Gamma and X-ray imaging with Timepix3: Spectrum and image reconstruction using subpixel hit mapping and depth of interaction determination

Jan Jakubek, D. Turecek, E. Trojanova, D. Doubravova
ADVACAM
ADVACAM Group

- ADVACAM s.r.o., Prague: **imaging cameras and solutions** (since 2013)
  Spin-off from Institute of Experimental and Applied Physics, Prague
  - 24 employees (+ 10 in two daughter companies)

- ADVACAM Oy, Espoo: **semiconductor sensors & modules** (since 2012)
  Spin-off from VTT Technical Research Centre of Finland
  - 12 employees

- USA ADVACAM, representative office

Selected clients

- NASA certified quality
Basic principle: **Digital Photon Counting in every pixel**

- Technology based on CERN CMOS chips Medipix/Timepix

**Advantages:**
- **Direct conversion:** Radiation quantum $\Rightarrow$ electric pulse $\Rightarrow$ digital count
- **High resolution:** 55 microns (or better see later).
- Provides energy sensitive imaging (spectral too)
- Very high SNR (~800) and CNR (SNRn even higher)
- High speed (up to 1700 fps).
- **TDI mode for continuous industrial scanning** implemented in hardware

---

Large area CdTe:

Largest area (6.5 Mpixel):
Large area detectors for hard X-ray imaging:

Medipix3
WidePIX L CdTe MPX3: Wide 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 ...

Jan Jakubek | IWORID 2019
Automatic line for mineral sorting in mines:

- Dual (or up to 8 channels) energy X-ray transmission.
- To be combined with data from XRF detectors and 3D stereoscopic optical cameras.

Example of installation under conveyor belt:

- Belt speed: 0.5-4 m/s
- 26,000 pixels = 1.5 m in 5 seconds = 100 MPixels
- 3,840 pixels
- 7x stapler clip
Resolution and contrast

• Class B (50 µm wire pair) image quality achievable for inspection of stainless steel parts!

• 4 mm thick stainless steel

Flat bottom hole: 32 µm deep CNR=2.5

Spatial resolution: Duplex Image Quality Identifier (smallest feature 50 µm)

Last wire pair 13D Wire:Gap:Wire = 50:50:50 µm

27.5%
WidePIX 5x5 CdTe:
The large area CdTe imaging detector with continuous sensitivity

Features:
• Pixel size of 55 µm
• 1280 x 1280 pixels = 1.6 Mega pixels
• Sensitive area of 70 x 70 mm² (can be larger if needed)
• Gap-less tilling:
  o Gaps between modules smaller than quarter of the pixel
  o Edge pixels of 100 µm

Supported sensor types:
(Bias voltage +/- 500 V)
• CdTe 1 mm
• CdTe 2 mm
• Si 300 µm
WidePIX 5x5 CdTe: Flat-field and stability image

Flat field at 60 kVp

Relative noise image over 5 minutes (300 frames)
StdDev/sqrt(Avg) ... Should be =1 for poissonian distributed counts

Average: 0.97912 ± 0.18481
Median: 0.97382

Median = 0.97
Material sensitive imaging with WidePIX 5x5 CdTe

**Example 1: PCB**

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

High pass filter

No tilling artifacts
Fully spectral imaging: Timepix3
The R&D of AdvaPIX TPX3 was finished in 2017 and the new product was introduced to market in November.
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.
  \[\Rightarrow\] 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.
Timepix3 + different sensor types

Supported sensor types:
- Silicon 100-1000 µm thick: Particle tracking, electron microscopy …
- CdTe 1000 and 2000 µm thick: Hard X-rays, Gamma, PET, SPECT …
- CZT 2000 µm thick
- GaAs 625 µm thick
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

**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 (distance \(d\), height \(h\))
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.

---

Eu-152 gamma spectrum

Ba-133 gamma spectrum

**Compton edge**

**Peak separation improved**

**E=E1+E2**

**Compton scattering**
Depth difference measurement in CdTe

- Pair of events occurring in different depths of the sensor
- Use time of charge collection
- Calibration with cosmic muons

Bias voltage of 450 V: Time domain

Bias voltage of 200 V: Time domain

Energy ~ 44 keV/pix

Charge collection time as function of bias voltage

Depth resolution: 28.5 µm (RMS)

Depth resolution: 31.5 µm (RMS)
Extracting position with subpixel precision

- For each photon energy, depth of interaction and subpixel position there is **typical pattern of cluster**.

- Photons of one specific energy interact in depth according to **exponential attenuation law** $\Rightarrow$ probability of interactions in specific depth is known.

- **Model describing the response** of pixels can be calculated. Model parameters are: Repulsion constants, energy threshold, particle energy, speed of charge collection.

$\Rightarrow$ The response has to be calibrated for every subpixel position and each energy in the spectrum.

$\Rightarrow$ For calibration purposes the **uniform irradiation can be used** $\Rightarrow$ All subpixel positions occur with same probability $\Rightarrow$ Continuous density of impacts

$\Rightarrow$ The cluster centroid **correction vector map** is calculated from calibration data to fulfill condition of homogenous occurrence of hits.
Cluster volume depends on subpixel position: Am-241

Average energy in dependence on centroid subpixel position (4 pixels):

Cluster size depends on depth of interaction and energy:

This knowledge can be used for further correction of energy calibration (centroid+depth):

Original: Sigma=5.9 keV
Corrected: Sigma=4.5 keV
Example of subpixel calibration

Sensor: 2 mm CdTe at bias of 450 V
X-rays: 160 kVp, 5 mm Fe filter, events over 40 keV used

Images show occurrence of centroids within the pixel area for specific cluster size (all energies summed up).

Comparing these data to model yields to error (displacement) map. Knowing such map it is possible to correct the position of event accordingly.
Example for Eu-152 gamma peak of 120 keV
**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 better 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 with the **Newest Duplex Image Quality Identifier**

**Conditions:**
- 160 kVp, 500 μA,
- 5 mm Fe filter,
- 100 s exposure

**Original resolution**

**Subpixel 6x (9 μm):**
Conclusions:

The high resolution imaging with hard X-rays or gamma rays:

Spatial resolution of 9 µm with 2 mm thick CdTe sensor

Spectrum restoration:

Correction for
- internal XRF and Compton scattering
- incomplete charge collection (depth)
- Fine cluster position with respect to pixels

⇒Peak positions restored, resolution improved by 30%

Energy dispersive XRD analysis

XRF imaging

Advacam
Imaging the Unseen
High performance customized devices: 
Timepix3 based Large area detector of 12 modules

12 x Timepix3 module (30 Gb/s)
6 computers for data readout, each handles 5 Gb/s
Specialized software for **parallel on-line data processing**
Installed to synchrotron INFN Frascati in October 2018
Thank you for your attention

Questions?