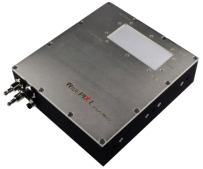
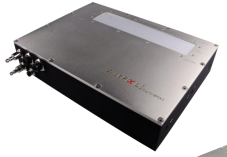
X-ray and Gamma ray imaging: from art to industry

Large area and/or high resolution

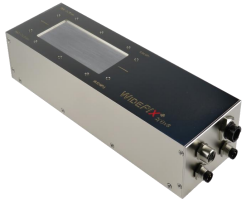
ADVACAM

AdvaPIX:
Timepix3





WidePIX
Medipix3



ADVACAM Group

- ADVACAM s.r.o., Prague: **imaging cameras and solutions** (since 2013)
  Spin-off from Institute of Experimental and Applied Physics, Prague
  - 25 employees (+10 in two daughter companies: InsighArt, Radalytica)
- ADVACAM Oy, Espoo: **semiconductor sensors & modules** (since 2012)
  Spin-off from VTT Technical Research Centre of Finland
  - 12 employees

Selected clients/partners

Certified quality

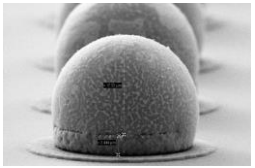
Advacam activities

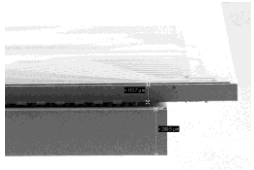
- **ADVACAM offers:**
  - Semiconductor **sensor fabrication** and micro-packaging
  - High-resolution particle counting **imaging detectors** with energy sensitivity
  - Development of new radiation **imaging solutions and methods**

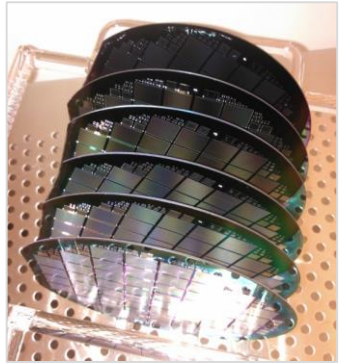
- **ADVACAM covers all process:**
  - **All key technologies available in-house** (semiconductors, HW, SW, labs, methods)
  - Novel technologies protected by patents (in average **1 new patent every 6 months**)
  - High scientific level of the R&D team, professional engineering, **certified production**.

- **ADVACAM intensively collaborates with major companies and institutions in the field**
  - Science: CERN, NASA, ESA, JINR Dubna, DTU, INFN, CEA, BAM …
  - Industry: STATOIL (EQUINOR), GE, Thermo Fisher, Applus RTD …

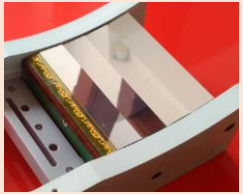
Semiconductor technologies and micropackaging



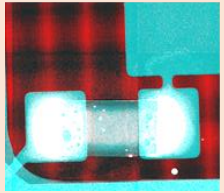




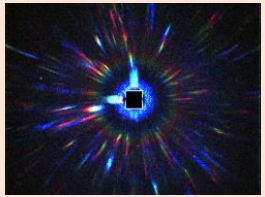
Custom devices



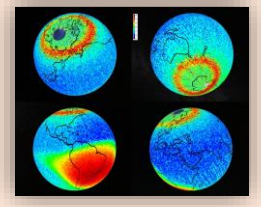
Color XRT



Color XRD



Space

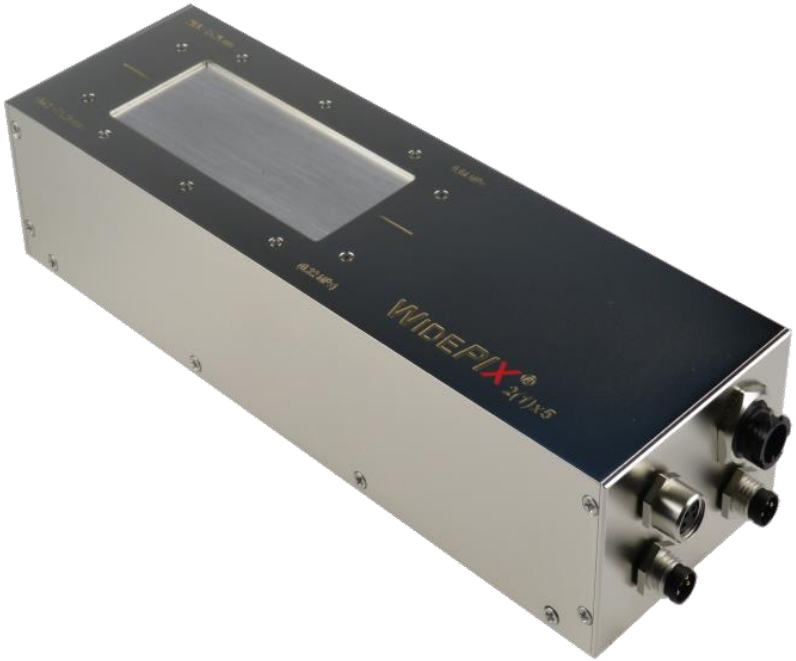


Examples of ADVACAM cameras: ***The world largest particle counting detector*** *with continuously sensitive area (left) is the WidePIX10x10 with 2560x2560 pixels, smaller units such as WidePIX2x5 (1280x512 pixels) or even* ***miniaturized to USB stick size camera*** *MiniPIX. Custom sizes and shapes are possible.*

Large area detectors for X-ray imaging:

Medipix3 based

Imaging with Medipix3: Static & moving

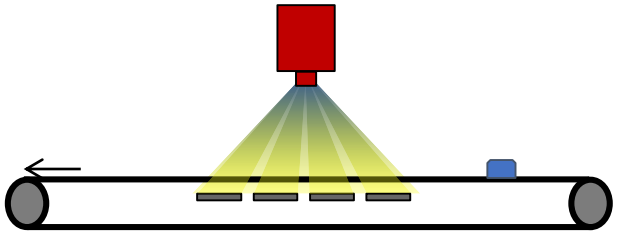


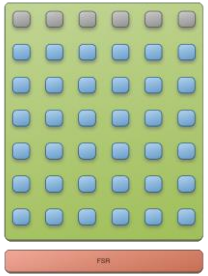
Features:

- Medipix3 technology:
  - 2 thresholds with pixel size of 55 µm
  - 8 thresholds for 110 µm pixels
  - Charge summing logic
- 1280 x 512 pixels = **0.65 Mega pixels (70 x 30 mm^2)**

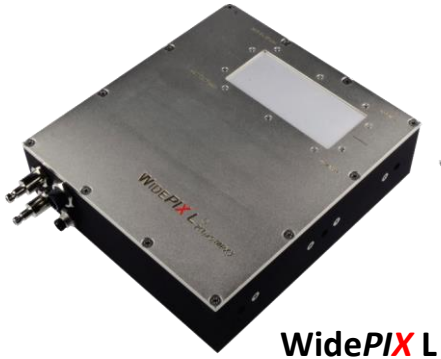
Integrated TDI mode (unintentional feature):

- For continuous scanning of moving objects
- Image integration during readout (row by row)
- Expose => read last row => Expose => read row => ….





WidePIX-L MPX3 family: detectors for CT and scanning



WidePIX L 2(1)x5
1280x512 pixels
70x30 mm

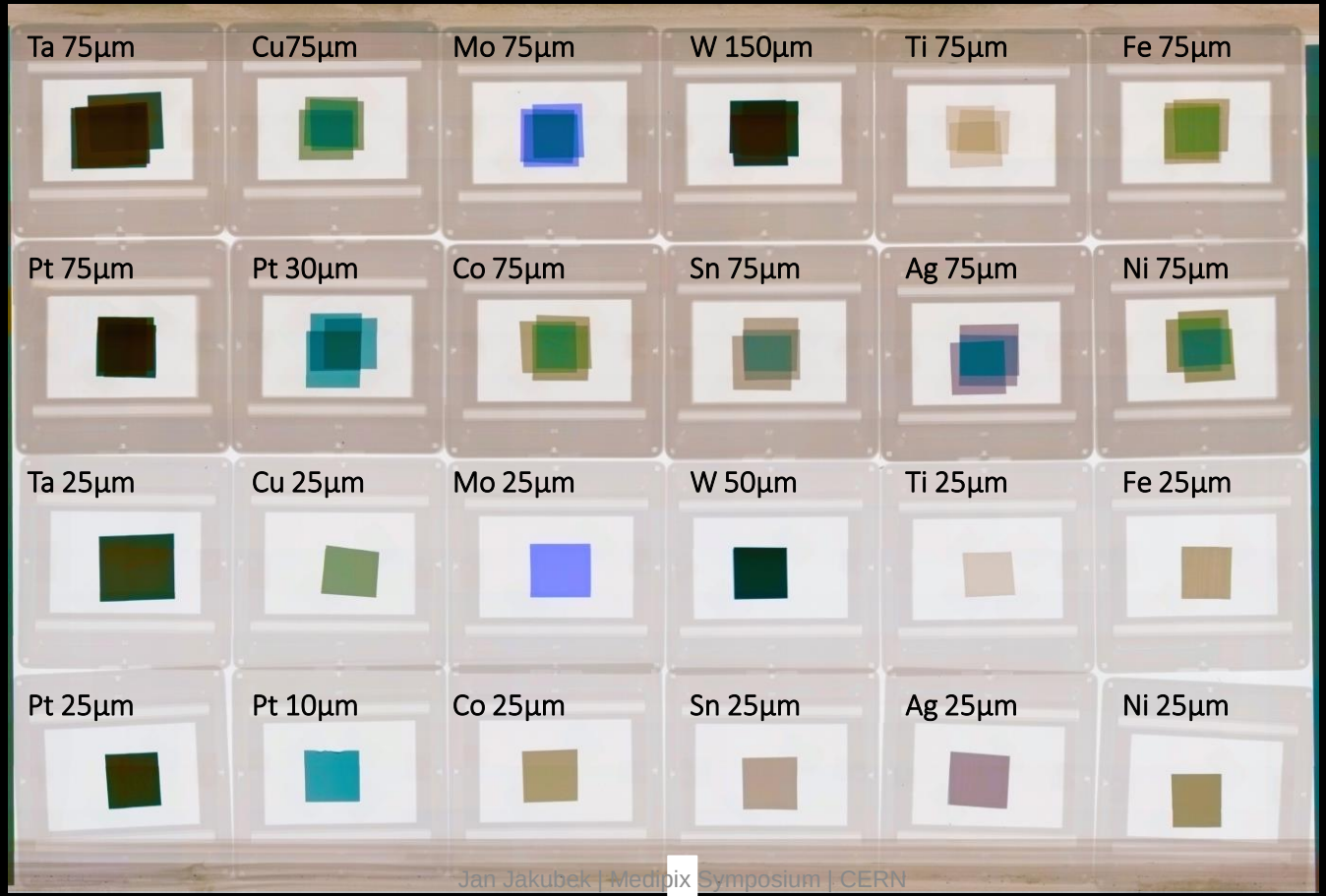
WidePIX L 2(1)x10
2560x512 pixels
140x30 mm

WidePIX L 2(1)x15
3840x512 pixels
210x30 mm

Features:
55 µm pixels: 2 thresholds
110 µm pixels: 8 thresholds

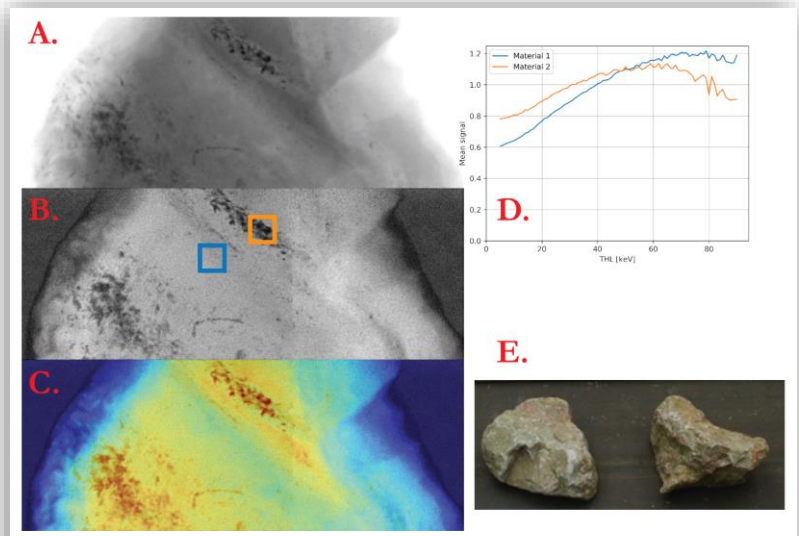
Suited for:
CT scans, **TDI scans** (e.g. conveyor belts, welds), robotic scans …

The regular vs “colour” X-ray imaging of test samples

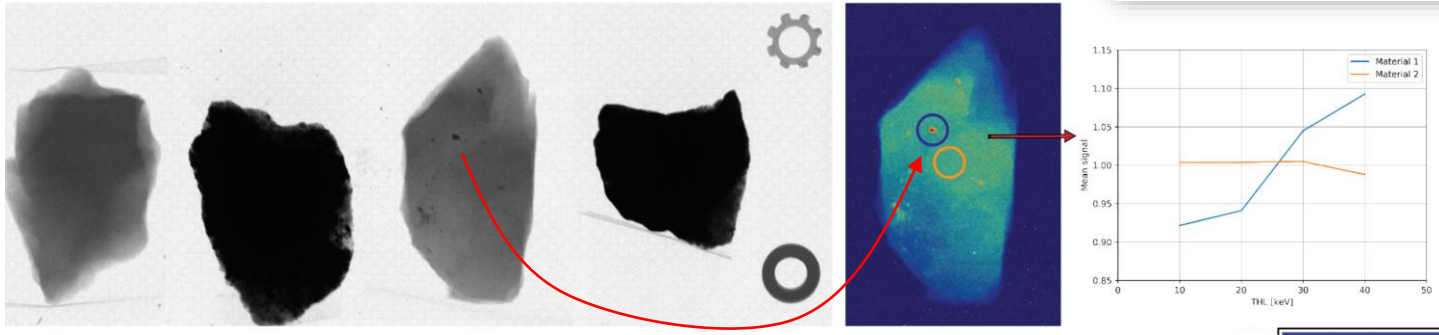


Mineral samples on conveyor belt
Ore quality identification

- **Mineral analysis and sorting of rock samples**
- Samples are continuously moving ion top of conveyor belt
- **Belt speed: 0.5-4 m/s**



Iron ore with high density intrusions. Acquired at COMEX laboratory (COMEX SP. Z O.O., Poland)



Advantages:
- Material separation
- Resolution => small intrusions
- Speed=> fast belt

This project has recieved funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 730270

WidePIX L series: connectivity & speed

3 versions according to speed:

	Status	Connectivity	Frame rate [fps]	TDI speed [m/s]	Comment
Normal speed	Ready, available	USB 2.0	40	0.6 m/s	
High speed	Ready, under tests	1 GB Ethernet	200	2.8 m/s	
Ultra high speed	Prototype	USB 3.0	300	4.2 m/s	
Ultra high speed + embedded PCs	Coming	10 GB Ethernet (wi-fi, optical …)	300	4.2 m/s	Local data processing

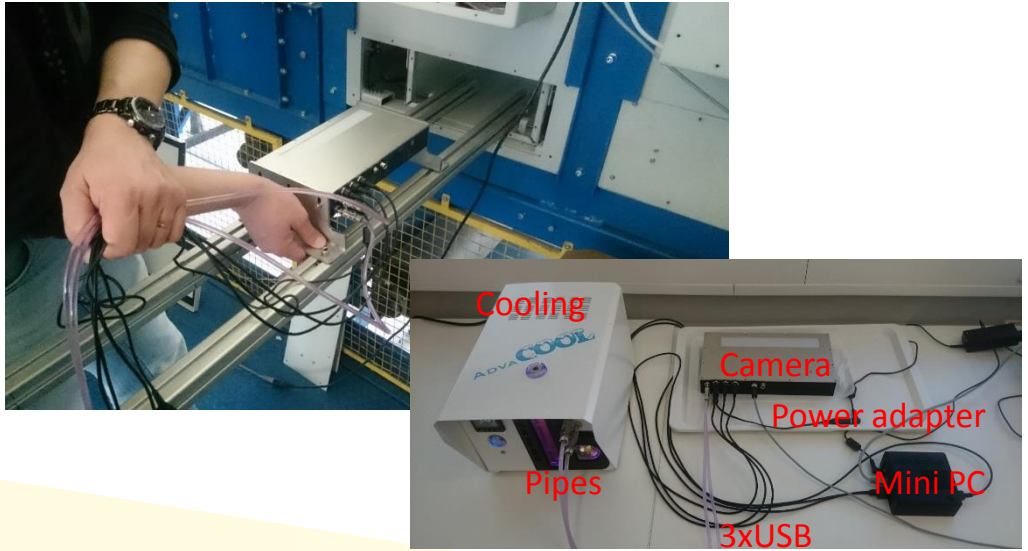
Modular structure:

- **One module = 5 chips** (1280 x 256 (or 512) pixels, 55 µm pitch)
- Modules are stitched forming longer rows (2, 3, 6 modules) and/or doublets (no TDI)
- **Each module has own communication channel => the speed is independent of number of modules**

Example of installation under conveyor belt

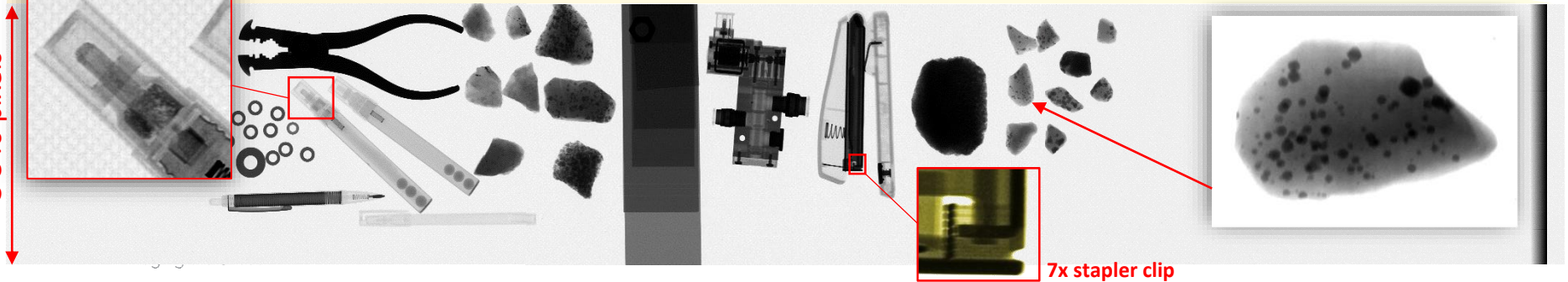
Automatic line for mineral sorting in mines:

- **Dual energy X-ray transmission**
- To be combined with data from XRF detectors and 3D stereoscopic optical cameras



26 000 pixels = 1.5 m in 3 seconds = **100 MPixels**

3 840 pixels



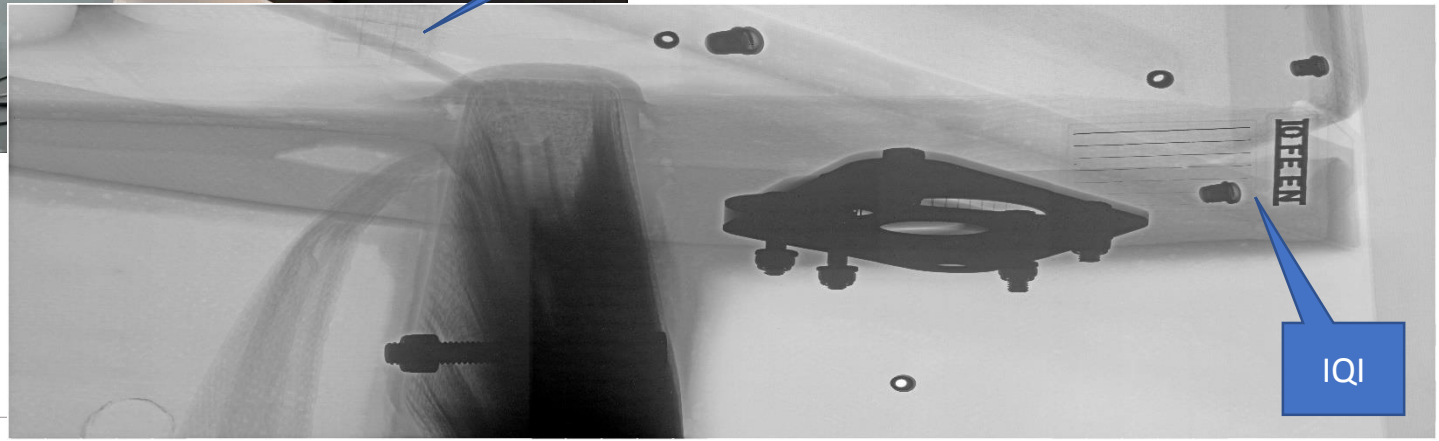
Robotic scanning of large and complex objects

Robot with X-ray trube

Patch = old repair

Robot with detector

To be checked:
Bottom part of fuselage of ultralight plane



IQI

radalytica®

ADVACAM
Imaging the Unseen

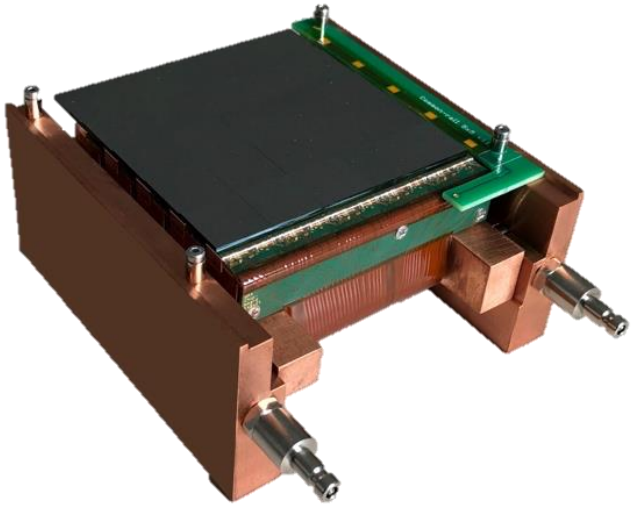
WidePIX 5x5 CdTe:
The first large area CdTe imaging detector with continuous sensitivity (no gaps)

Features:

- Pixel size of **55 µm**
- 1280 x 1280 pixels = **1.6 Mega pixels**
- Sensitive area of **70 x 70 mm^2 (can be larger if needed)**
- **Gap-less tilling**:
  - Gaps between modules smaller than quarter of the pixel
  - Edge pixels of 100 µm

Supported sensor types:
(Bias voltage +/- 500 V)

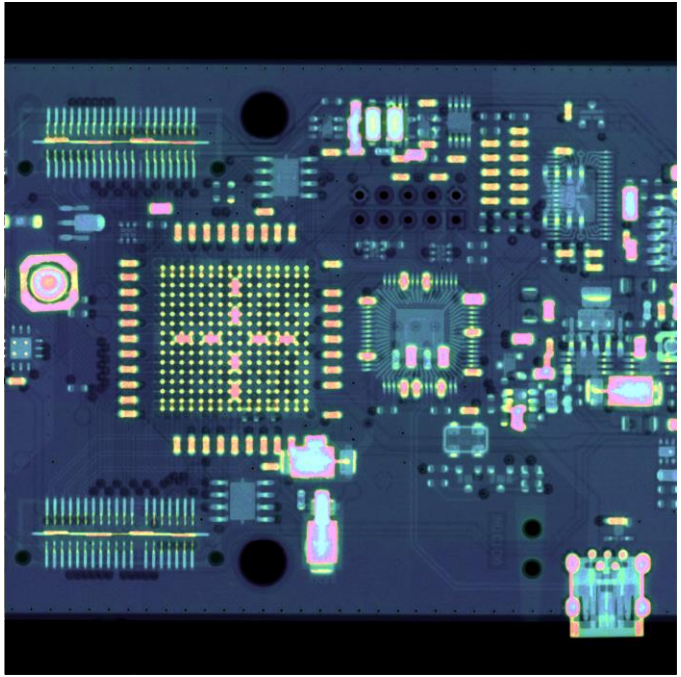
- **CdTe 1 mm**
- CdTe 2 mm
- Si 300 µm

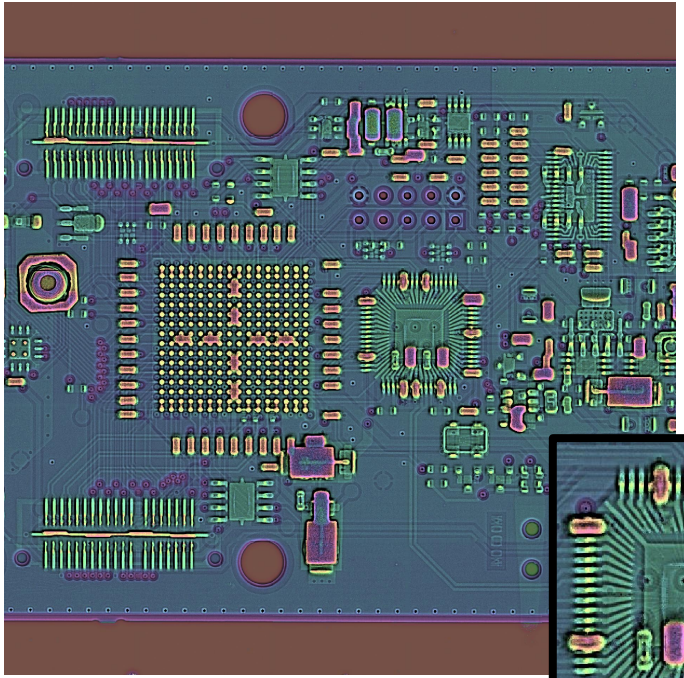


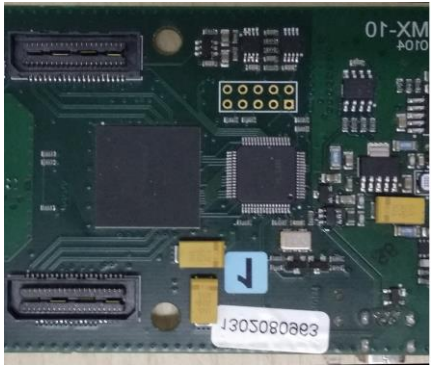
Material sensitive imaging with WidePIX 5x5 CdTe

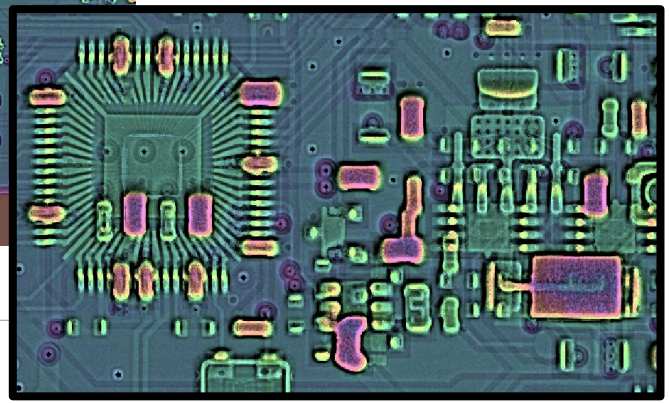
Example 1: PCB

60 kVp, 3 thresholds (7, 20, 35 keV)









High pass filter

No tilling artifacts

Application:

Authentication of art: Paintings

Card Players, signed Schikaneder, 20th century, oil on canvas.

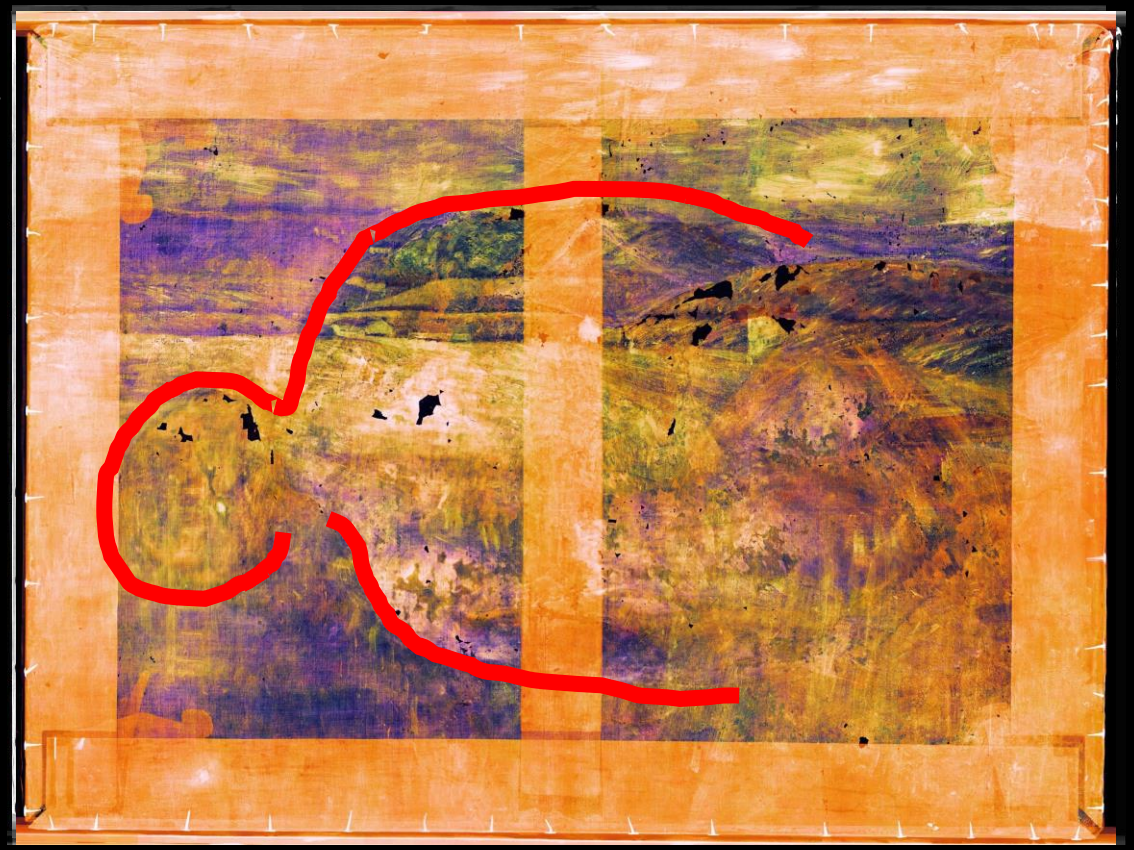
Where is the hat?

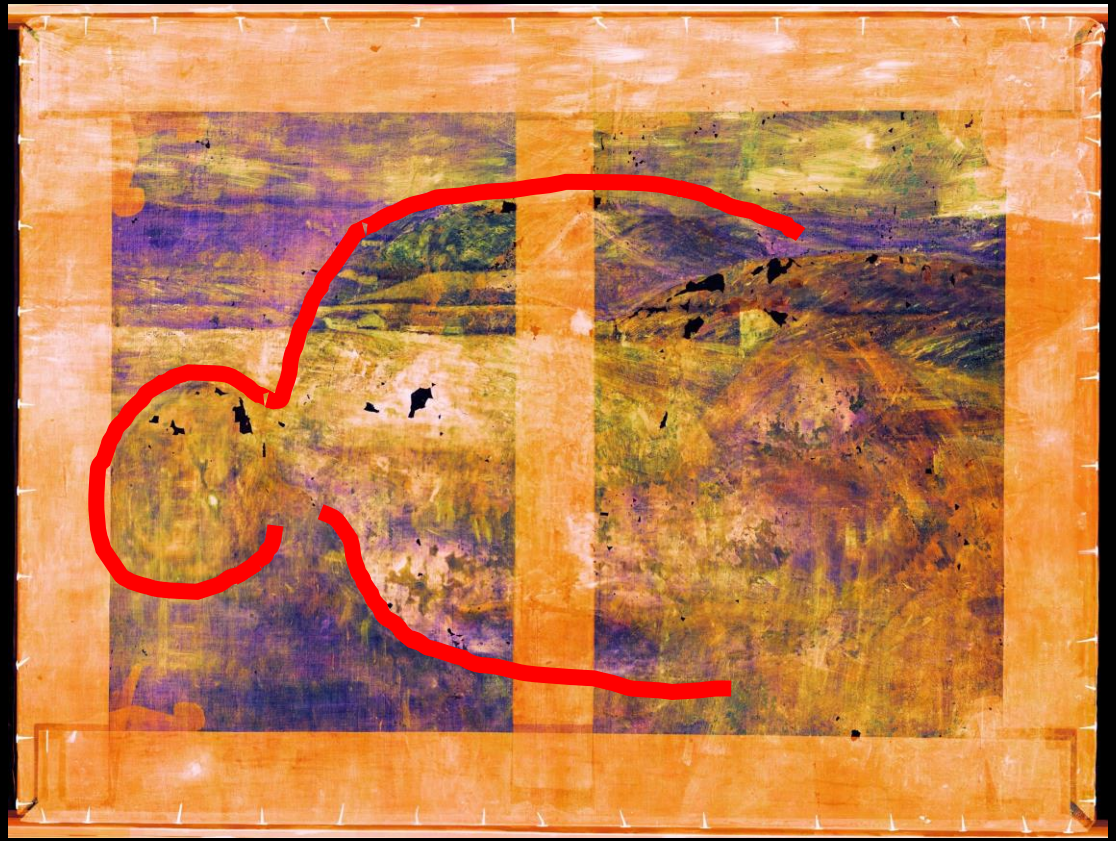
Signed

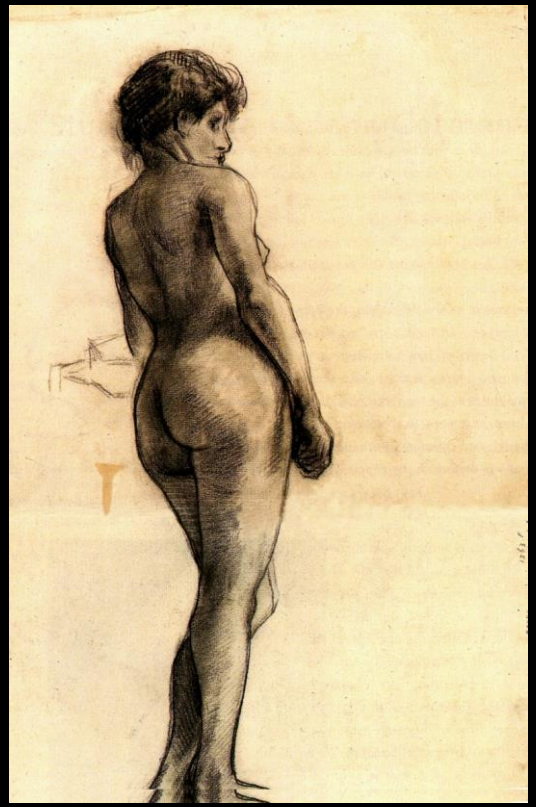
Vincent van Gogh

La Crau with Montmajour in the backgroud

~1888







Timepix3:

⇨ **Fully spectral imaging**

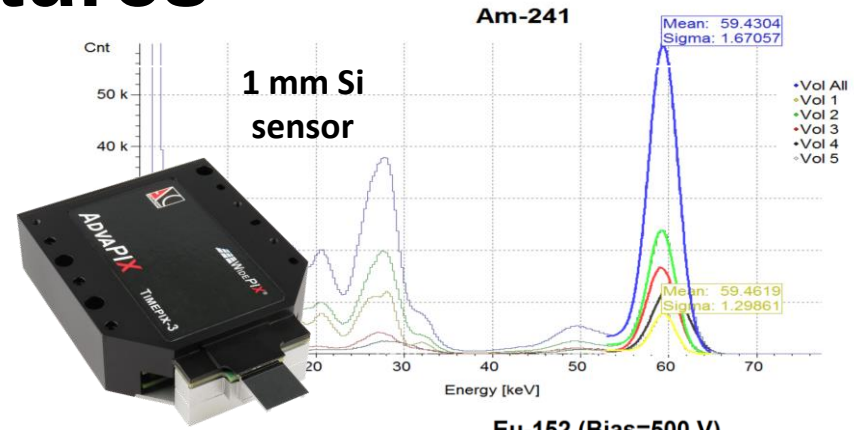
ADVAPIX TPX3: Features

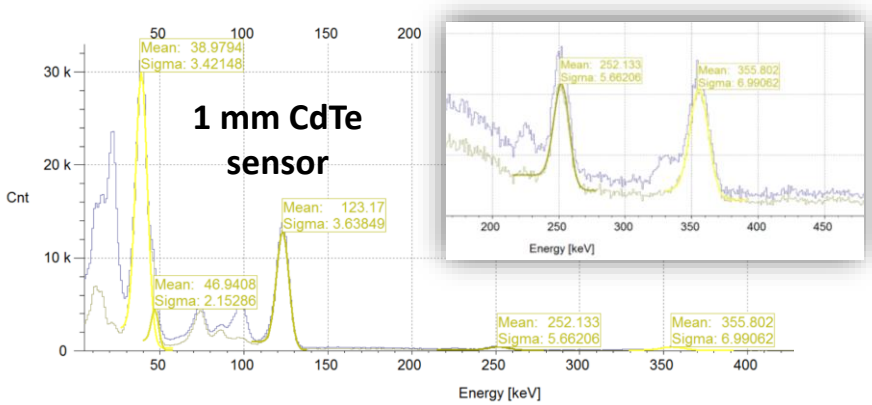
Timepix3:

- Successor of Timepix: 256x256 pixels, 55 µm pitch
- **Event based readout** (Not frame based as for Timepix): Each hit pixel transmits the hit information immediately.

⇒ No dead-time for readout of complete frame.

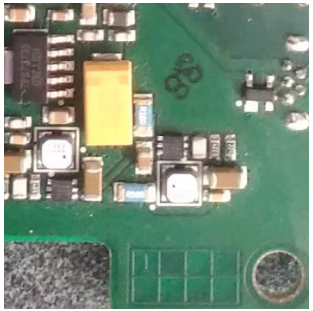
- Ability to measure Energy (ToT) and Time of arrival (ToA) concurrently.
- Time is measured with precision of 1.56 ns
- Chip can produce data stream of 5 Gbit/s.





Example:

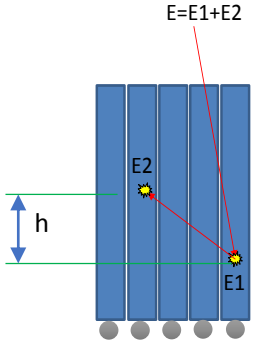
X-ray fluorescence (XRF) imaging



Gamma spectrum reconstruction for CdTe

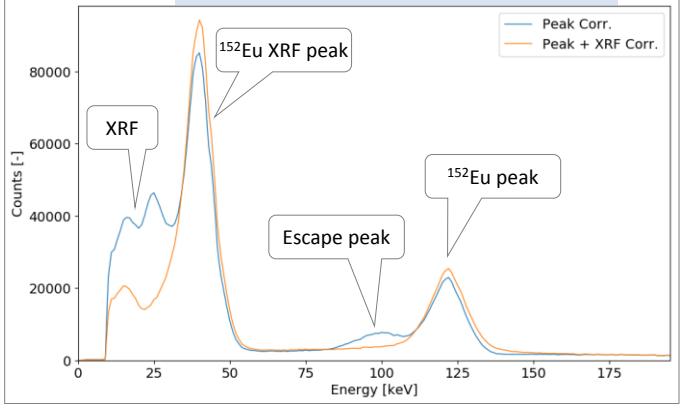
- 2 mm thick CdTe sensor: Efficiency for 120 keV of about 70%
- Coincidence technique removes artifacts and suppresses internal Compton scattering

False events:

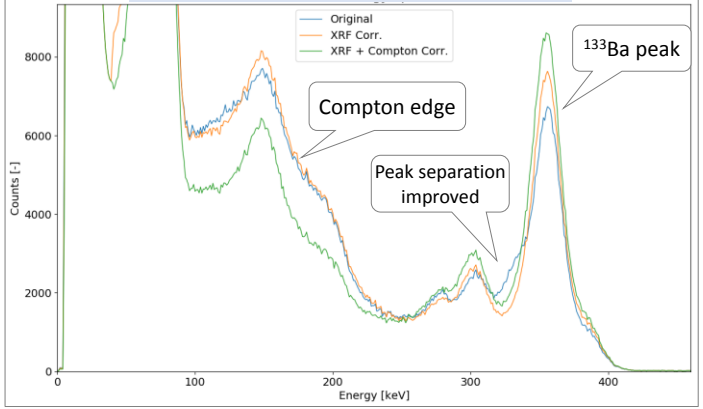


Effects:
- XRF
- Compton

Eu-152 gamma spectrum



Ba-133 gamma spectrum



Internal XRF reconstruction:
1. Coincident events E1, E2 recognized
2. One of them fits to XRF energy of Cd or Te say E2
3. Event E2 is removed.
4. Energy E=E1+E2 is assigned to E1.

Compton effect reconstruction:
1. Coincident events E1, E2 recognized
2. Compton and Klein-Nishina formula evaluated for E1 and E2
3. More likely scattering scenario is chosen
4. Energy E=E1+E2 is assigned to correct point.

ADVAPIX CdTe 2 mm: Subpixel resolution

Principle:

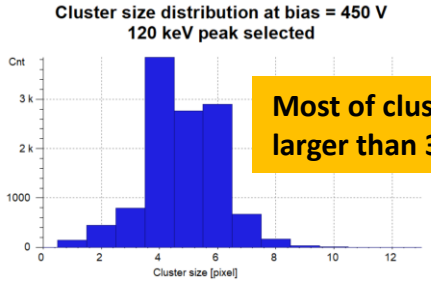
1. Single photon is creates signal in several adjacent pixels => cluster
2. The energy is measured by each hit pixel
3. Position can be calculated with subpixel precision

Real case:

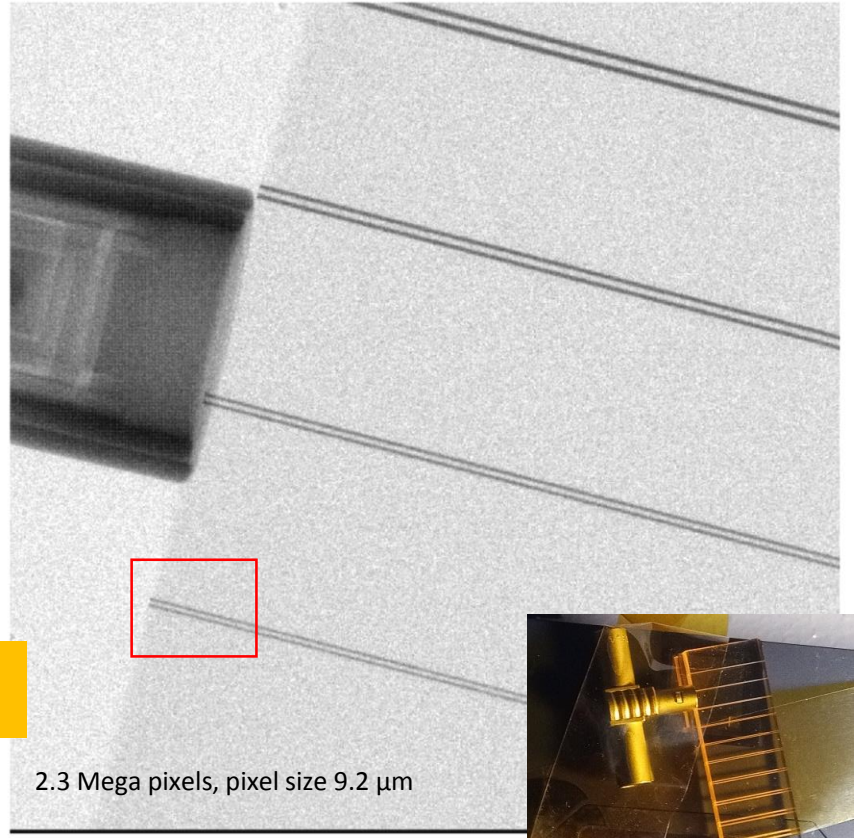
At 160 kVp with **5 mm steel filter**

⇒ Effective energy is 100-120 keV

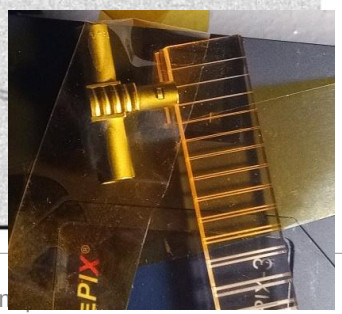
⇒ Average cluster of 5 pixels



Most of clusters are larger than 3 pixels!

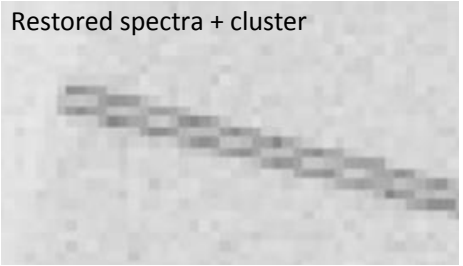


2.3 Mega pixels, pixel size 9.2 µm

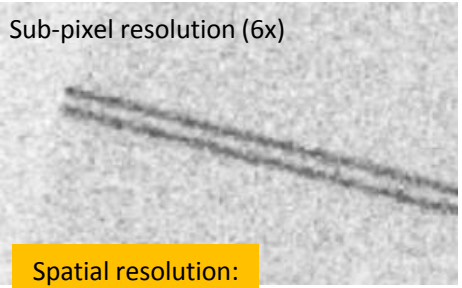


Unprocessed data

Restored spectra + cluster



Sub-pixel resolution (6x)

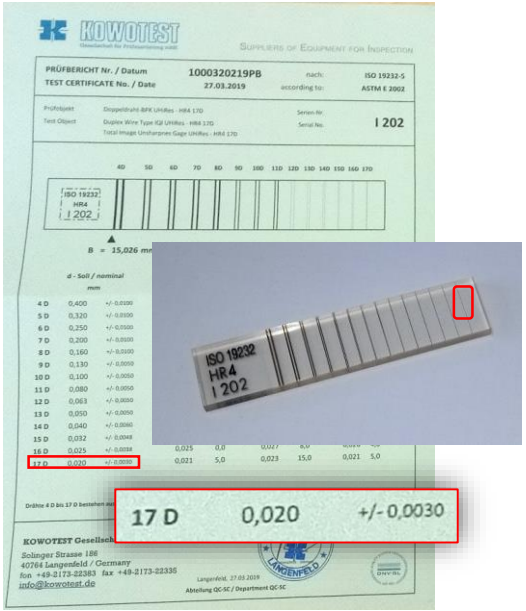


Spatial resolution:
9 µm (RMS)

Subpixel resolution test: The finest Duplex Image Quality Identifier

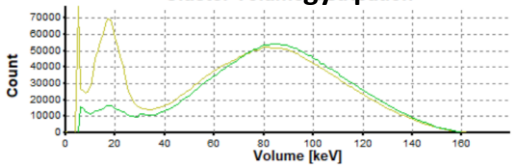
Image quality identifier (IQI) is used in industry for evaluation of quality of imaging systems.
The **Duplex Wire type IQI** is used for spatial resolution tests. It should be placed in front of object to be imaged (e.g. welded iron sheets). The last recognized pair of wires determines the resolution (the wires are recognized if the transmission signal between them reaches at least 20% of max – see picture).

The finest Duplex IQI has the last pair made of wires of 20 µm in radius with gap of 20 µm.

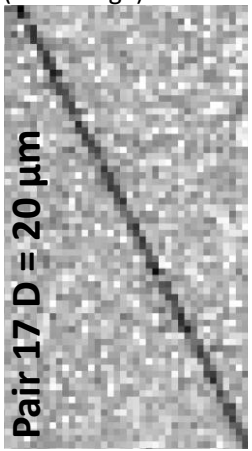


Conditions: 160 kVp, 100 µA, 100 cm distance
5 mm iron sheet,
100 s exposure

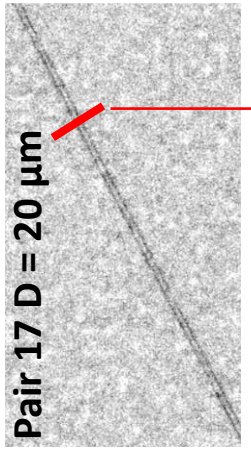
Measured energy spectrum

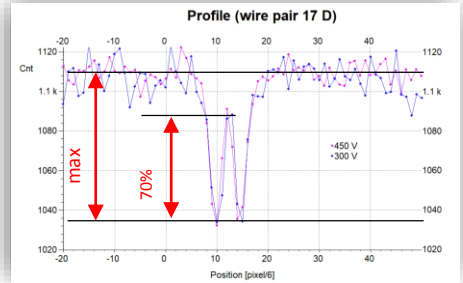


Original resolution (Raw image)



Photon by photon processing Subpixel 6x (9 µm):

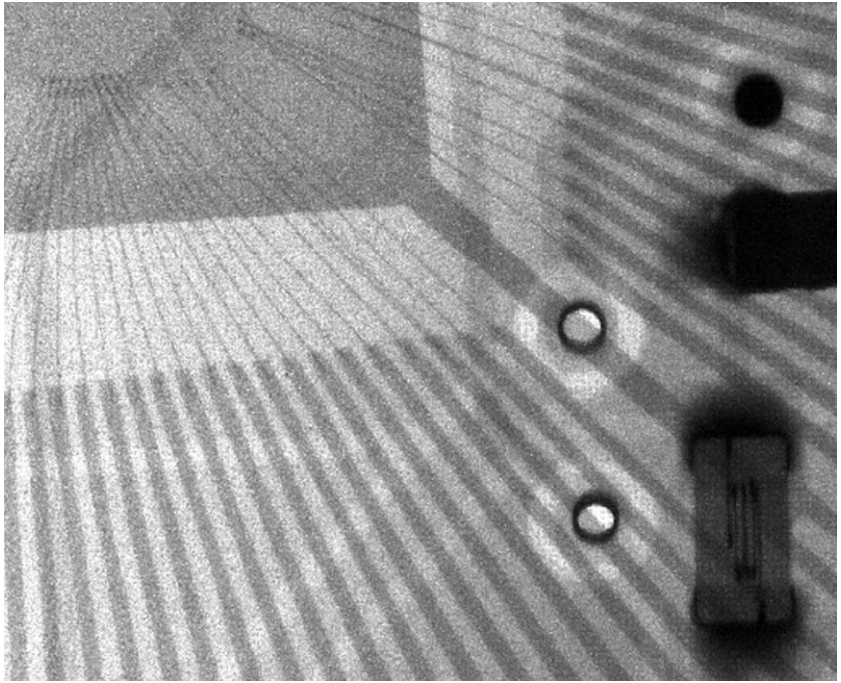


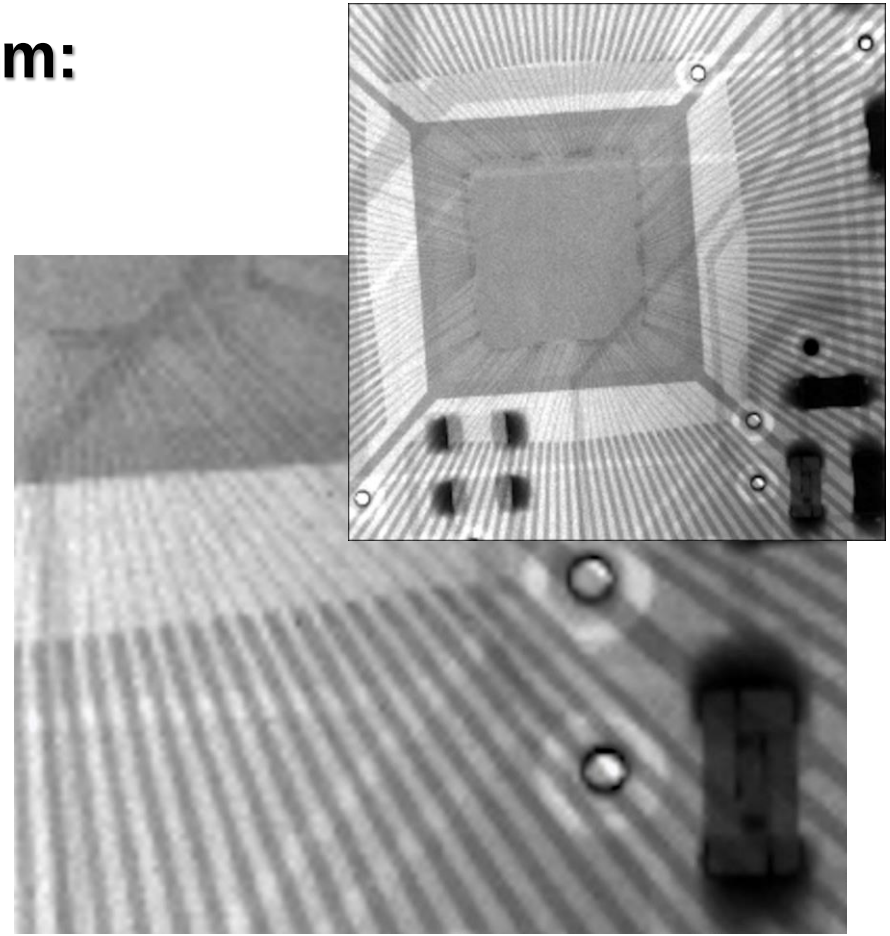


Result:
- The last pair of wires recognized easily
- Signal between wires = 70% of maximum

⇒Resolution cannot be determined with the best Duplex IQI

ADVAPIX TPX3 CdTe 1 or 2 mm: Deeply subpixel resolution





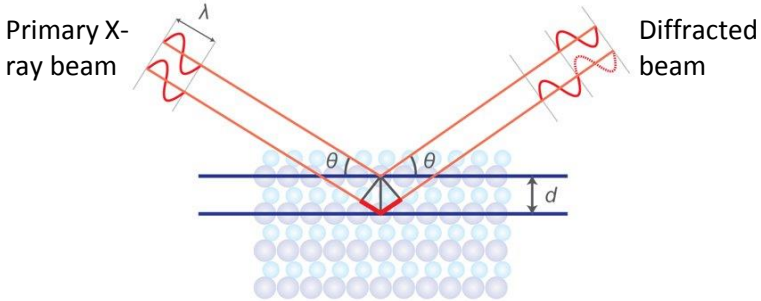
Application:

➡ X-ray diffraction

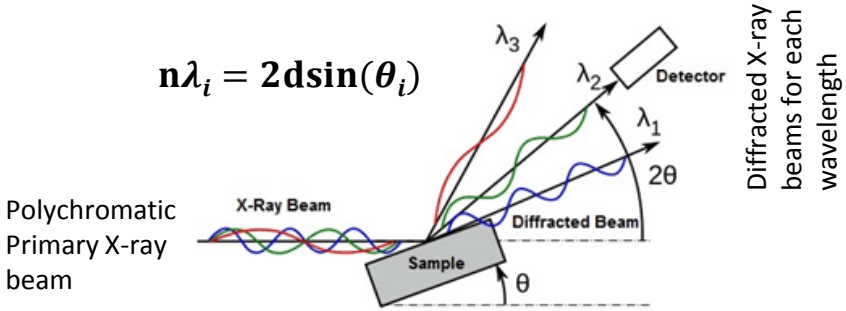
The new application field for ADVACAM

XRD: X-ray diffraction – basic principles

XRD near the surface

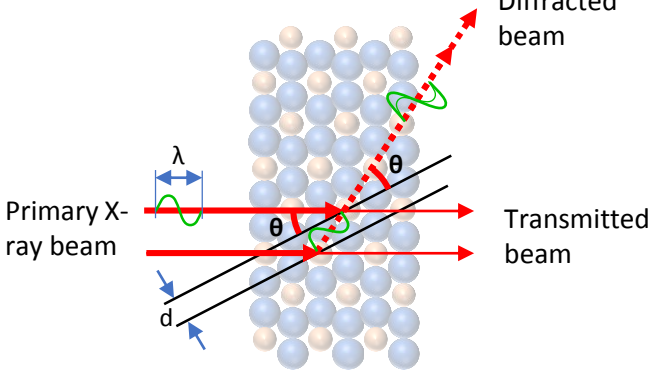


$$n\lambda_i = 2d\sin(\theta_i)$$



XRD through the volume (transmission geometry)

$$n\lambda = 2d\sin(\theta)$$

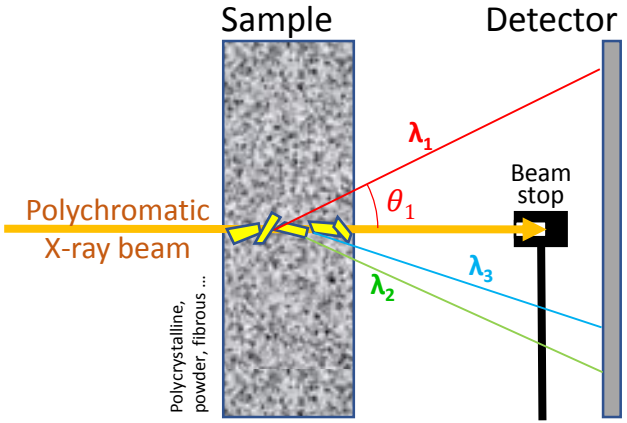


Applications:

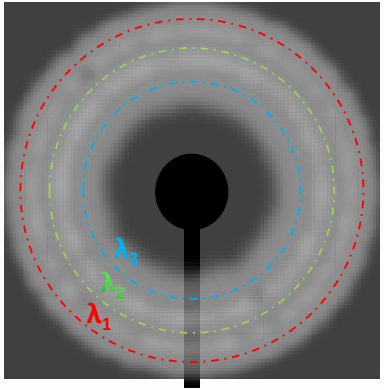
- Analytical method for identification of crystalline materials
- Almost any material can be made crystalline (even large biomolecules).
- **Industry**: alloys (metallurgy), minerals (geology), polymers …

Powder diffraction

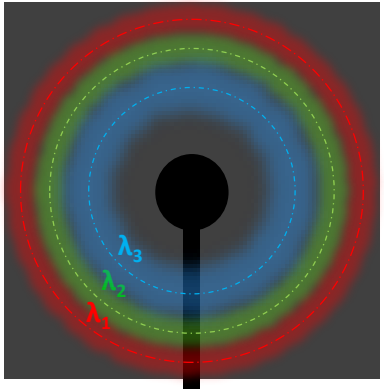
Powder = many small crystals with random orientation
Alloy = many small crystals, some orientation can prevail



Standard detector

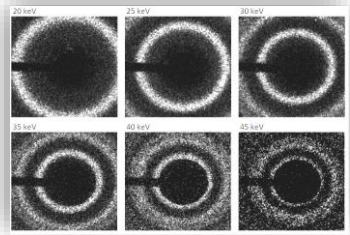


Energy dispersive (spectral)



Each energy channel forms one diffractogram

Channels (width 1 keV):



$$n\lambda_i = 2d\sin(\theta_i)$$

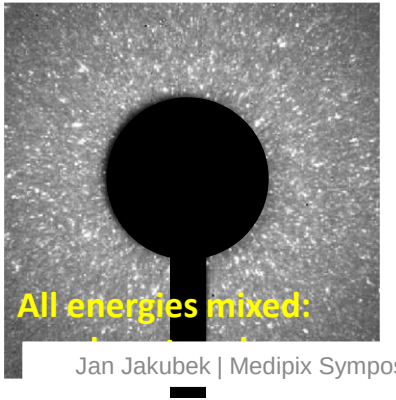
Final diffractogram:

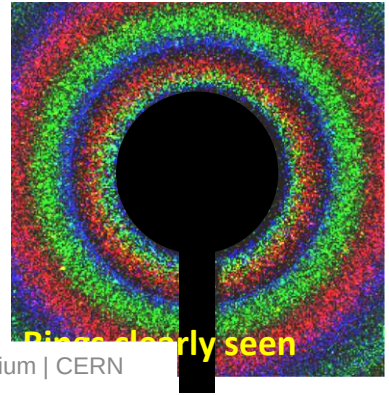
Diffraction angle θ_i:

$$n\lambda_i = 2d\sin(\theta_i)$$

⇒ Angle measured with one wavelength can be recalculated for another wavelength.

Real measurement
Silicon powder

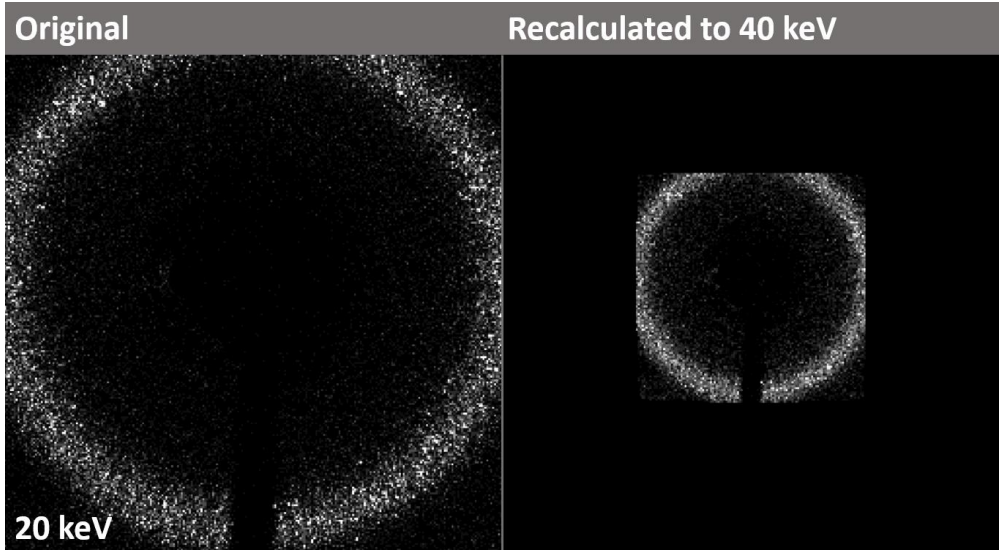




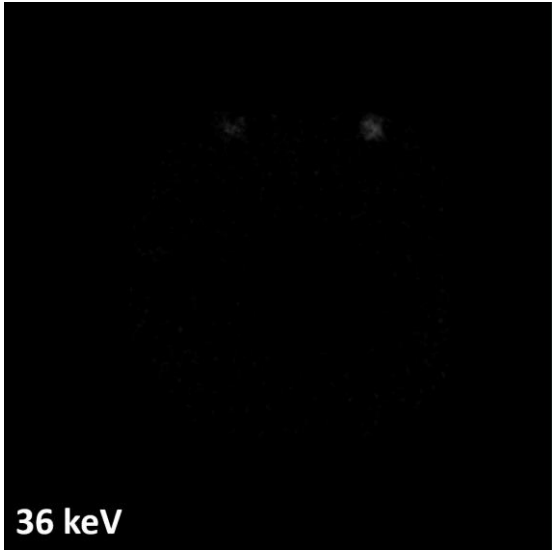
ADVACAM
Imaging the Unseen

Recalculation to single energy and summing results

Silicon powder diffraction

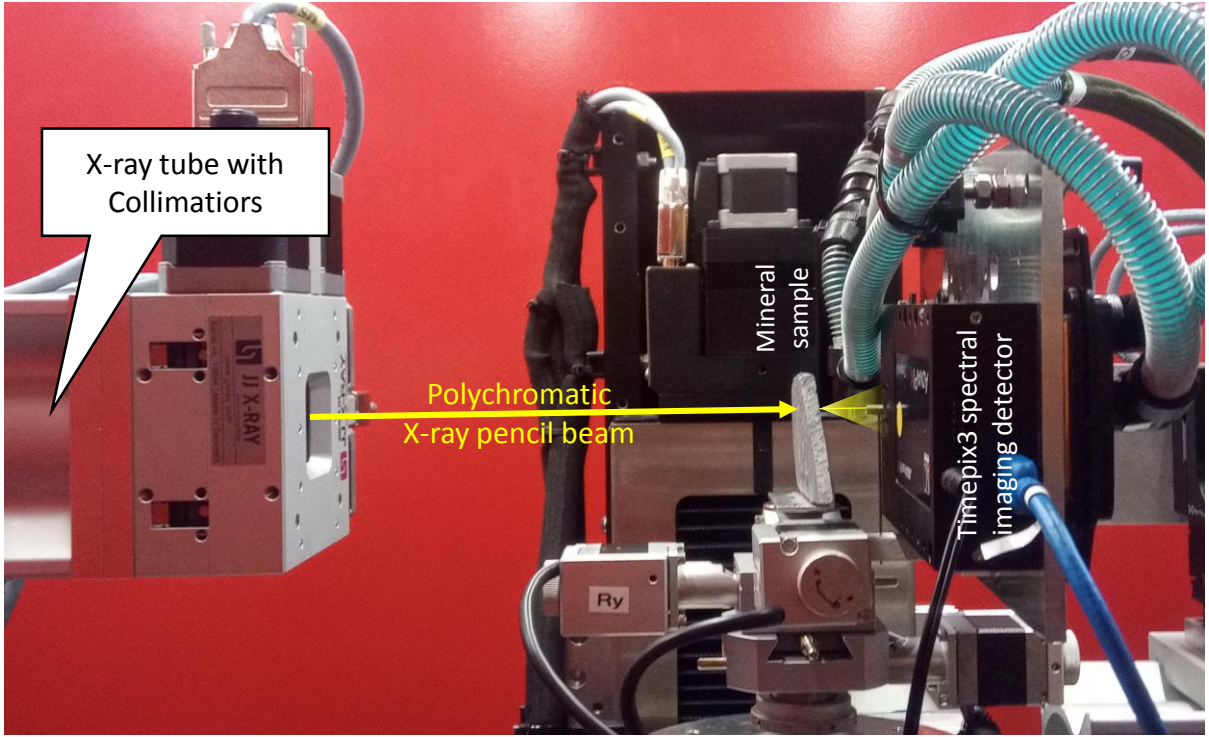


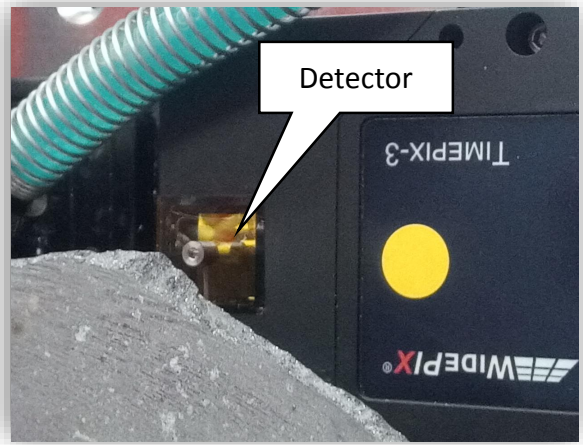
Silicon single crystal (wafer)

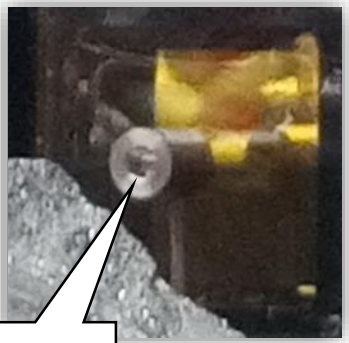


$$\mathbf{n}\boldsymbol{\lambda}_{\mathbf{i}} = \mathbf{2d}\sin(\boldsymbol{\theta}_{\mathbf{i}})$$

Real system


X-ray tube with Collimatiors
Polychromatic X-ray pencil beam
Mineral sample
Timepix3 spectral imaging detector
JJ X-RAY
Ry


Detector
TIMEPIX-3
WIDEPIX

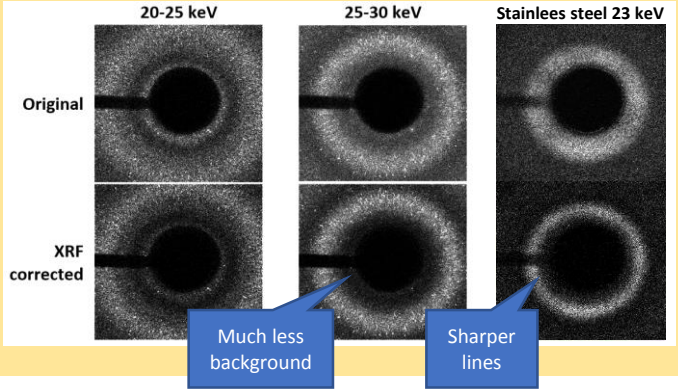

Beam stop

Advantages of Timepix3 for XRD

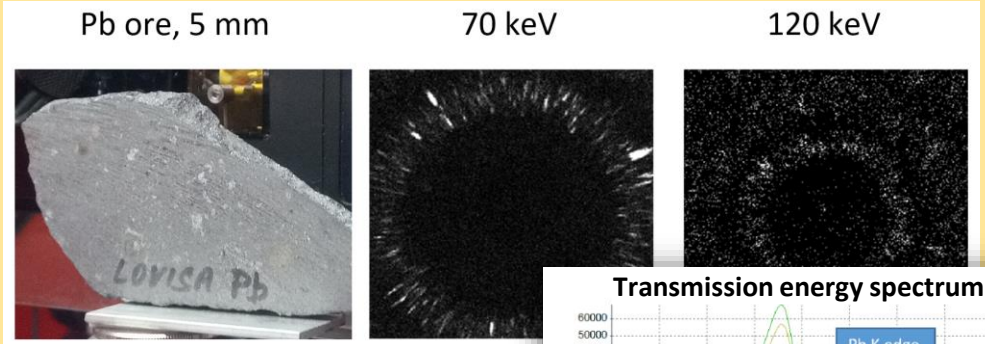
Polychromatic X-ray beam can be used => no monochromator => high intensity => **high speed**
The difractograms measured for individual energy bins can be recalculated to single energy (monochromatized).
The internal sensor artifacts can be removed (internal XRF, Compton scattering).

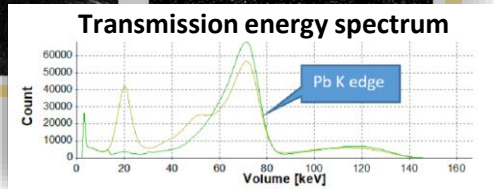
High energy XRD can be performed (100 keV range) =>
=> Thick or highly absorbing samples -> Industry (metallurgy, composites, mining …)
This was possible only with large synchrotron accelerators so far !!!

Internal CdTe XRF signal removal



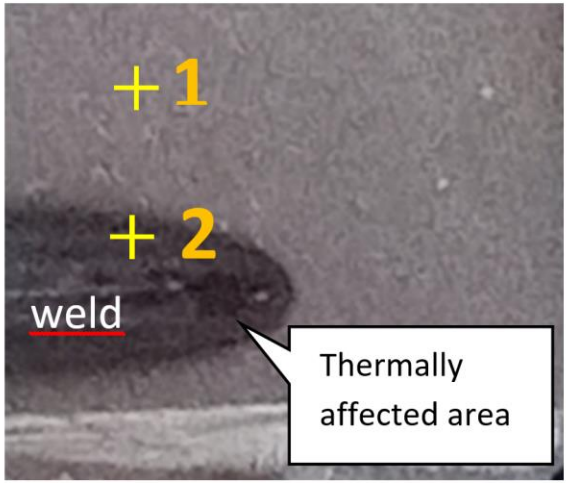
Thick and highly absorbing sample



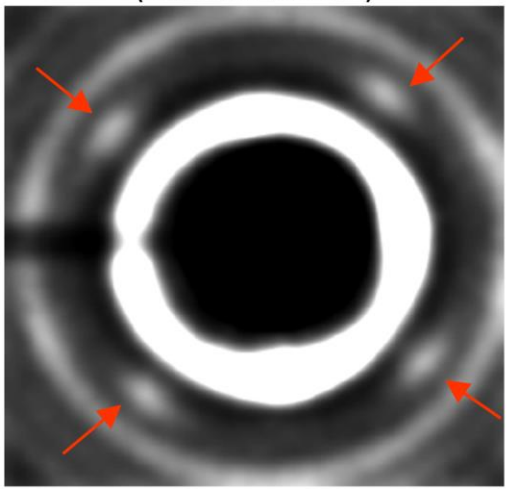


Two welded sheets of stainless steel

Photograph of the sample surface

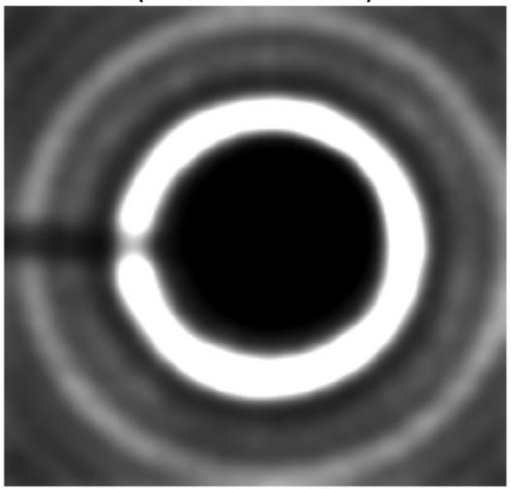


XRD pattern in spot 1 (channel 50 keV)



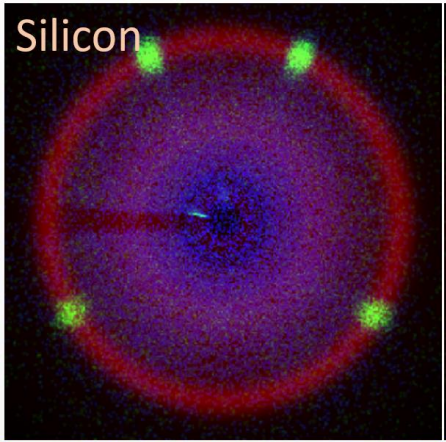
Texture visible out of the weld

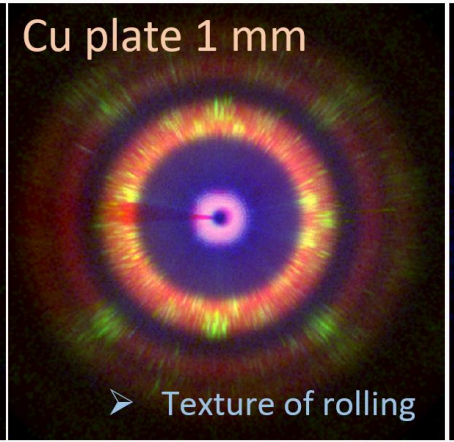
XRD pattern in spot 2 (channel 50 keV)

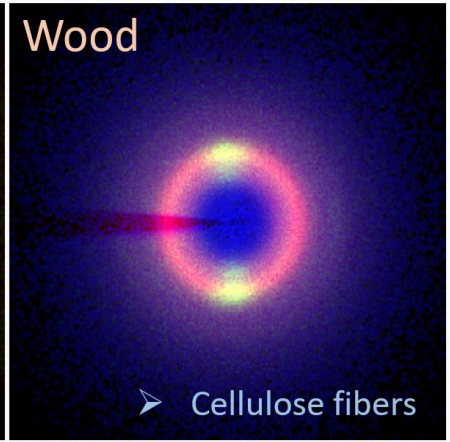


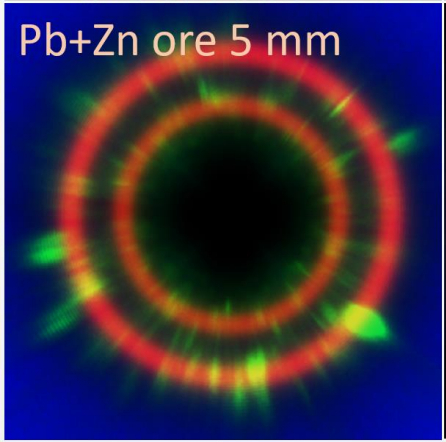
Texture annealed out near weld

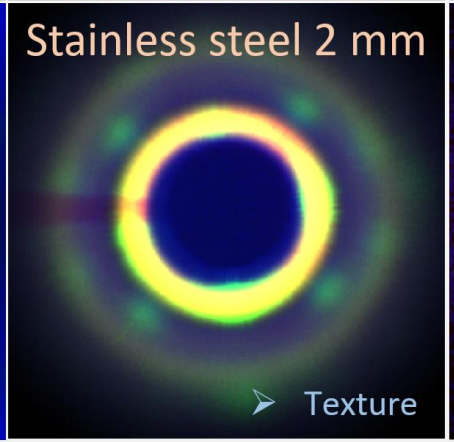
Fig. 10. Transmission XRD measurement of the welded sample (two sheets of stainless steel with total thickness of 2 mm): *Left* – photo with two marks in positions where the measurements were performed, *Middle* – XRD image (channel 50 keV) in position 1 (far from weld), *Right* – XRD image (channel 50 keV) in position 2 (close to weld). The measurement was performed at 160 kVp.

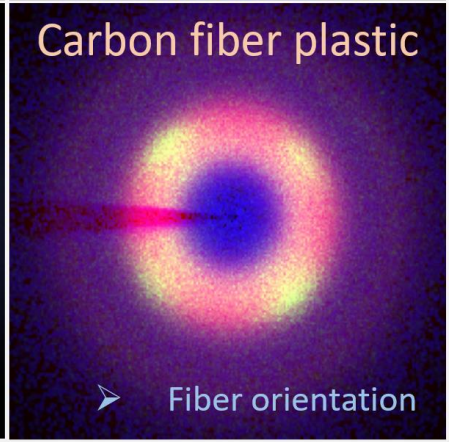

Silicon

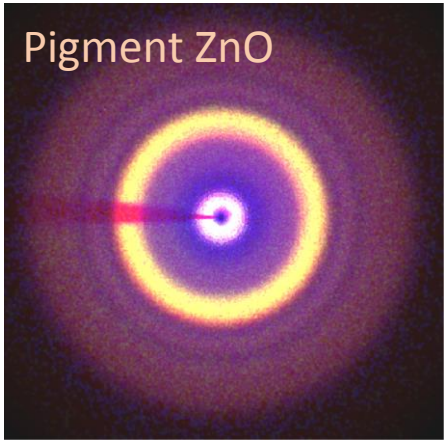

Cu plate 1 mm
➢ Texture of rolling


Wood
➢ Cellulose fibers

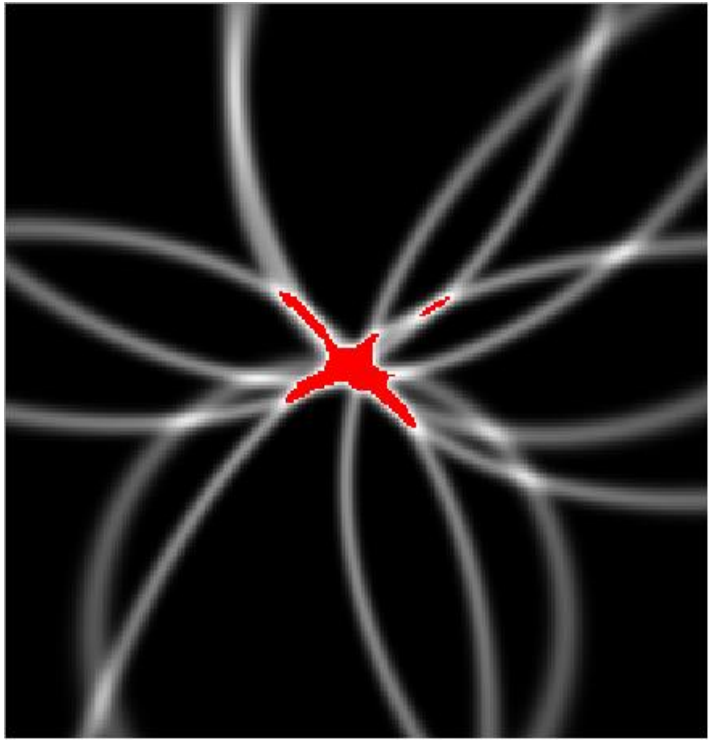

Pb+Zn ore 5 mm


Stainless steel 2 mm
➢ Texture


Carbon fiber plastic
➢ Fiber orientation

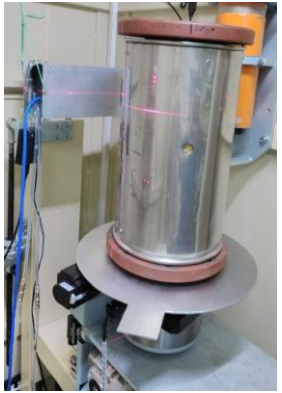

Pigment ZnO

Thank you for your attention

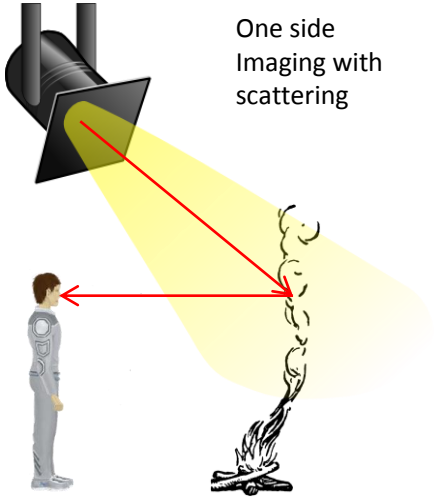


Questions?

Back-scatter imaging:
Corrosion under insulation



Imaging with one side access

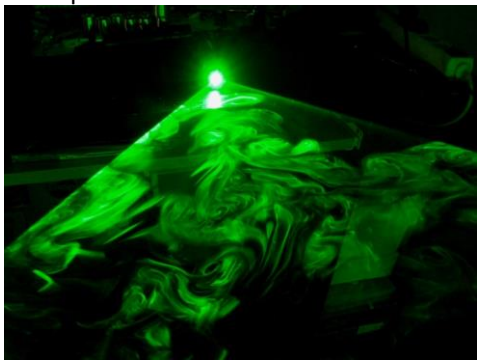


Back-scattering of radiation passing through the sample

- This principle is well known with visible light passing through transparent environment.
- Some part of the light can be scattered back e.g. by fog, smoke, dust …
- Color (wavelength) of scattered radiation (light) carries information about material

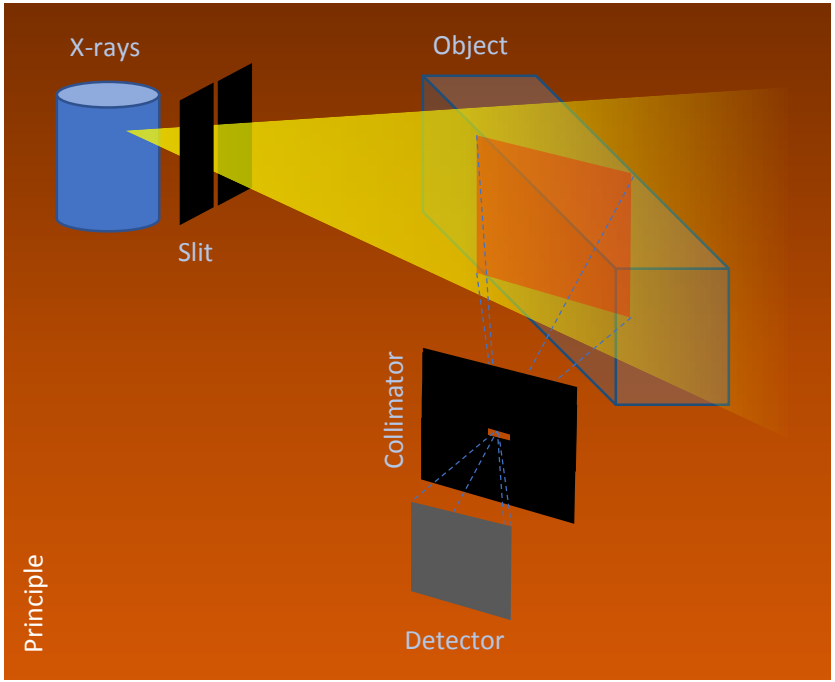
Energy (color) = material

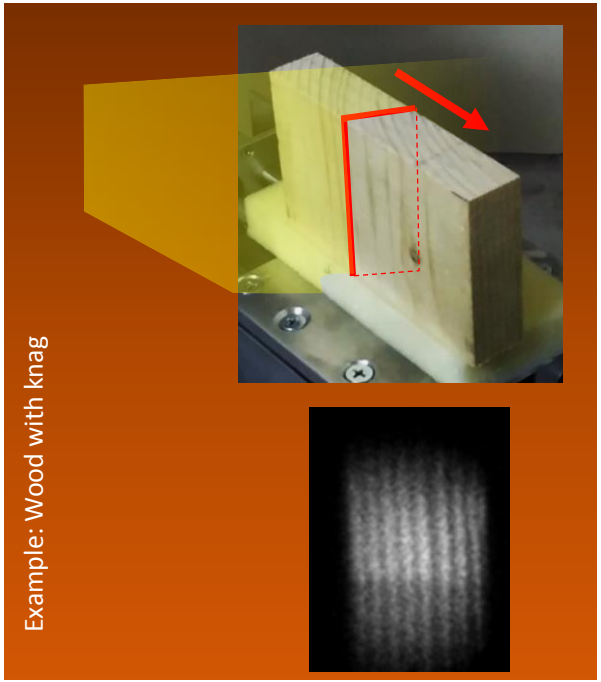
One plane illuminated => cross section



3D imaging based on back scatter

- X-ray or gamma radiation penetrate deep into heavy materials
- Part of radiation passing through the sample scatters back, part is absorbed and part transmits through (similarly as light in fog).





Corrosion under insulation proof of Concept
Full Field Irradiation

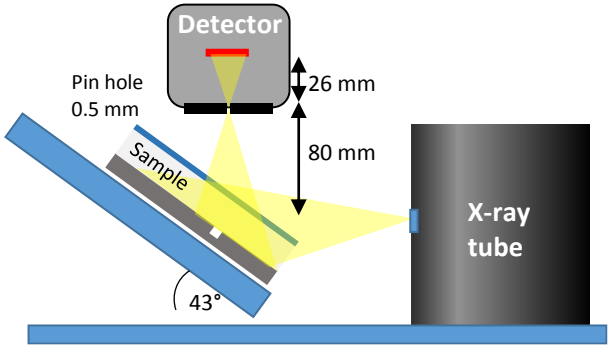
Principle :

- Source collimator not present
- Geometry parameters: to fit the whole sample area on sensor field
- 2D image of surface: all 3D features summed up

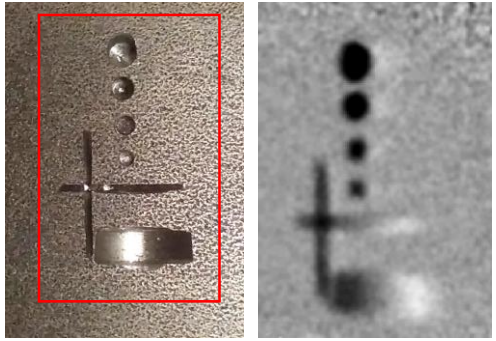
Advantage: Fast, One shot image, Easy for orientation

Disadvantage: No real 3D information, but stereoscopy possible

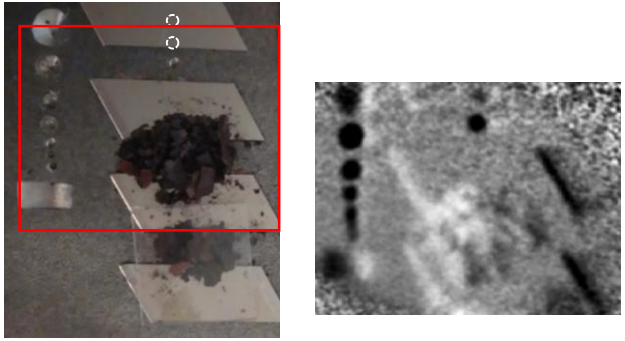
Set-up geometry (COMET 160 kVp, 1 kW)



Area 1



Area 2



Pinhole size => resolution

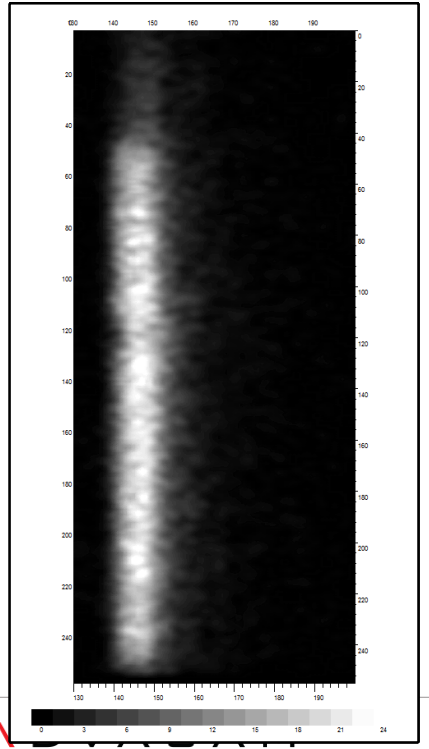
	pixels	mm
Sigma	4.62	**0.25**
FWHM	10.87	**0.60**

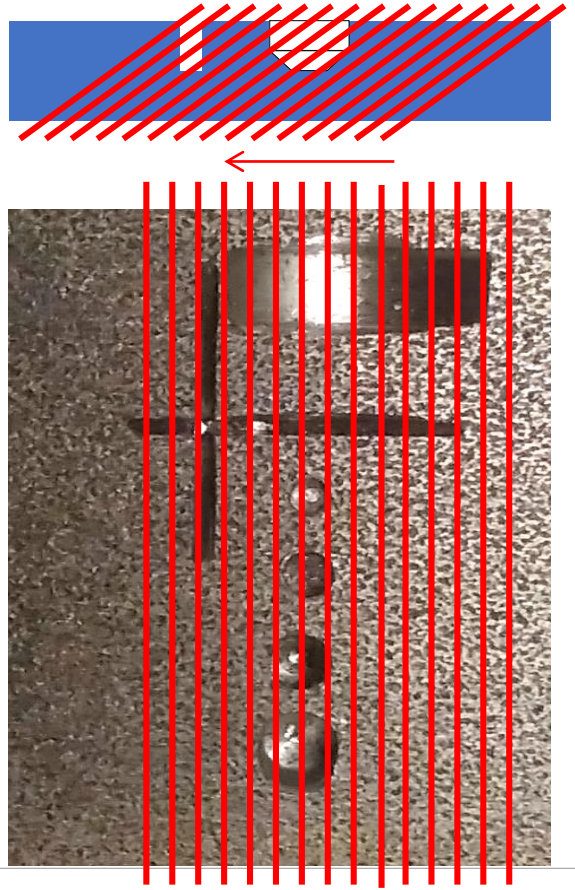
Background	cnt	[%]
Total sum	2.27E+07	100.0%
Sum out of beam	54111	**0.2%**
Beam signal	2.27E+07	99.8%

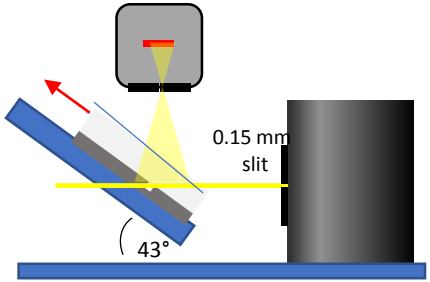
Depth Sliced Scanning: Linearly Collimated X-ray beam

Scanning parameters:

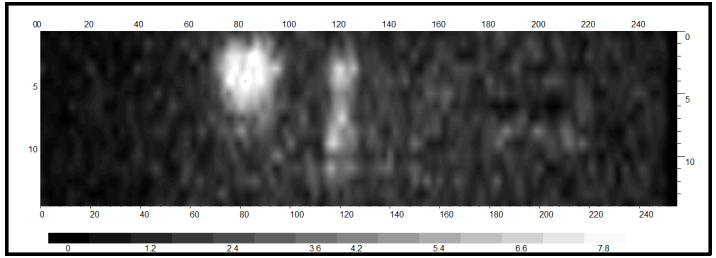
- Scan step: 1 mm, 60 s per slice
- Mean statistics:





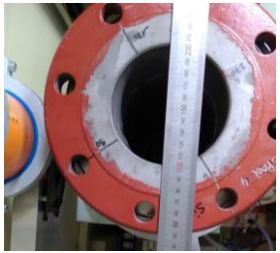


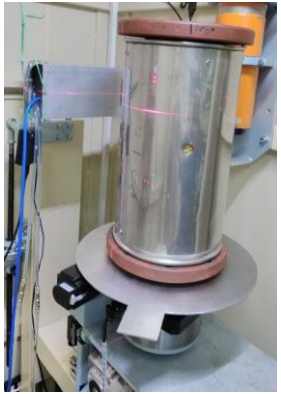
Horizontal slices calculated:

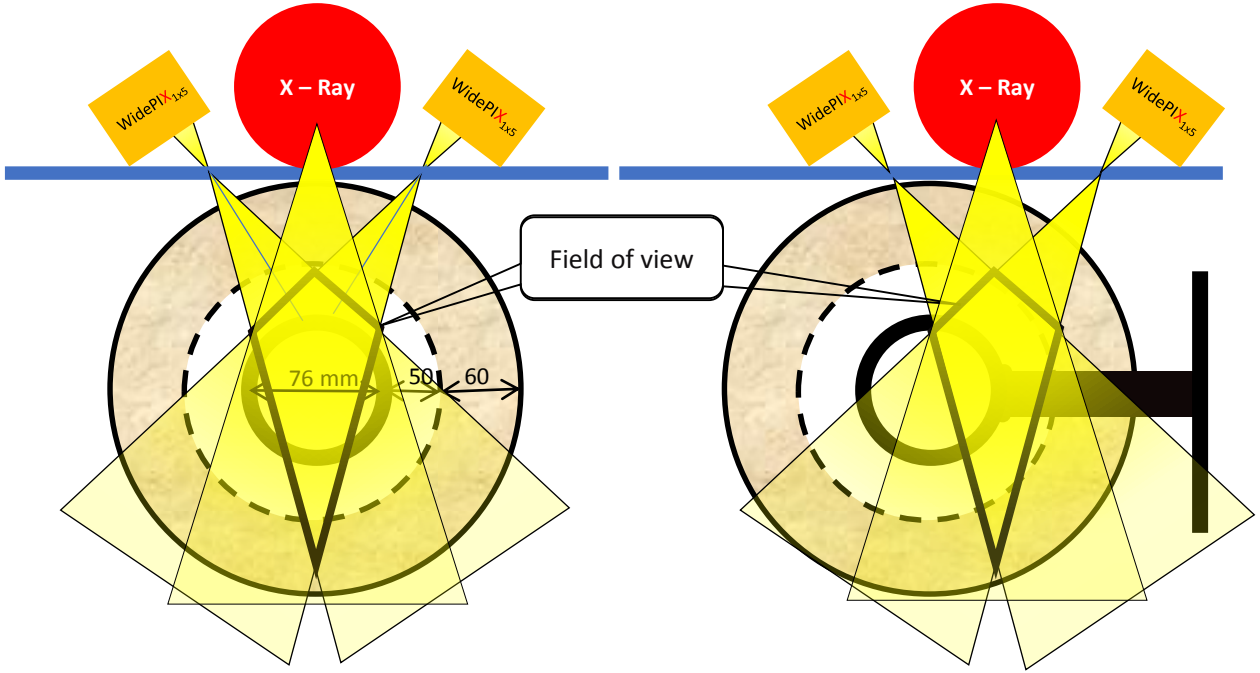


Goal: Imaging of corrosion under insulation

Sample pipes with insulation and stainless steel mantle



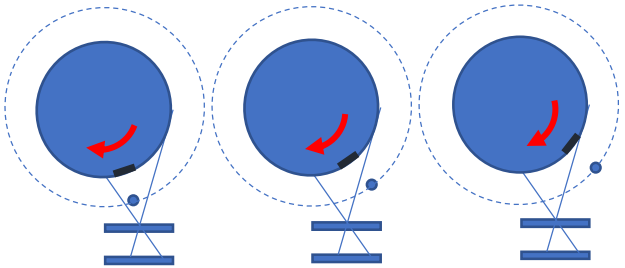




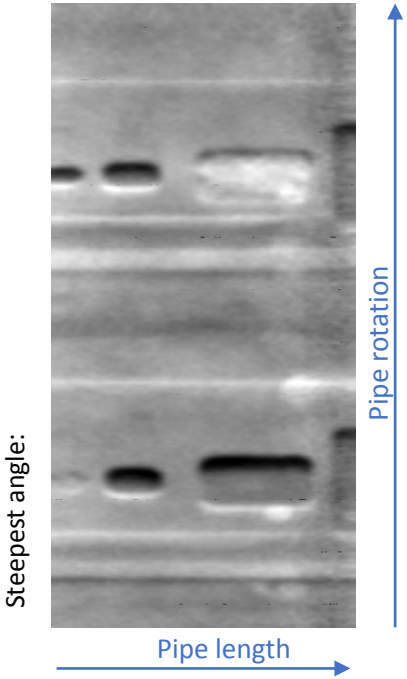
For default geometrical parameters assumed 3 inch pipe with spacer
Designed field of view to cover both pies versions, or pie support

Semi 3D: Combining several angles

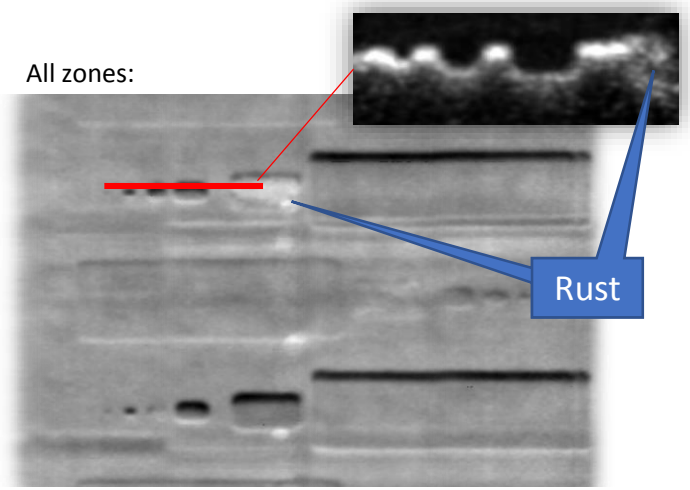
- Rotation step is 10 degrees while field of view covers more than 60 degrees => **each point of the surface is seen in 6 images**
- Mantle imperfections smaller than 10 degrees can be suppressed selecting best view (one of six) for every point.



Zone 3:

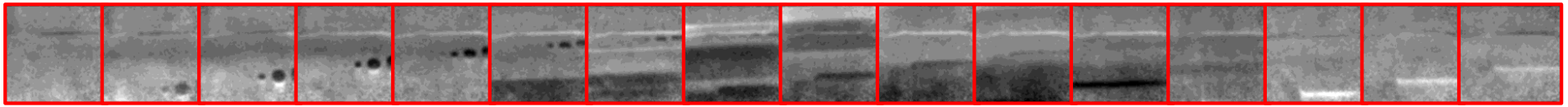


All zones:



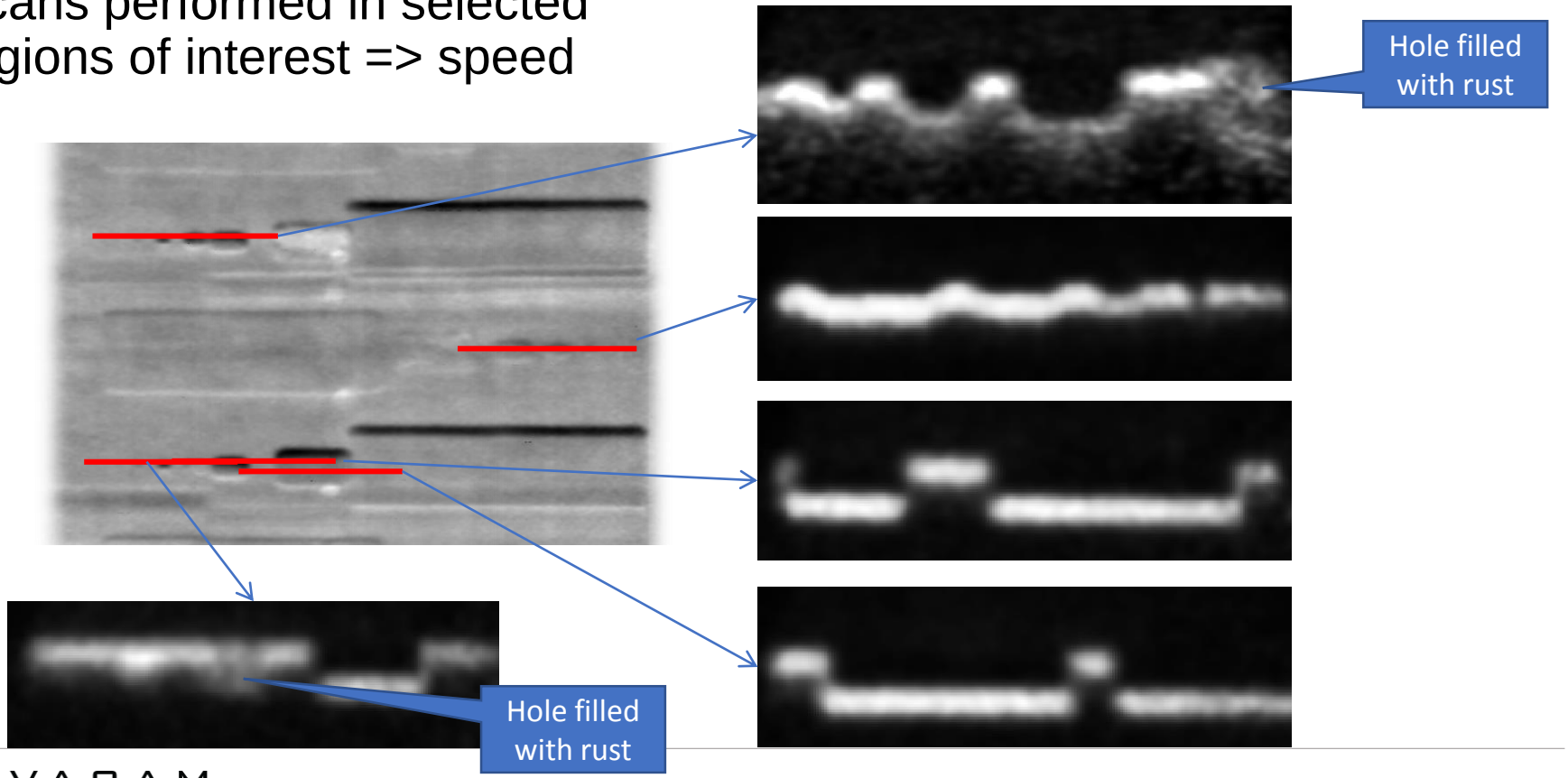
A 3D information **on surface morphology** can be obtained comparing different angles.

Individual images taken (step=10 deg)



Sliced scanning of artificial defects in 3D

- Scans performed in selected regions of interest => speed



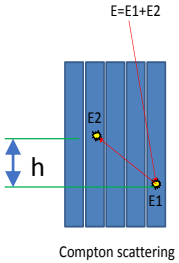
Gamma camera with Timepix3

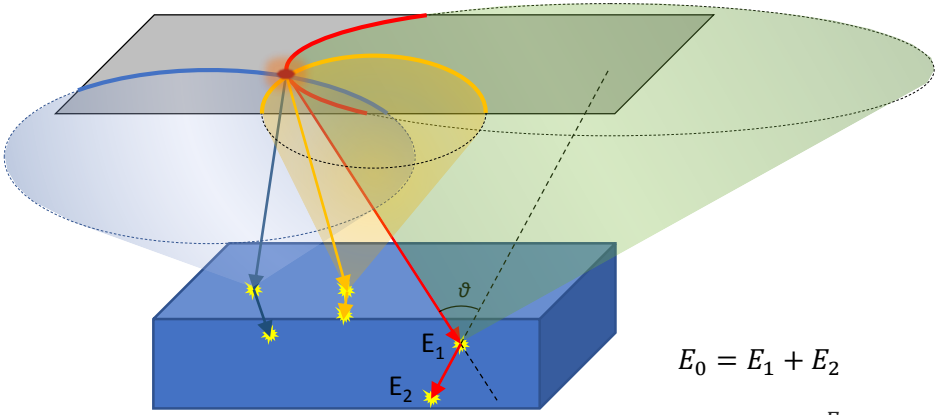
Single layer Compton camera: TPX3 + 2 mm CdTe

For each Compton scattering event we can:

- Detect coincidence
- Measure both energies: E_1 and E_2
- Measure both positions in 3D

=> We can reconstruct Compton cone:

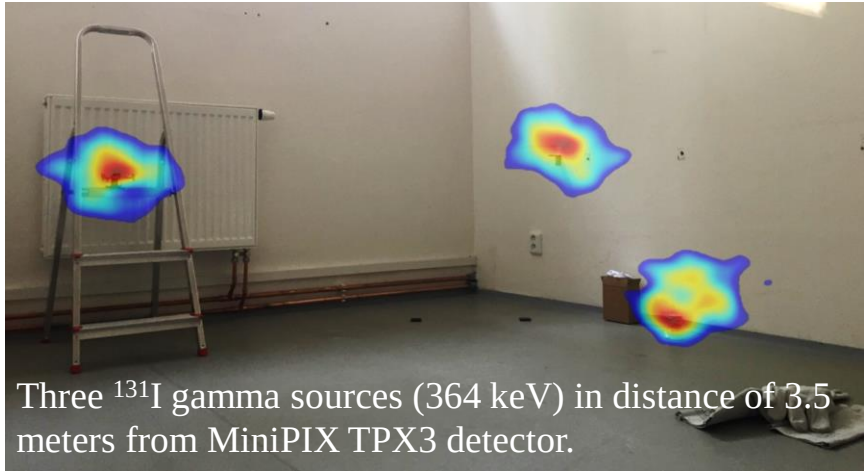




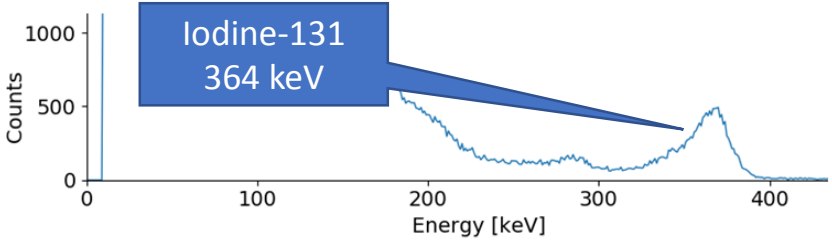
Timepix3 CdTe detector

$$E_0 = E_1 + E_2$$

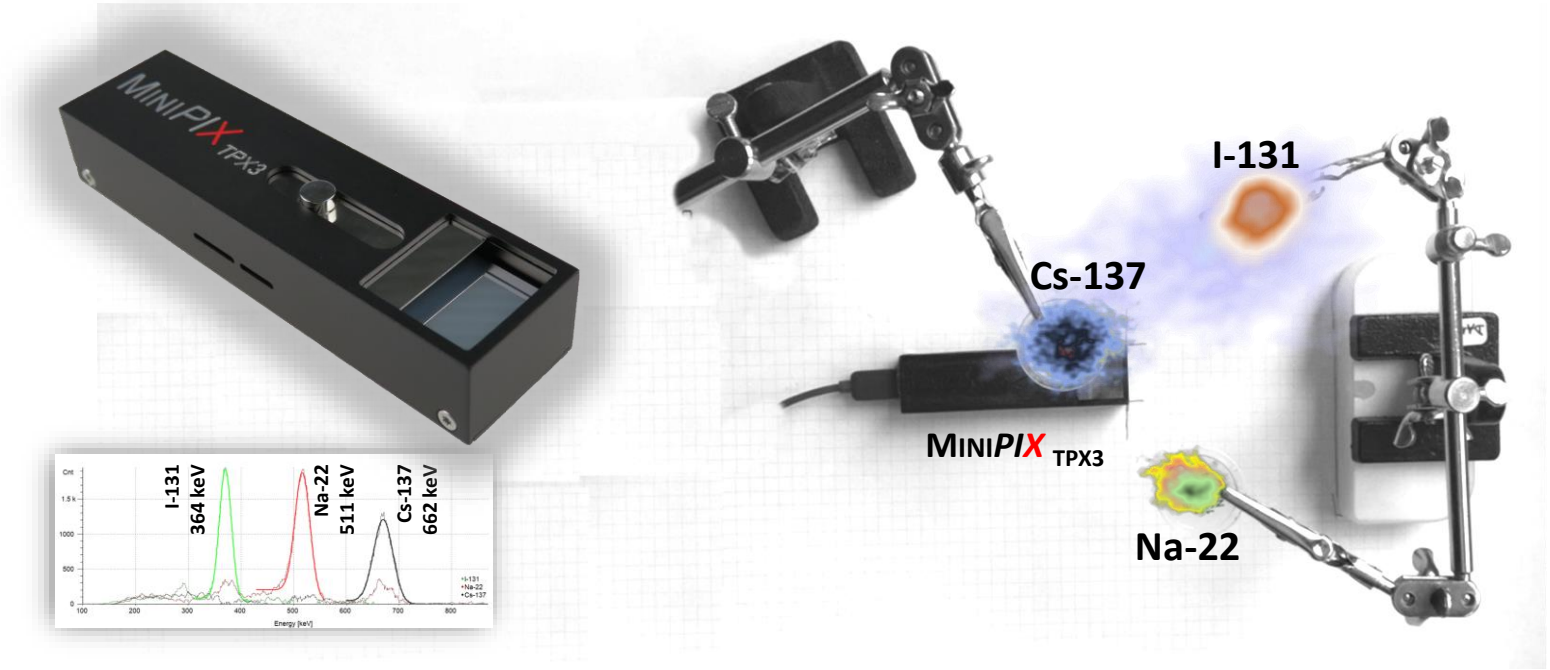
$$\cos\theta = 1 - m_e c^2 \frac{E_1}{E_2(E_1 + E_2)}$$



Three ^{131}I gamma sources (364 keV) in distance of 3.5 meters from MiniPIX TPX3 detector.



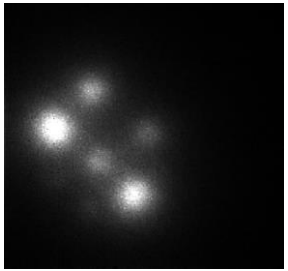
Miniaturized Compton camera: Source identification



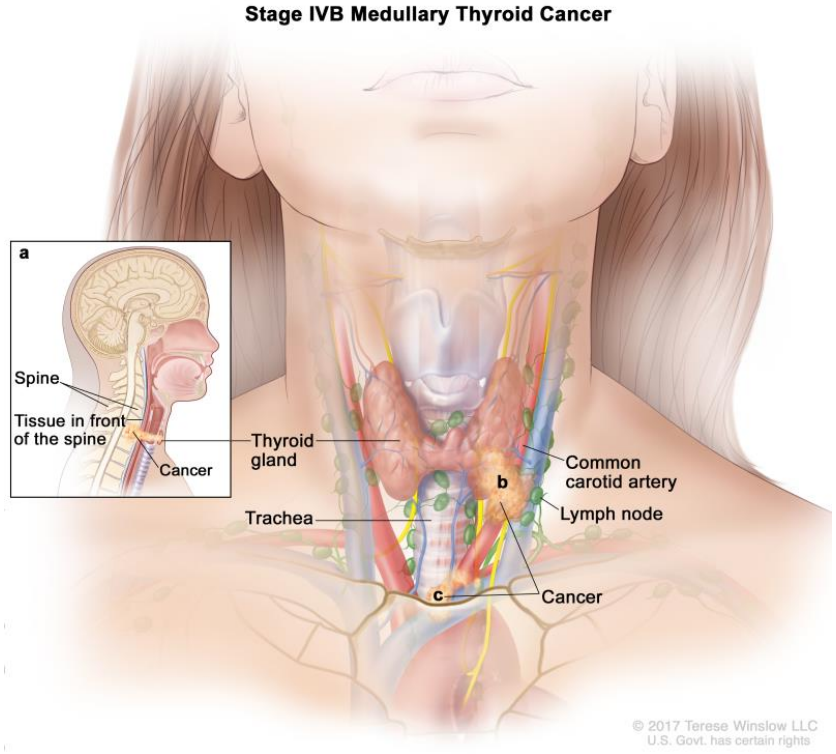
Gamma camera application:
Thyroid diagnostics

Thyroid cancer diagnostics and treatment monitoring:

- The second most frequent cancer for women (after breast cancer)
- Current imaging methods offer resolution of about 12 mm in 2D
- **Our technology allows**
  - **5 times better resolution and 3D** (2.5 mm)
  - **4 times lower dose**



- Principle:
  - Single layer Compton camera



Highly miniaturized spectral camera supporting Si and CdTe sensors

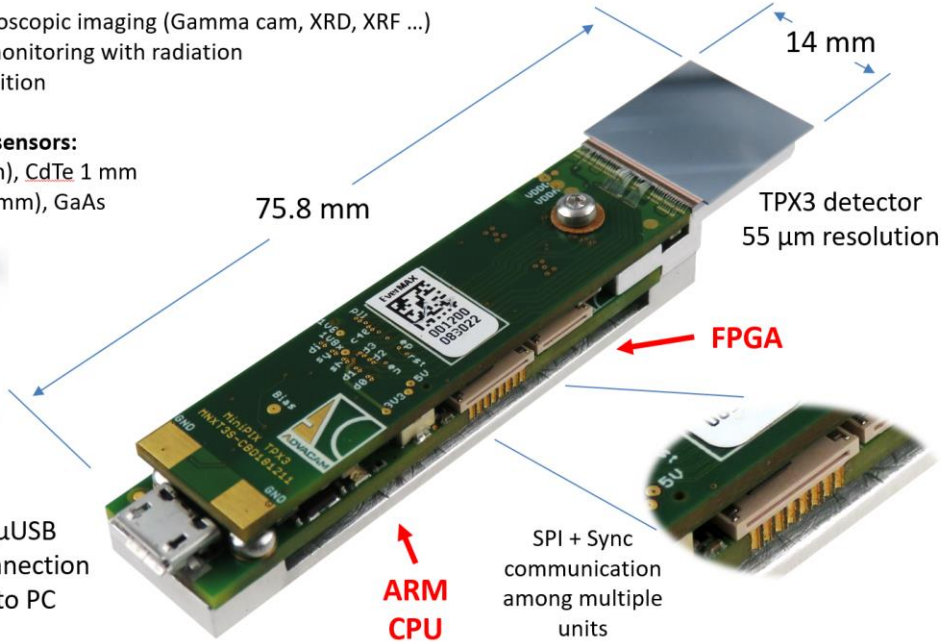
MiniPIX TPX3: radiation imaging/tracking

ADVACAM
Imaging the Unseen

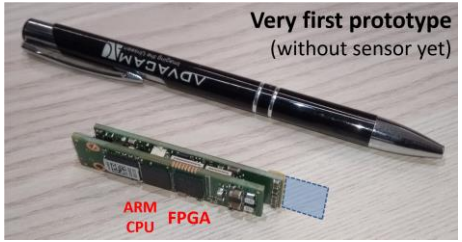
Compact, low power, vacuum compatible …
Each single ionizing particle is registered measuring its
- position, energy, time of arrival and track shape

⇒ Fully spectroscopic imaging (Gamma cam, XRD, XRF …)
⇒ Radiation monitoring with radiation type recognition

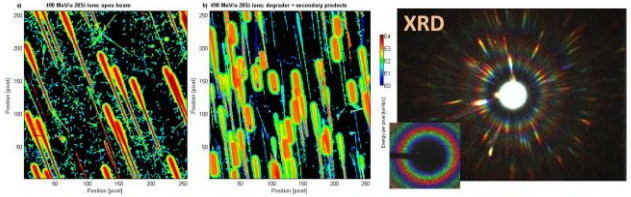
Available with sensors:
Si (100-1000 µm), CdTe 1 mm
coming: CZT (2 mm), GaAs



Its really small ..



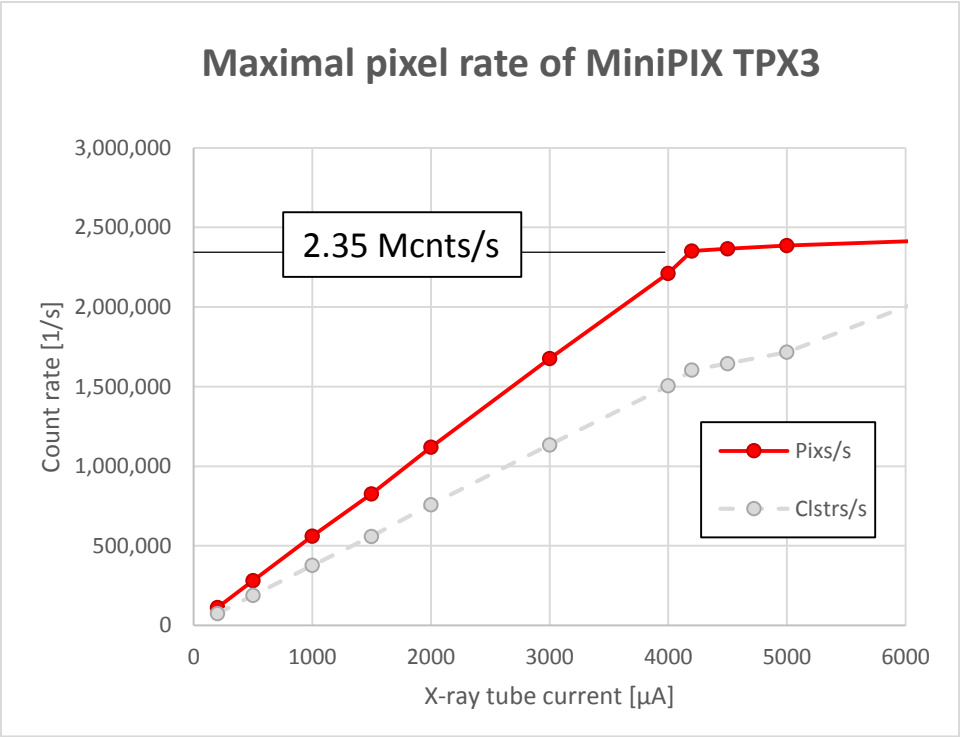
Applications:
- X-ray radiography
- XRF, XRD, SWAXS
- Gamma camera (SPECT)
- Radiation monitoring
- Compton camera
- Space



MiniPIX TPX3 count rate in event mode

Maximal speed is limited to reduce power consumption (

Max count rate measured with
- 300 µm Si sensor at threshold of 3 keV
- 17 keV semi-monochromatic X-rays



More than sufficient for imaging with isotopes.