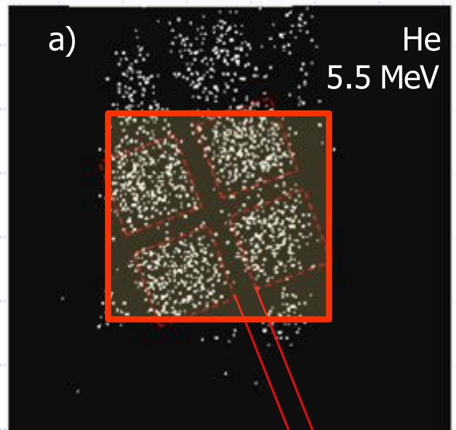
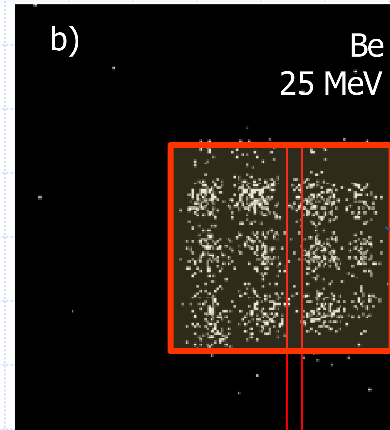


Copper grid for electron microscopy
a) 25 μm
b) 12.5 μm

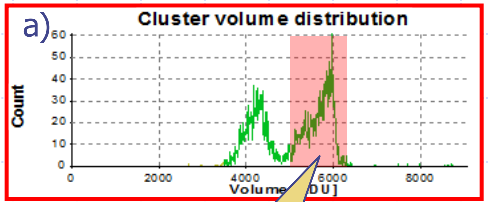


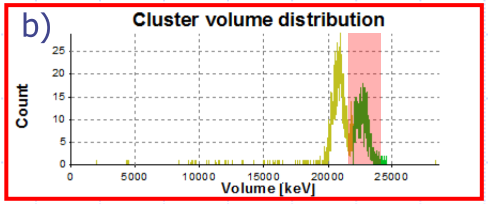
5 μm



Pixel size

2.5 μm





Energy used for image

High resolution energy sensitive radiography with ions:

Sample object: Spider skin (slough)

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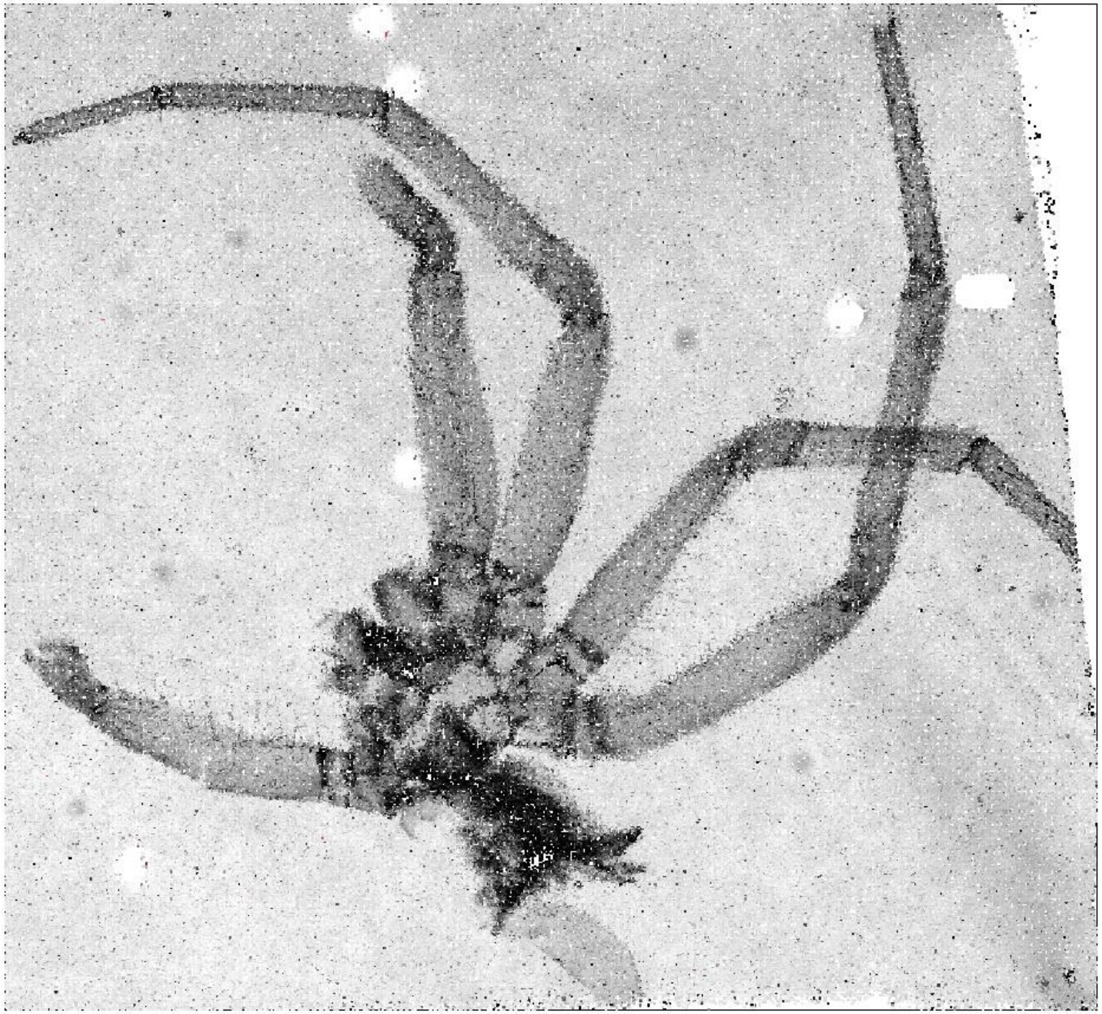

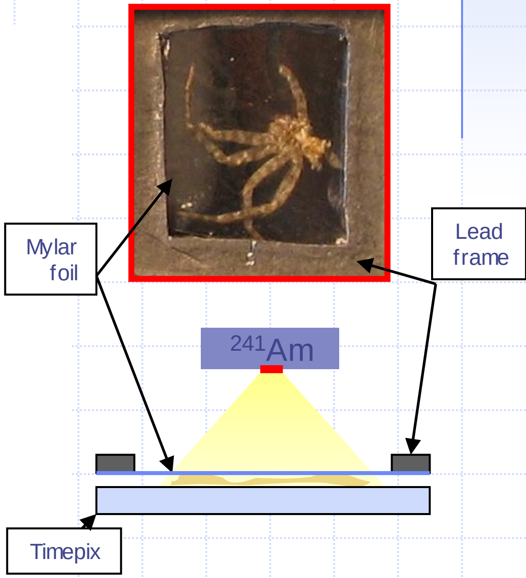

16 x

(1 Mpixels)

~0.7 particles per pixel

Proton tracking:
Determination of direction from recorded tracks - protons

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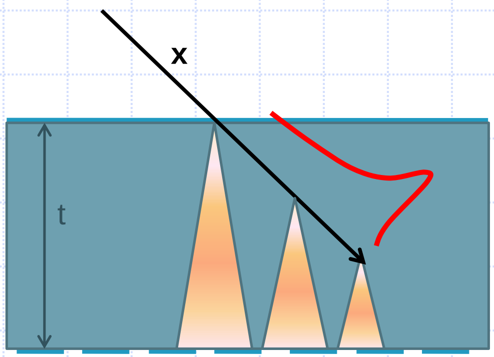
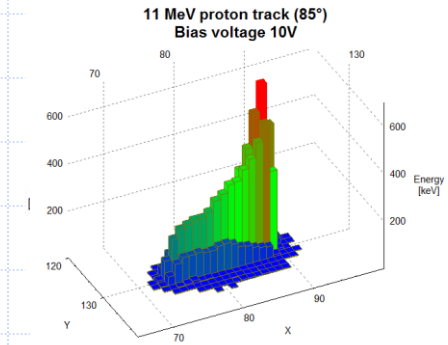
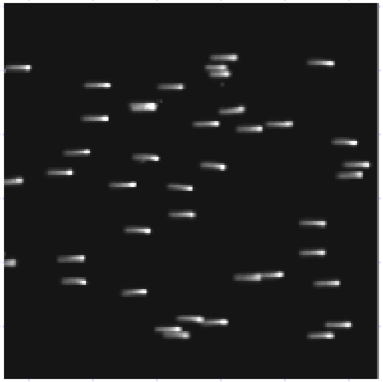


=>

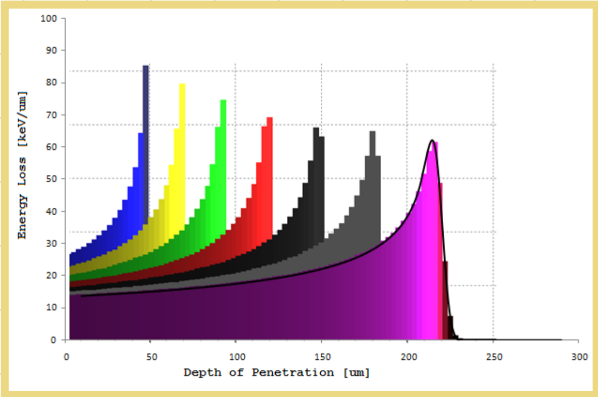
Asymetric clusters



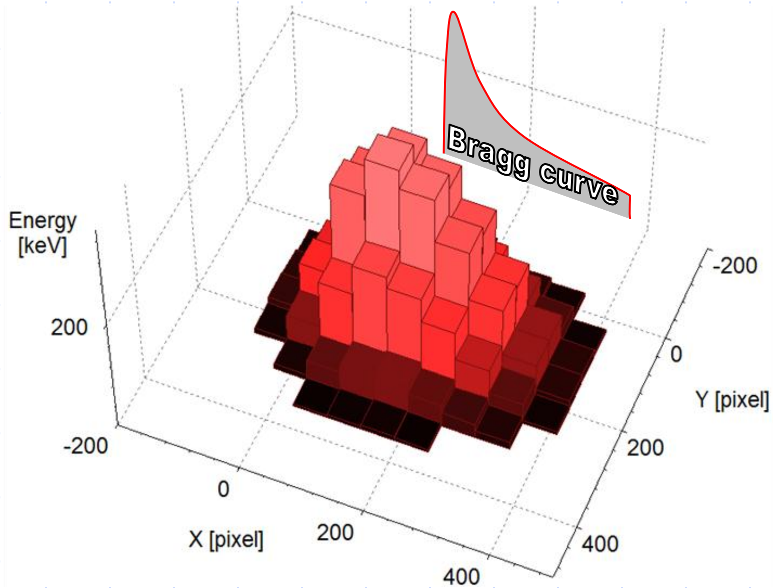


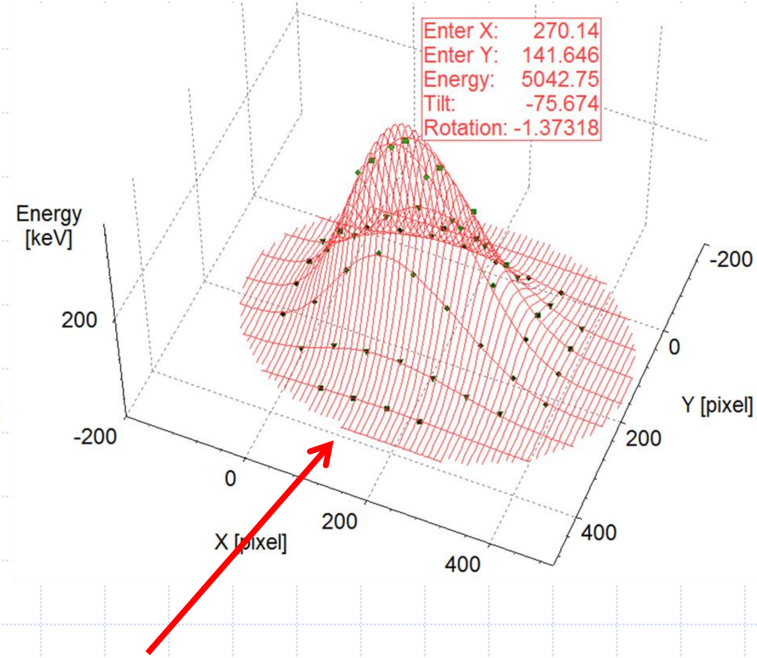
11 MeV protons at 85 deg

- Energy losses defined by Bragg curve => model needed
- The charge is collected from different depths
- At low bias voltage the diffusion dominates => Gaussian charge spread



Asymetric clusters fitting





Mathematical model:

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

Simplified

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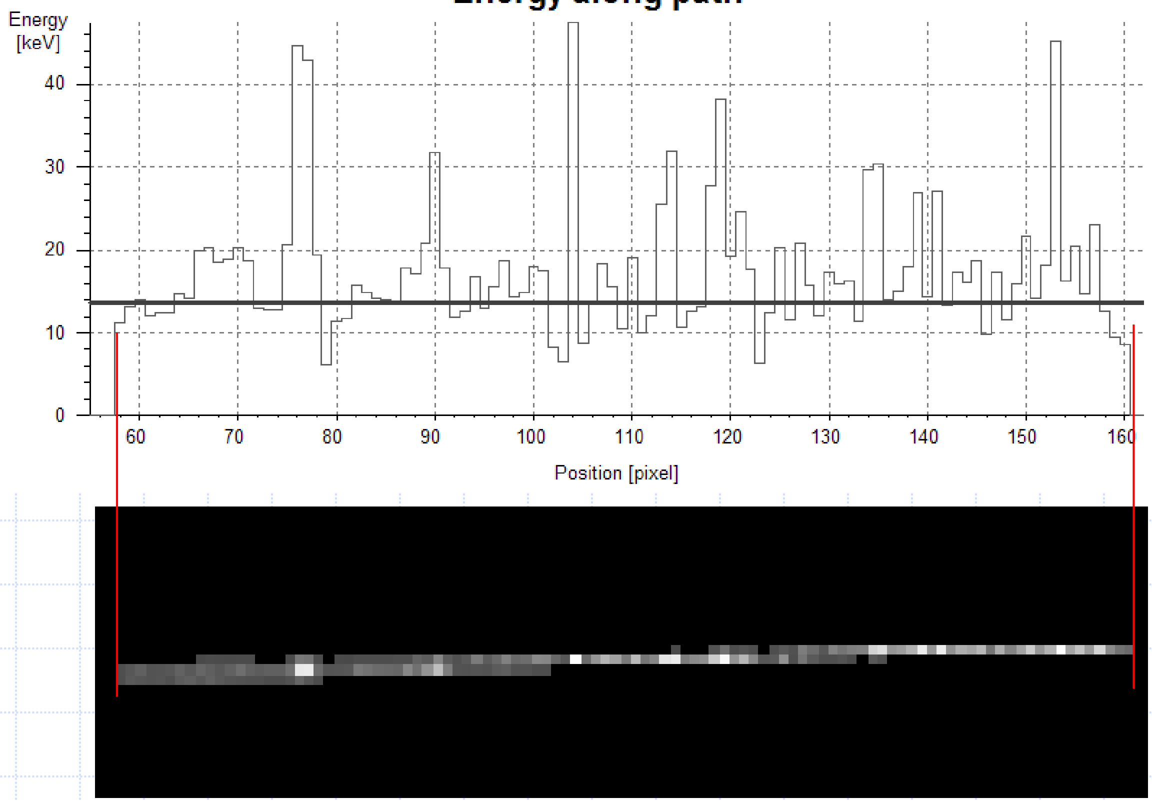
Charge sharing effect:

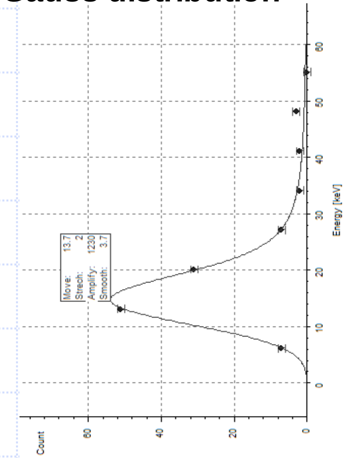
Tracks of MIP particles – Cosmics

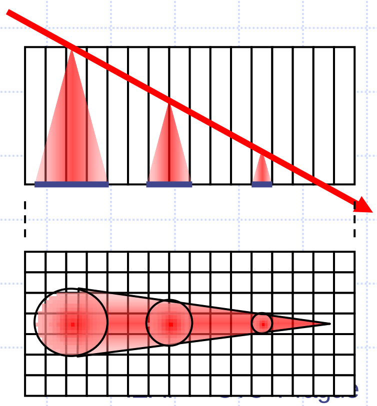
Energy along path



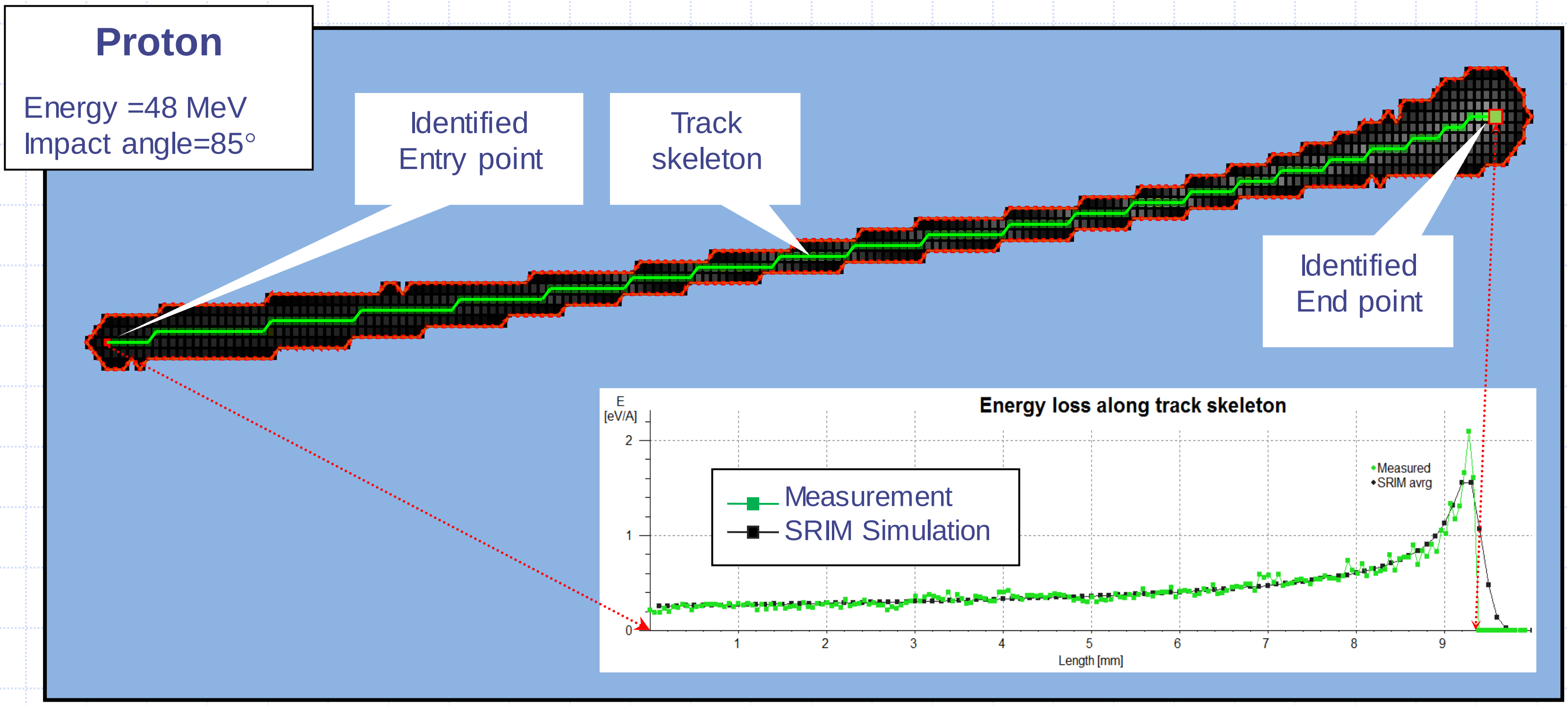
Track recorded by TimePix device

Energy distribution fit by convolution of Landau and Gauss distribution





Proton track: LET and Bragg curve



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Energy sensitive X-ray imaging with Timepix device

XRF Imaging …

… event by event processing

Experimental setup and samples

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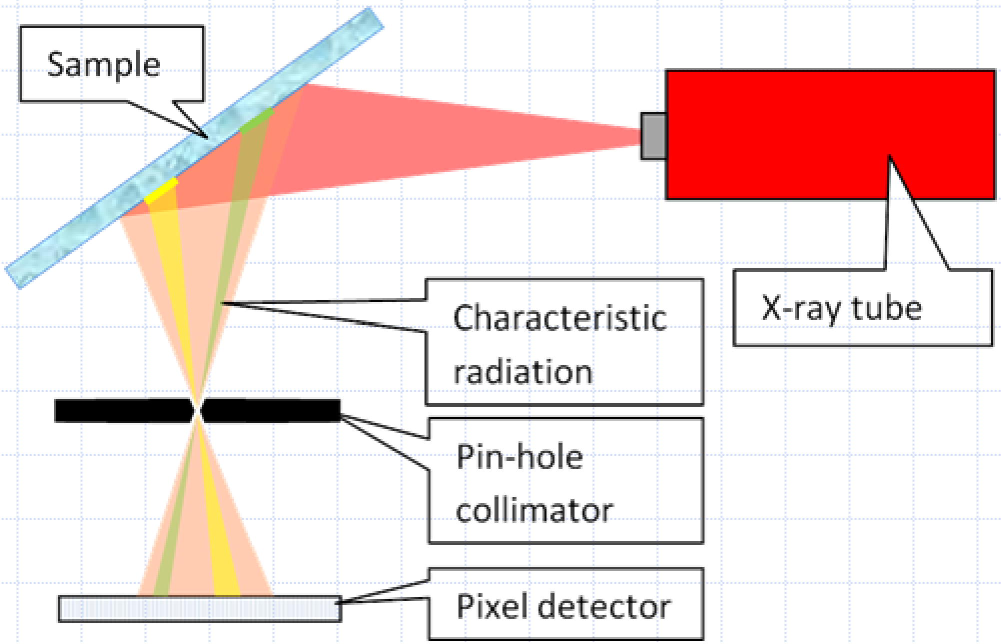
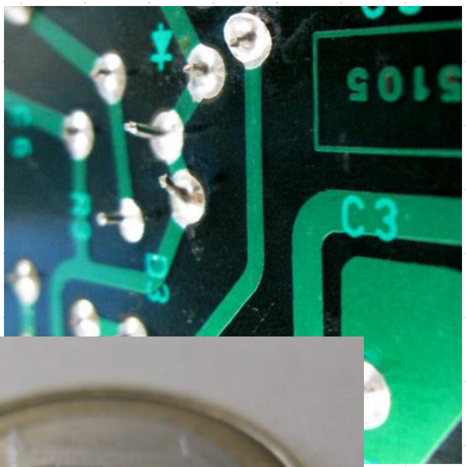


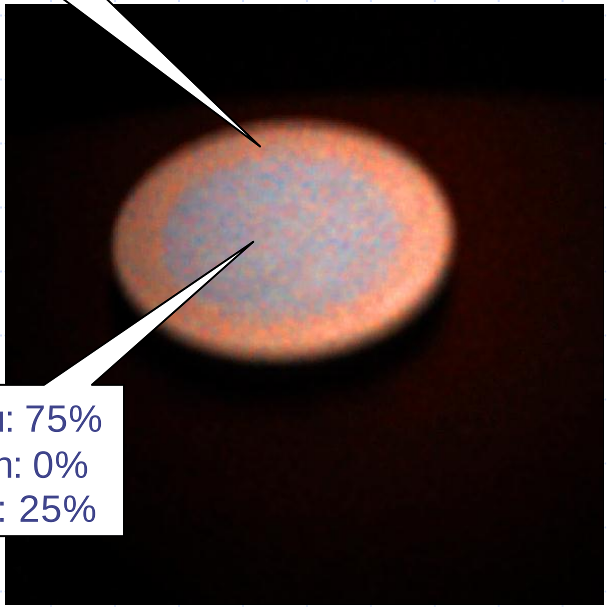
Piece of PCB



One Euro coin

X-ray fluorescence imaging:

Results



Color coding:
Cu = Red, **Pb** = Green, **Sn** = Blue

Color coding:
Zn content is displayed in Pink

Energy sensitive X-ray imaging with Timepix device

Multichannel transmission imaging …

… event by event processing

Color radiography:

Event by event imaging

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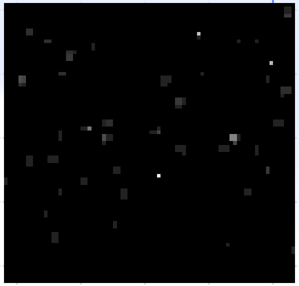
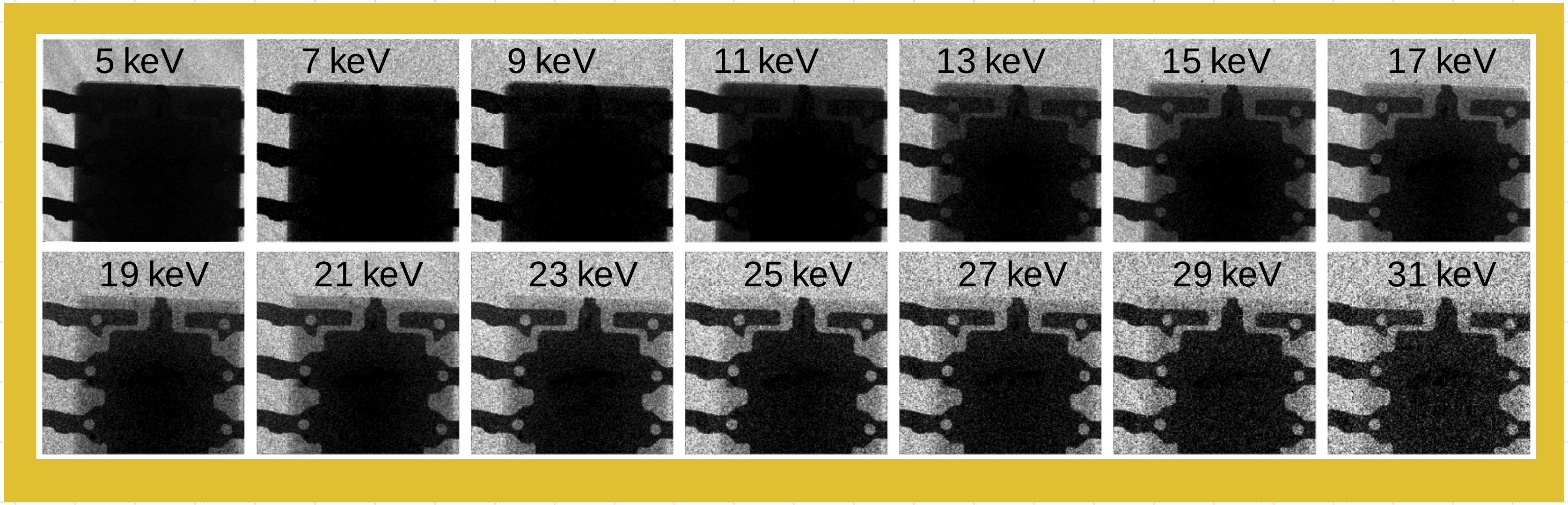
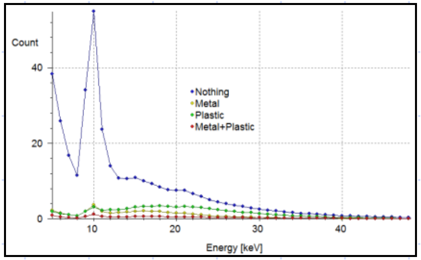


- Exposure time reduced to avoid overlapping clusters
- Clusters in each frame identified, energy determined by summation
- Many frames taken (14 000 000 clusters analyzed) in 2 hours



- Per pixel spectra determined
- Allows material reconstruction



Enhancement of spatial resolution using centroiding

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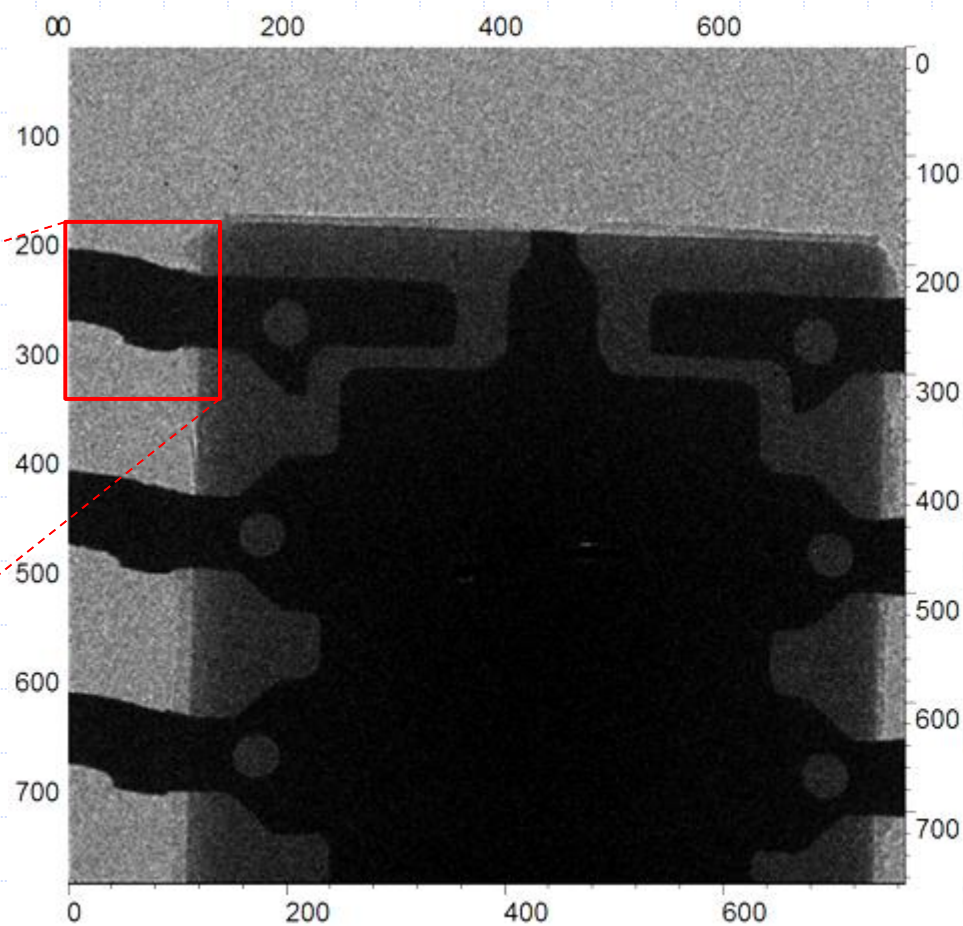
- Just round clusters larger then 3 pixels used for enhancement.
- The same experimental data reprocessed.

1 x 2 x 3 x



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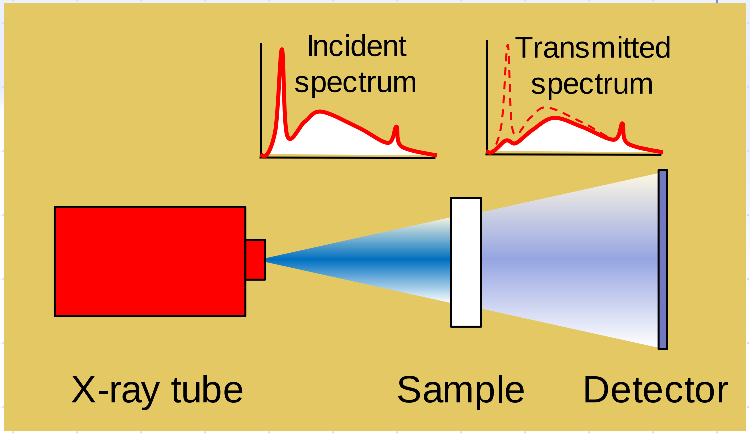
X-ray transmission radiography:

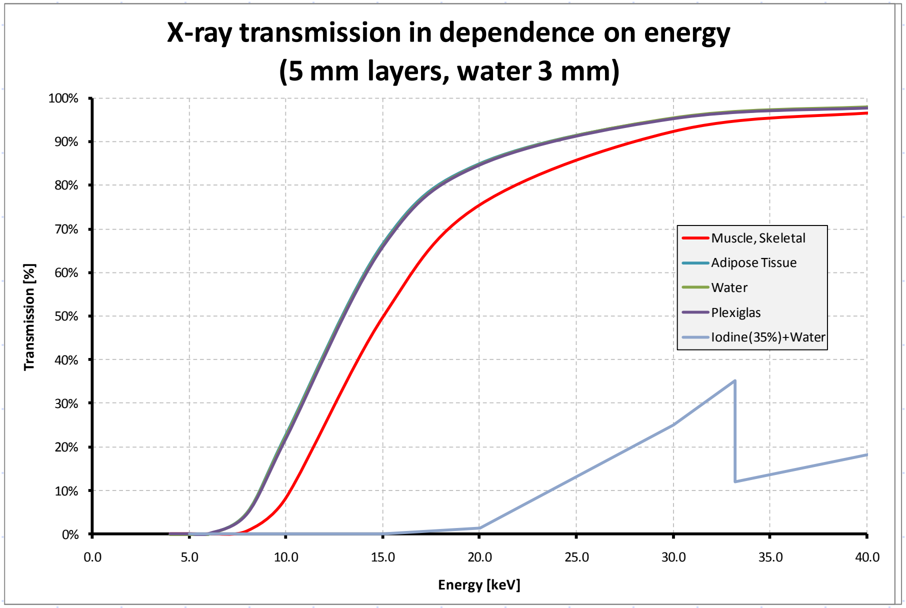
Material recognition

- Energy dependence of X-ray absorption is given by the material composition => material recognition
- Recognition is simpler for materials with edges in absorption spectra, often just several energy windows are needed
- **Absorption spectra of soft biological materials differ just slightly => real per pixel spectroscopy is needed.**

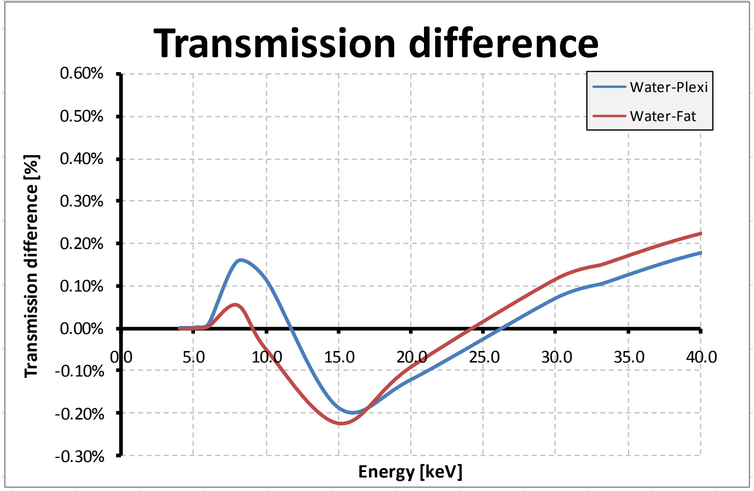


Thickness alternation:

- The transmission curves are similar
- At certain thickness it can be almost same



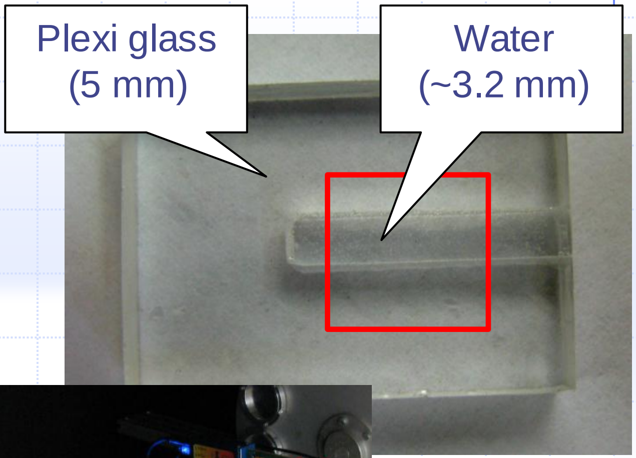
Can we recognize them?

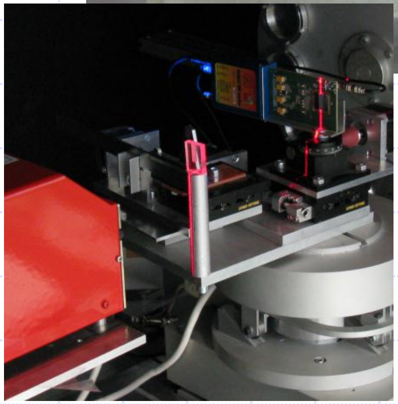


X-ray transmission radiography:

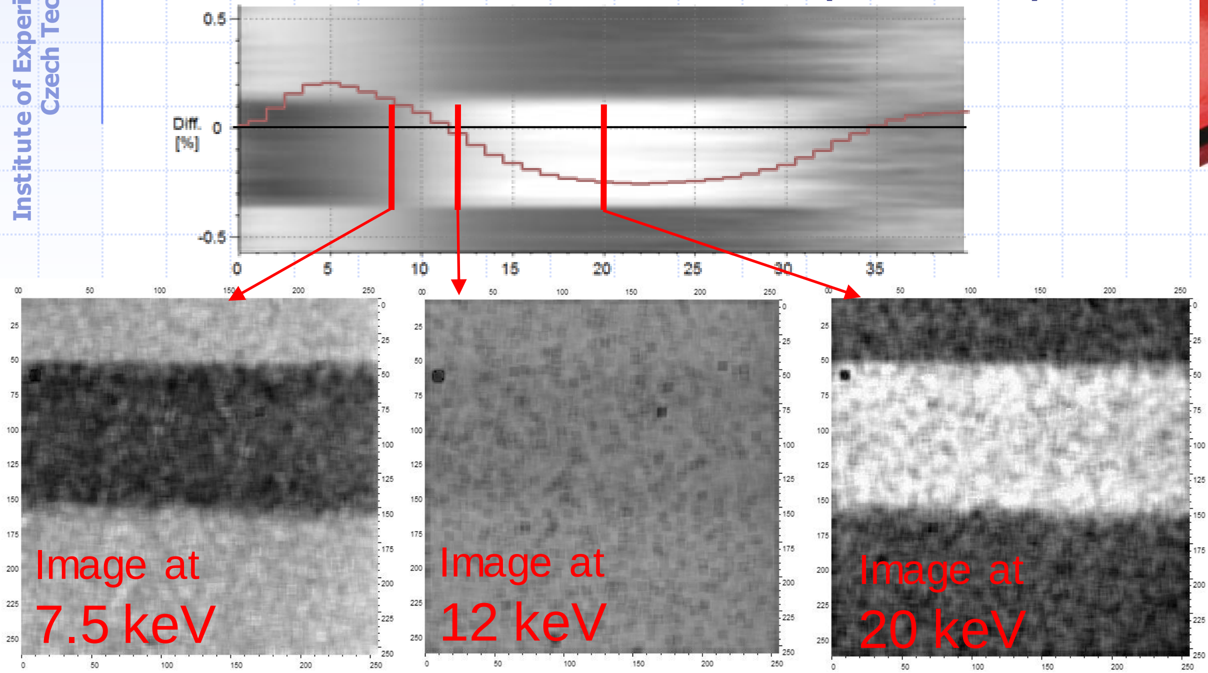
Soft tissue recognition

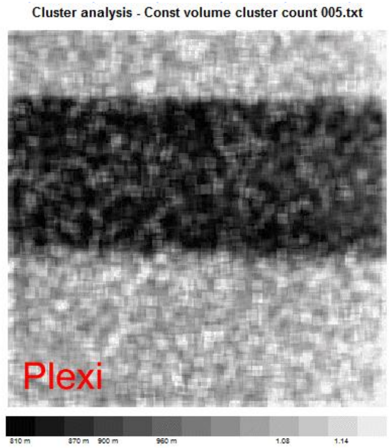
- Phantom sample made of Plexi glass and water
- Irradiated with tungsten X-ray tube at 40kV and just 2uA
- Integral intensity image shows very low contrast
- Per pixel transmission spectra recorded in each pixel (80000 frames a 1ms => 80 sec exposition





Measured transmission difference (normalized)





Material sensitive X-ray transmission radiography:

Complete transmission model

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Complete Model:

1. The incident spectrum has to be known (analytical or Monte-Carlo model or measurement by detector with very good energy resolution)
2. The standard attenuation law in absorber is applied to each energy channel
3. The resulting spectrum is corrected according to detector response
   - Pileups
   - Silicon absorption
   - Threshold and energy resolution of Timepix

The reconstruction of unknown material composition can be performed by iterative process (Expectancy maximization):

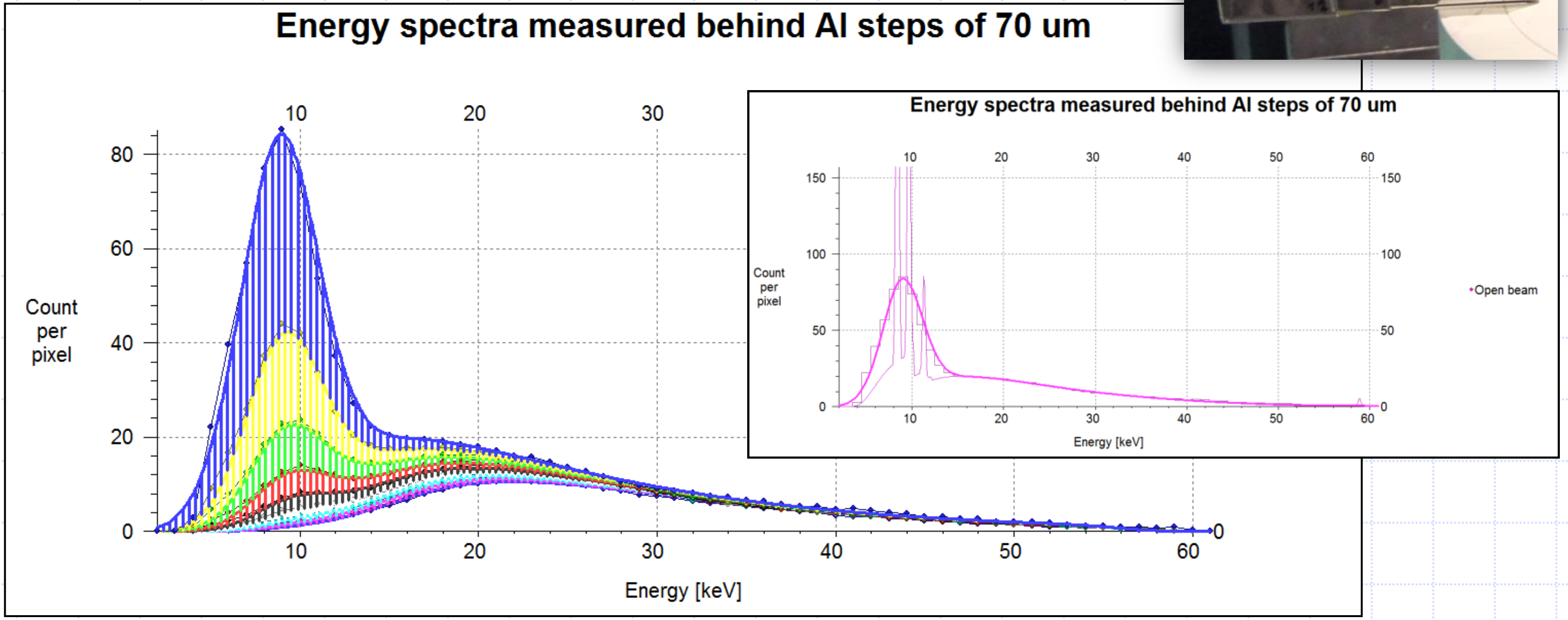
1. The sample composition is estimated using a priori knowledge (**trial point**)
2. The attenuated spectrum behind the sample is computed using complete model
3. The spectrum is compared with measurement
4. Material composition of the sample is adapted
5. Go to 2 for next iteration.

X-ray transmission radiography:

Test of complete transmission model

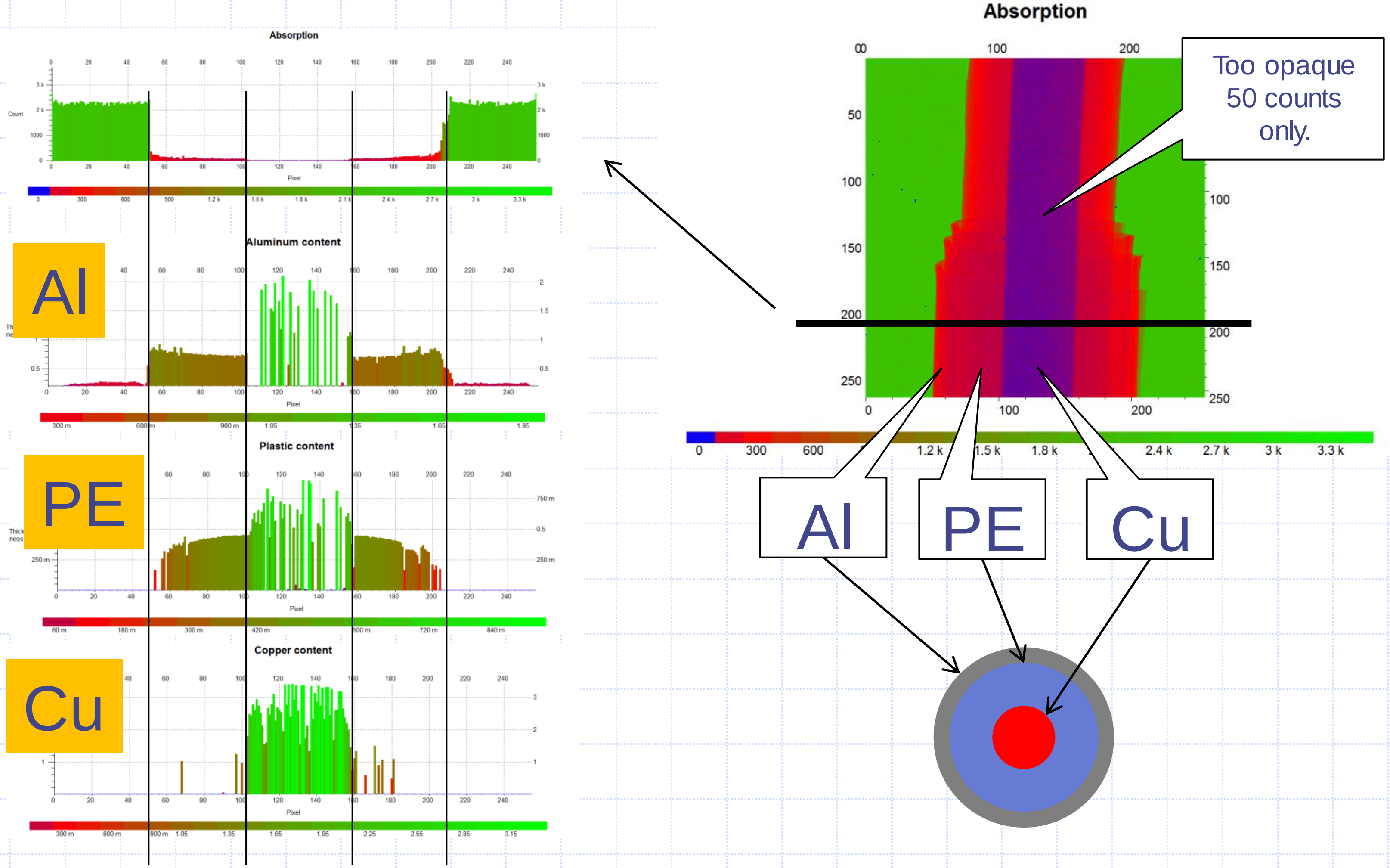
1. The X-ray tube spectrum was parameterized (Bremstrahlung, XRF peaks, target absorption, sample absorption … together 15 parameters) and such model was fit to spectra measured with sample of known material composition (Aluminum steps).
2. The parameters of incident X-ray spectrum were determined this way.

=> The shape of incident spectrum is known now.



X-ray transmission radiography:

Example: Cu wire in plastic and Al



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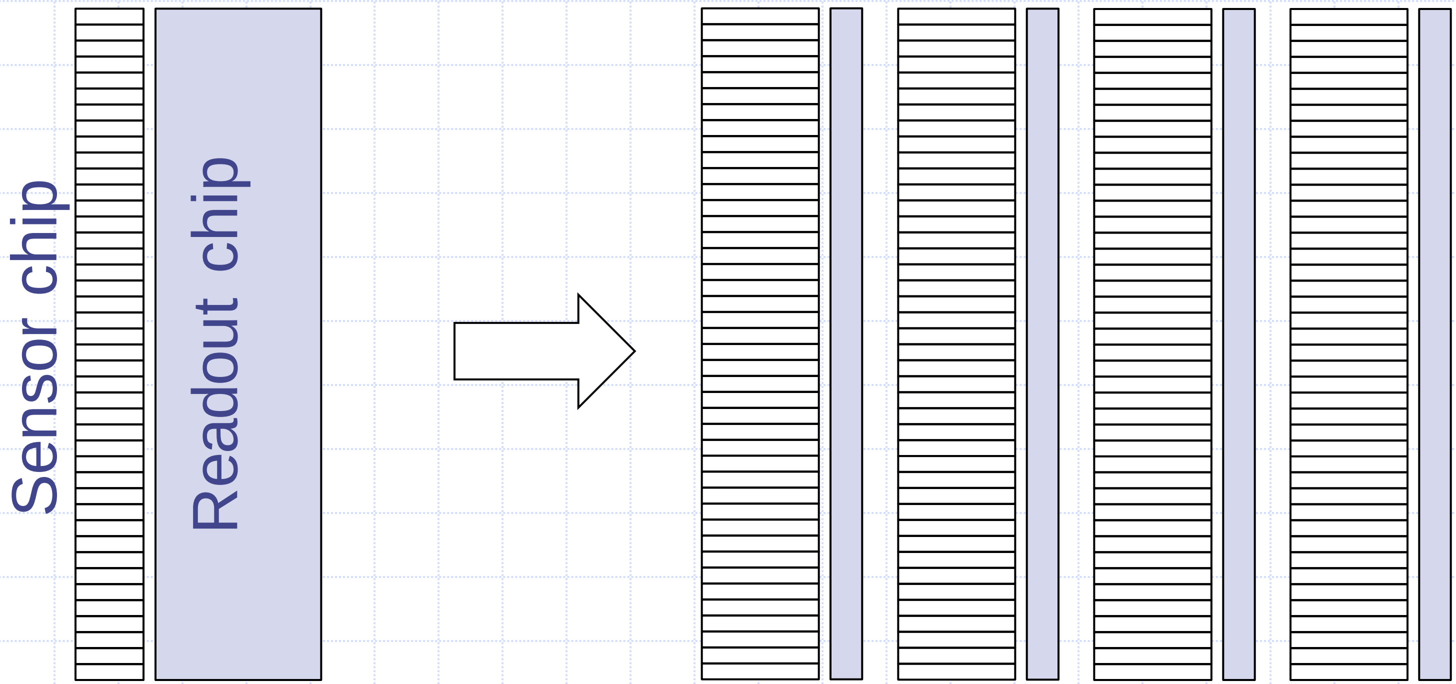
Voxel detector
concept and first tests

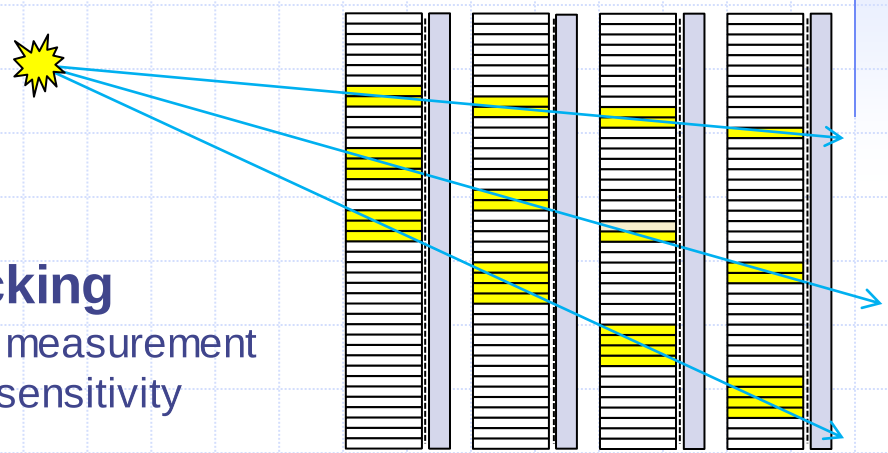
Voxel detector concept

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

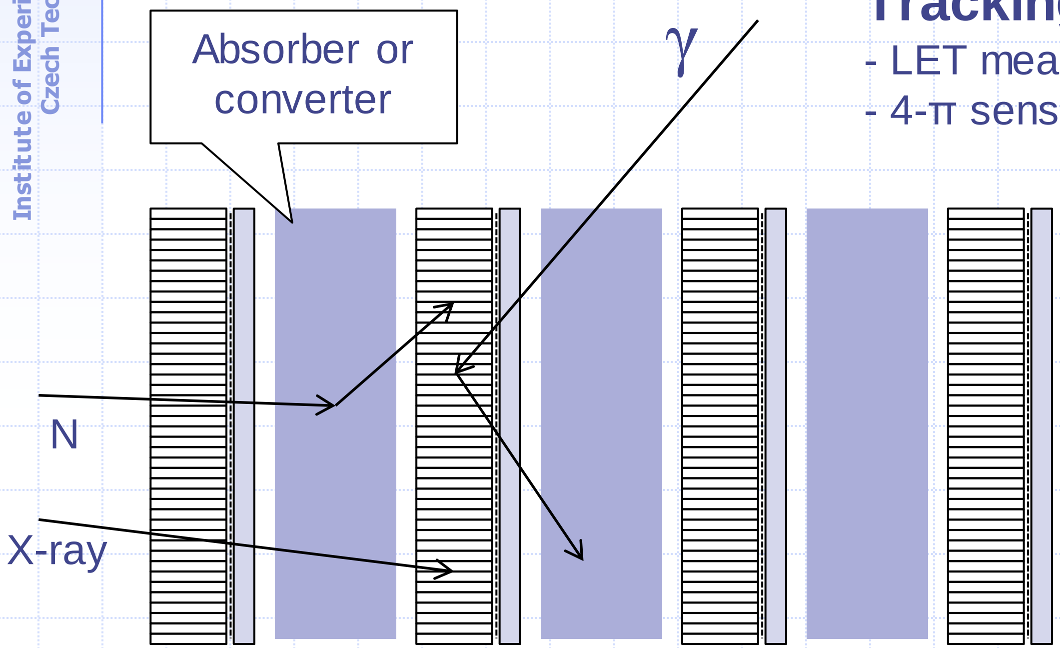


Applications:
Tracking, tracking imaging, dosimetry

- Tracking (MIPs, Ions, …)
- Tracking imaging: Proton CT, Compton camera, Fast neutron camera …



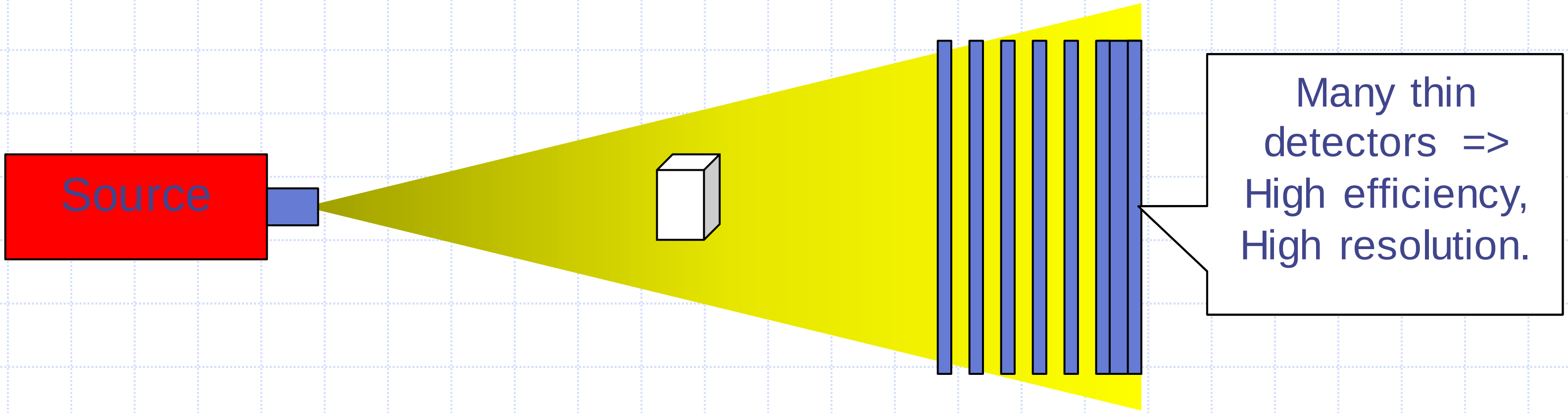
Tracking
- LET measurement
- 4-π sensitivity



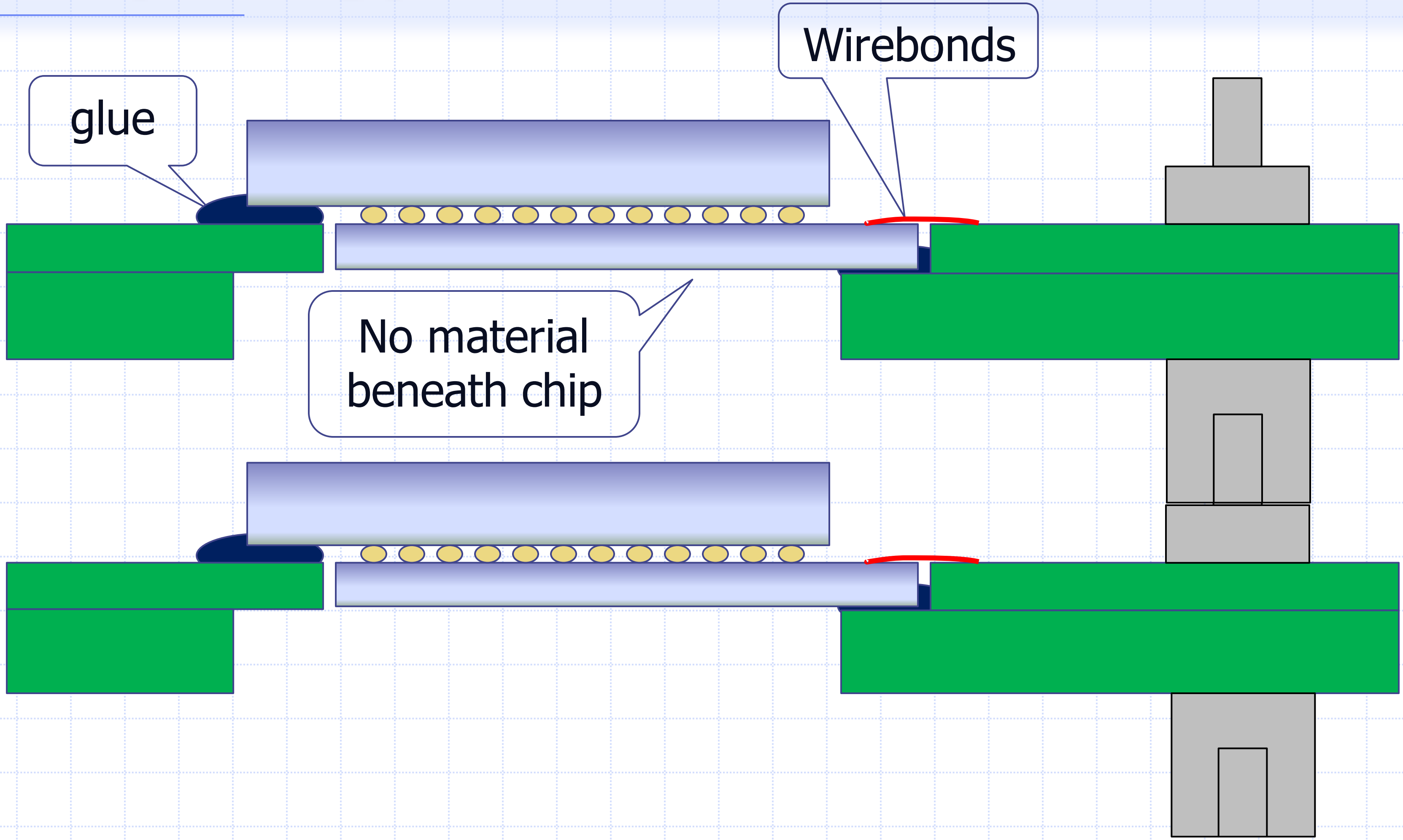
Dosimetry or radiation monitoring
- Sensitive to photons, electrons, ions, gammas, can be sensitive to neutrons …
- Total thickness < 200 um
- Energy deposition measurement
- Particle identification

Applications:
Transmission radiography
(X-rays, slow neutrons, …)

- Detection efficiency can be increased using thicker sensor implying decrease of spatial resolution.
- Voxel detector allows to increase the detection efficiency preserving very high spatial resolution.
- Energy sensitivity due to beam hardening effect.
- Possibility of source position reconstruction (direction and distance) directly from measured data (for robotic radiography).



Chip assembling, PCB with 3D morphology and micro connectors



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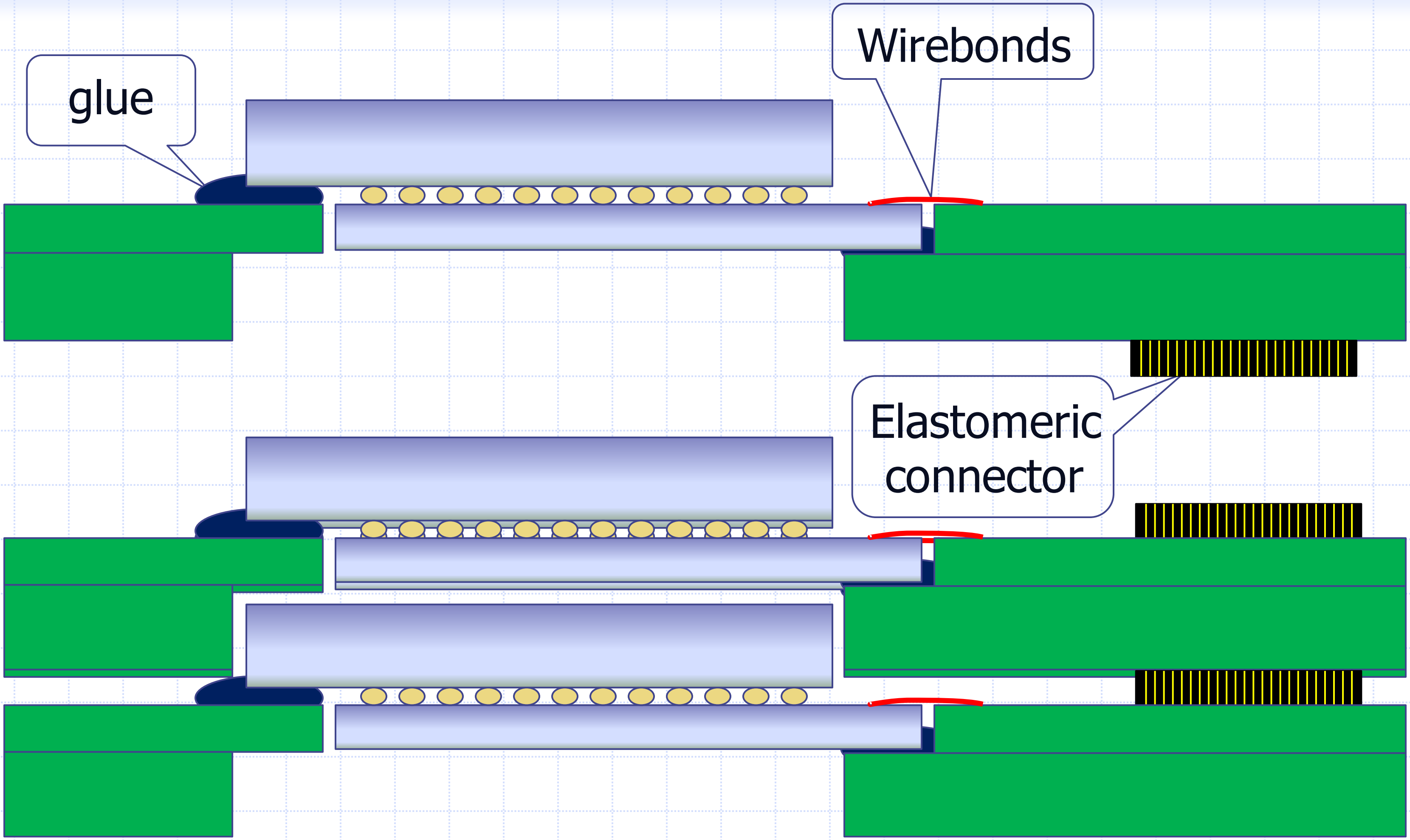
Chip assembling, PCB with 3D morphology and flexible connectors



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Chip carrier details
(with normal connectors)

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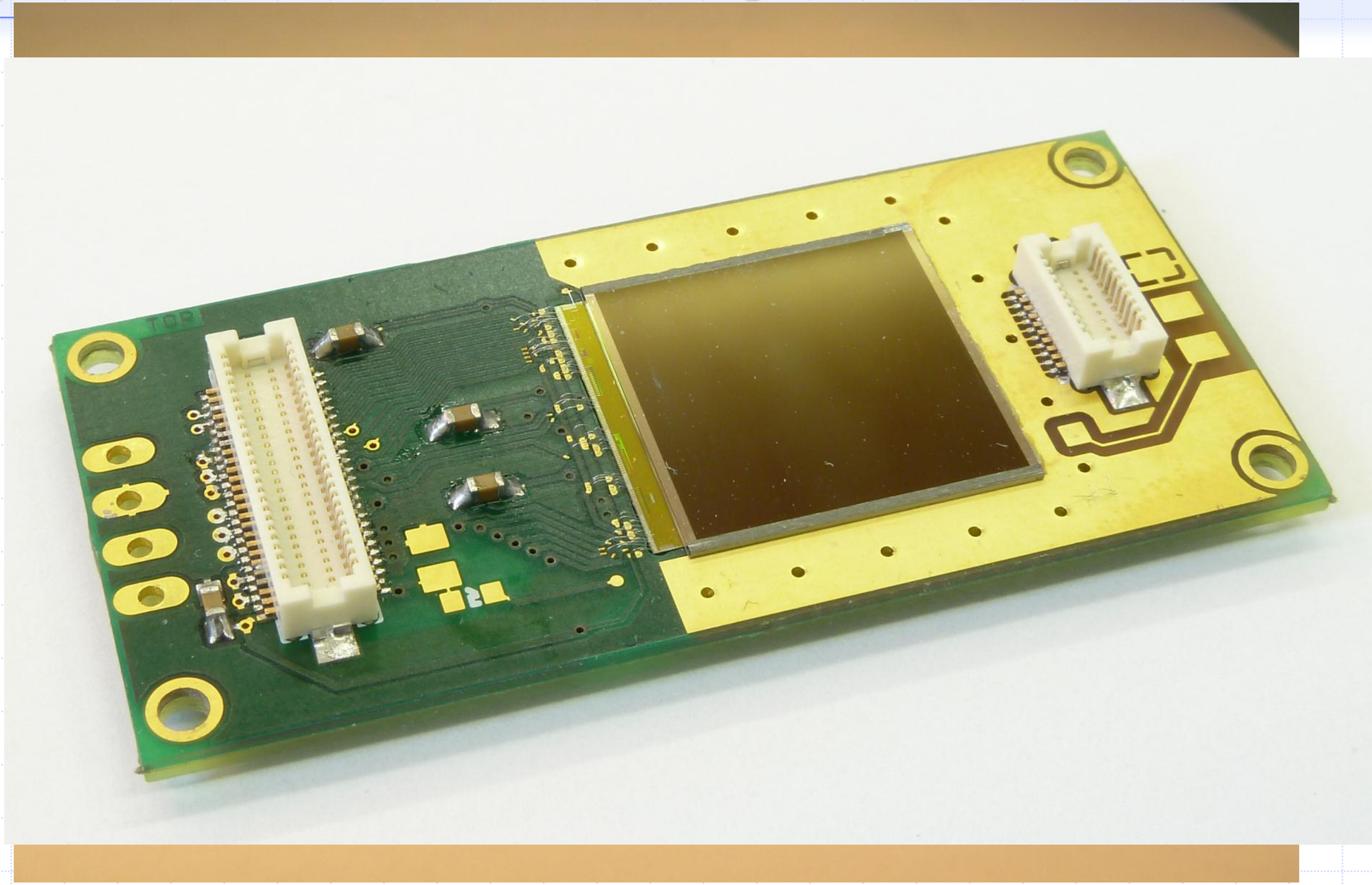

Whole assembly

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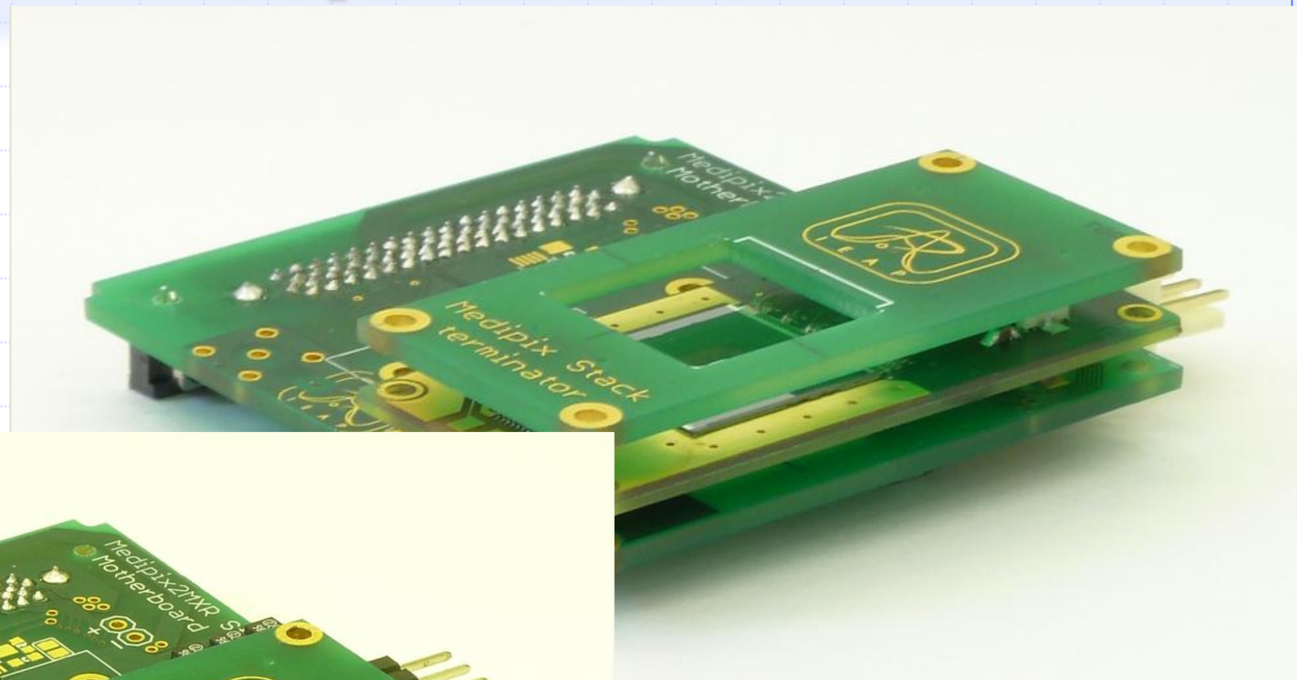

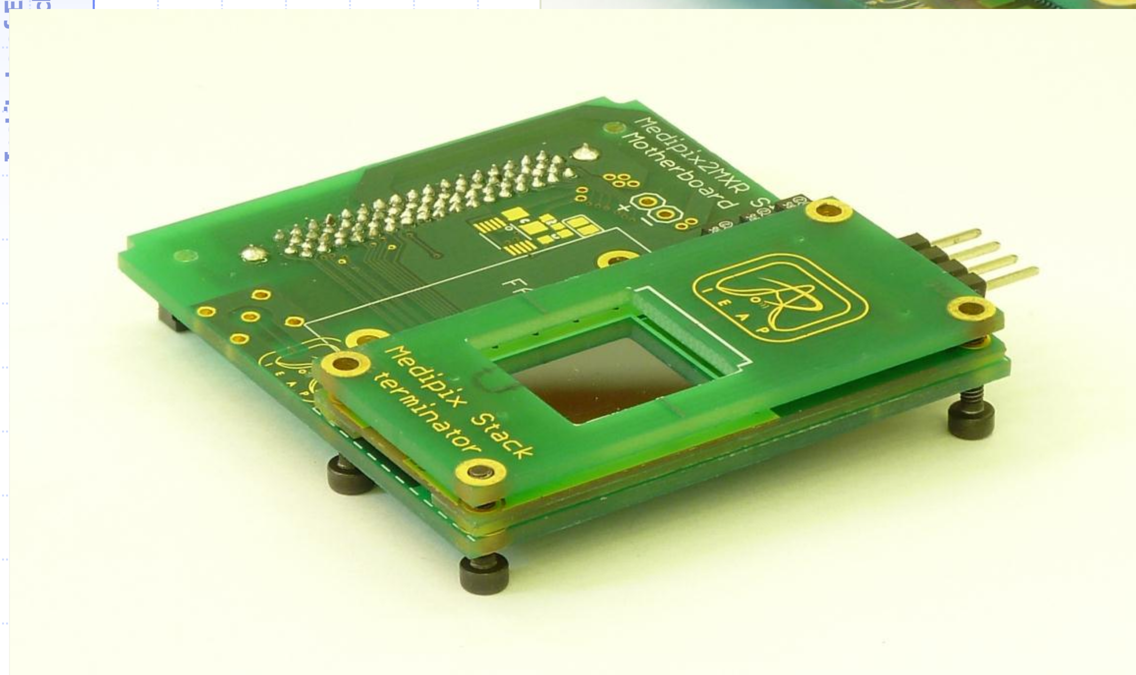

Variable setup:
Any number of chips can be stacked

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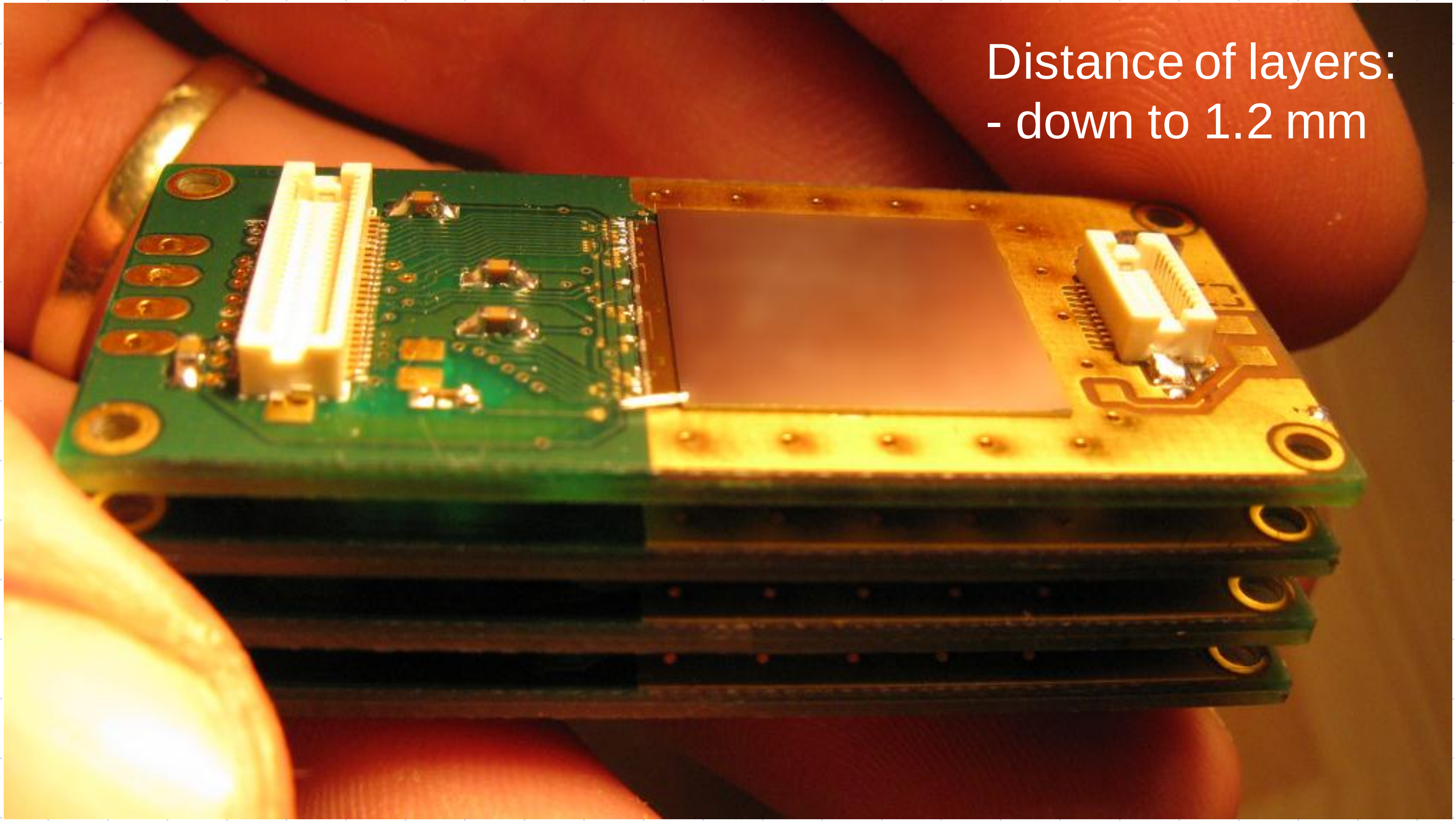

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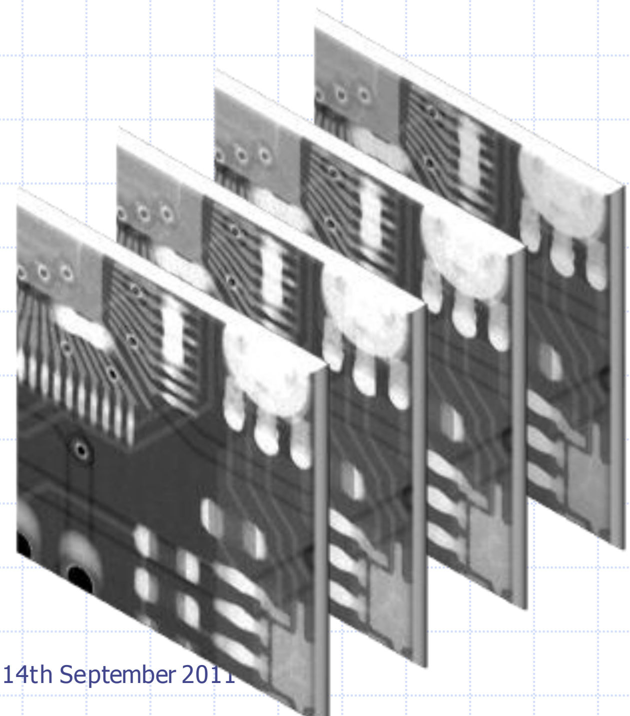
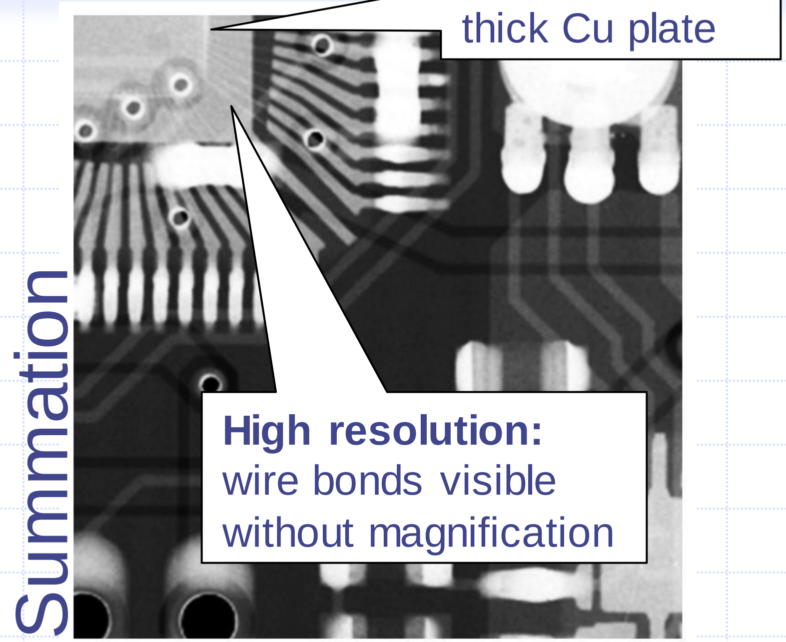
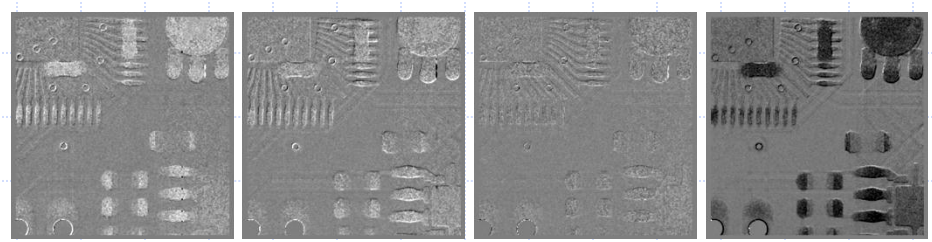
First tests:
X-ray transmission radiography

- Stack of four layers used to image the PCB structure (Tungsten X-ray tube at 70 kV).
- Total efficiency gain: 2x
- Detectors act as filters
  - => each of 4 images taken at different spectrum
  - => multichannel imaging (colors)
  - => material sensitivity





Differences = material info



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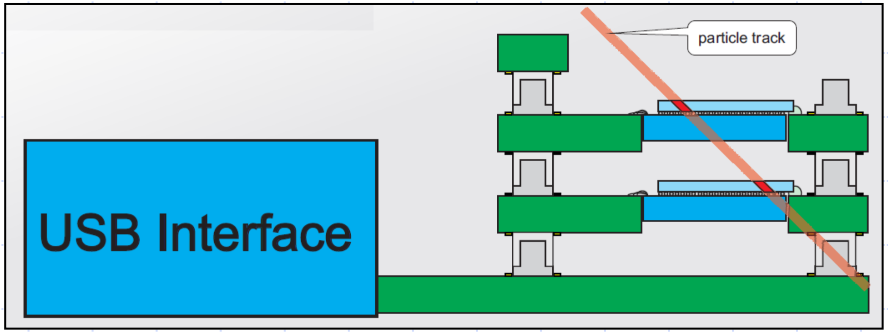
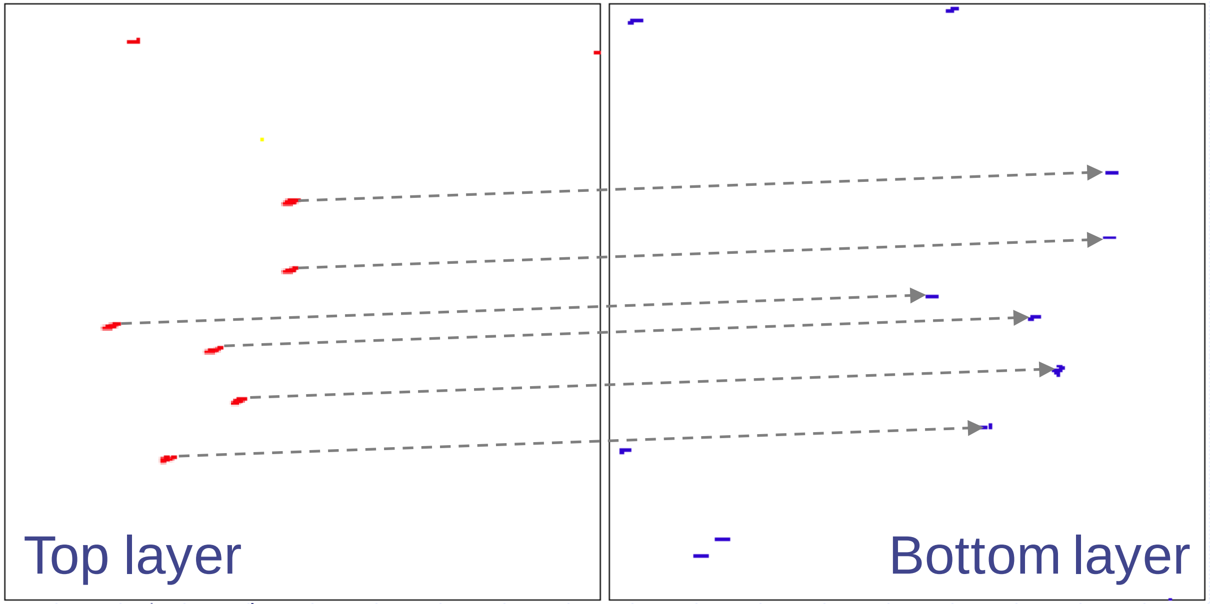
First tests:
Tracking of MIP particles

- Two layers exposed to muon beam of SPS facility in CERN.
- Both layers operated synchronously, no triggering.

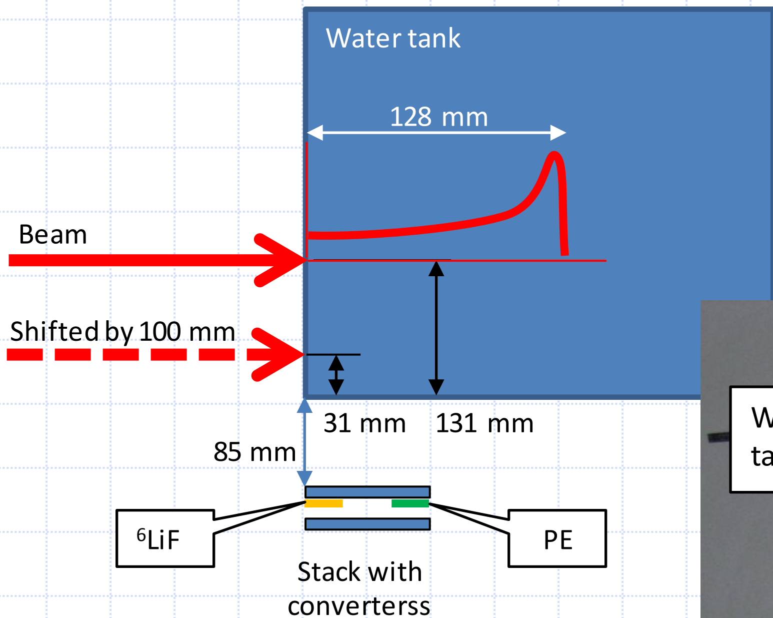


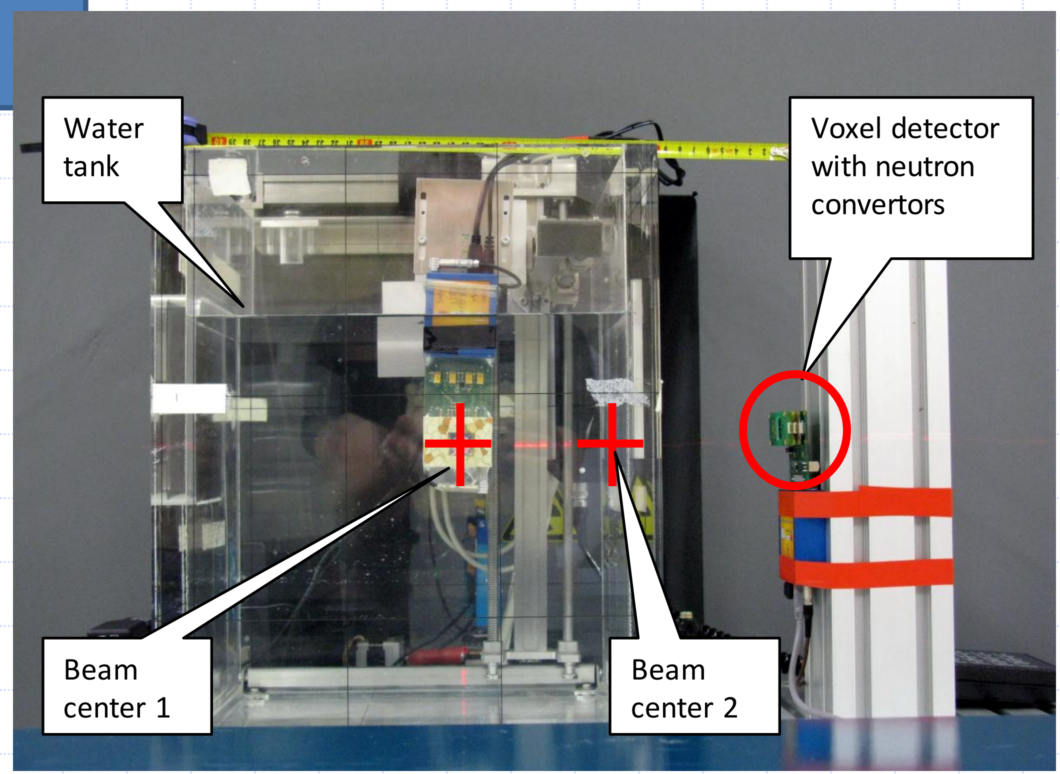


Small USB interface and laptop computer used for readout

Palm-top Tracking system

Imaging of secondary radiation produced by Medical Ion beam





Beam: Carbon 250 MeV/u

Data processing: Sample frame

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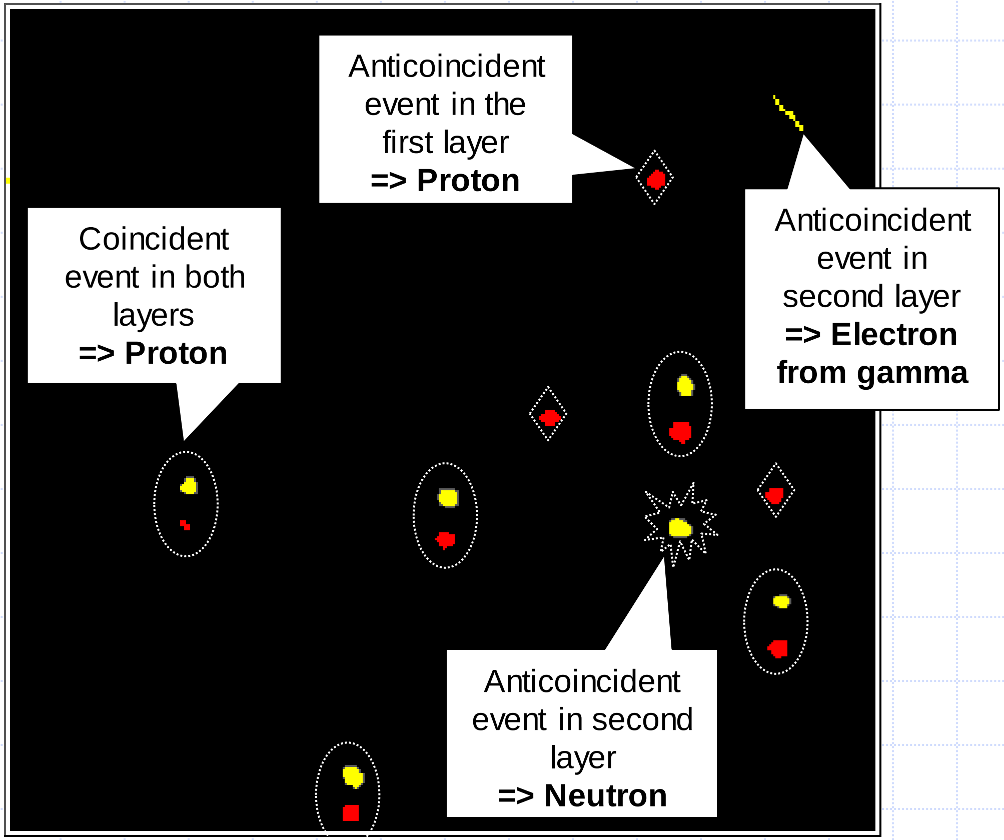

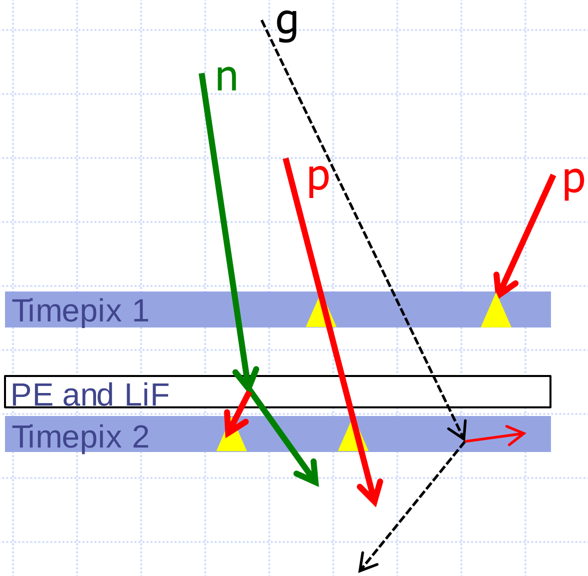

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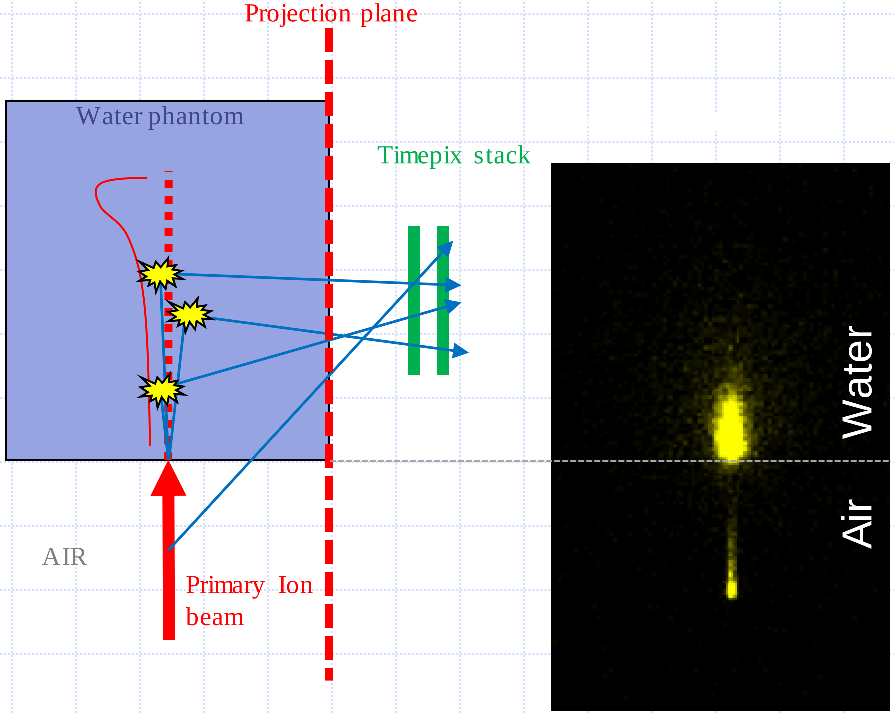
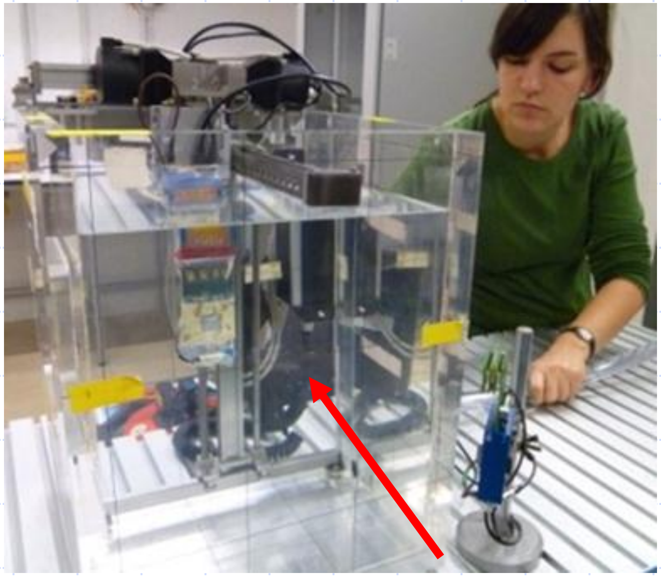
Coincident events:
Ions (mostly protons)

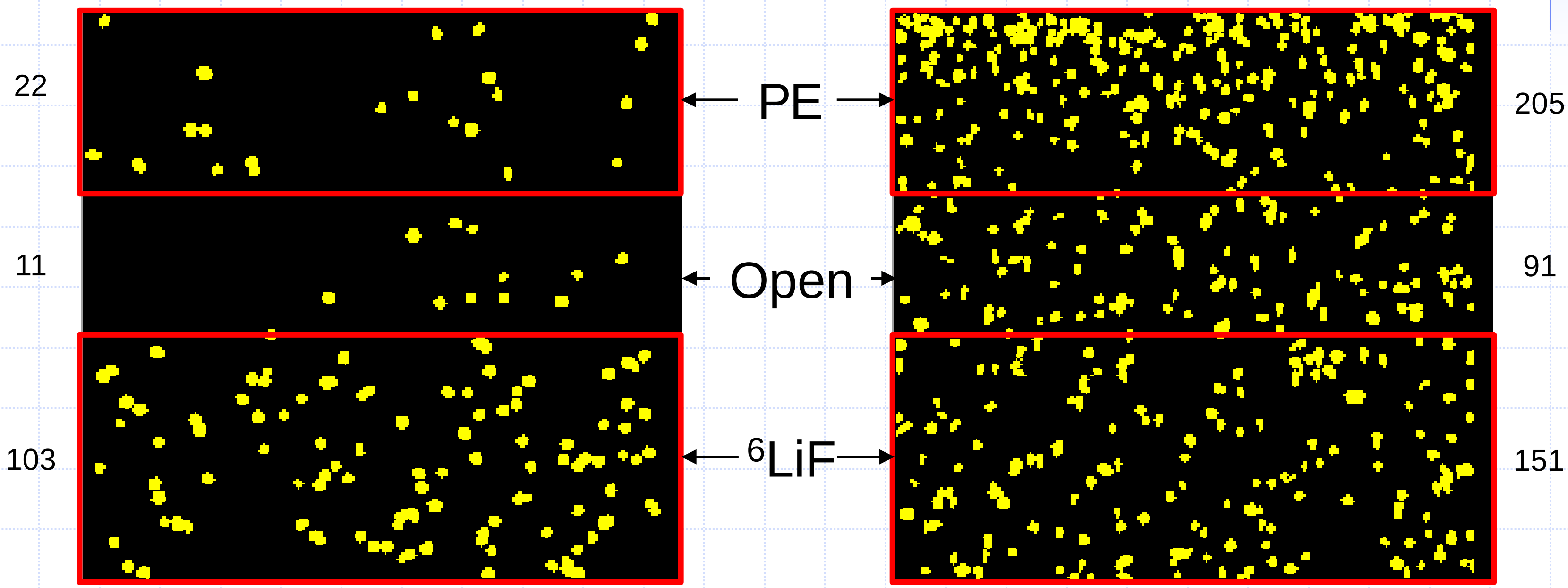




Anticoincident events:
Slow and fast neutrons

Beam 1: 13 cm from tank edge

Beam 2: 3 cm from tank edge



Beam pos	Slow	Fast	Fast/Slow
1 (center)	82.2	37.0	**0.45**
2 (near edge)	49.9	334.1	**6.70**

Other techniques:
Imaging based on ion scattering

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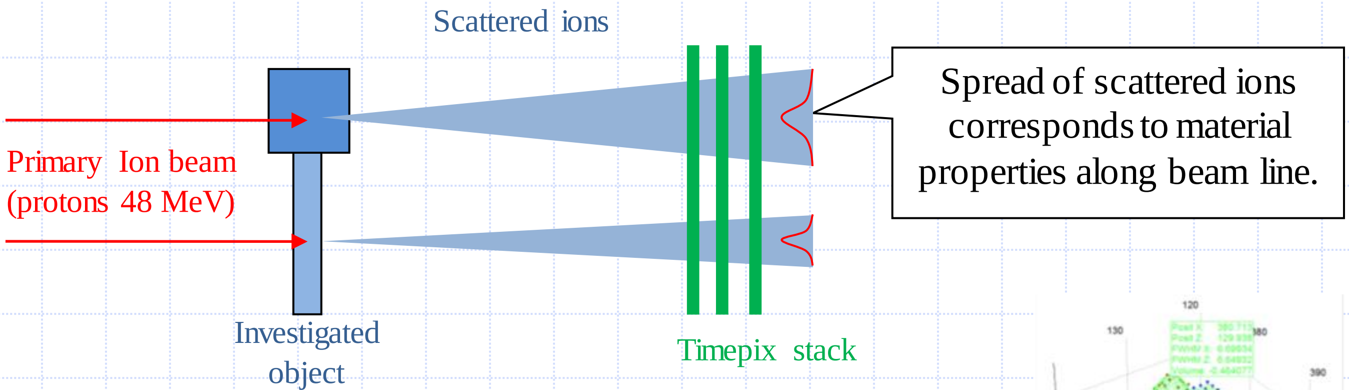


Four PMMA plates with thickness from 2-9 mm

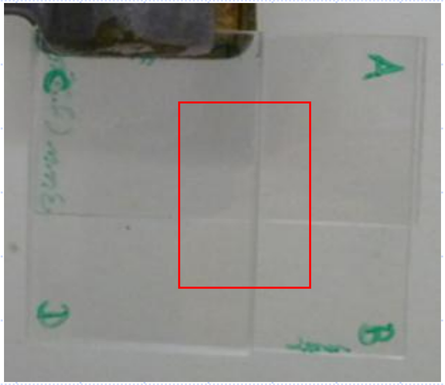
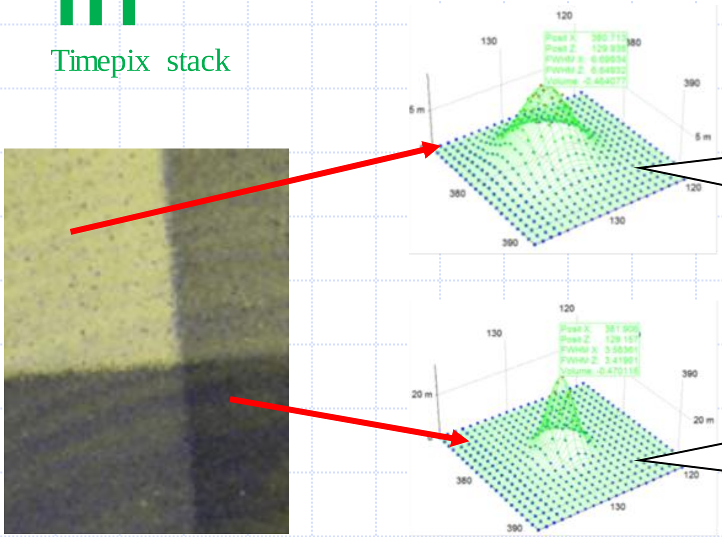


Image reconstructed from scattering data in each point



Wider distribution behind of thicker part of object

Narrower distribution behind of narrower part of object

Conclusions

Two main directions in development of pixel detectors:

- **More sophisticated data processing on the pixel level**.
- **Application of tracking approach** for imaging provides very complex information about each event => requires very high data throughput and complex data processing.

Steady development in the field of sensors and readout is required.

Thanks for your attention