Institute of Experimental and Applied Physics
Czech Technical University in Prague

Future Directions of Pixel Detectors and their Applications in Life Sciences

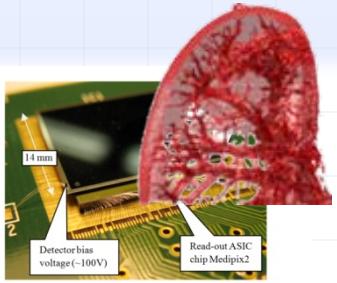
Jan Jakůbek

Institute of Experimental and Applied Physics, Czech Technical University in Prague

Outline

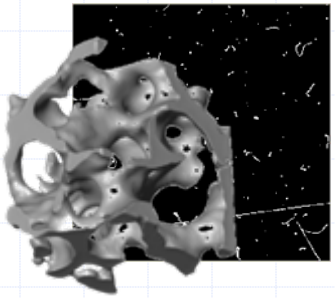
Introduction

- Radiation imaging
- Imaging pixel detectors (particle counting) – *Pilatus, Medipix2 and Timepix*



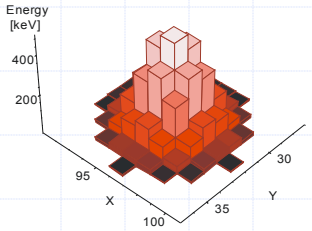
Applications of pixel technology - Imaging

- Life sciences
- And some others ...



Problems of current devices

- Charge sharing deteriorates spectrometric performance
- Dead-time between exposures



Future directions (with respect to applications)

- Higher complexity of pixel cells – more functionality (*Medipix3 concept*)
- Separate event by event processing – tracking (*Timepix2 concept*)

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

Imaging detectors of radiation
(for radiography)

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Film emulsions	**Charge integrating devices**	**Single particle (counting) pixel detectors**
change of chemical or physical properties after interaction with radiation. Needs special treatment (developing process, scanning, …).	Ionizing radiation creates charge which is collected and integrated in pixels (CCDs, CMOS sensors, Flat panels, …)	Ionizing radiation creates charge which is compared with threshold and registered digitally in pixels
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 +
Nonlinear response Limited dynamic range Needs processing -	Dark current Noise Limited dynamic range -	? -

Particle counting pixel detectors

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Pilatus - PSI

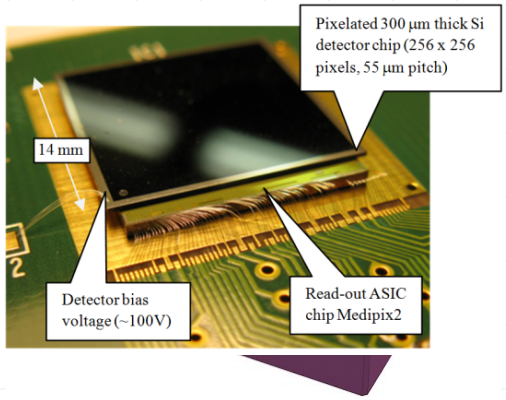
- 60 x 97 pixels
- Pitch of 172 um
- Counter: 20 bits
- Single threshold
- Module 16 chips
- Large area - tilling

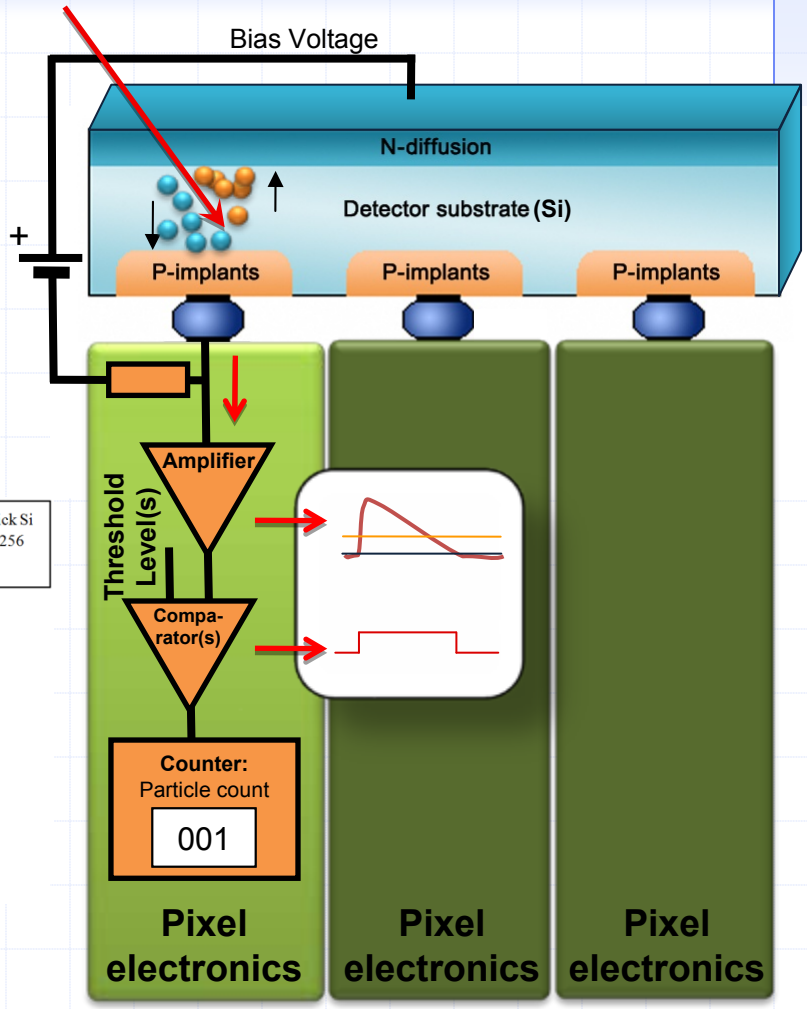
Medipix2 – CERN

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

Timepix - CERN

- Time stamp
- ToT mode

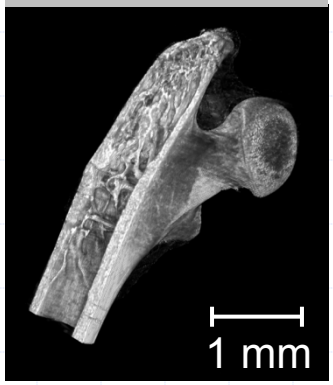




Institute of Experimental and Applied Physics
Czech Technical University in Prague

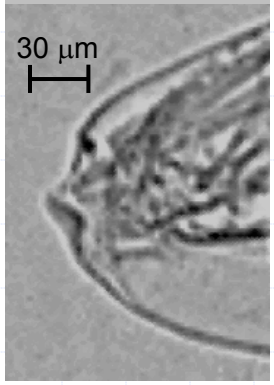
Applications:

X-rays: intensity

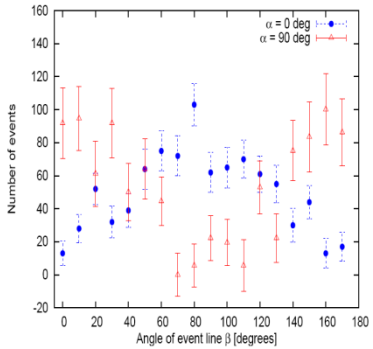


X-rays: energy

X-rays: phase

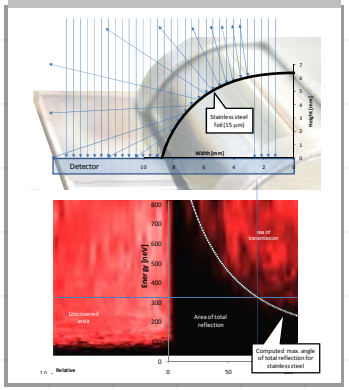


X-rays: polarization



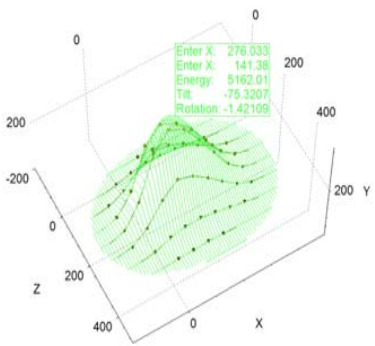
Neutrons: intensity

Neutrons: energy



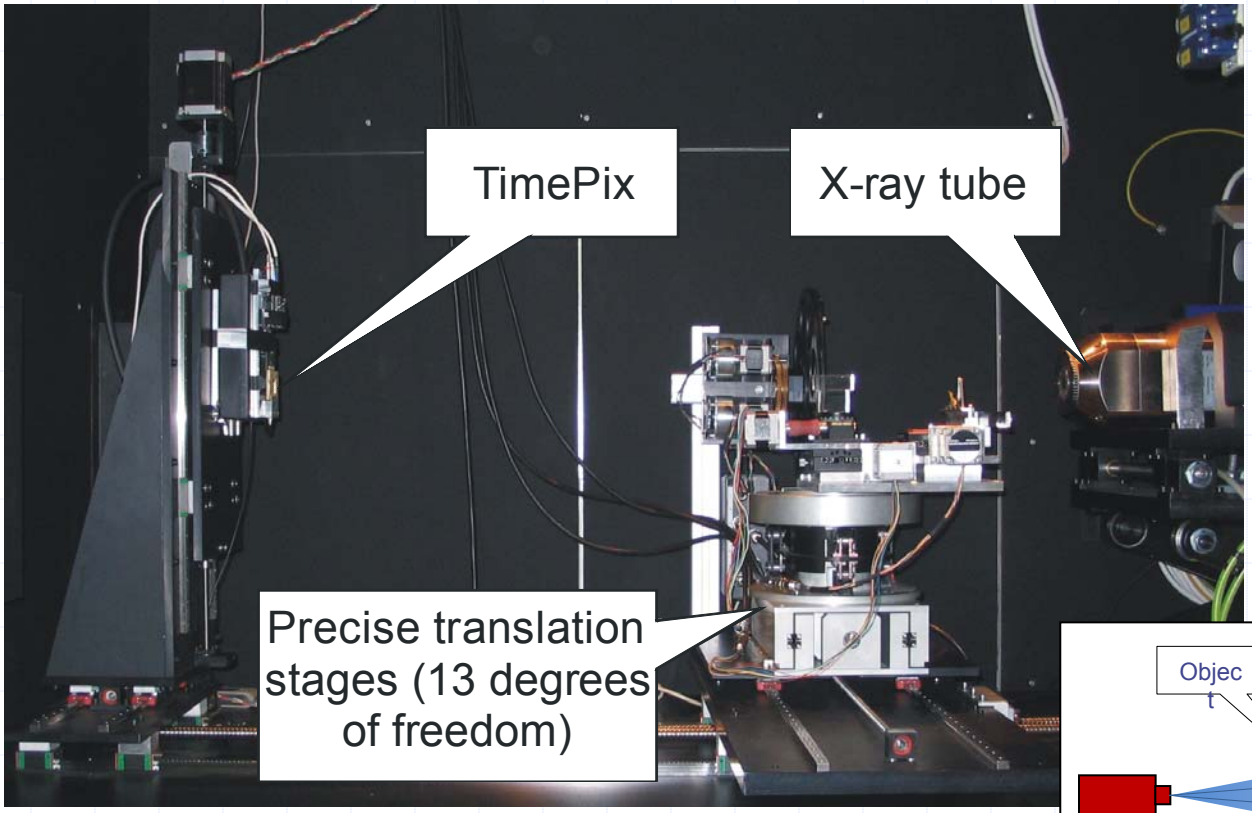
Ions: energy

Ions: direction

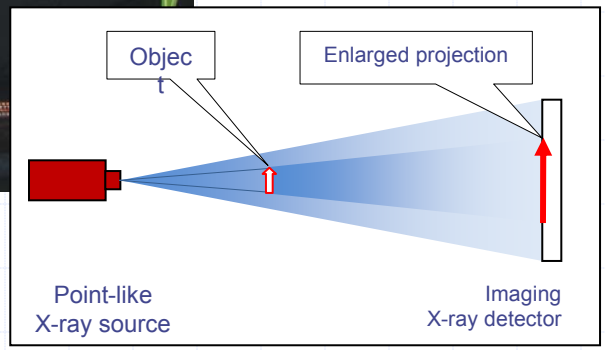


High resolution X-ray radiography:

Tabletop micro-radiographic system

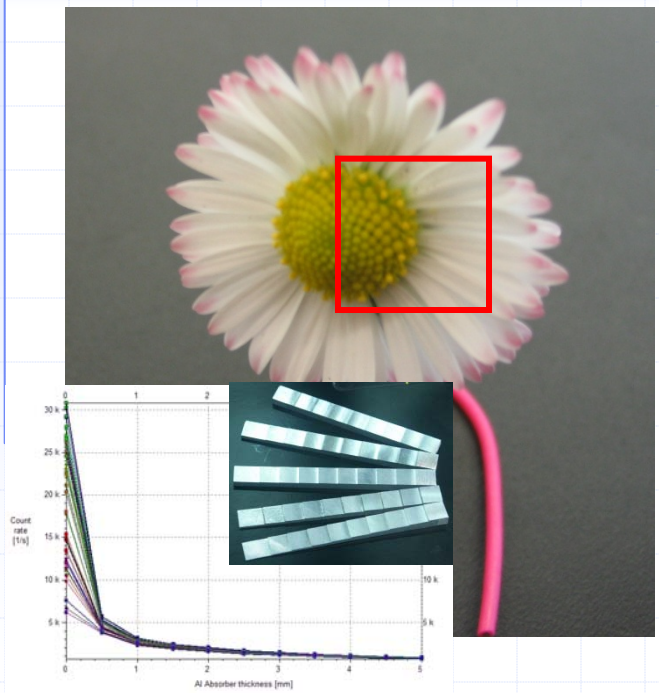


Features:
-Temperature and humidity control.
-Placed on independent floor to reduce vibrations
-Submicron spatial resolution (~300 nm)



High resolution X-ray radiography:

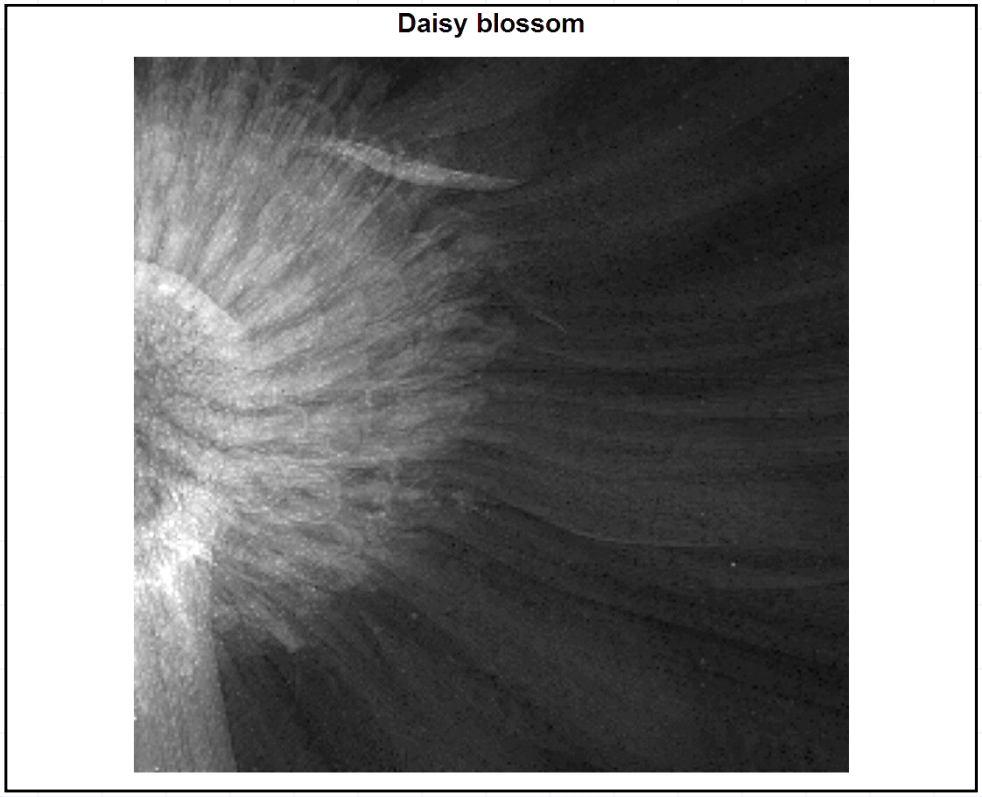
Detector response has to be known !!



- Polychromatic source is used
- Energy spectrum differs from point to point
- Dependence of efficiency on the energy has to be known for each pixel !!

Daisy blossom

(almost transparent for X-rays)



High contrast X-ray imaging:

Example: Living mouse

Example 1:

X-ray transmission

Single image of mouse head

(dose 0.9 mGy)

Single photon counting device can count unlimited number of photons, noise in images is given just by poissonian statistics:

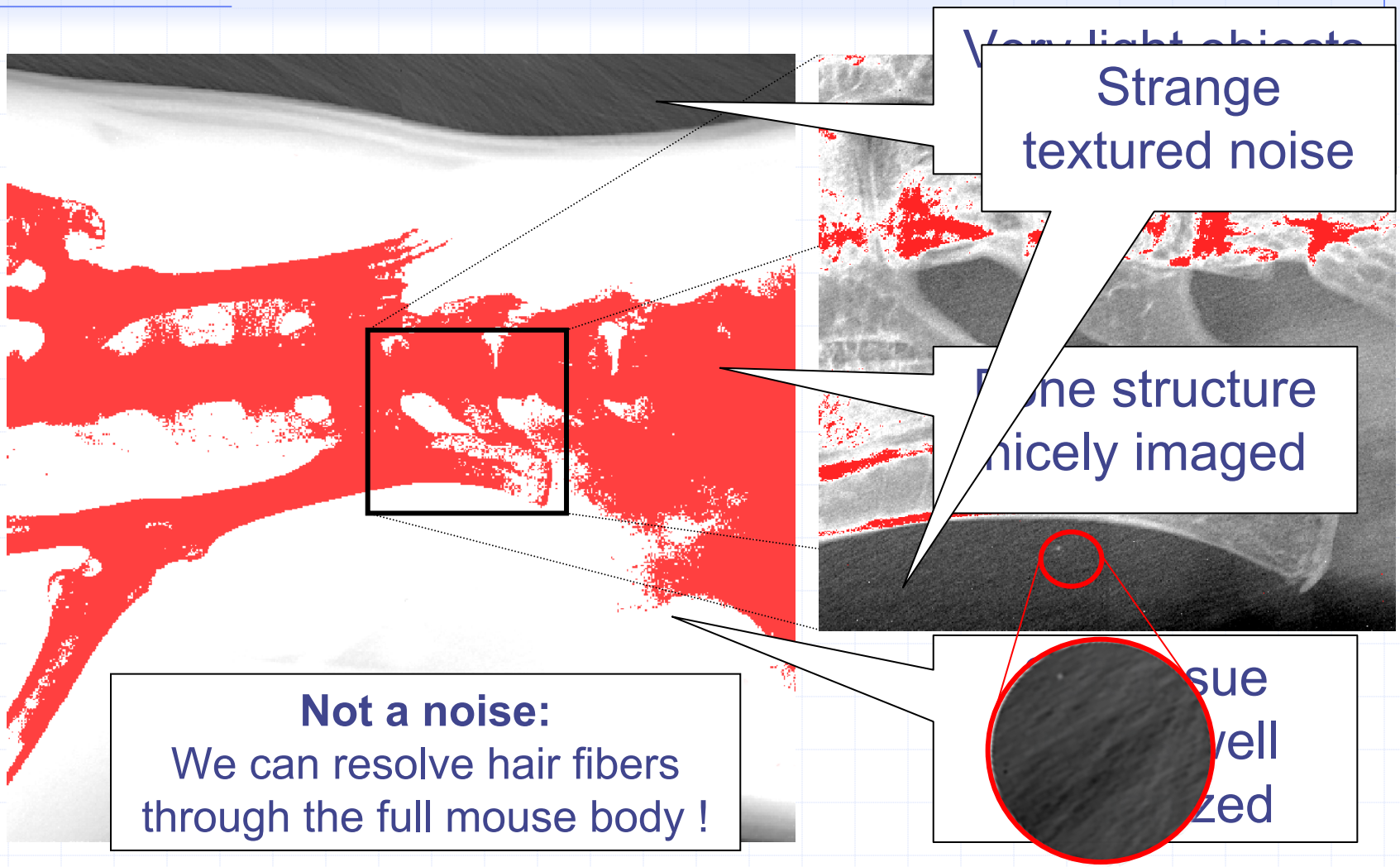
=> Unlimited number of gray levels in images depending just on the beam intensity and exposure time.

=> Almost unlimited contrast

High contrast X-ray imaging:

Example: Living mouse 2

Institute of Experimental and Applied Physics
Czech Technical University in Prague

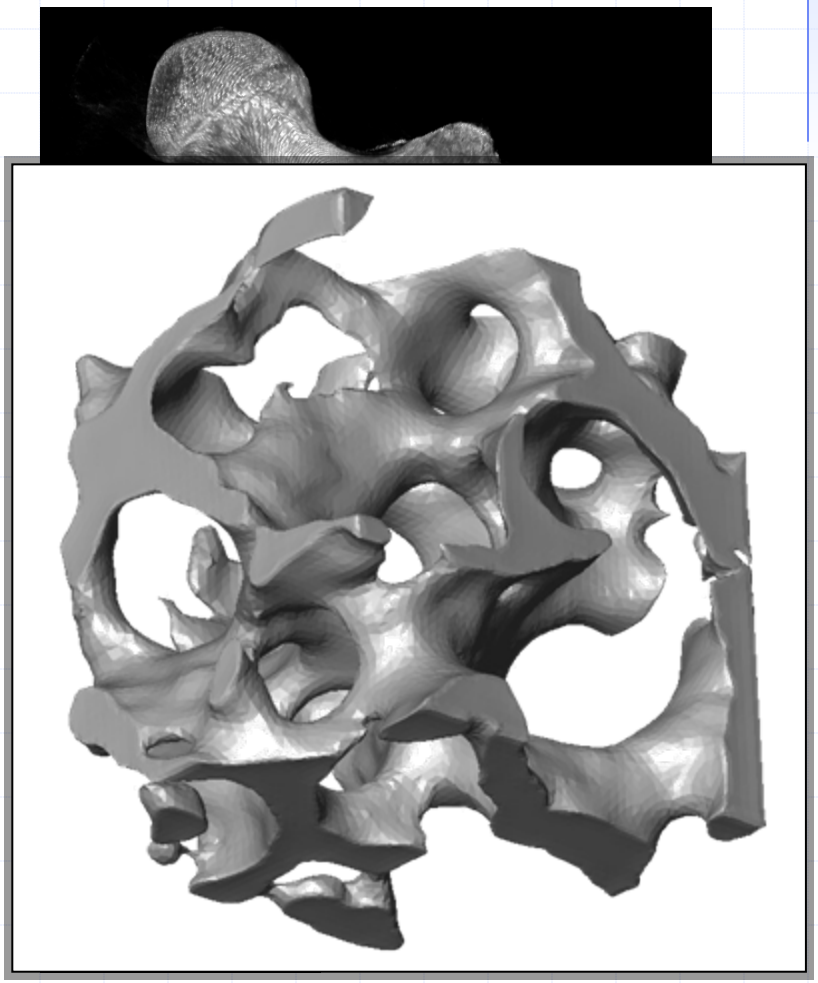


Not a noise:
We can resolve hair fibers through the full mouse body !

High resolution X-ray tomography:

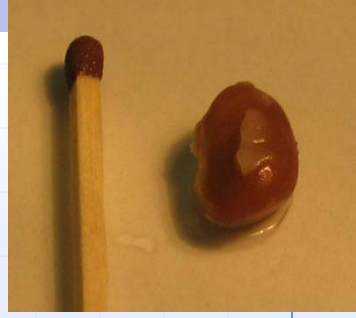
Mouse bone structure

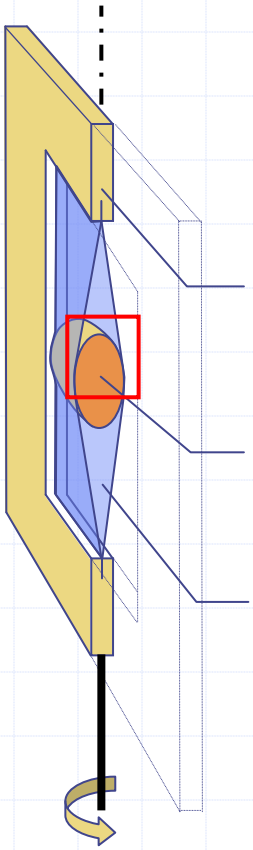
Institute of Experimental and Applied Physics
Czech Technical University in Prague



High contrast X-ray tomography:

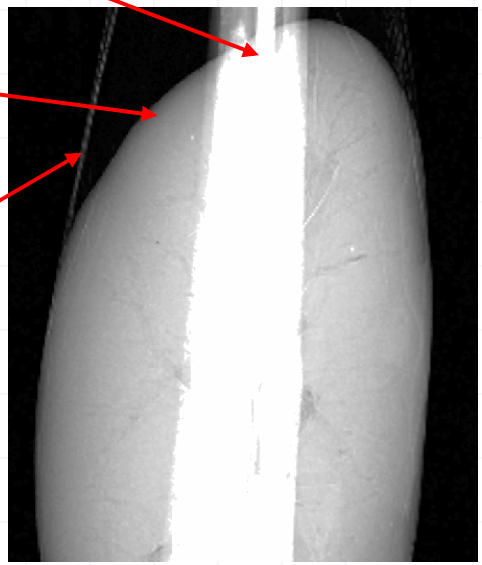
Mouse kidney

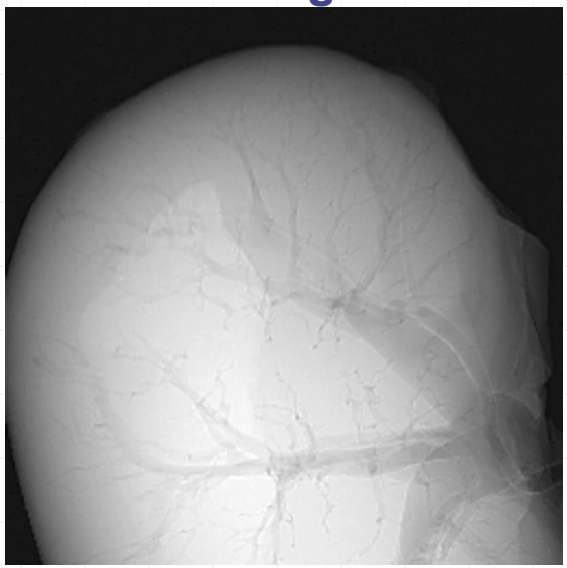




- 90 projections, 20 seconds each =>1800 s = 30 min => too much (drying causes significant changes)
- Drying avoided by placing object into the frame between two thin mylar foils.
- Projection of the holding frame overlaps the object for several angles => just 72 angles are usable.

No contrast agent used !

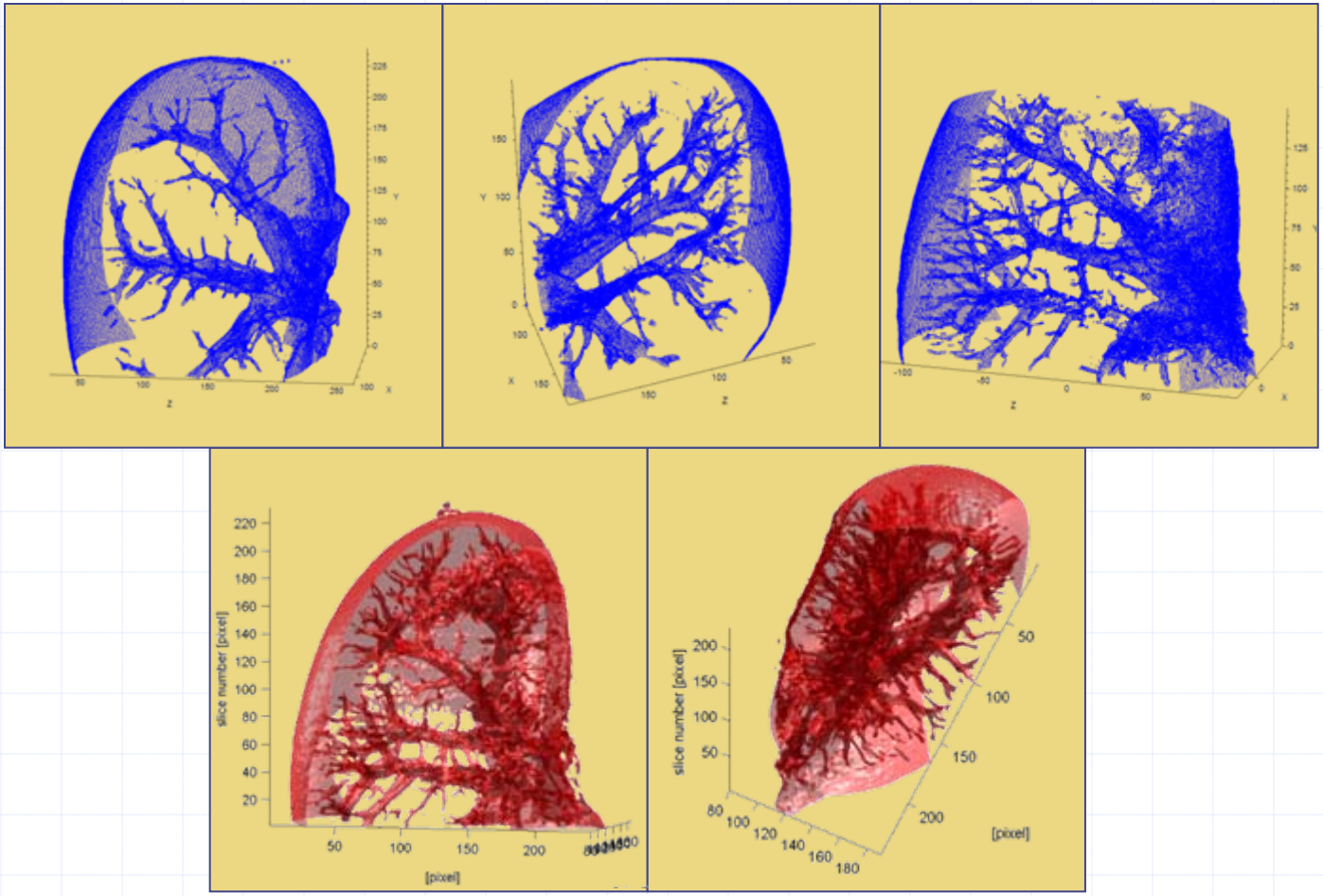




High contrast X-ray tomography:

Mouse kidney - result

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



Applications:

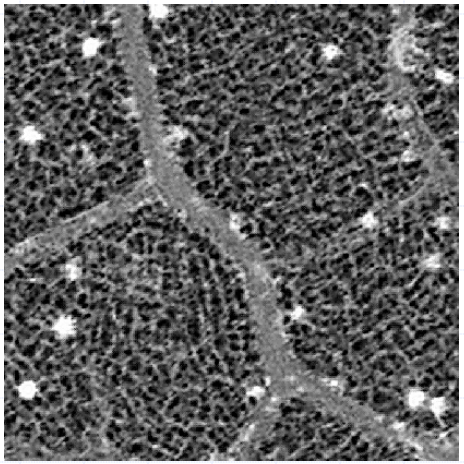
Biology: Leaf Miner story

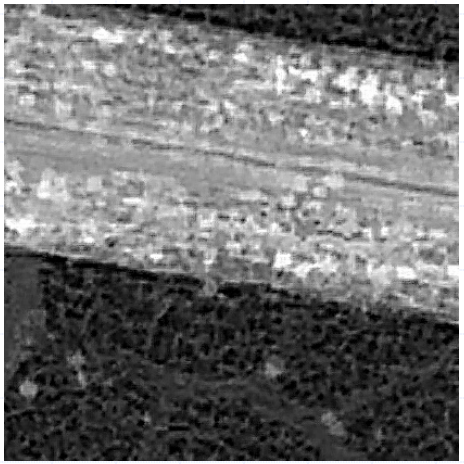
(skip)

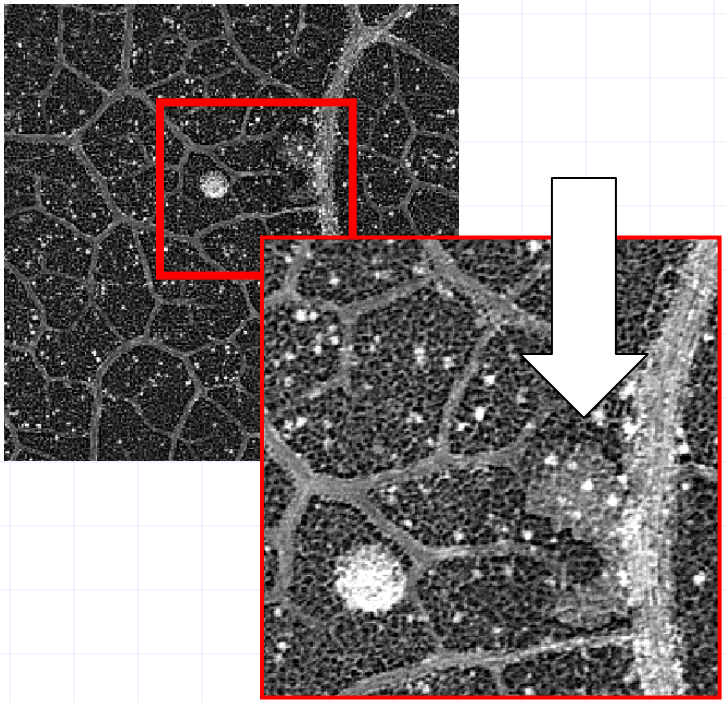
High resolution X-ray radiography:

Example: Leaf Miner story

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





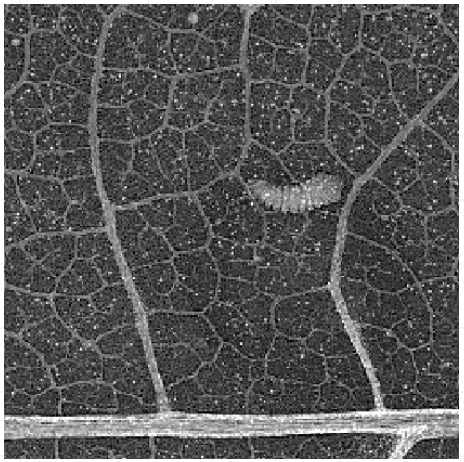


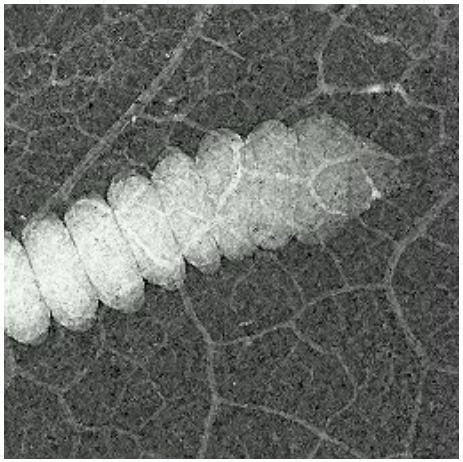
Healthy chestnut tree leaf structure (no parasite) – cellular structure of leaf is nicely observed (resolution below 1 um). The white spots are small drops of resin secreted by the leaf.

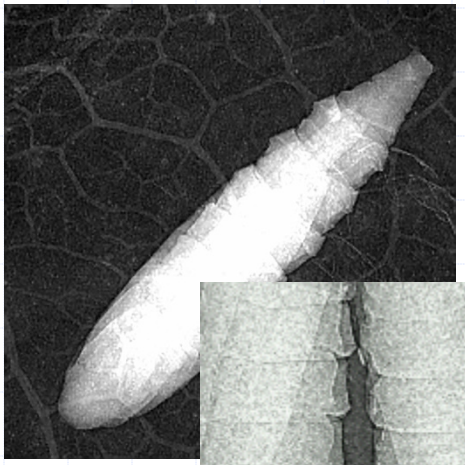
High resolution X-ray radiography:

Example: Leaf Miner story

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







Several collected pupas

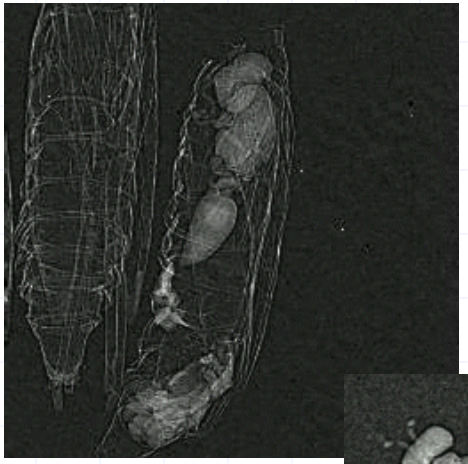
High resolution X-ray radiography:

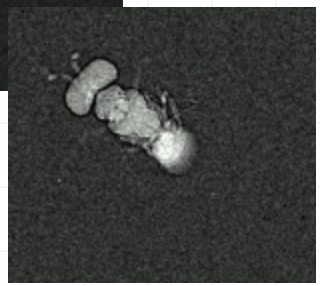
Example: Leaf Miner story - Cure

The best cure: natural enemy (parasitic wasp)

Certain small wasps can put eggs into leaf miner pupas

Parasite inside of parasite:





Parasite kills the pupa and leaves it as adult wasp

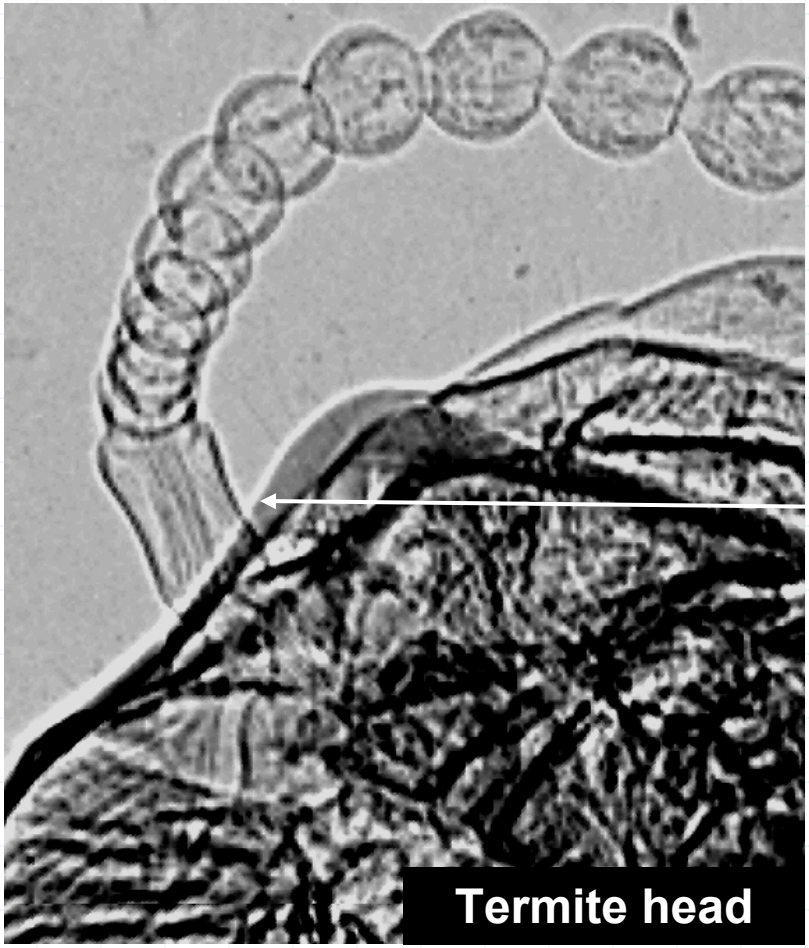
Applications:

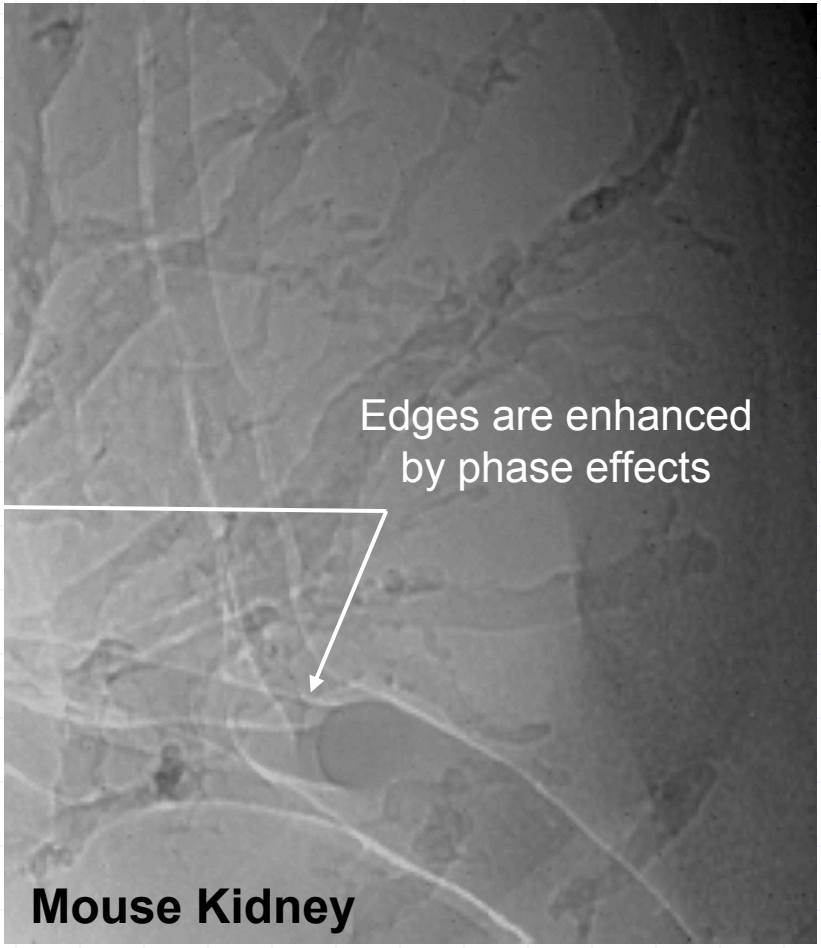
Phase contrast imaging

(skip)

X-ray phase contrast imaging:

Edges are enhanced in radiograms



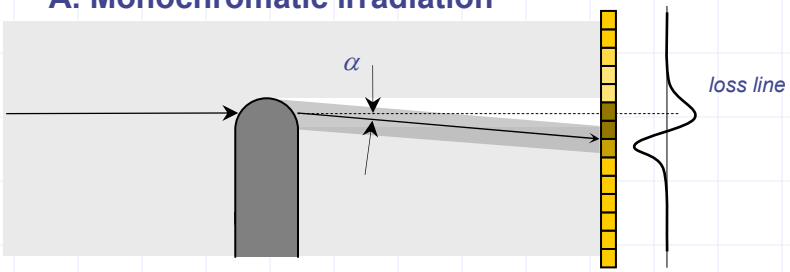


Physical applications:

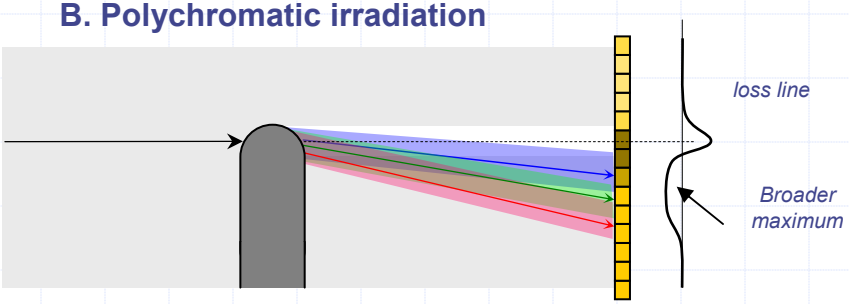
Phase contrast imaging

- Changes of X–ray wave passing a sample are described by the **complex index of refraction** $\mathbf{n = 1 - \delta - i\,\beta}$
- The **phase term** δ contains refractive effects (causing **phase shift** φ). Material inhomogeneities in the object produce changes in the **phase** δ.
- **Phase contrast** imaging: $\delta \sim 1/E_\gamma^2$
- Absoption imaging: $\beta \sim 1/E_\gamma^4$
- For X–rays in light elements, δ can become orders of magnitude greater than the absorption term β. Thus, **phase contrast** can be observed while absorption contrast may be negligible.

A. Monochromatic irradiation



B. Polychromatic irradiation



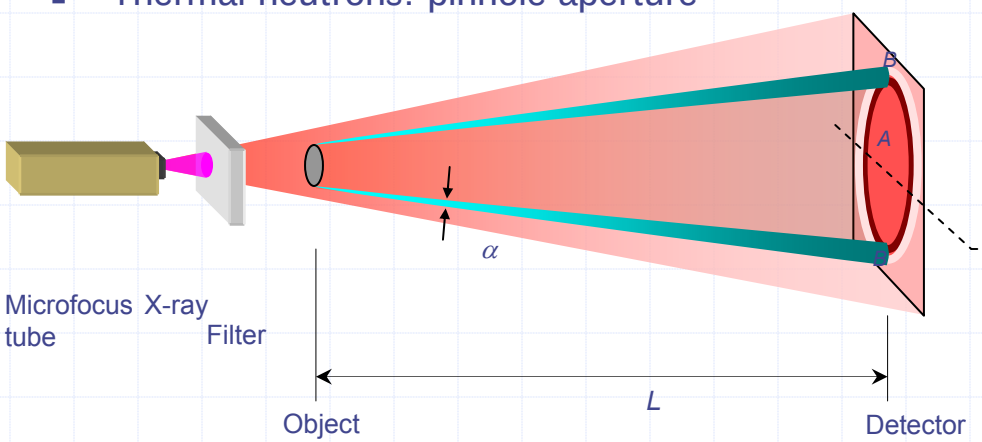
Physical applications:

In-line Phase Contrast Imaging

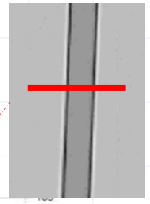
Institute of Experimental and Applied Physics
Czech Technical University in Prague

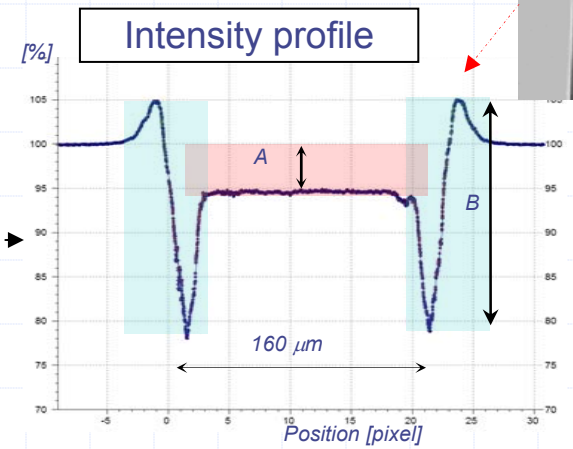
Spatial coherence ensured by small size of radiation source (point source):

- X-ray: Microfocus X-ray tube
- Thermal neutrons: pinhole aperture

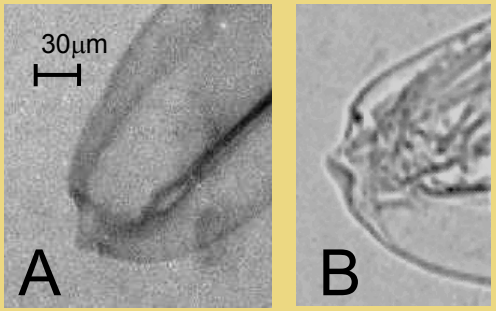


160μm PE strip





Termite knee



Microfocus X-ray tube:

- **A) Absorption** (contact geometry) image taken by CCD camera with scintillator.
- **B) Phase enhanced** image taken by Medipix2 at distance of 60cm revealing fine internal structure

In-line phase enhanced imaging with **microfocus** X-ray tube. In the intensity profile it can be seen that signal caused by phase shift (B) is significantly larger than signal caused by intensity attenuation (A). Intensity profile was measured with a 1mm thick and 160μm wide PE foil and tungsten X-ray tube at 40kV, L=60cm.

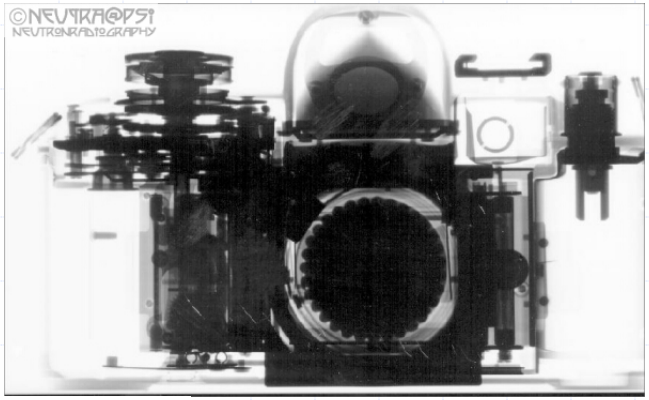
Applications:

Neutron transmission radiography

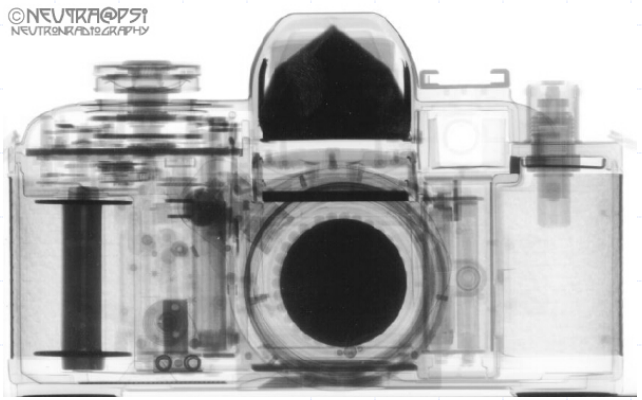
(skip)

Neutron Radiography

- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



X-rays



Neutrons

(courtesy NEUTRA facility at PSI)

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts.

CCD camera with scintillator filled by converter material

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Offers:
- Good efficiency
- Large field of view
- Digital output
  => OK for tomography

But:
- Low spatial resolution
- Dark current

=> Limited exposure time

=> Limited dynamic range

A flower was measured through a "wall of granite bricks" and shows a fascinating high contrast (compared to the stones) because of the strong attenuation of the involved hydrogen.

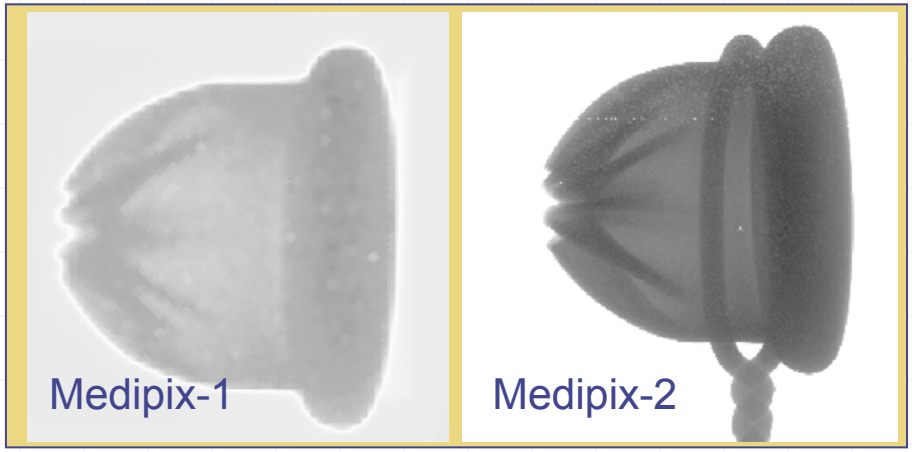
(courtesy NEUTRA facility at PSI)

Neutron radiography with Medipix coated by ^{6}LiF:

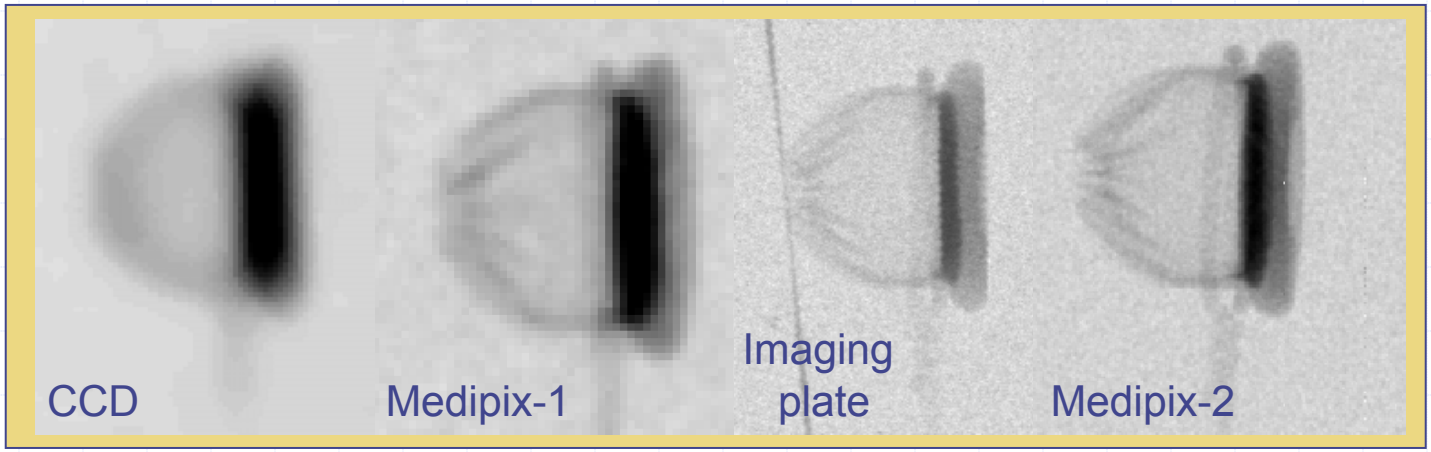
Samples: Blank cartridge

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Rentgenography



Neutronography

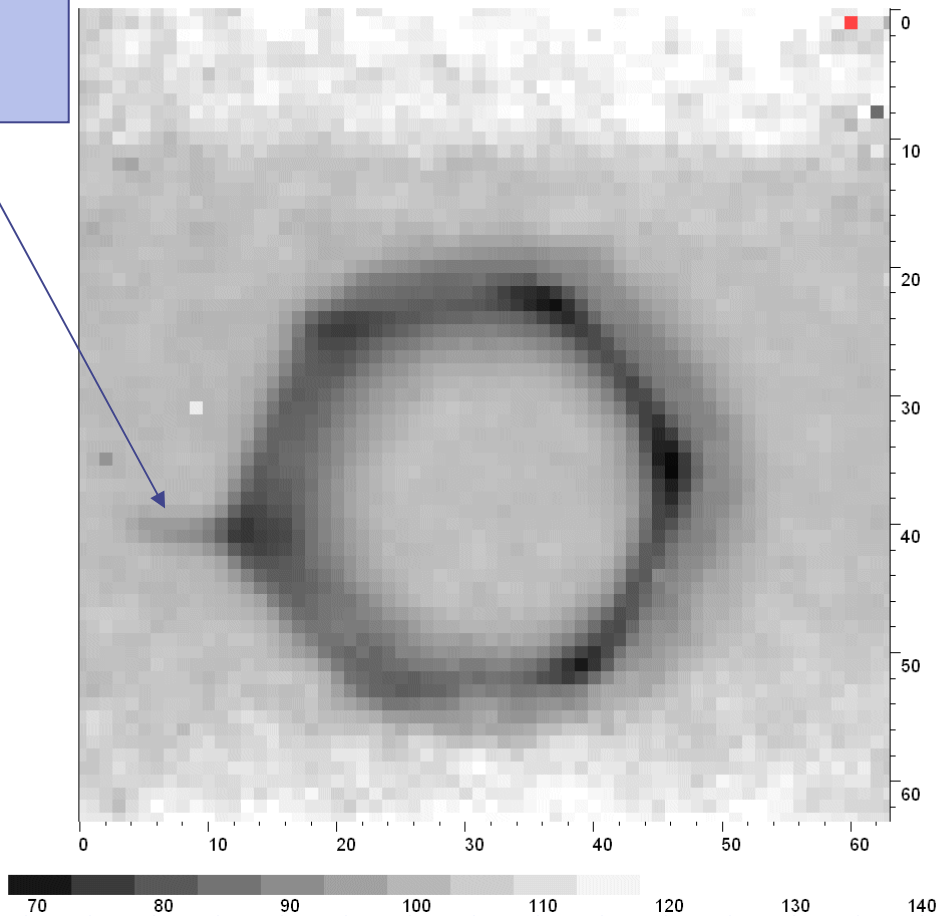


Neutron radiography with coated Medipix:

Samples: Glued Al pieces

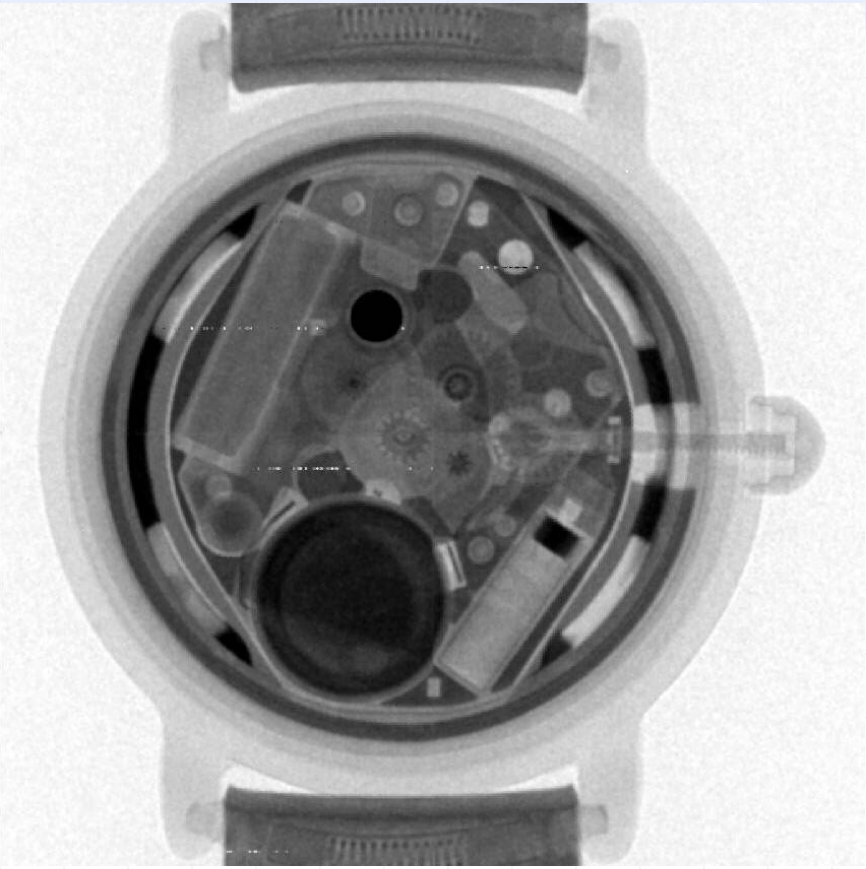
Institute of Experimental and Applied Physics
Czech Technical University in Prague

Glue raised through capillary attraction



Neutron radiography with coated Medipix2-Quad:

Wrist watch



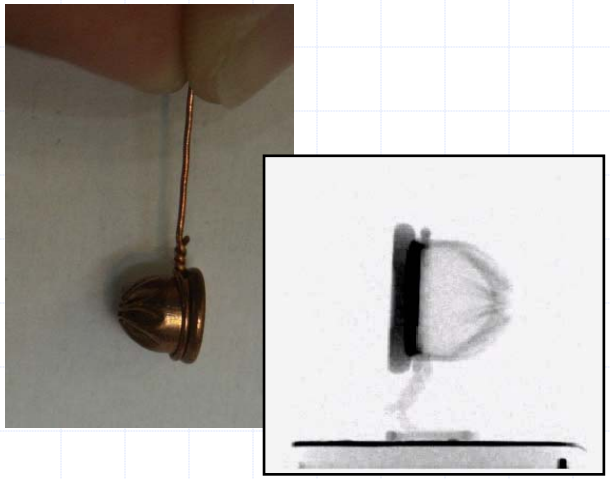
Metallic cover was fixed on watch in time of measurement !

Exposition time = 500 seconds

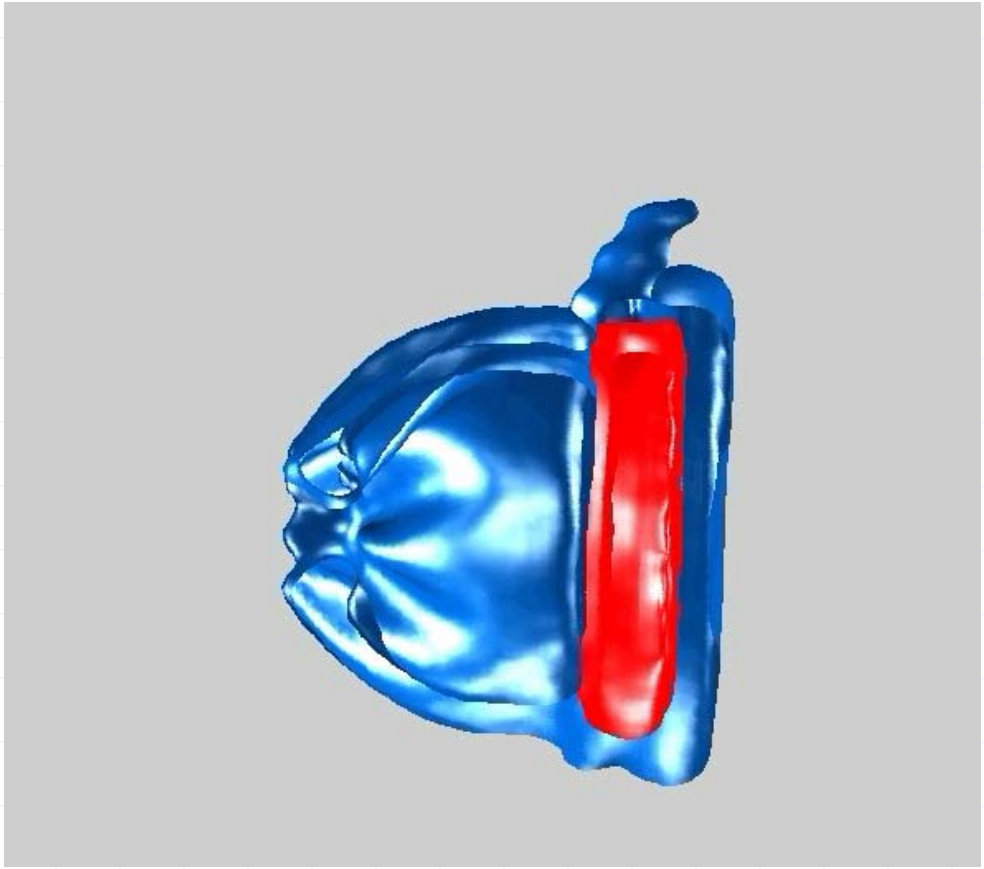
Neutron microtomography

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Blank cartridge
Explosive filling clearly visible



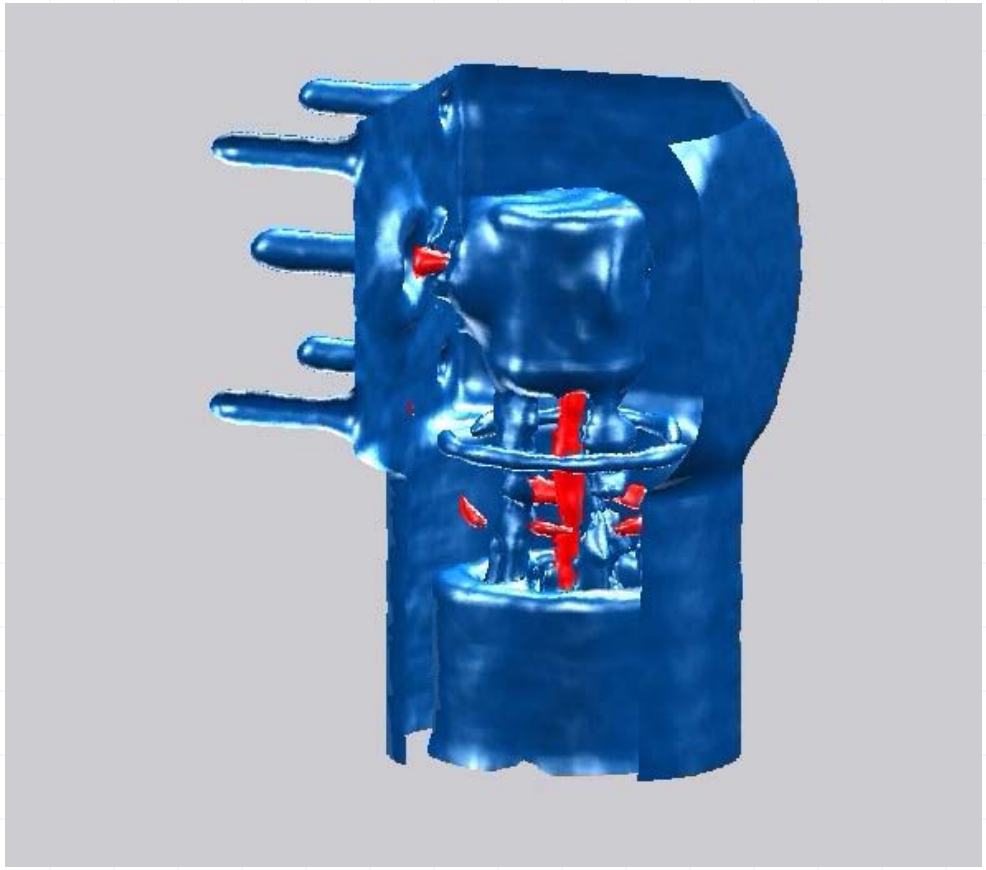
Taken 100 projections 150 seconds each. Reconstruction using filtered back-projection algorithm.



Neutron microtomography

Lemo connector
Golden contacts inside

Taken 100 projections
150 seconds each.
Reconstruction using filtered back-projection algorithm.



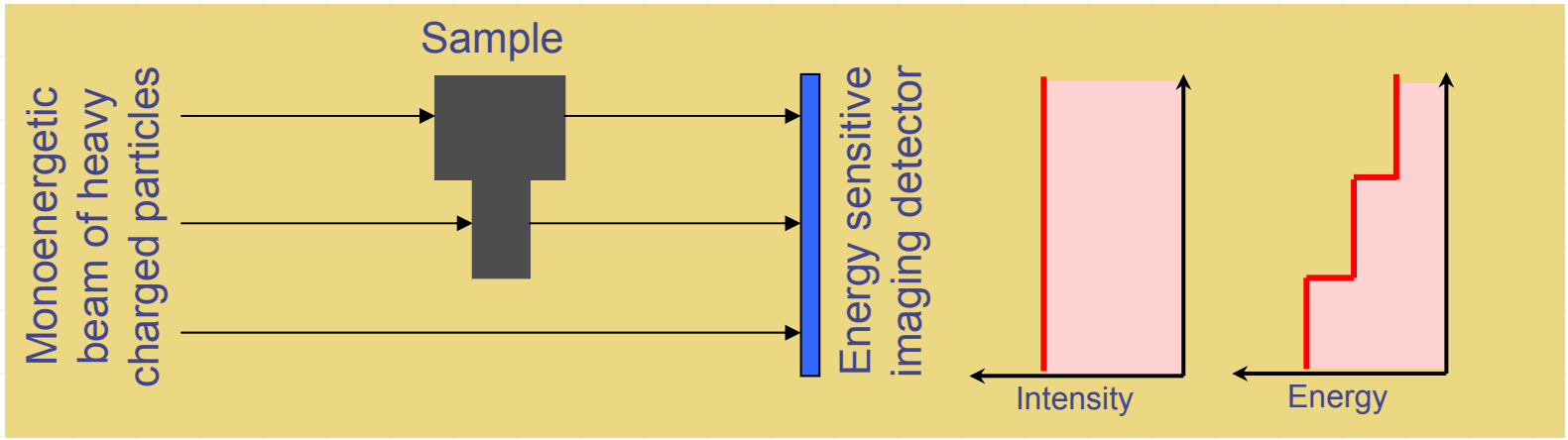
Applications:

Radiography with highly ionizing particles

(skip)

Application:

Radiography with highly ionizing particles



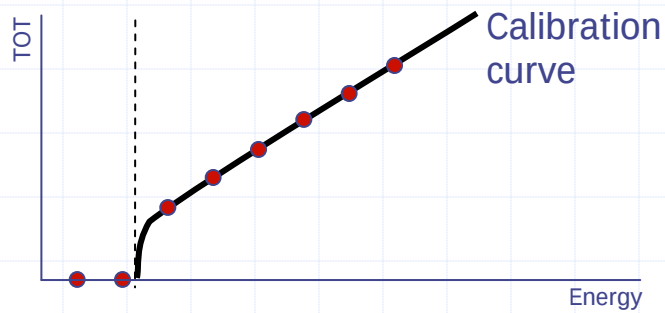
- **Heavy charged particles** (protons, deuterons, tritons, alphas, ions) can be used (impossible with photons, difficult with electrons due to huge change of direction).
- Instead of transmitted beam intensity the **energy losses** of individual particles are measured.
- Just single particle is needed to measure material “density”.
- With common sources of heavy charged particles (isotopes, ion beams) it is feasible to inspect just small (thin) objects (thin layer, foils, cellular structures)
- **Precision of thickness measurement can be in nanometer scale**.

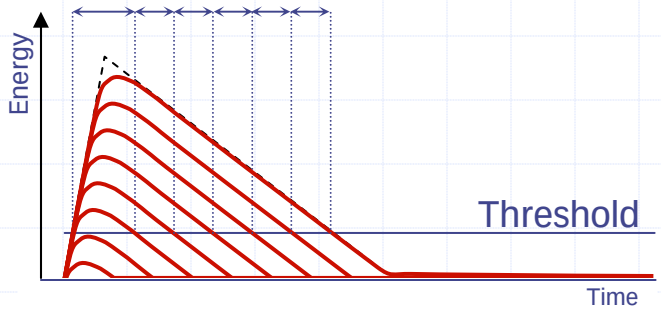
Need of per pixel energy measurement:
TimePix and its TOT mode

Institute of Experimental and Applied Physics
Czech Technical University in Prague

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.





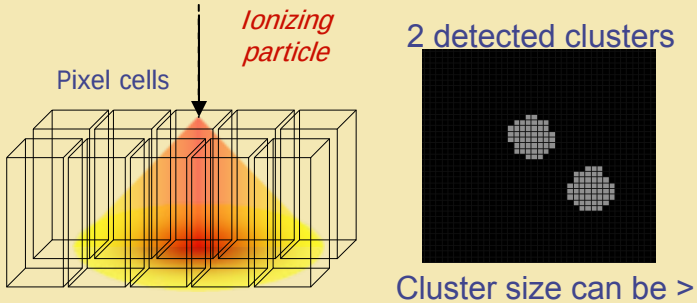
- If the pulse shape is triangular then Time over Threshold is proportional to collected charge i.e. to energy.
- Due to limited bandwidth the pulse can be NEVER perfectly triangular.
- Non-linear TOT to energy dependence

Jan Jakůbek

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

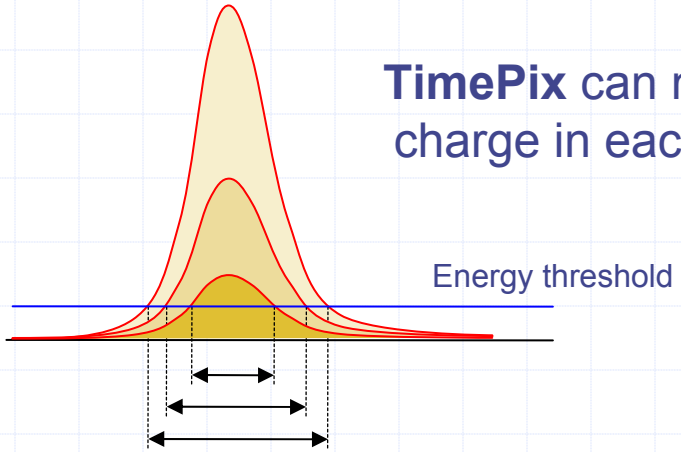
Ionizing particle can creates huge charge signal in several adjacent pixels forming **cluster**.
Cluster volume depends on particle energy.



Cluster size can be >100

The Cluster size depends on:

- Particle Energy
- Depth of interaction
- Detector Dias Voltage



TimePix can measure charge in each pixel !

TOT mode calibration:

Why to calibrate?

If particle hits a border between pixels then:

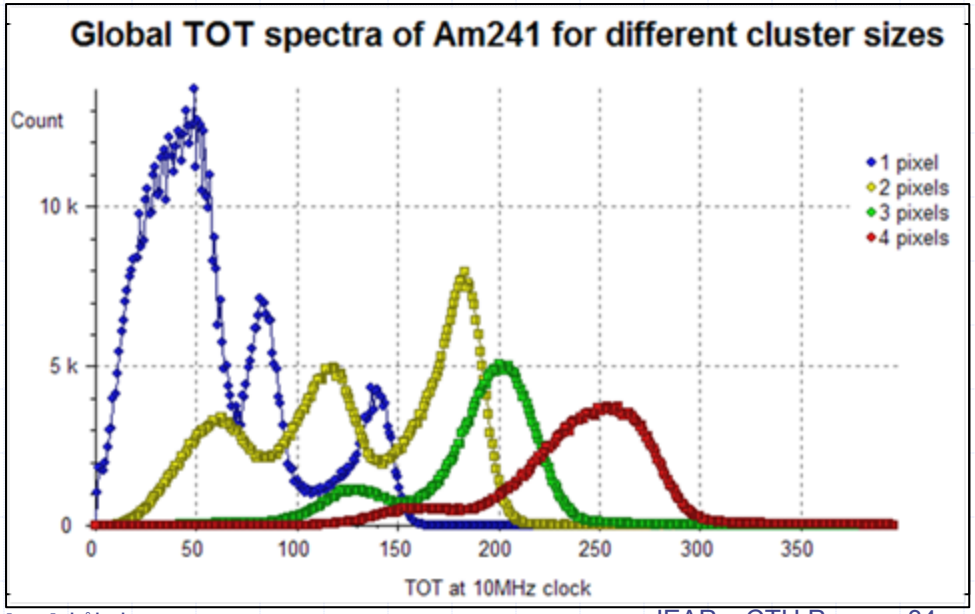
⇒ charge is collected by more than one pixel

⇒ to recover original charge it is possible to sum energies measured by all hit pixels (compute cluster volume)

Test without calibration:

^{241}Am: 59.5keV, 26.3keV

For 59,5keV are two and three pixel clusters more frequent then singles.



TOT mode calibration:

How to calibrate?

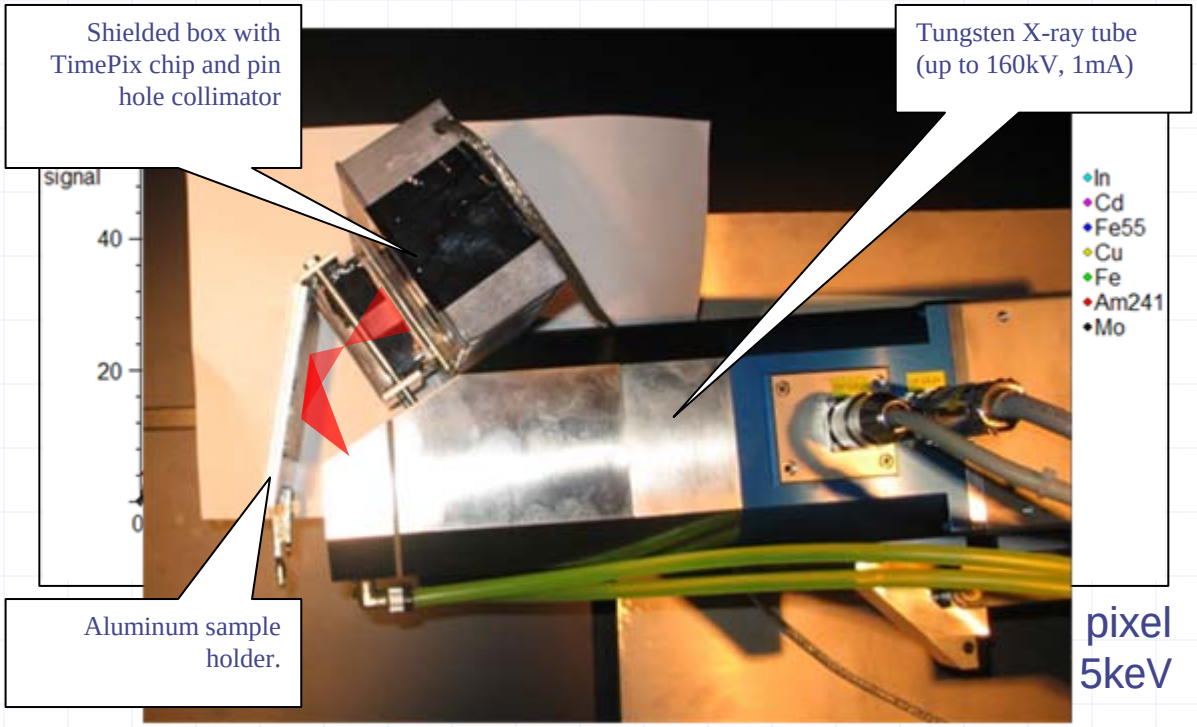
- Test pulse
- Gamma or X-ray sources taking into account just **single pixel clusters**.
  => charge leak to adjacent pixel is under threshold

Radioactive sources

^{55}Fe:	5.9	keV
^{241}Am:	59.5	keV

Fluorescence from

Fe:	6.4	keV
Cu:	8.0	keV
Zr:	15.8	keV
Mo:	17.5	keV
Cd:	23.2	keV
In:	24.2	keV



pixel
5keV

Jan Jakůbek

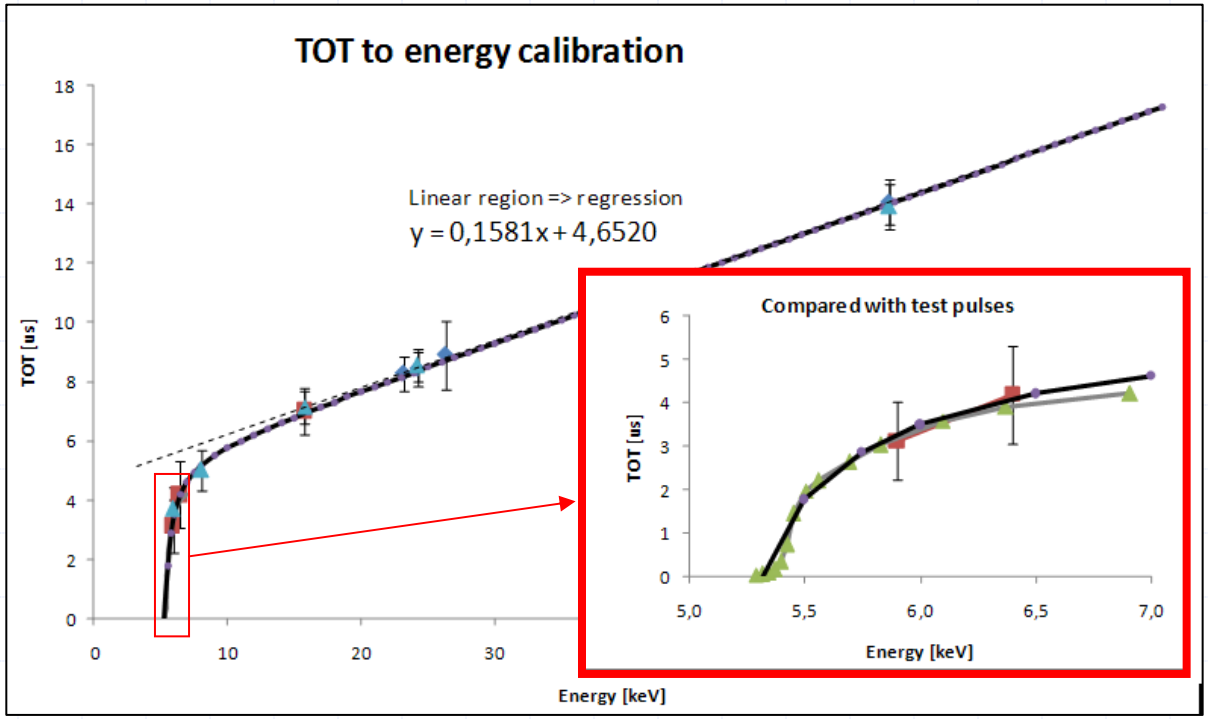
TOT mode calibration:

Surrogate calibration function

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

Meaning of parameters:

a,b – linear regression in high energy range
c – curvature (extent and symmetry)
t – threshold



Parameters computed Using global calibration data:

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

Jan Jakůbek

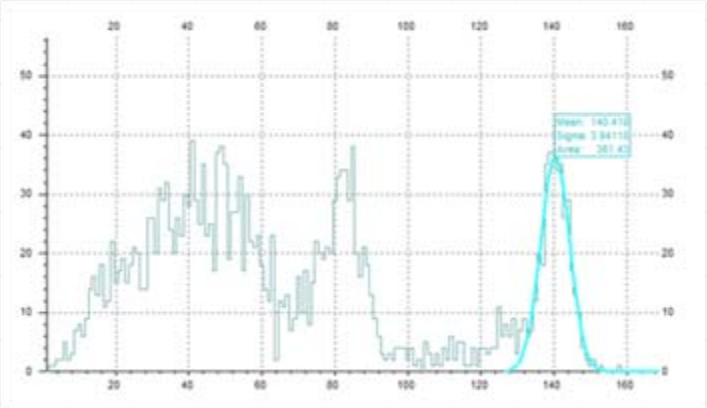
TOT mode calibration:

Per pixel calibration

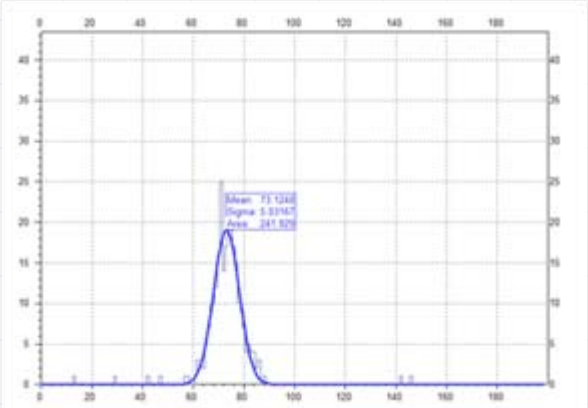
Institute of Experimental and Applied Physics
Czech Technical University in Prague

- 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.

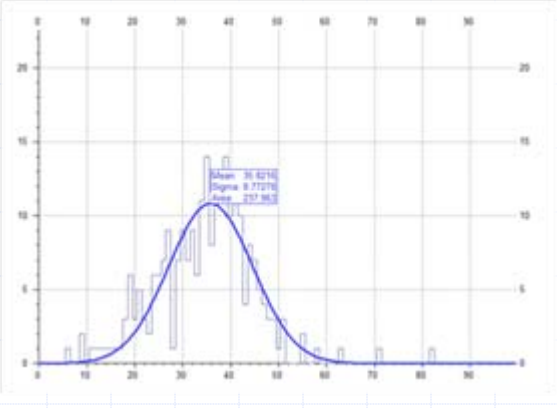
Am241 (59.5keV):



Zr (15.8keV):



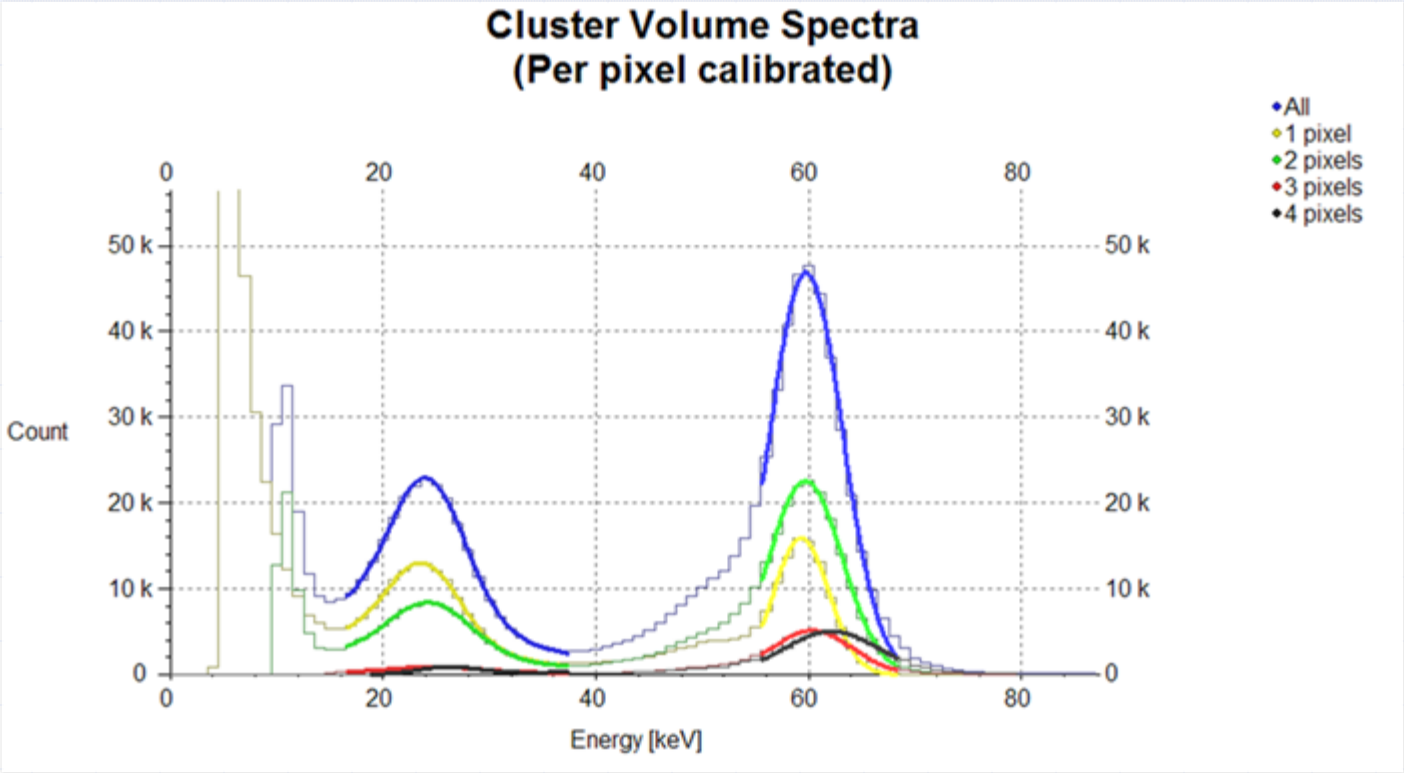
Fe55 (5.9keV):



Jan Jakůbek

TOT mode calibration:

Tests with per pixel calibrated TimePix



^{241}**Am**: 59.5keV peak sigma = 3.3keV

Jan Jakůbek

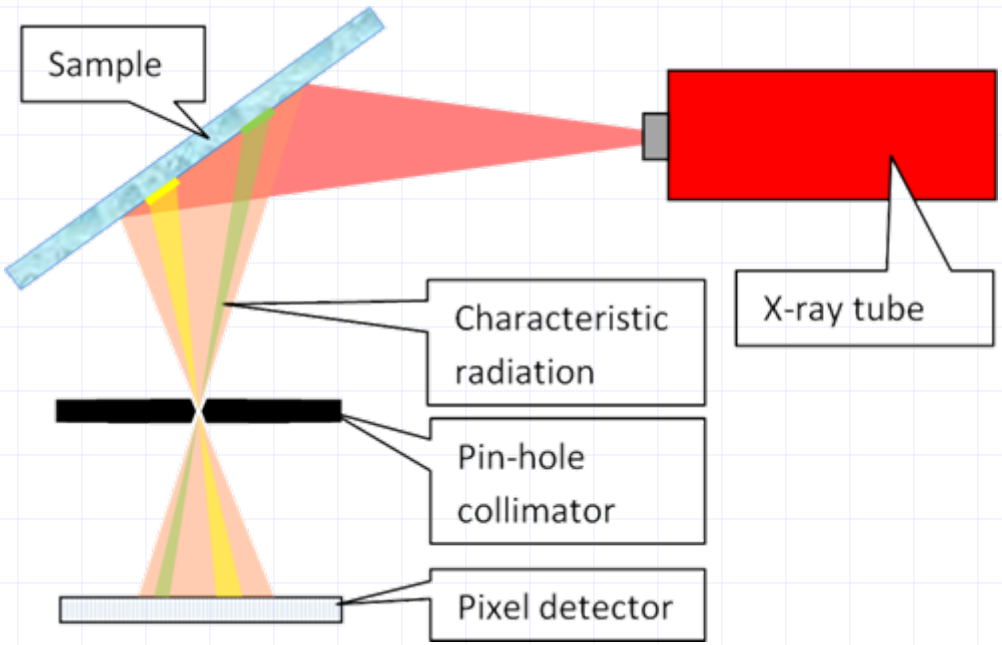
Small digression

XRF Imaging ...

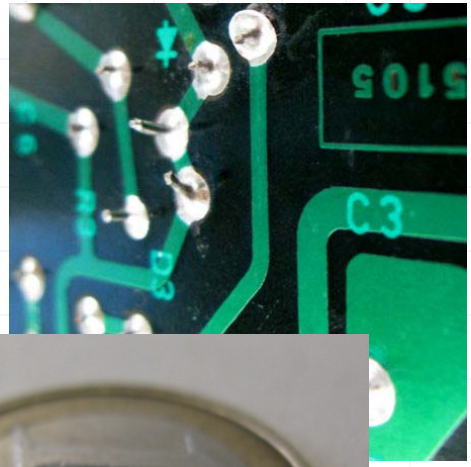
... event by event processing

X-ray fluorescence imaging ?

Experimental setup and samples



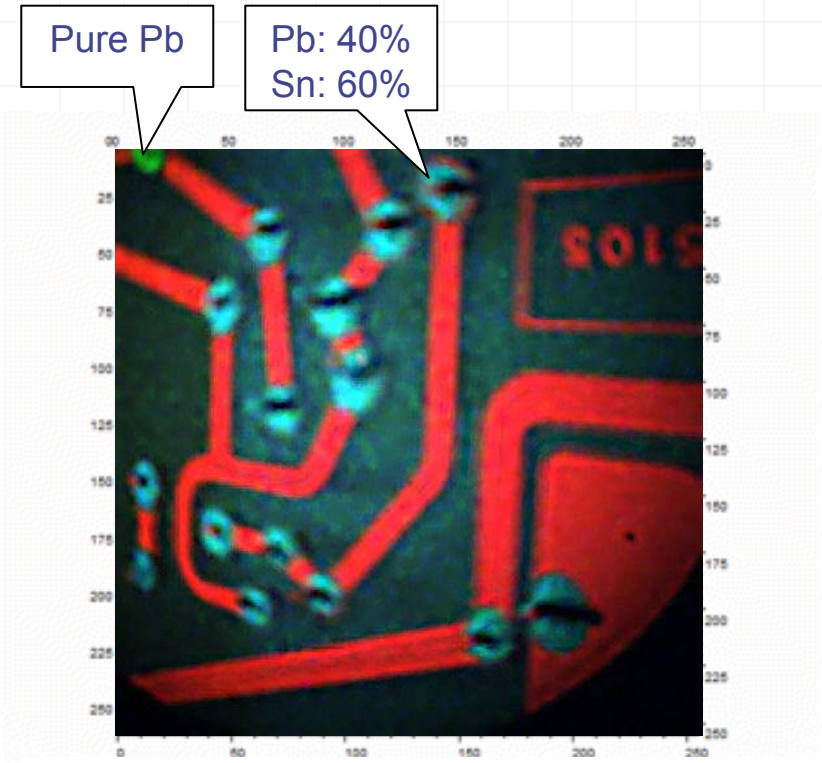
Piece of PCB



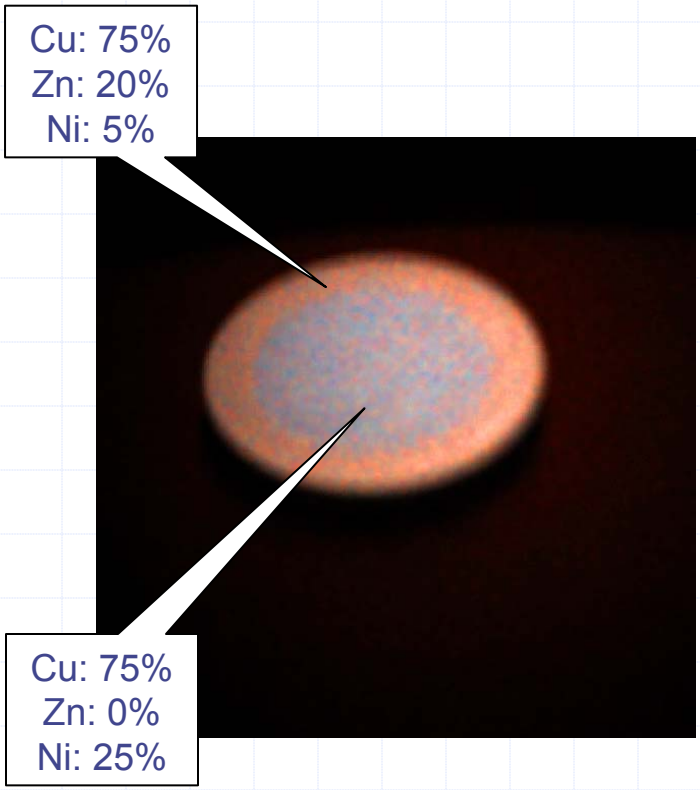
One Euro coin

X-ray fluorescence imaging:

Results



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



Color coding:
Zn content is displayed in Pink

Another digression

Energy sensitive X-ray transmission imaging with TimePix device ...

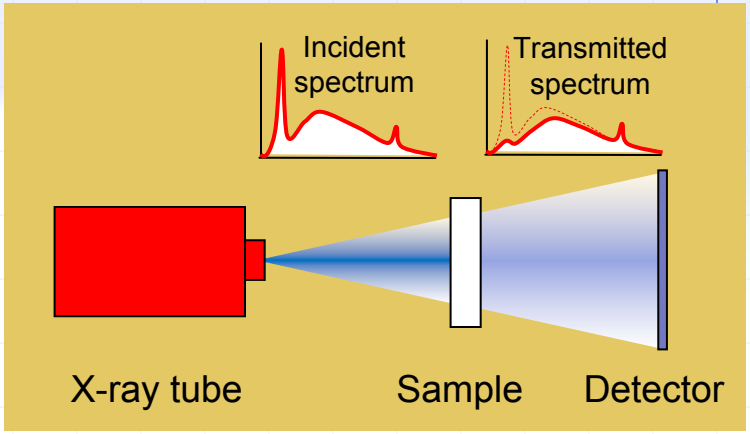
... event by event processing

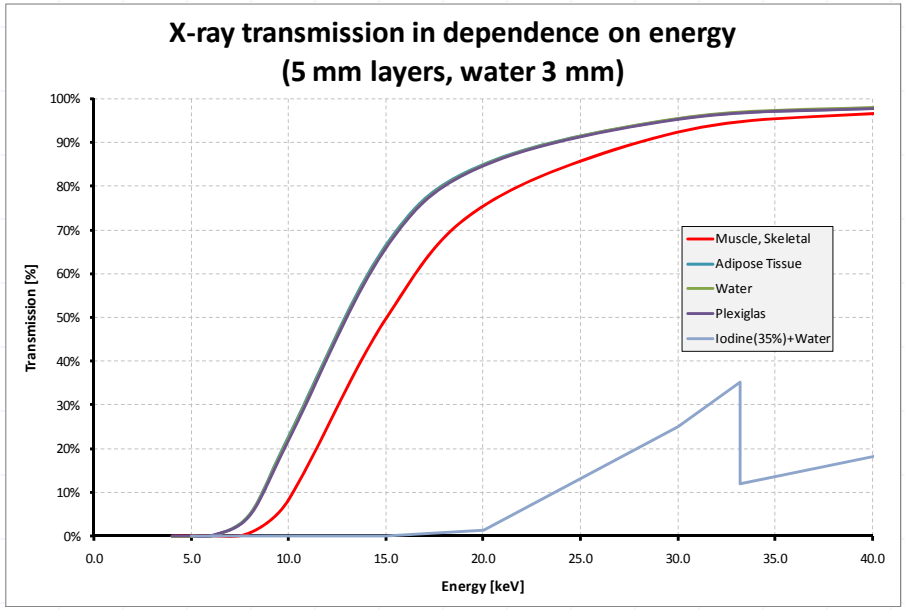
Institute of Experimental and Applied Physics
Czech Technical University in Prague

X-ray transmission radiography:

Material recognition

- Energy dependence of X-ray absorption is given by the material composition => 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**.

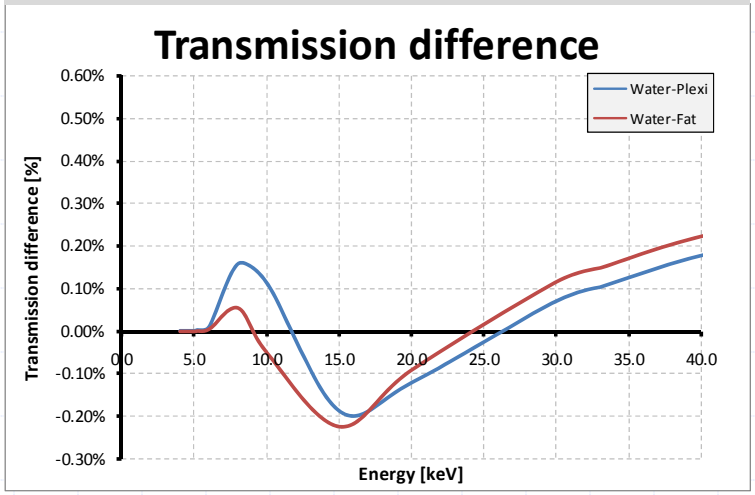




Thickness alternation:

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

Can we recognize them?

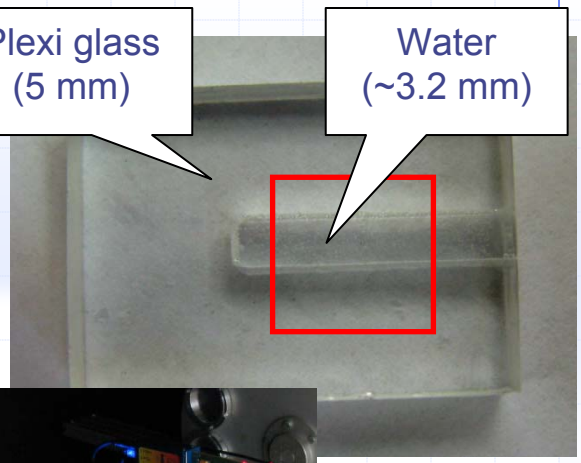


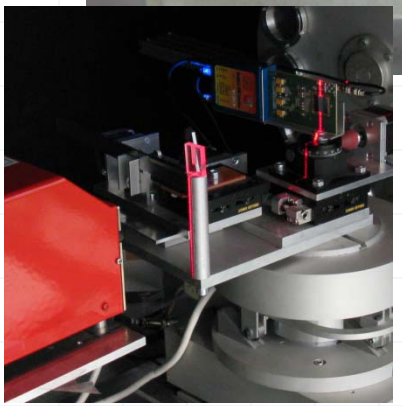
X-ray transmission radiography:

Soft tissue recognition

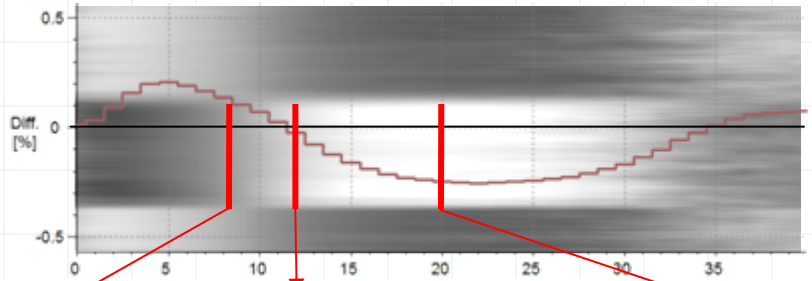
Institute of Experimental and Applied Physics
Czech Technical University in Prague

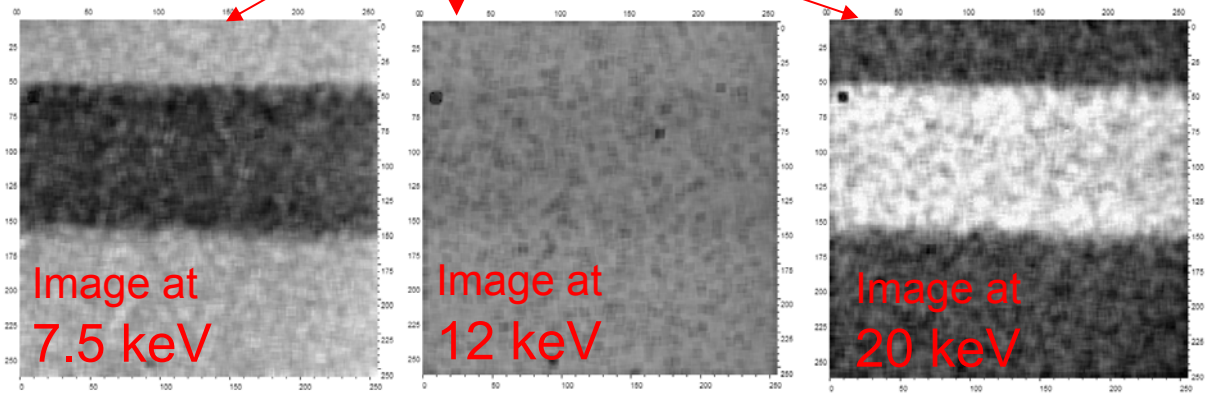
- Phantom sample made of Plexi glass and water
- Irradiated with tungsten X-ray tube at 40kV and just 2uA
- Integral intensity image shows very low contrast
- Per pixel transmission spectra recorded in each pixel (80000 frames a 1ms => 80 sec exposition

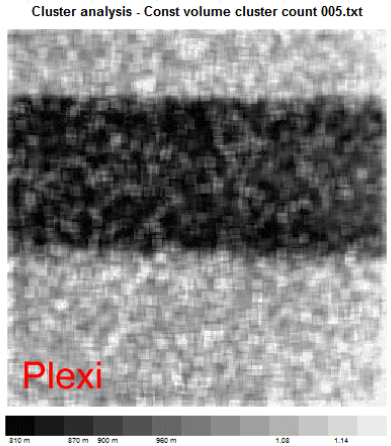




Measured transmission difference (normalized)







STOP !

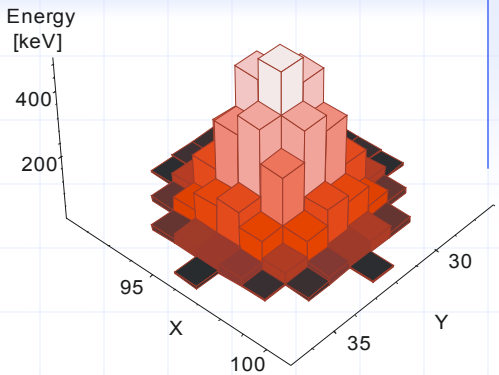
Let us return to heavy charged particles

(skip)

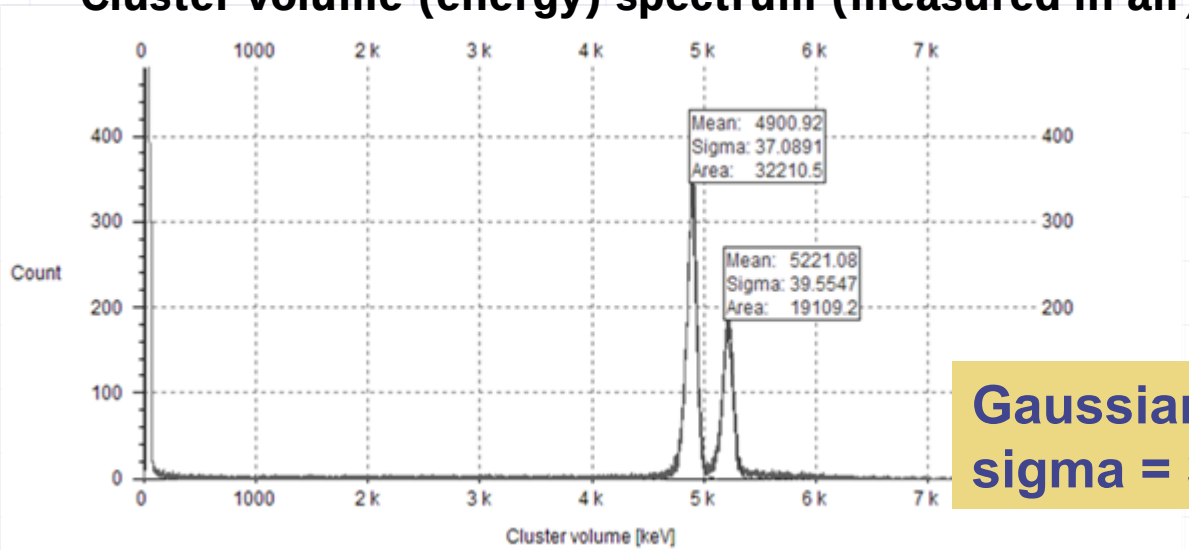
TOT mode calibration:

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)



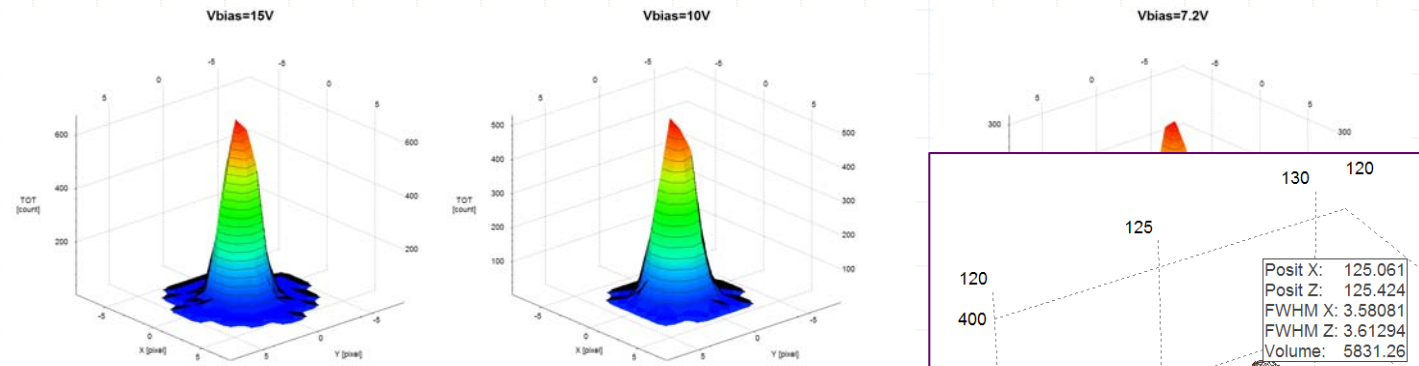
Gaussian fit sigma = 37 keV

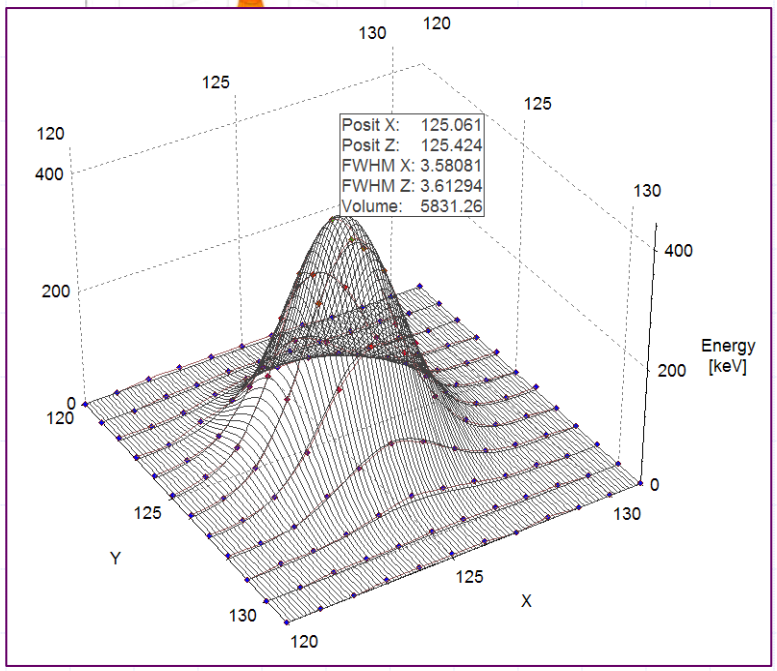
Jan Jakůbek

Heavy charged particles:

Subpixel resolution

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





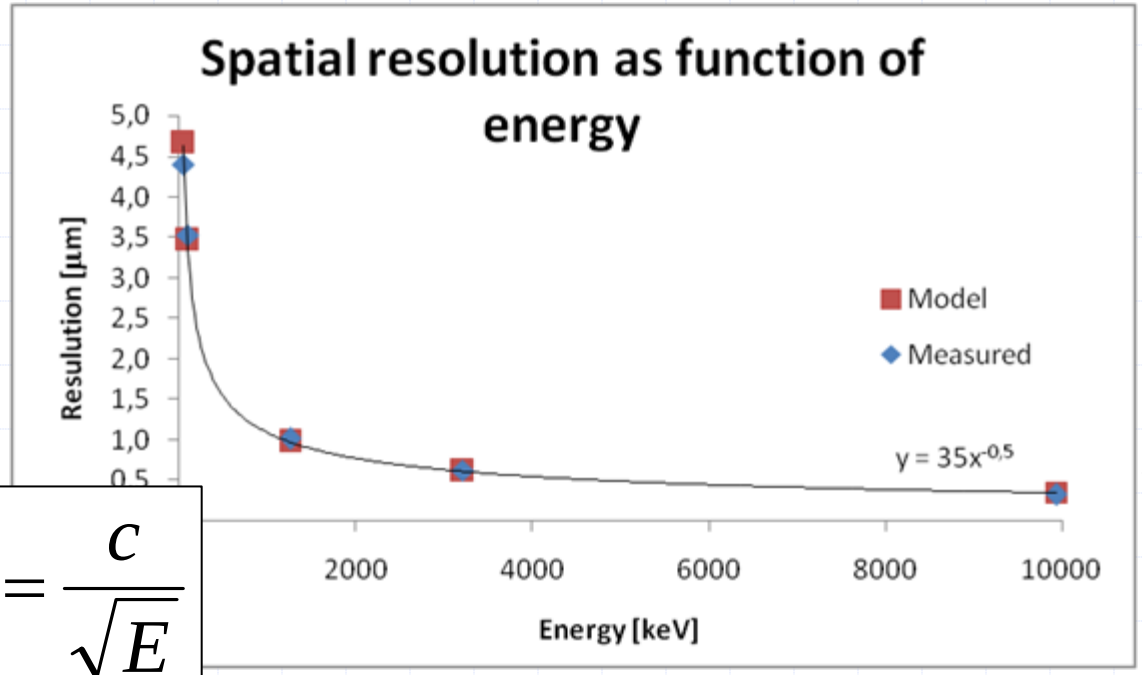
⇒ Subpixel resolution is be reached by Gaussian fit.

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

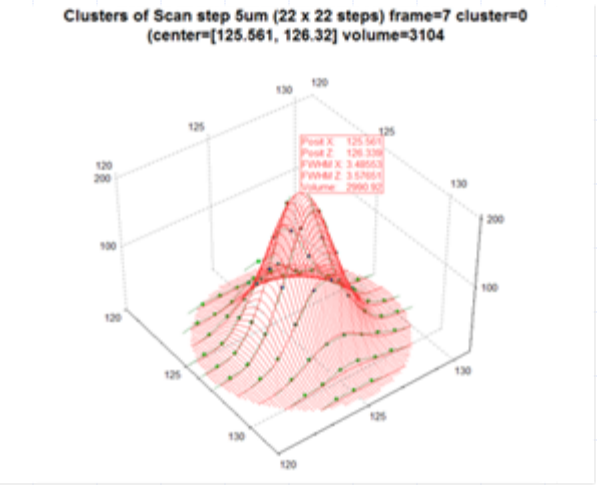
Spatial resolution determination:

Spatial resolution as a function of energy

- LASER test performed for different equivalent energies of 50keV, 120keV, 1.2MeV, 3.2MeV and 9.9MeV



$$r = \frac{c}{\sqrt{E}}$$

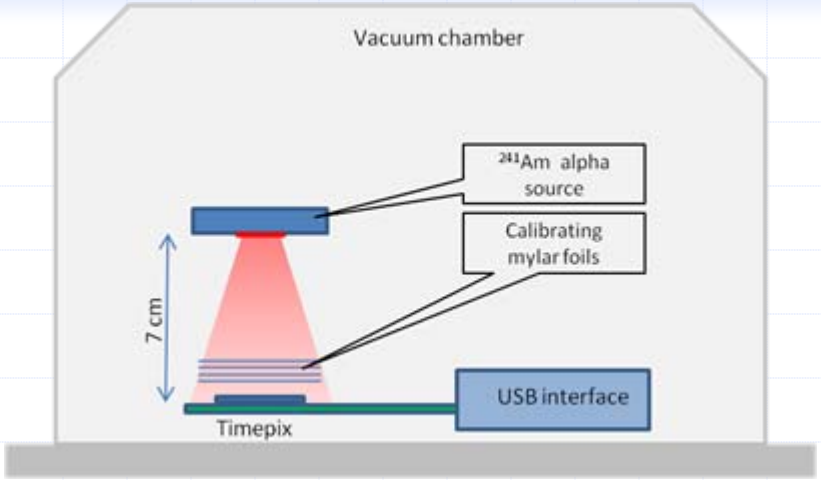


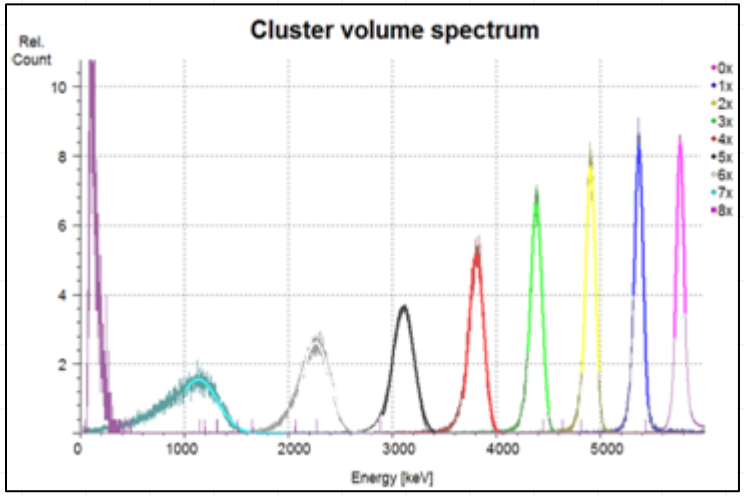
Radiography with heavy charged particles:

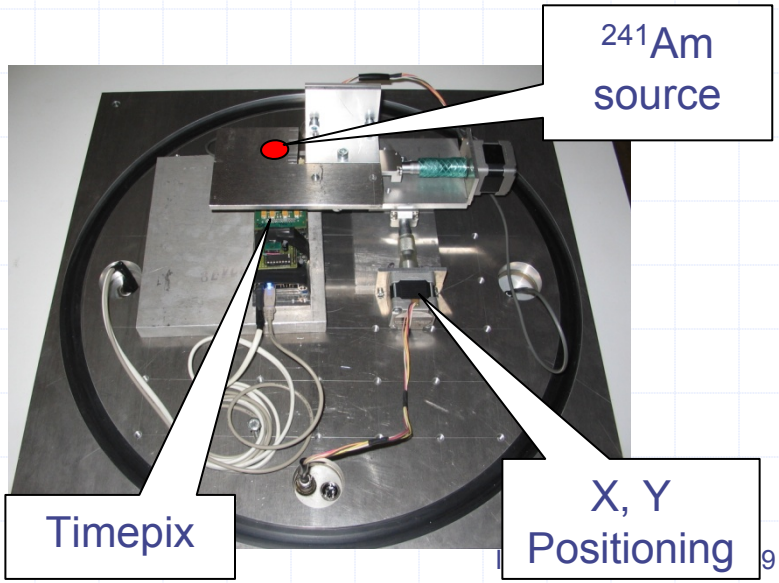
Example with TimePix

Institute of Experimental and Applied Physics
Czech Technical University in Prague

- ^{241}Am alpha source used
- Set of Mylar foils used to attenuate energy
- Measurement performed in vacuum



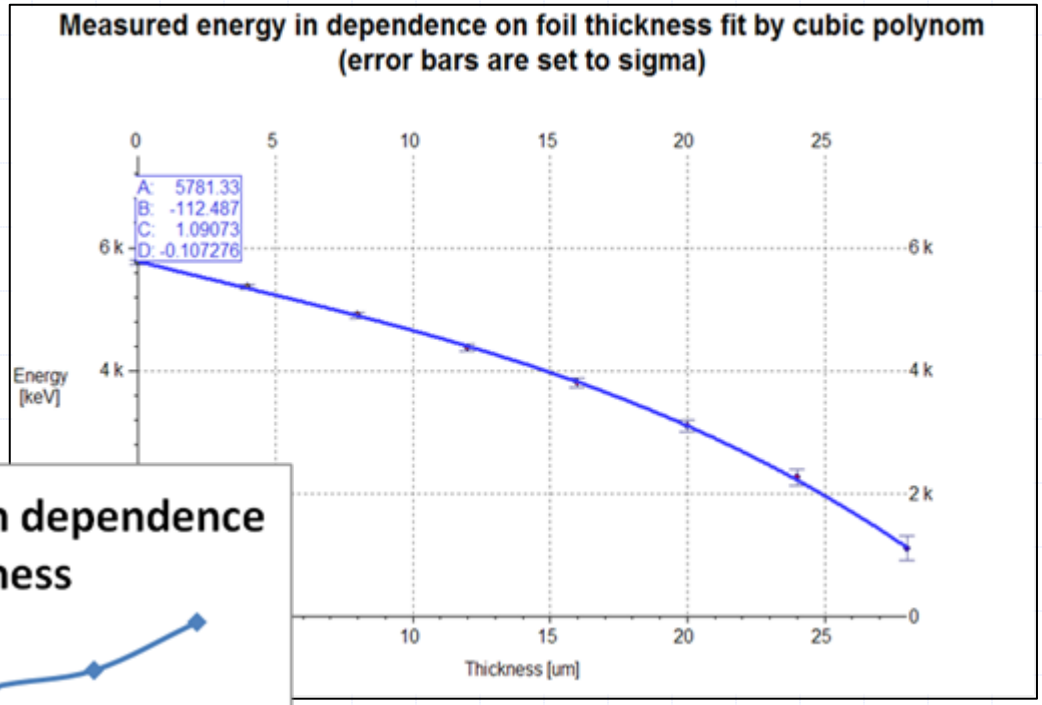


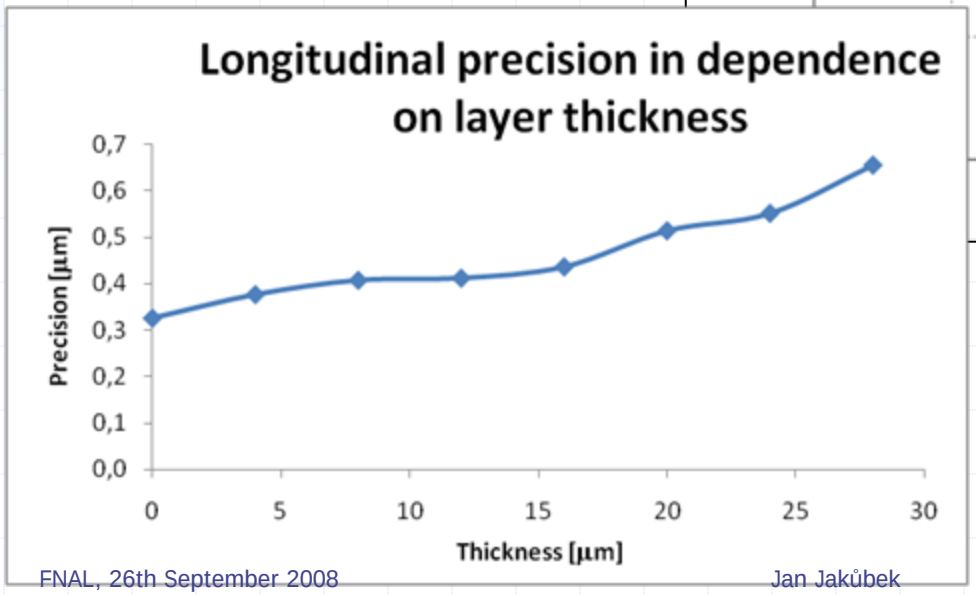


Radiography with heavy charged particles:

Determination of longitudinal precision

- Thickness of thin layer is measured with single alpha particle with precision of **320 nm**
- If 100 particles are averaged then precision reaches **30 nm**

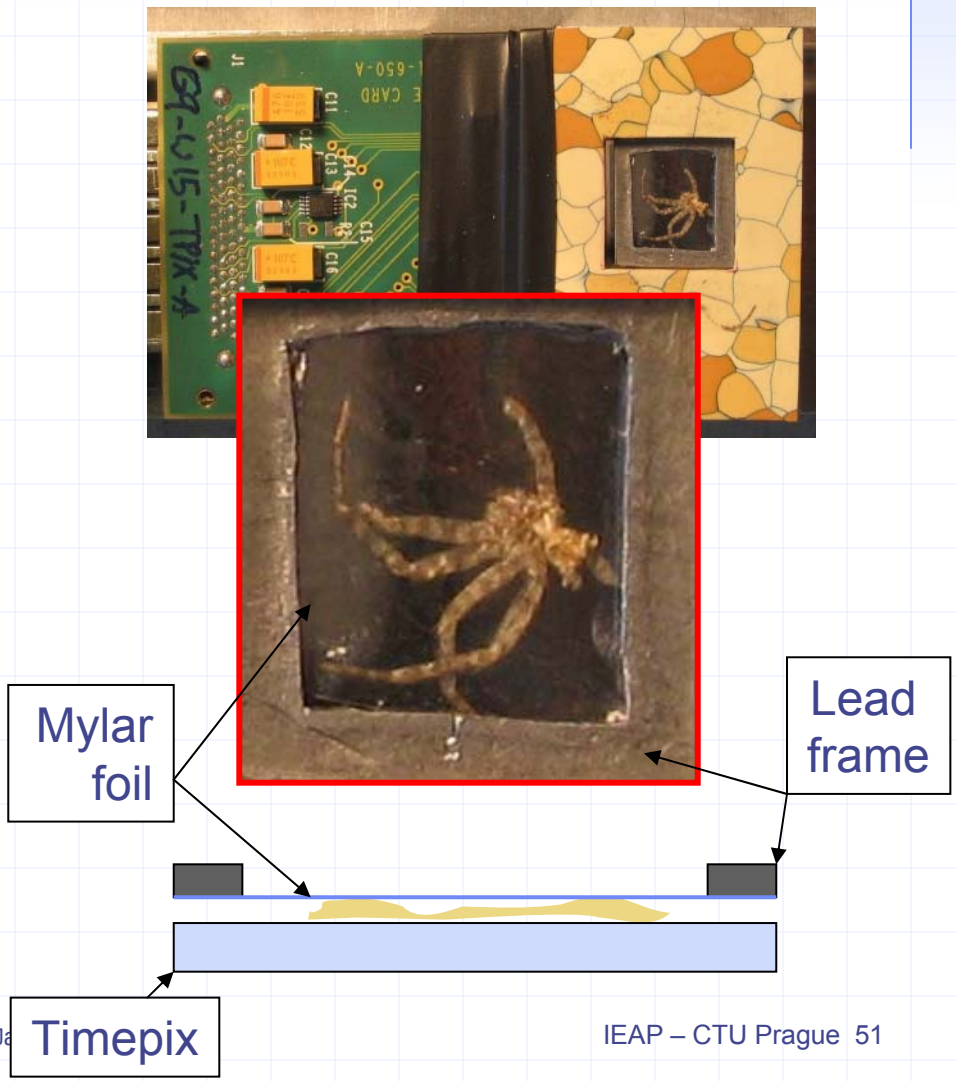




Radiography with heavy charged particles:

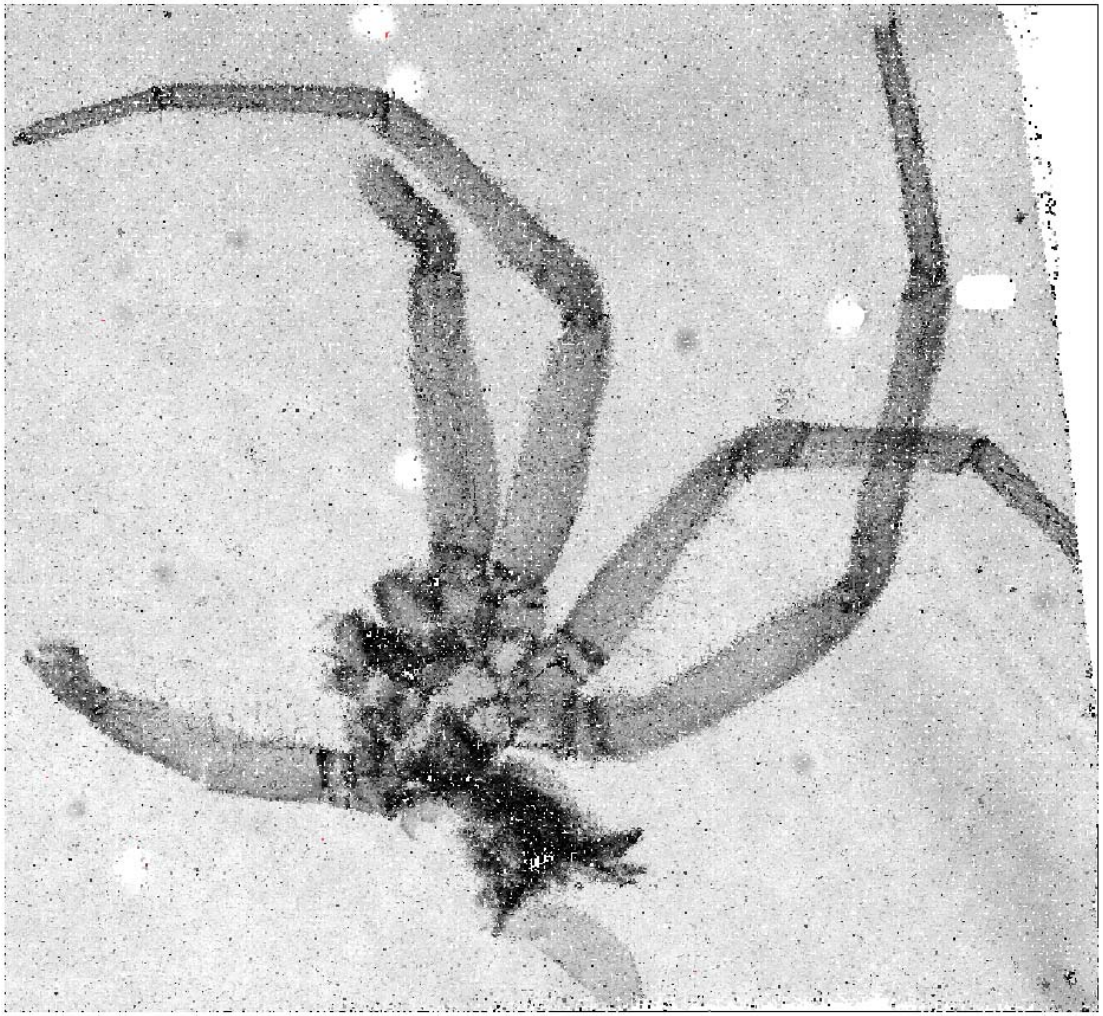
Sample object: Spider skin (slough)

- Skin thickness ~3μm
- Very weak alpha source ~ 12 particles per frame (1 second)
- 60000 frames taken
- 750 000 clusters analyzed
- Not enough particles for “deep” subpixelization



Radiography with heavy charged particles:

Sample object – Spider skin (slough)



16 x

(1 Mpixels)

~0.7 particles per pixel

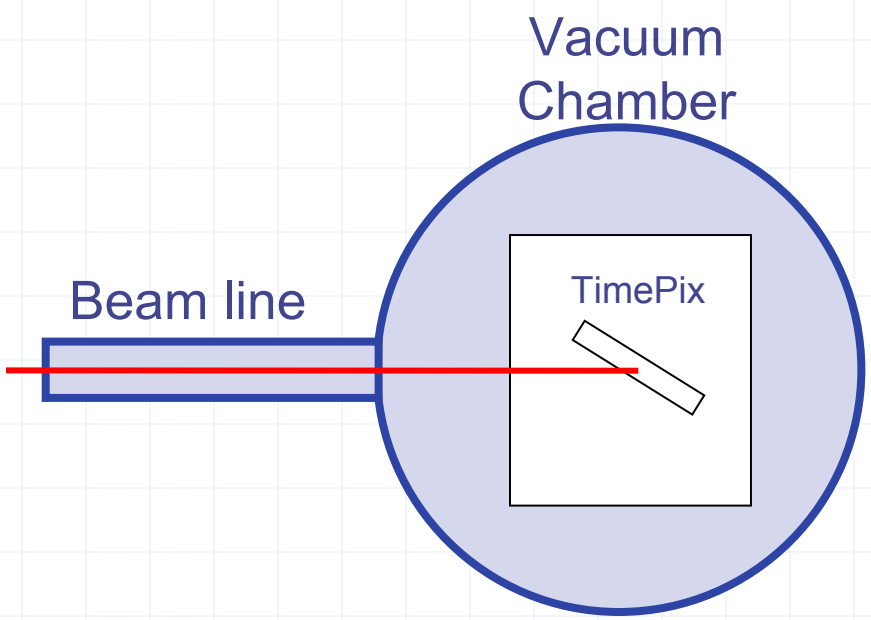
Applications:

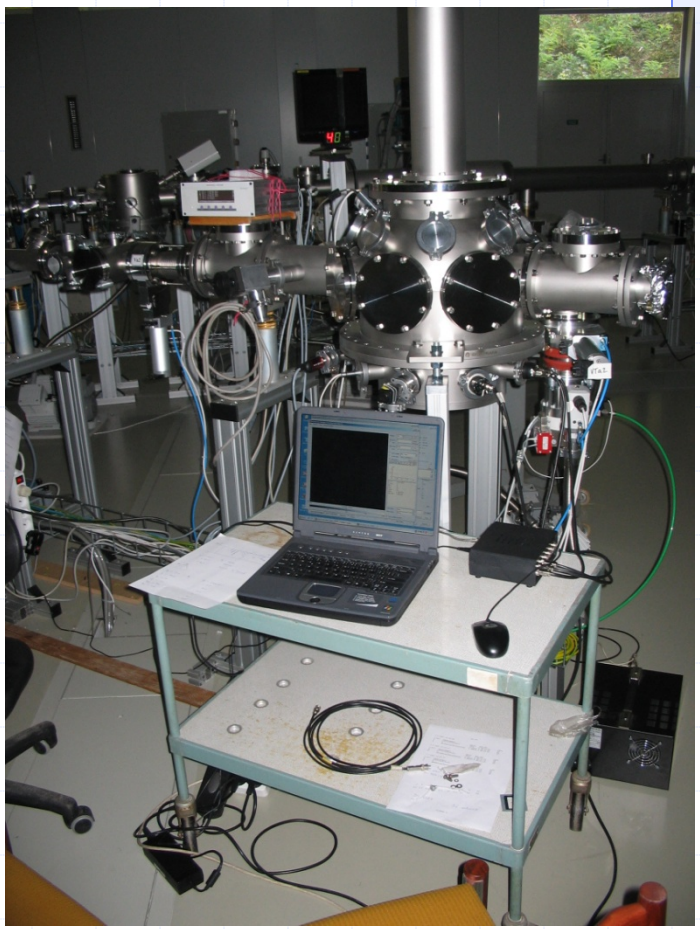
Tracking of heavy charged particles (Timepix as a Bragg detector)

(skip)

Proton tracking

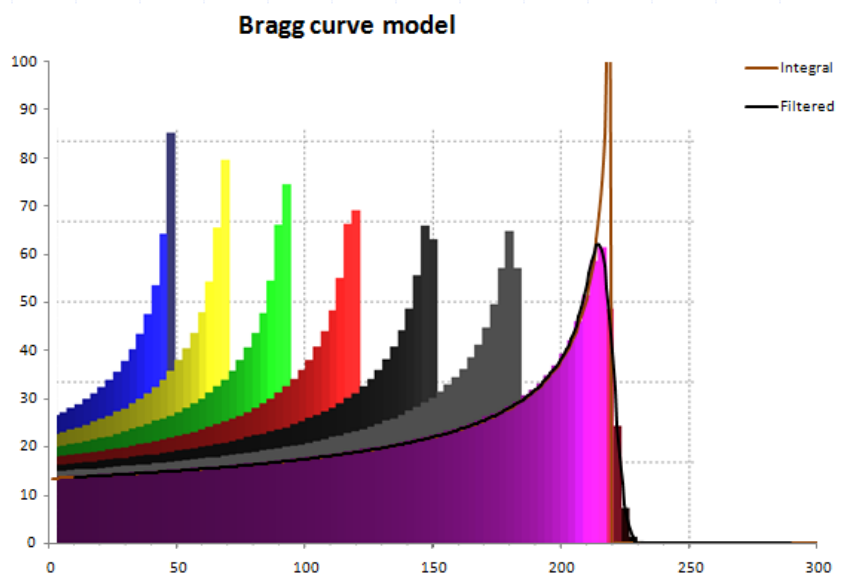
- Tandetron facility (Řež) used for basic tests.
- Defocused proton beam (low intensity).
- TimePix with positioning in vacuum chamber

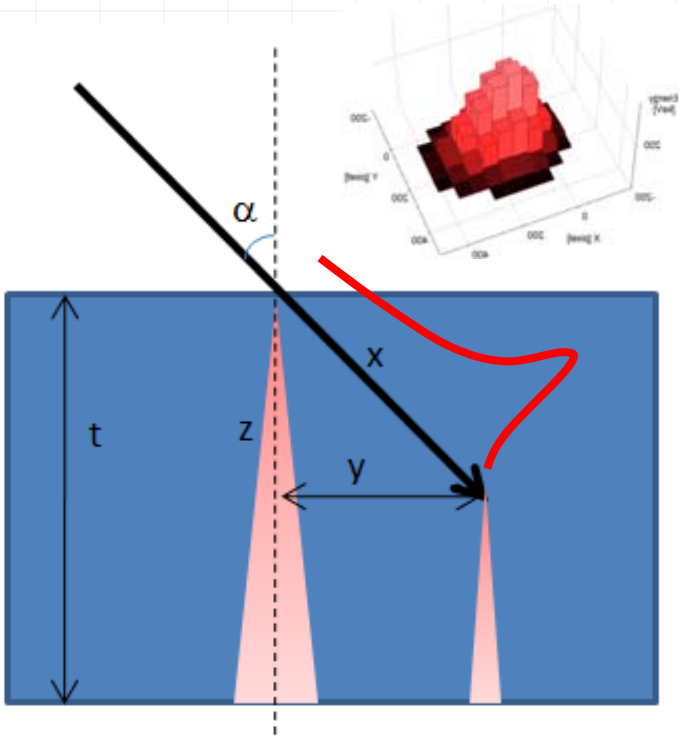




Proton in Silicon

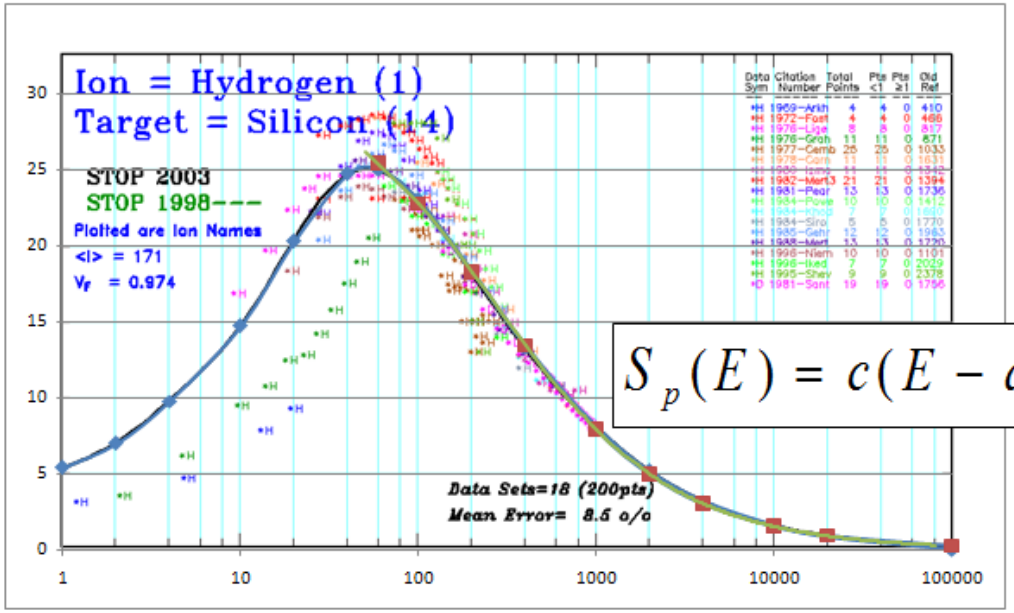
- Energy losses defined by Bragg curve => model needed
- The charge is collected from different depths
- Bias voltage set to 7.2V => diffusion dominates => Gaussian charge spread





Bragg curve modeling

- **Stopping power** of Silicon for protons is characterized by surrogate functions (see inset in chart below)
- By its integration the energy profile along the track is determined as a function of initial energy.



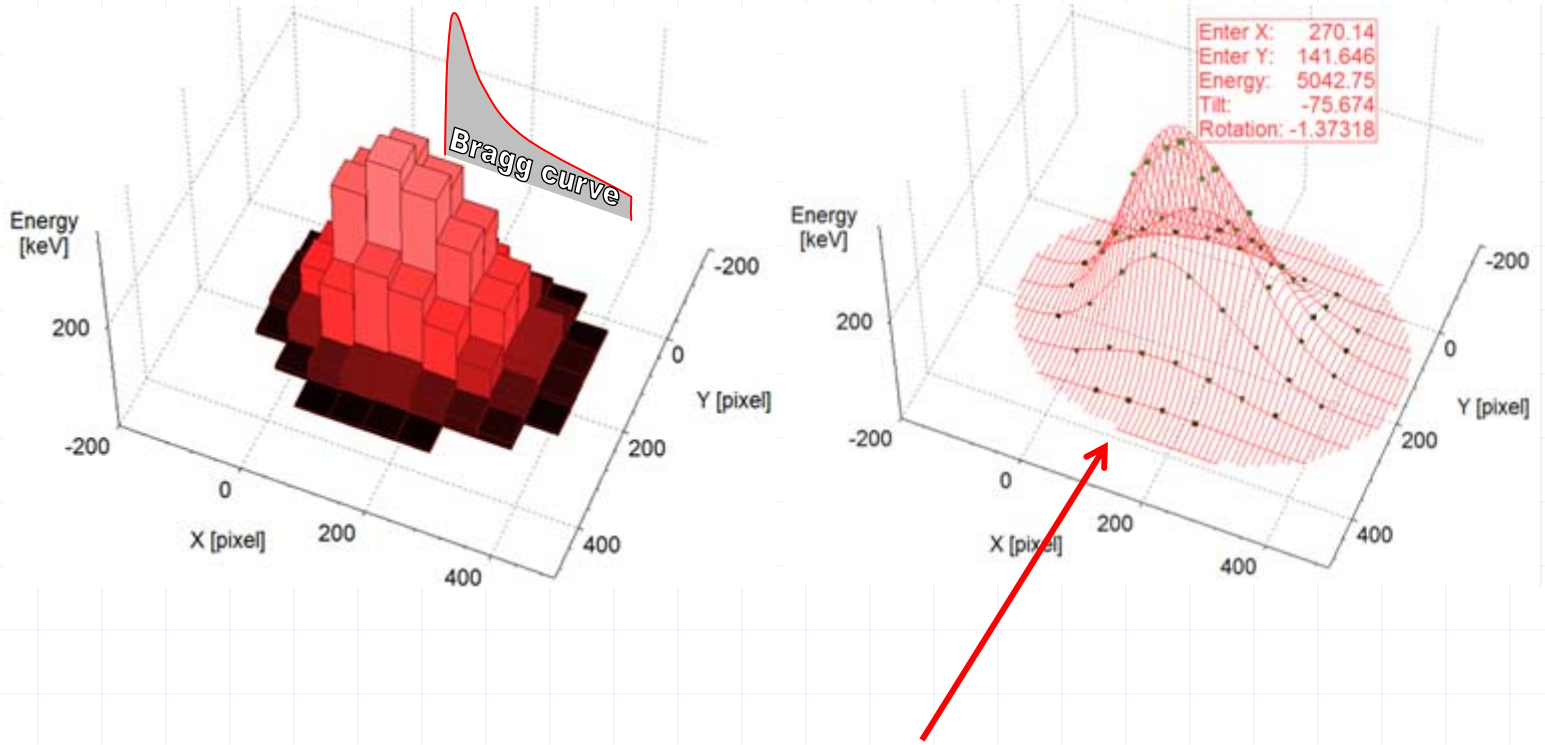
$$S_p(E) = c(E-a)^e$$

Bragg curve:

$$\frac{d}{dx}E(x) = -c\left((E_0-a)^{1-e} - c(1-e)x\right)^{\frac{e}{1-e}}$$

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Clusters and fits



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

Applications:

(Very) Low energy physics
Detection of ultra-cold neutrons

(skip)

Detection of ultra cold neutrons

- Ultra-cold neutrons (UCN) are neutrons with small kinetic energy (~300 neV). The energy is so small that they are totally reflected from the surface of most materials under any angle of incidence so they can be trapped by the effective Fermi's material potential. This energy corresponds to a velocity of less than 7 m/s, an effective temperature of 0.005 K or wavelength of about 1000 Å.
- UCNs can be stored in “bottles” for times approaching the β decay lifetime of the neutron (~ 900 s).
- Experiments with bottled UCN can offer orders-of-magnitude improvement for various precise measurements of neutron properties that are sensitive to physics beyond the standard model.
- UCNs are generated in several world laboratories (ILL Grenoble, Los Alamos NL, PSI Villigen,…).

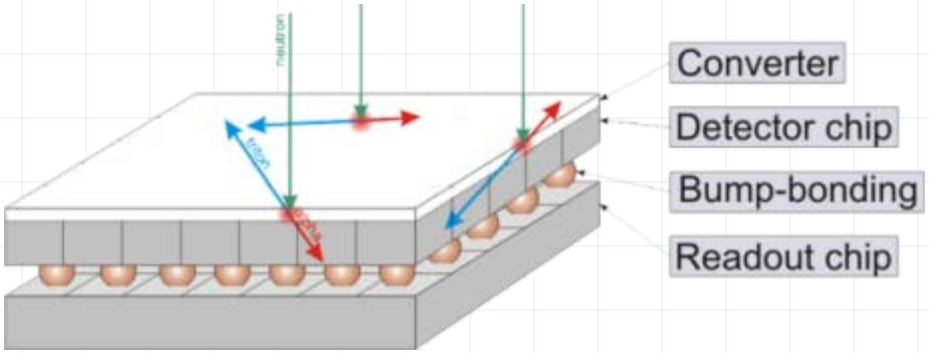
Detector design

- The pixel detector TimePix working in its TOT mode allows to detect heavy charged particles with very high subpixel spatial resolution.
- This feature can be used for precise detection of UCNs via their conversion to heavy charged particles.
- The conversion can be performed in layer of ^{6}Li (in form of ^{6}LiF) or ^{10}B deposited on the sensor surface. Since energy of UCN is very low, the cross-section of both materials for UCN capture is extremely high and conversion layer can be very thin.

^{6}Li: $^{6}Li + n \rightarrow \alpha\ (2.05\ MeV) + {}^{3}H\ (2.72\ MeV)$

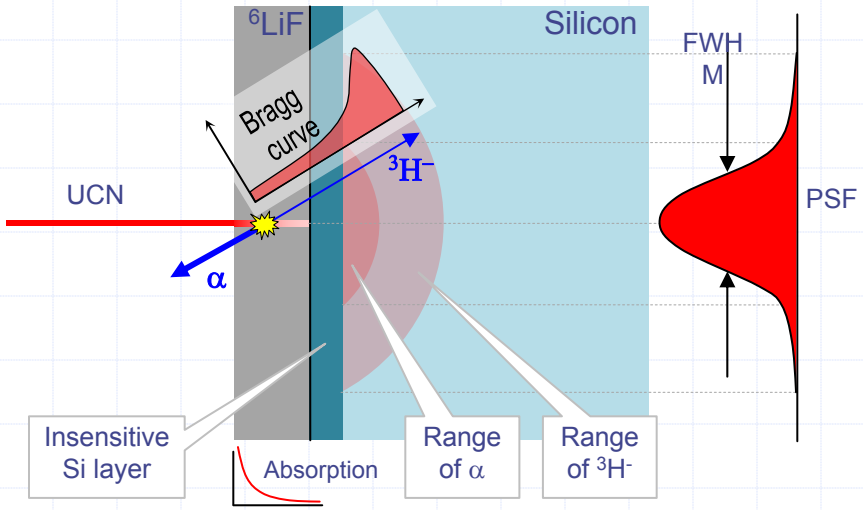
^{10}B: $^{10}B + n \rightarrow \alpha\ (1.47\ MeV) + {}^{7}Li\ (0.84\ MeV) + \gamma\ (0.48 MeV)$ (93.7%)

$^{10}B + n \rightarrow \alpha\ (1.78\ MeV) + {}^{7}Li\ (1.01\ MeV)$ (6.3%)



Monte-Carlo simulations

- Simulations performed using MCNP, SRIM and Matlab
- Aim: To estimate detection efficiency and spatial resolution



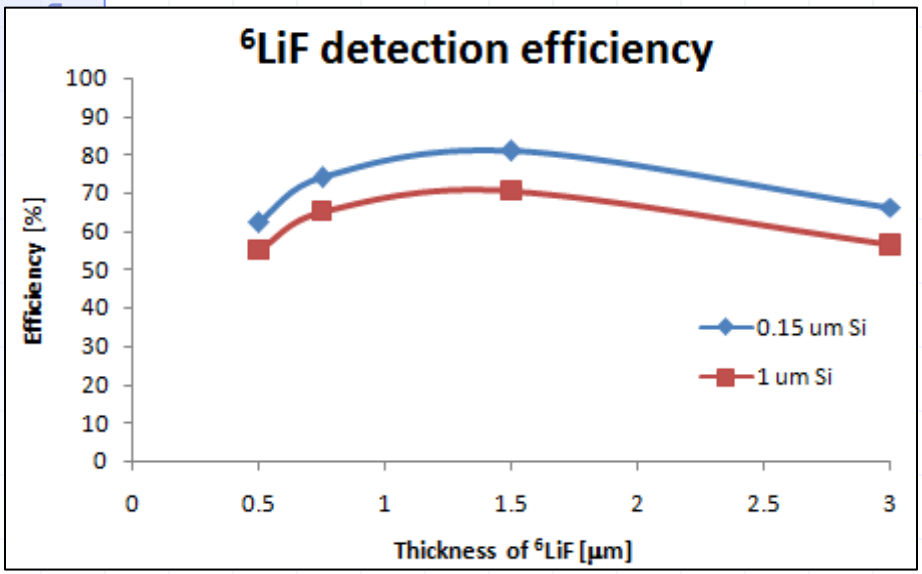
Geometry used in simulations

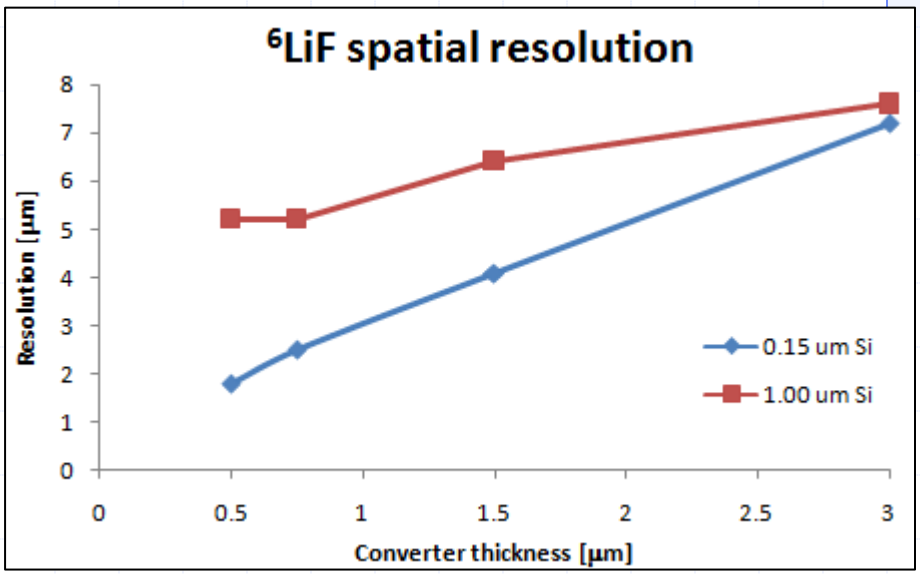
Expected UCNs velocity: 500 cm/s. For such neutrons the cross section of ^{6}Li increases to **0.34 Mbarn**. The cross section of ^{10}B reaches **1.67 Mbarn**.

50% of such UCNs are fully absorbed in ^{6}LiF layer of 85 ug/cm^2 (~ 320 nm thickness). For ^{10}B it is layer of 7 ug/cm^2 (~ 30 nm thickness).

Used ^{6}LiF density of 2.65 g/cm^3 and ^{10}B density of 2.35 g/cm^3.

Simulation results for ^{6}LiF

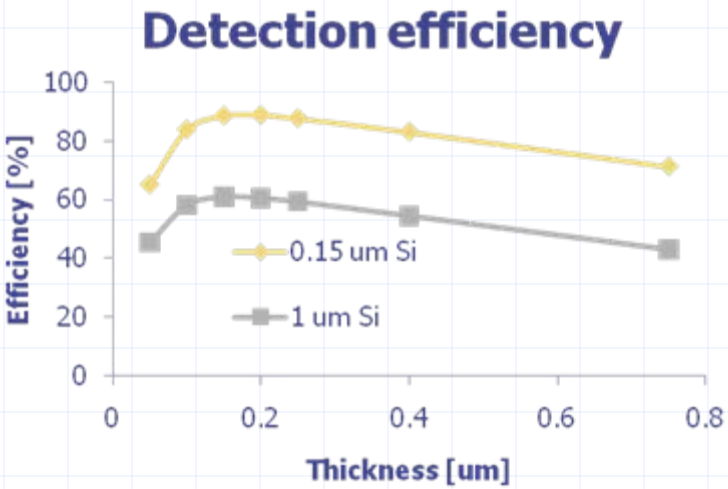


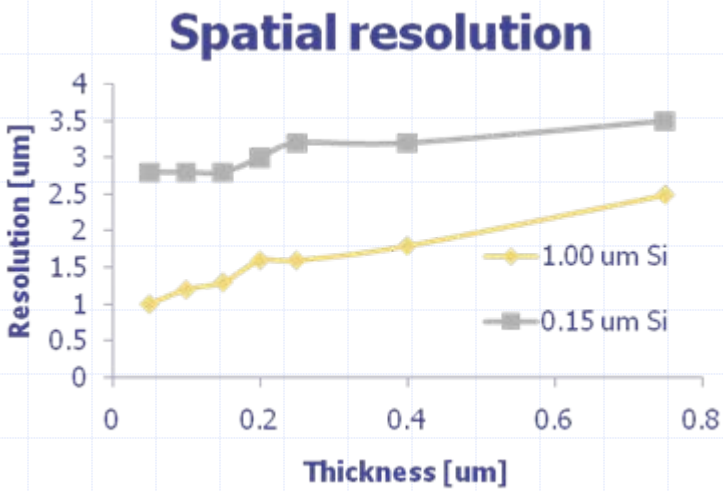


The converter thickness maximizing efficiency is about 1.5 um thick. Resulting efficiency is 81% for Si layer of 0.15 um resp. 71% for Si layer of 1 um.

Dependence of spatial resolution (in terms of FWHM of PSF) on thickness of ^{6}LiF coating. The resolution for 1.5 um thickness is about 4.1 um for Si layer of 0.15 um resp. 6.4 um for Si layer of 1 um.

Simulation results for ^{10}B



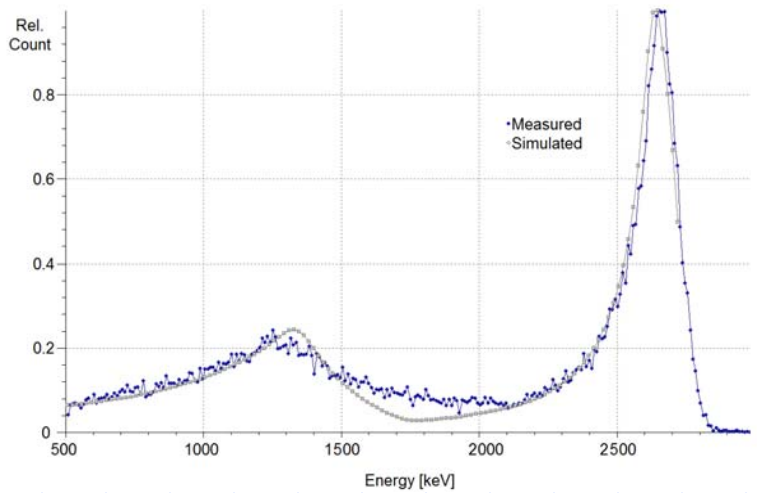


The converter thickness maximizing efficiency is about 1.5 um thick. Resulting efficiency is 89% for Si layer of 0.15 um resp. 61% for Si layer of 1 um.

The resolution for 1.5 um thickness is about 1.6 um for Si layer of 0.15 um resp. 3.0 um for Si layer of 1 um.

Experiment 2: Deposited layer of ^{6}LiF

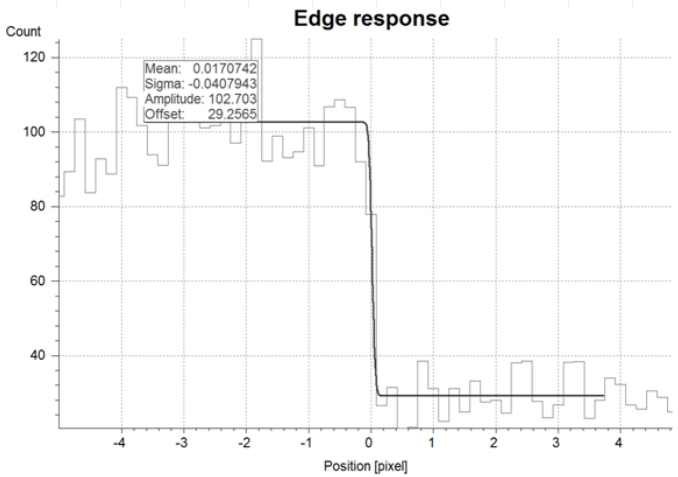
- 400 ug/cm^2 of ^{6}LiF was deposited onto Timepix sensor surface by evaporation (~ 1.5 um).
- Spectrum was measured and compared with simulation (thickness of insensitive Si layer tuned to achieve the best agreement).

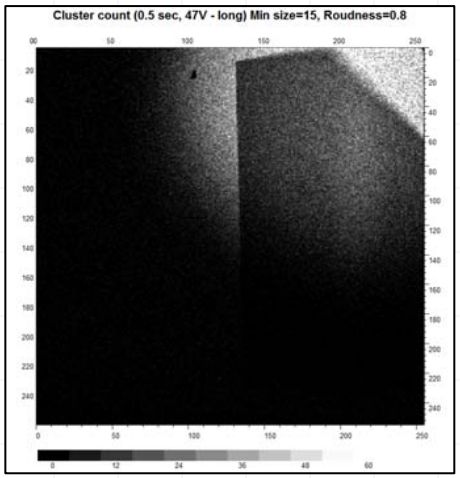


- The insensitive layer thickness is ~ 1 um.
- Detection efficiency ~ 70%.

Spatial resolution

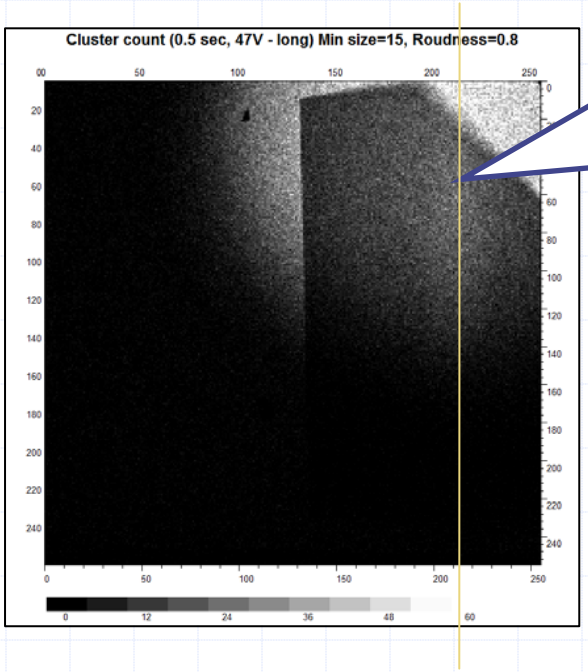
- Straight edge made of stainless steel (50 um thick) placed on detector surface.
- Positions of all detected clusters evaluated with **subpixel** precision.



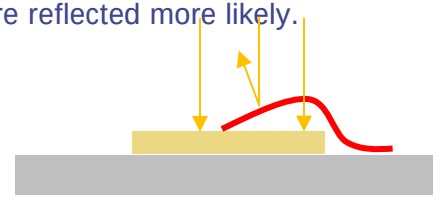


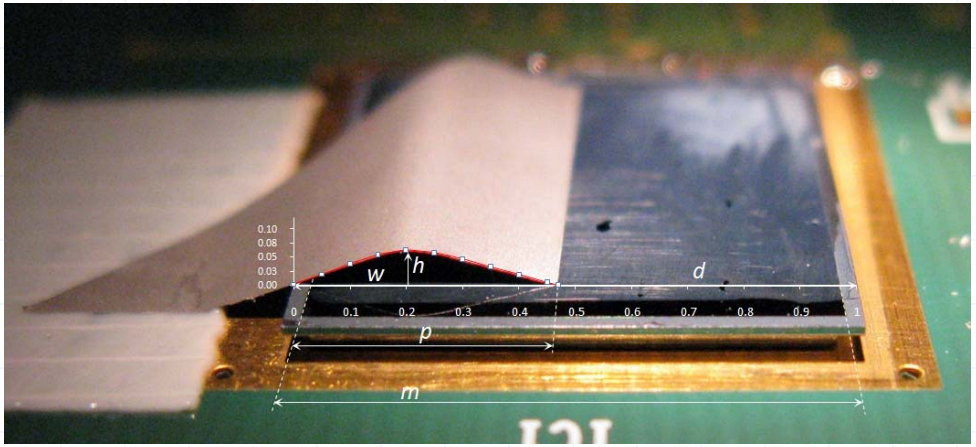
- A spatial resolution of **2.3 µm** (sigma of the error function) was measured this way. This result corresponds to 5.3 µm of FWHM of point spread function.
- The method is very promising for many experiments with UCNs => it is supported by ILL project PF2 UCN 3-14-239 (got 25 days of beam time for 2008).

Transparency depends on UCN energy



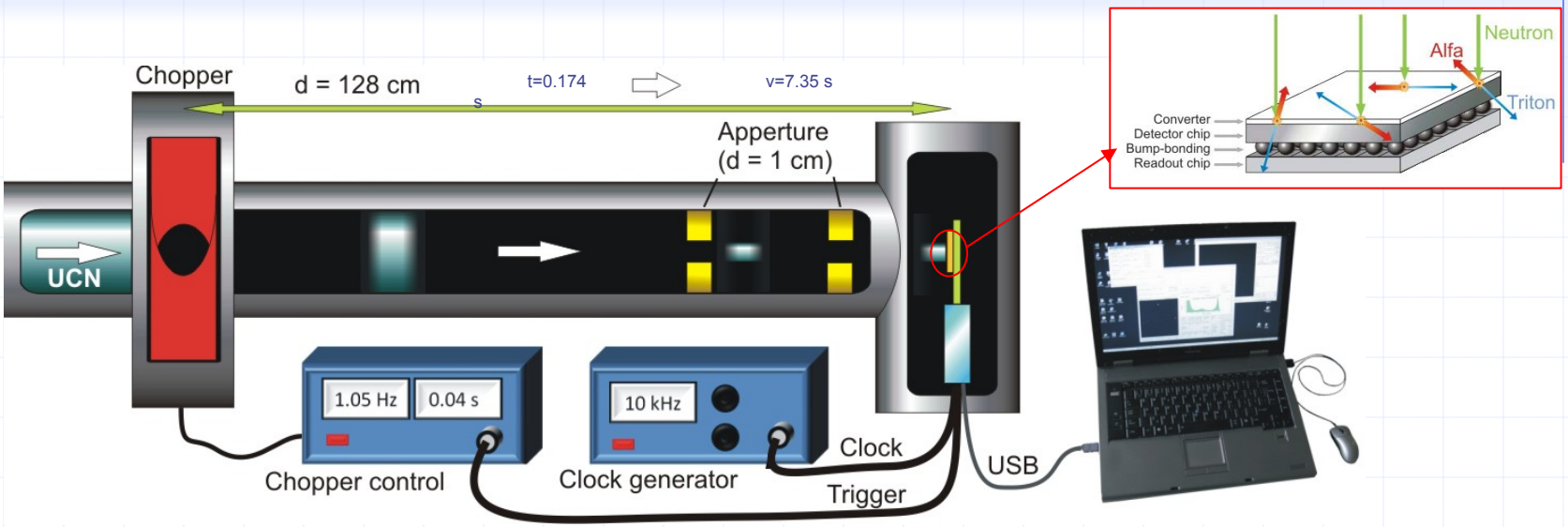
The neutrons with energy high enough comming perpendicularly to the foil surface are able to penetrate. When they are hiting tilted part of the foil they are reflected more likely.

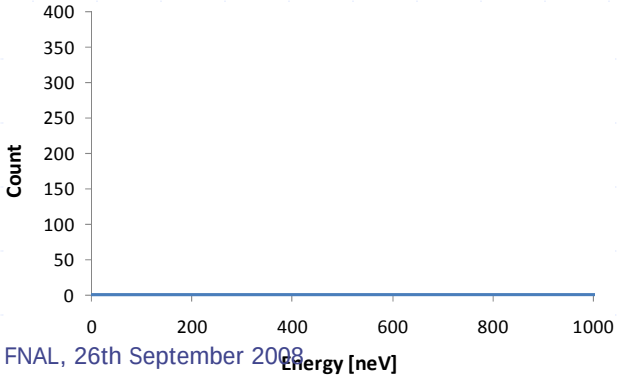




Time Of Flight measurement
= Position sensitive neutron spectroscopy

Institute of Experimental and Applied Physics
Czech Technical University in Prague

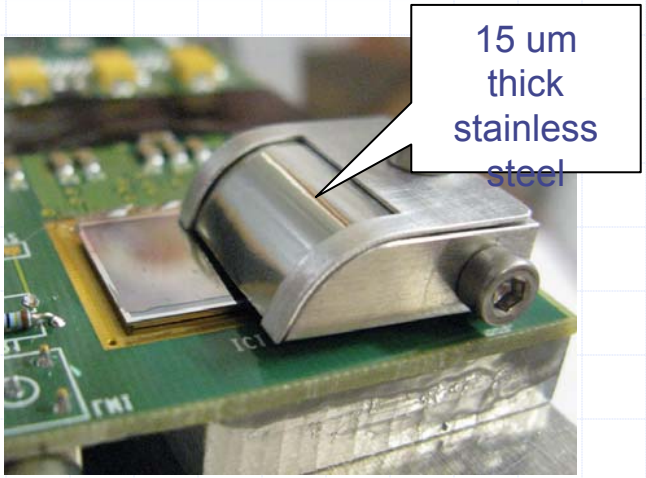


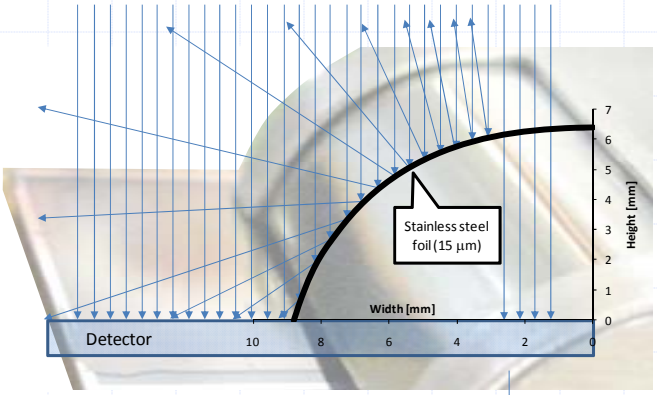


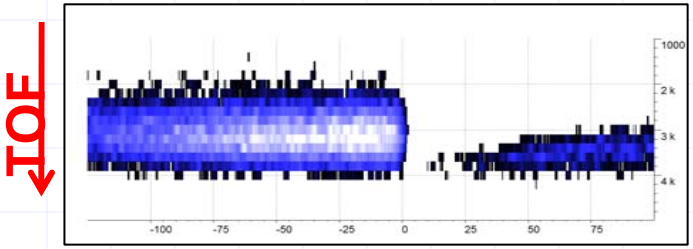
Energy spectrum of UCNs
Computed from TOF data

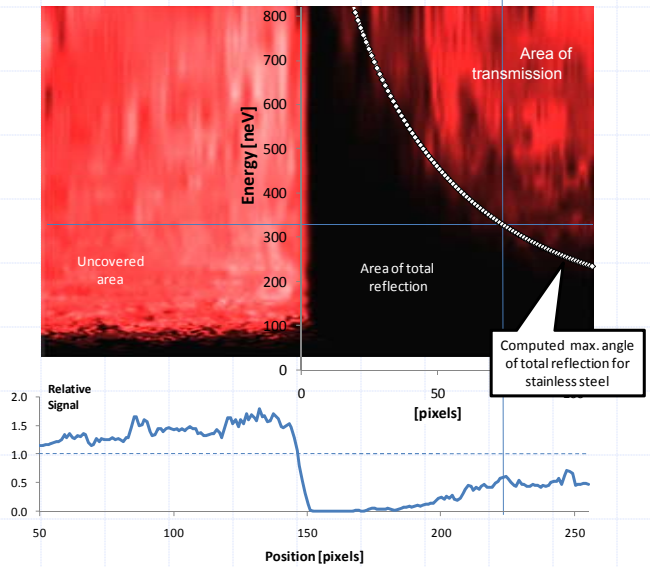
Position sensitive TOF spectroscopy of UCNs

Institute of Experimental and Applied Physics
Czech Technical University in Prague









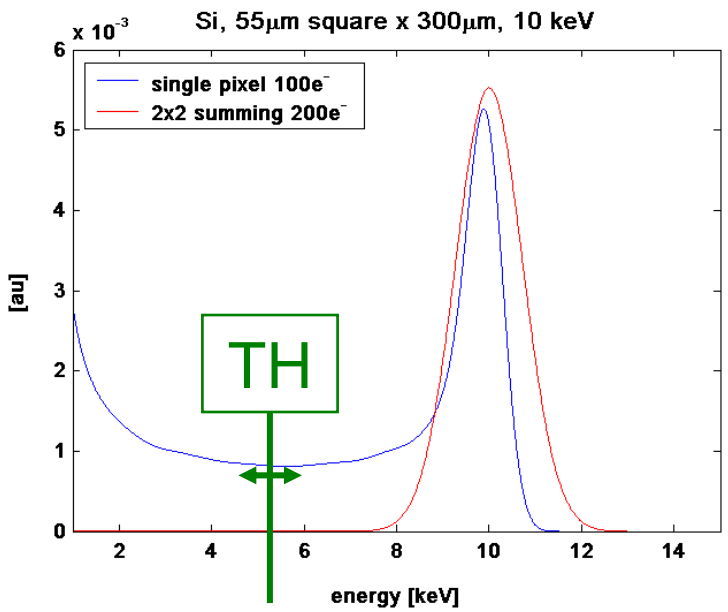
Summary:

Issues of current devices

Issues to be solved:

Particle counting – charge sharing

In particle counting mode the charge sharing deteriorates spatial resolution and spectrometric properties



Threshold variation produces fixed pattern noise in the image

Basic cluster analysis on pixel level (cluster charge summing)

Issues to be solved:
Dead time

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Detector is blind during readout => Dead time.

Continuous operation i.e. TWO COUNTERS in each pixel

Faster data transfer (data sparsification or compression)

New devices are coming:

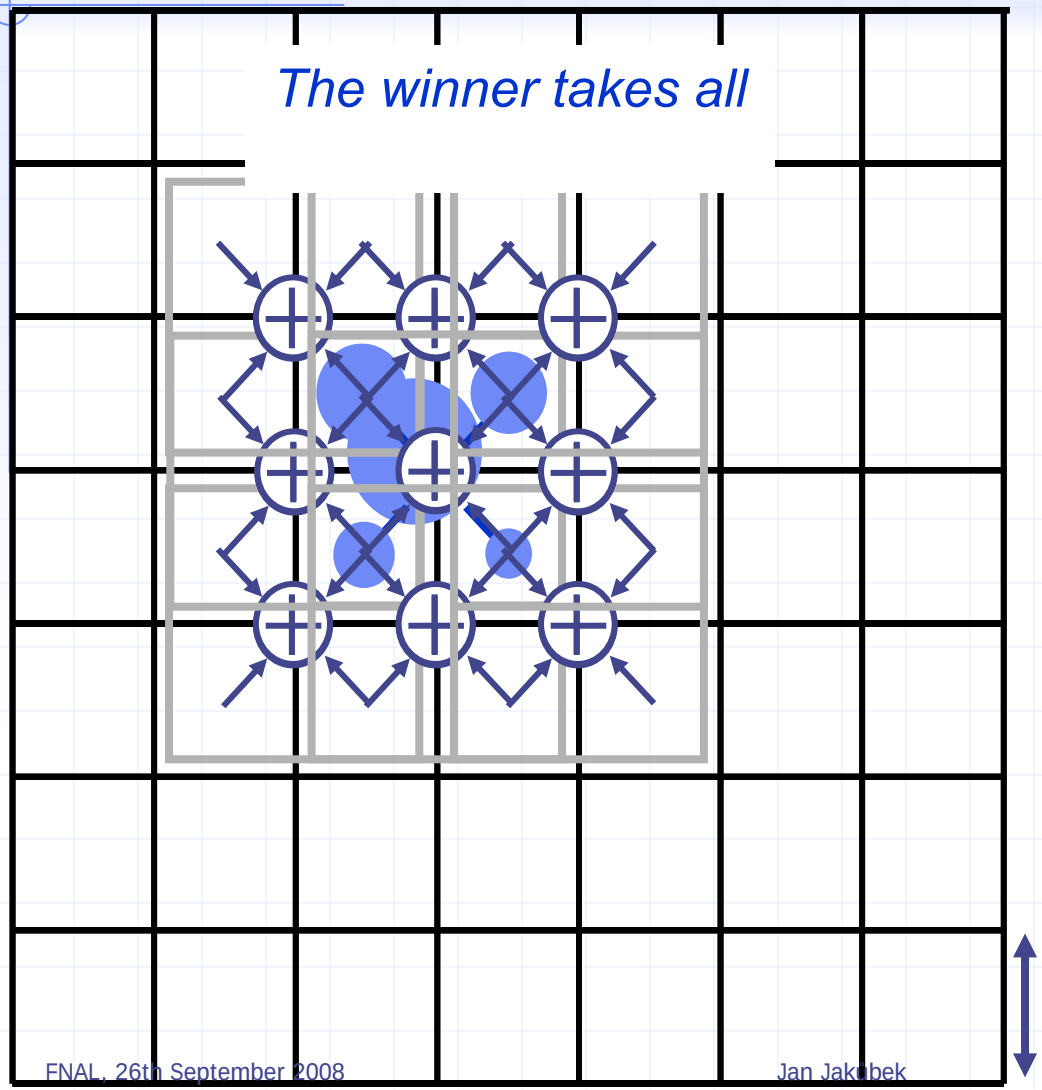
Medipix3 and Timepix2 concept

Medipix3

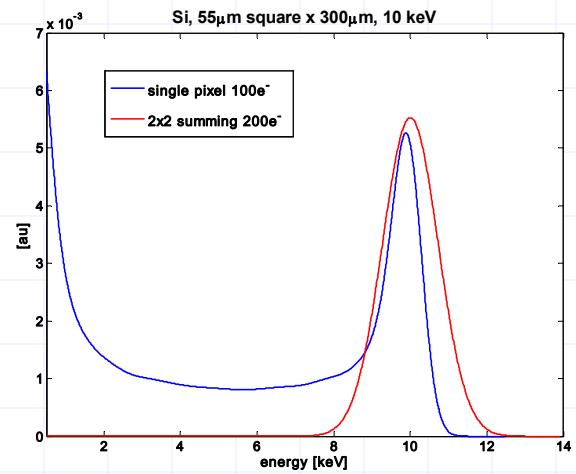
- Two configurable counters per pixel.
- Charge summing scheme improves spatial resolution, noise and spectrometric properties.
- Two modes of sensor bonding (either 55 x 55 or 110 x 110 um). When larger pixels are connected then they can use all circuitry => 8 thresholds and 8 counters.

Medipix3 – charge summing concept

Institute of Experimental and Applied Physics
Czech Technical University in Prague



- The incoming quantum is assigned in a single pixel cluster on an event-by-event basis



Timepix2 concept

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Not decided yet !

Possible ways:

- Two configurable counters per pixel enabling parallel energy and time determination
- Self triggering – FAST OR logic
- Fast reset
- Sparse data readout
- Improved preamplifier (noise)

And many other possible requirements ....

Conclusions

In the field of imaging there are two main directions:

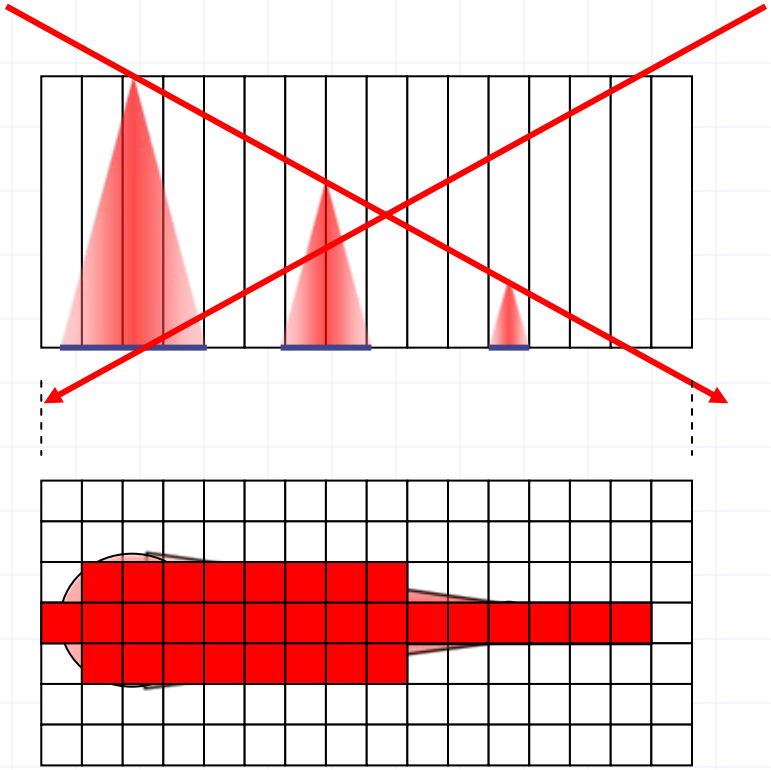
- **More sophisticated data processing on the pixel level**.
- Application of **tracking approach** for imaging providing as complex information about each event as possible (Even charge sharing effect can be exploited) => request of very high data throughput.

Steady development in the field of sensors is required.

Thanks for your attention

Charge sharing effect:

Tracks of MIP particles

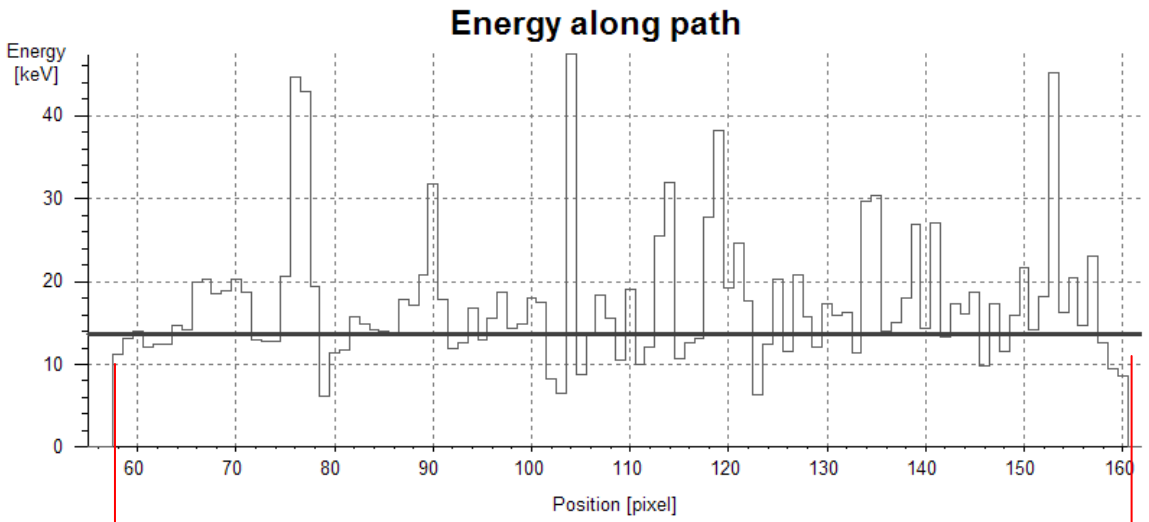


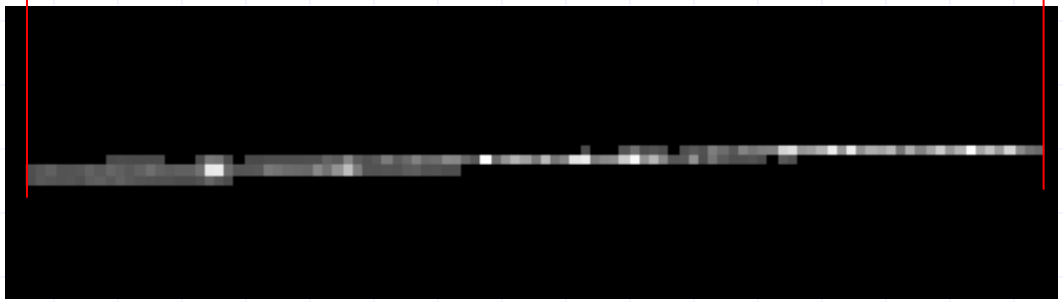
- Ionization by MIP particles doesn't depend on depth and follows Landau distribution
- Charge sharing effect is more significant if charge is generated near the surface

=> Charge sharing brings more information in tracking mode

Charge sharing effect:

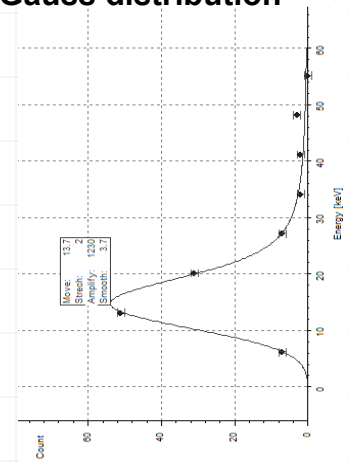
Tracks of MIP particles – Cosmics





Track recorded by TimePix device

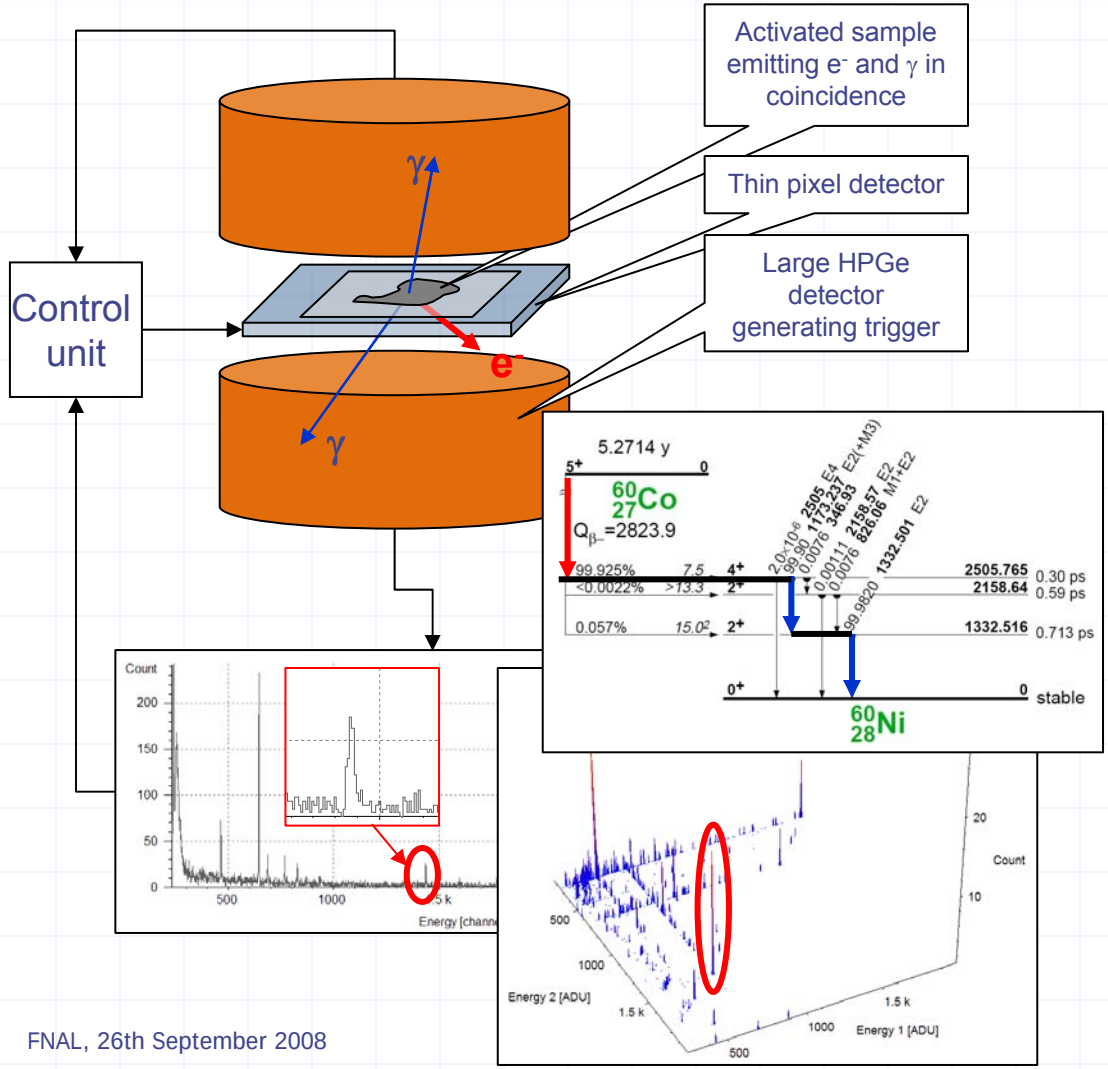
Energy distribution fit by convolution of Landau and Gauss distribution



Triggered image integration

Coincident imaging:

Coincident imaging with Pixel device



Application field:

- Imaging in Activation Analysis
- Prompt gamma imaging
- …

Activation analysis:

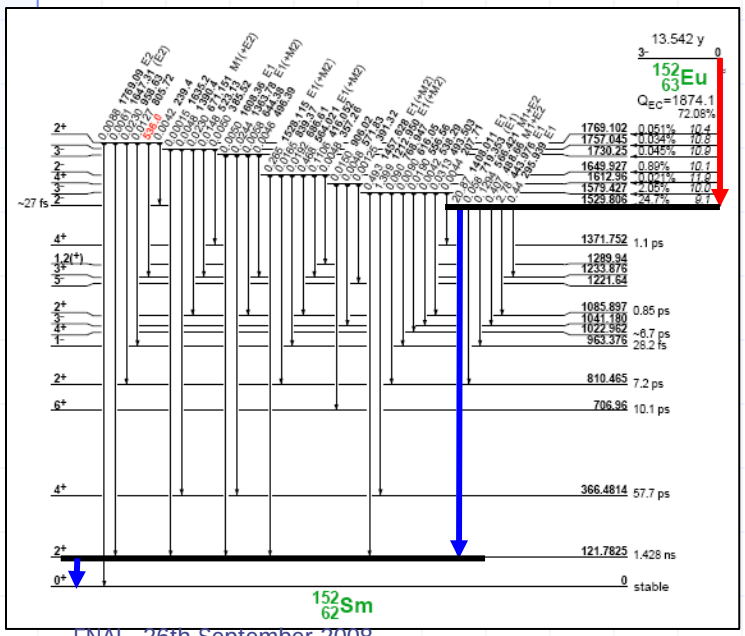
- Excited nucleus emits radiation
- Energy of emitted gamma is typical for each element => direct measurement of element concentration
- Very sensitive method (<ppm)
- To improve selectivity several detectors can be used in coincidence
- Electrons are often present deexcitation in cascades

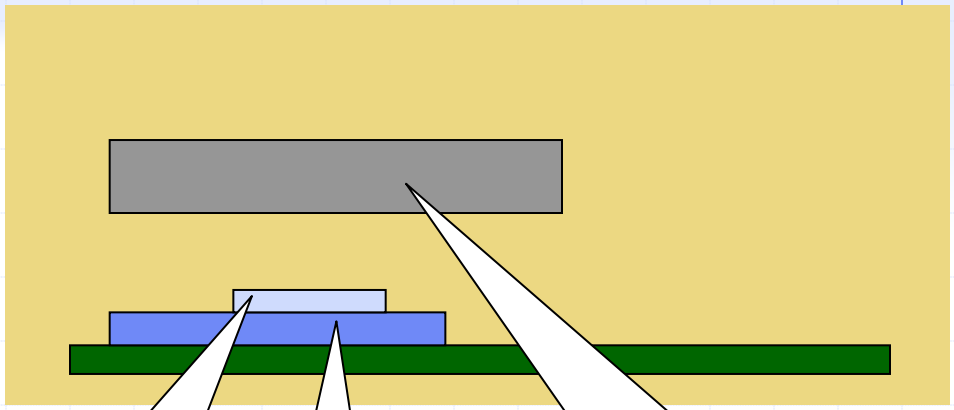
=> Chance for thin Si pixel detector

Coincident imaging:

Sample used for experiment

- ^{152}Eu sample (11 kBq) in form of 1mm dots on PE carrier.
- Non coincident electron background modeled by ^{90}Sr source 55kBq.

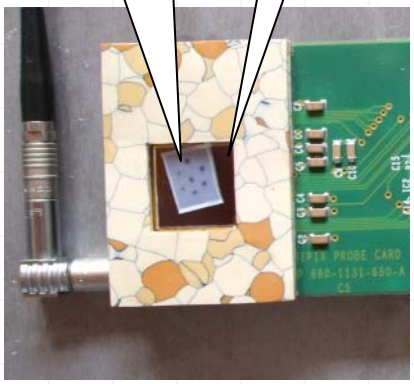


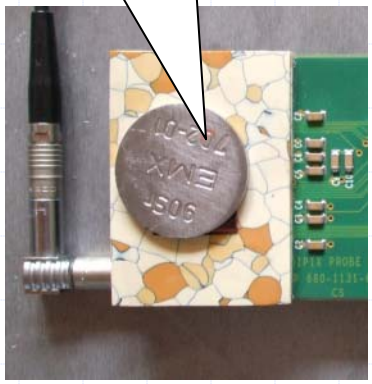


PE foil with dots of ^{152}Eu

Timepix

^{90}Sr source making heavy not coincident background

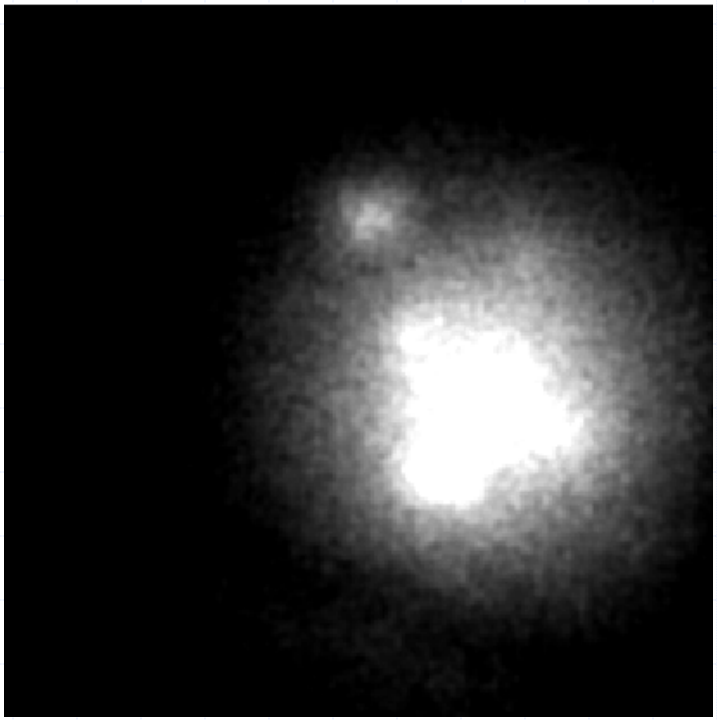




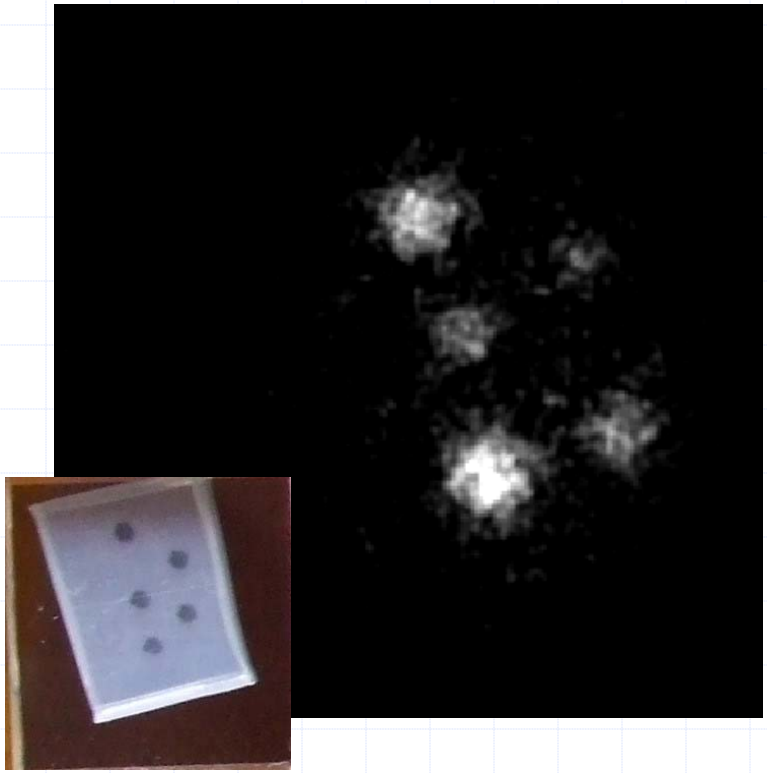
Coincident imaging:

Results

Non coincidence mode



Coincidence mode



Exposure time was in both cases 1 minute. All dots clearly resolved.

Enhanced compton camera

... coincidence + energy

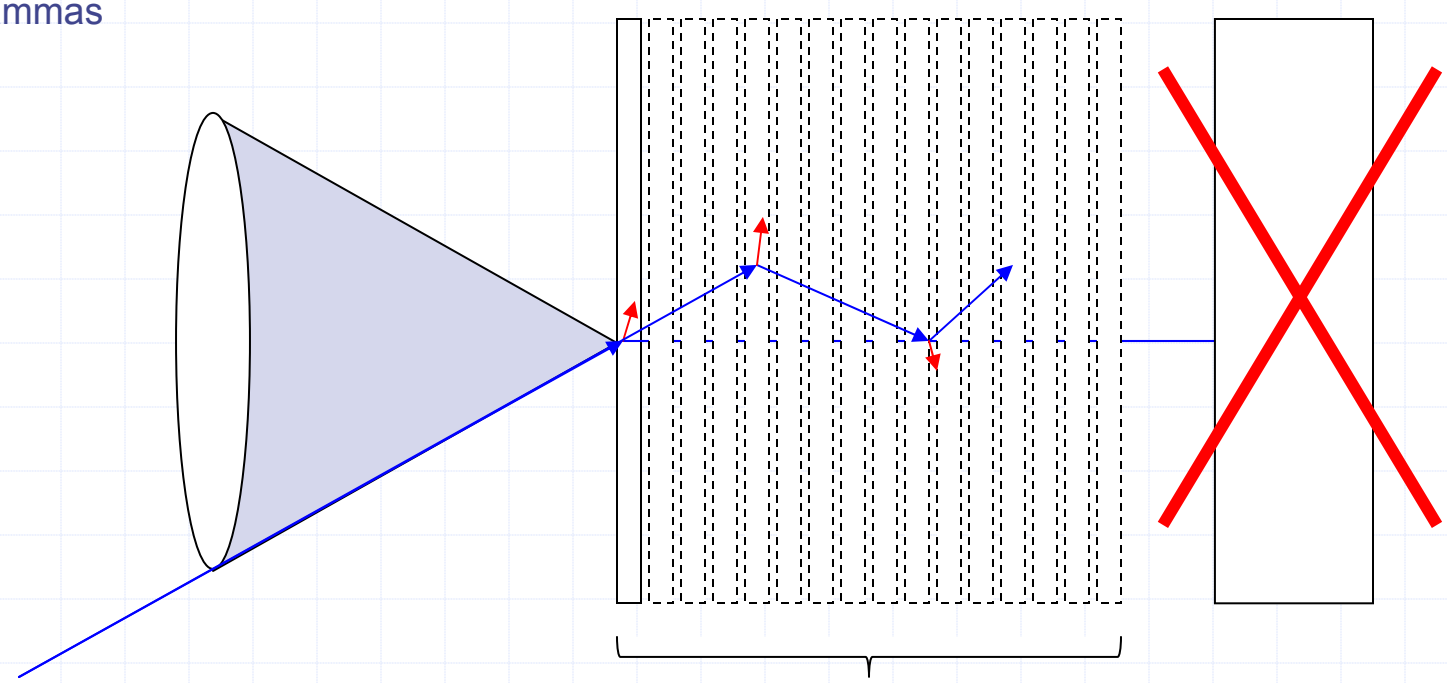
Compton camera enhancement

Institute of Experimental and Applied Physics
Czech Technical University in Prague

Compton effect efficiency with 300um Si sensor Is about **0.2%** for 500keV gammas

Thin position sensitive scatter detector

Thick position sensitive detector for full absorption

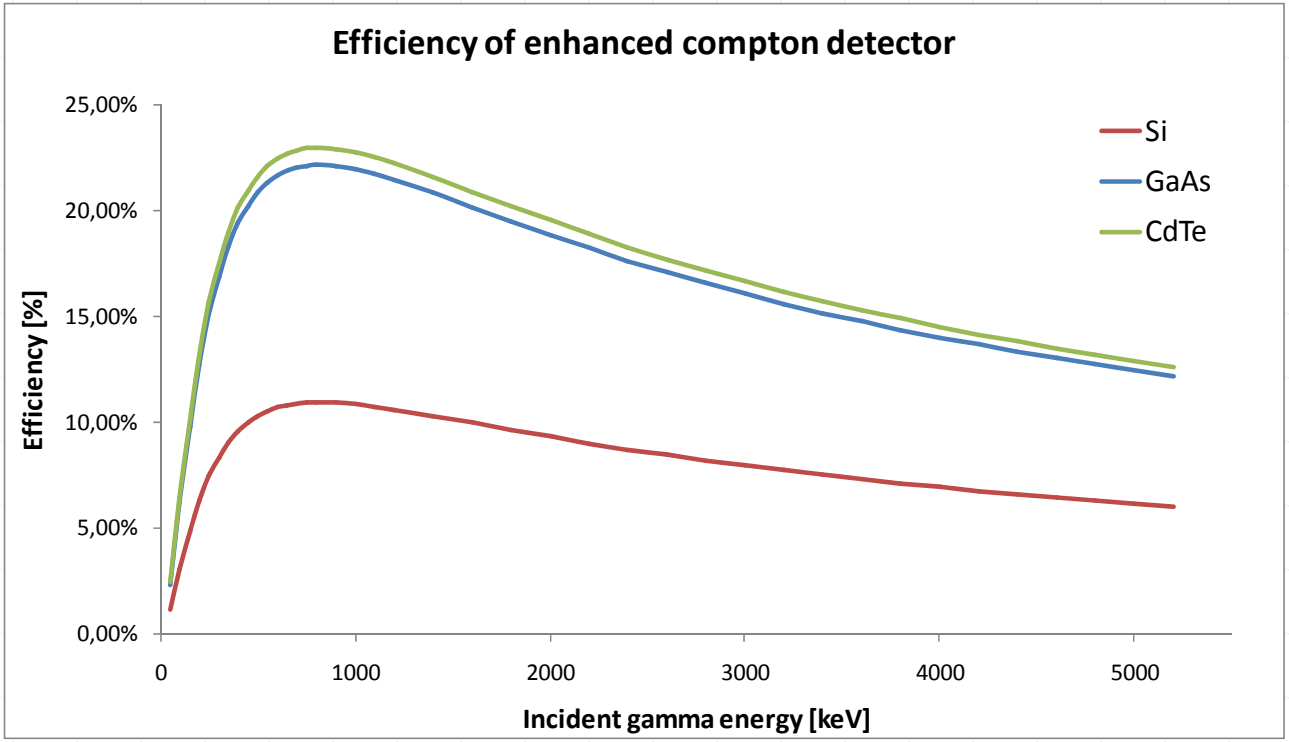


Thick position sensitive detector

=> Photon tracker

Efficiency

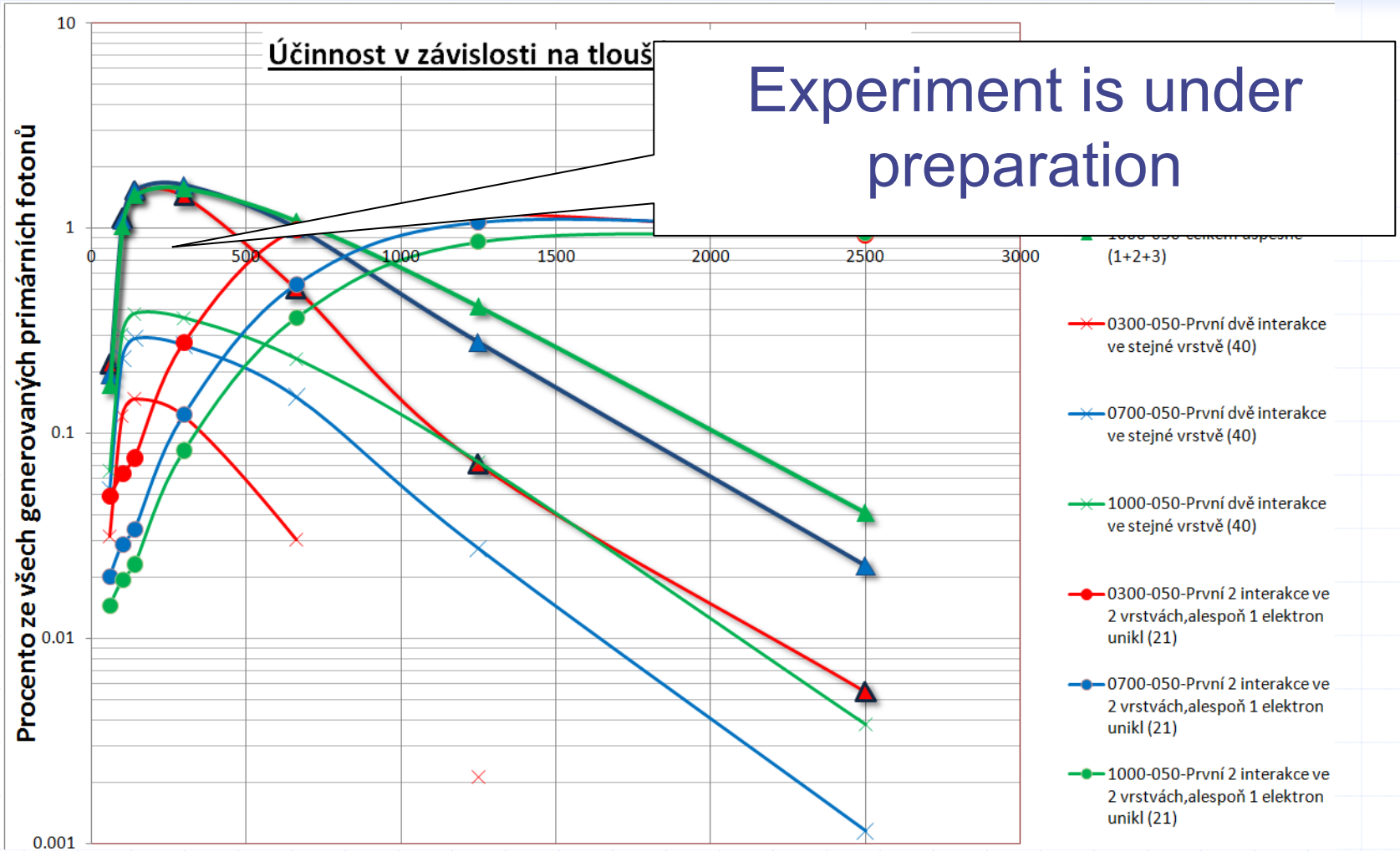
Institute of Experimental and Applied Physics
Czech Technical University in Prague



Detector geometry: 15 x 15 x 15 mm of sensitive material

Simulations of real geometry

Institute of Experimental and Applied Physics
Czech Technical University in Prague



Experiment is under preparation

Simulated images of point source

Institute of Experimental and Applied Physics
Czech Technical University in Prague