High contrast energy resolving digital radiography of microstructure using photon counting pixel detector Timepix with CdTe sensor

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Hybrid particle counting pixel detectors of Medipix family

Read-out chips developed by CERN based Medipix collaborations

**Medipix2 and Medipix3**
- 256 x 256 pixels, pitch of 55 µm
- Multiple thresholds (2 for MPX2, up to 8 for MPX3)
- Charge summing scheme & continuous readout for MPX3

**Timepix**
- 256 x 256 pixels pitch of 55 µm
- Selectable modes of operation in each pixel:
  - Counting,
  - Energy measurement (ToT)
  - Time stamp (ToA)

**Timepix3**
- 256 x 256 pixels, pitch of 55 µm
- Fast event based readout
- Energy & Time of arrival provided concurrently
- High time resolution of 1.6 ns
Timepix pixel device
single particle counting pixel detector

- Planar pixelated detector (Si, GaAs, CdTe, thickness: 150/300/700/1000mm ...)
- Bump-bonded to readout chip containing in each pixel cell: amplifier, discriminator, Counter or ADC or Timer
- Multichip assemblies with common sensor: Quad (30 x 30 mm), Hexa (45 x 30 mm)
- Multichip detectors with edgeless sensors: WidePIX_{10x10} (143x143 mm, 6.5 Mpixels)
Motivation for usage of photon counting pixel detectors

No noise added by detector (only natural Poissonian noise), very high contrast in X-ray projections, energy sensitivity.

**Photon counting: Ultra-high contrast**

Mouse: hair fibers are resolved through its body!

**Threshold: Material sensitivity**

Metals: Material differences are identified!
Spectroscopy in counting mode: Threshold scan

Spectroscopic properties of very standard silicon sensors (300 um):
- threshold scan with Timepix in counting mode
- Am-241 gamma source

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THL scan Am on gold foil (step=5 ADU, step time 5 s)
Correction of the raw radiographic data

- Each detector pixel is in fact independent detector unit => it has its own efficiency uniquely dependent on energy (mostly due to differences in pixel electronics)
- The response (efficiency) of each pixel is calibrated for different levels of beam-hardening effect with set of known flat filters (calibration depends on X-ray tube and threshold)
- Count rate is converted into Equivalent Thickness of reference material

**Spectra behind Al foils (70 µm step)**

**Count as function of Al thickness**

**Response of few pixels**

**Linearization feature of BH correction**

**Histogram of raw image**

**Histogram of corrected image**
Multi energy radiography

**Principle:**
- Make several radiographic images with different energy sensitivity (threshold) for material decomposition
- Convert all of them to equivalent material thickness
- The differences in resulting thickness indicate material
- The problem is linear up to certain thickness
Material recognition
(P. Soukup, J. Jakubek at. al. 2012)

Equivalent thicknesses determined for two thresholds for 6 different materials. The reference material was aluminum therefore, the curve corresponding to aluminum has slope of 1.

Linear combination of vectors in certain range of thicknesses.
Example: Aluminum + Paraffin

Object for mixed material decomposition test:
- Aluminum foils, 70 µm
- Paraffin steps, 2.5 mm

Fig. 6 Mixed specimen of Aluminum and Paraffin. Photo (left) and X-ray image (right).

Fig. 6 Mixed specimen of Aluminum and Paraffin before (left) and after (right) orthogonalization. Each intersection point belongs to the mean value of corresponding sub-area in Fig. 5 right.

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Example with WidePIX 10x10: PCB

Statistics: 300 s per image
4 energy channels: 5, 9, 13 and 17 keV
Sample: PCB with soldered components

Metal = cyan
Glass = red

Standard

Color
Imaging of highly absorbing materials: CdTe, CZT

Main goal: Spectroscopic imaging of high-Z materials => High kVp
Sensors: 1 mm thick CdTe Ohmic and Schotky, 2 mm thick CZT

Silicon 0.3 mm, 55 µm pitch: FWHM = 1.38 keV at 60 keV
CdTe 1 mm, 55 µm pitch: FWHM = 1.88 keV at 60 keV

Am-241
Summary for 1 mm CdTe sensors & counting mode

Spectrum of $^{241}$Am measured with 1 mm CdTe Ohmic Timepix (Threshold scan with Ikrum=5 and Bias=-500V)

$^{241}$Am γ-ray at 59.541 keV
$^{241}$Am α-escape at 36.435 keV
$^{241}$Am β-ray at 23.106 keV

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Spectrum of $^{241}$Am measured with 1 mm Shotky CdTe Timepix (Threshold scan with Bias=-500 V)

$^{241}$Am γ-ray at 59.541 keV
$^{241}$Am α-escape at 36.435 keV
$^{241}$Am β-ray at 23.106 keV

Ohmic

Schottky

90 kV, W target
40 mil cnts/mm²/s
1 mm CdTe ohmic sensor with Timepix: Imaging properties

Sensor: 1 mm thick CdTe with ohmic contacts (bias = -500V, Threshold 5 keV)

Pixels 55 x 55 µm²

Used flat-field correction only (just few defective pixels are seen in picture)

Almost ideal shape

Tails due to XRF of CdTe
Color imaging with CdTe sensor

Ohmic CdTe sensor in Micro XCT system

- Sensor: 1 mm thick CdTe with ohmic contacts (6 thresholds, a 5 keV)
- Object: SD card
- Polynomial spectra decomposition to base of 3 materials
Al-alloy sample with crack

- 5 mm thick Al-alloy plate with crack in center.
- X-ray energy range optimized for maximal contrast in spectrometric mode.
Imaging principle:

In-line Phase Contrast Imaging

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

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

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.

Termite knee

- 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
Energy dependence of absorption and refraction

X-ray image of a 500 μm thick and 160 wide μm polyethylene foil strip and intensity profile along the highlighted line measured with microfocus tungsten X-ray tube at 40 kV and Medipix2 detector (object to detector distance was 70 cm). Measurements done at different discrimination levels: 7 keV (red) and 11 keV (green).

Refraction effects are amplified over absorption effects for higher X-ray energy.
Steel with weld

- 3 mm thick slice through weld was taken
- No transition from weld to original material observed
- X-ray radiography with CdTe Timepix and 90 kVp tube taken

Two radiograms with two thresholds subtracted
Crossed plates of steel: Do we see grainy structure?

- Steel structure is very homogenous from point of view of X-ray absorption.
- The structure is seen due to deflection (phase effect) on grain boundaries.
- Phase effect depends on energy => multiple energy thresholds.

90 kVp Thl=10 keV
90 kVp Thl=50 keV
Difference
Material microstructure with X-rays: Speckles in radiograms

- Grainy structure of semi-homogeneous material presents changes in **refractive index**
- **The material grains can act as lenses**
- In proper distance the speckles can be observed
Speckles in Aluminum Alloy

High pass filter with radius of 10 pixels to suppress background

60 kVp  40 kVp  25 kVp

Thl=4 keV  Thl=9 keV  Thl=14 keV
Influence of object distance

- The object to detector distance is important.
- The magnification is of minor importance (as long as speckles are separated).

1.5 cm 5 cm 10 cm 20 cm
Biological objects – soft tissue: Agglomerations of cells

- Sample of prostate (of dog): Almost homogeneous soft tissue object => no structure observed with absorption
- Two images at two thresholds (4 and 14 keV at 25 kVp) taken and subtracted to get phase information.
- Material difference is highlighted as well
Direct observation of speckles in prostate:
Tuning energies and distance

- 25 kVp, 4 keV
- 40 kVp, 14 keV
- 60 kVp
Combining microstructure with macrostructure: Color images
Mouse lungs (deflated)

- Lungs have very typical granular structure of alveoli.
- => Can we set the system to identify them?
Mouse lungs: Combined image
Summary

- The energy resolution in counting mode is a very powerful tool for radiography.
- Phase sensitive imaging in in-line geometry is a simple method that brings important information describing the microstructure of the inspected sample.
- The speckles, as a special case of image features caused by the phase effect, can be measured very quickly with shorter exposure times than needed for standard absorption-based radiography.
- New CdTe sensors make this method applicable in fields where it was not possible before (structure of alloys and its changes due to processing/machining).
Thank you for patience!

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