M.4 Radiographic Testing

Numerical Modelling of Photon-Counting Detectors for Industrial Radiography Applications

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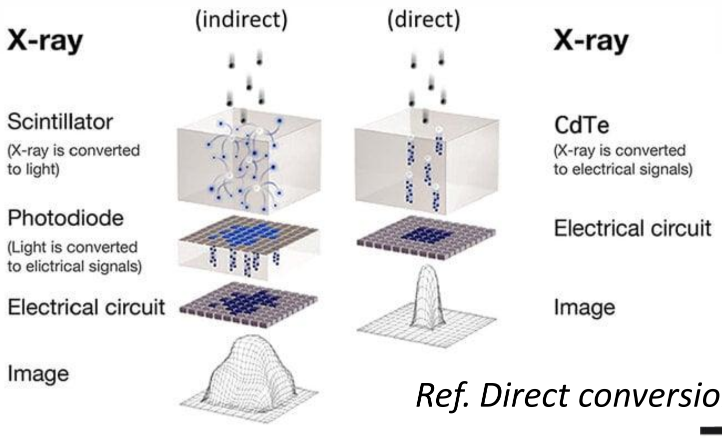
EXTENDE CIVA

OUTLINE

- Photon-counting detectors (PCD) introduction and benefits
- Introduction to modelling benefits and capabilities of the simulation in RT
  - State of the Art of CIVA RT simulation software
  - New improvements in CIVA RT, including PCD
- How the simulation can be of a great help in the framework of PCD
  - Application case 1
  - Application case 2
- Conclusion

PCD in a nutshell

- What is a PCD?
  - PCD stands for Photon-Counting Detector. It is an advanced X-ray imaging technology that represents the next generation of digital radiography and computed tomography
- How does it work?
  - Direct conversion Technology :Unlike conventional detectors (Energy-Integrating Detectors) that measure the total energy deposited by a burst of X-rays, a PCD counts individual X-ray photons and measures the specific energy of each photon.



Ref. Direct conversion

PCD in Medical applications

- Medical applications (State of the Art):
  - Unprecedented Resolution: Delivers ultra-high spatial resolution to visualize sub-millimetric anatomical structures (e.g., inner ear, stent struts),
  - Dose Reduction: Drastically reduces electronic noise, achieving superior image quality with a lower radiation dose for patients,
  - Spectral/Color Imaging: Sorts photons by energy levels to enable multi-energy imaging, allowing perfect tissue differentiation (e.g., separating iodine from calcium) in a single scan.

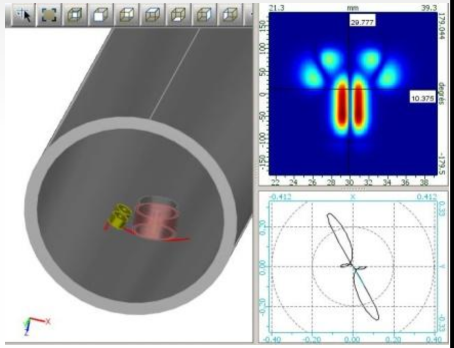
And for our NDT applications?

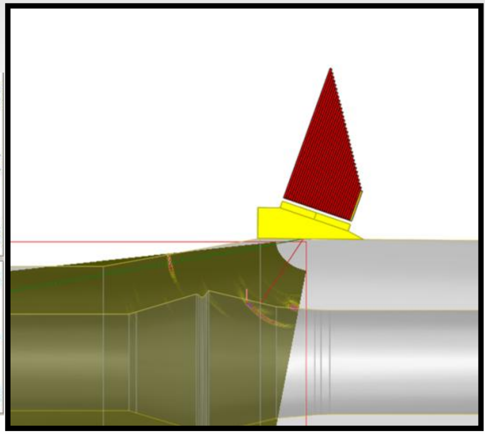
- And for NDT? Basically, the same advantages:
  - From 2D Images to a 3D Energy Dataset:
    - PCDs switch the paradigm from traditional integration to an Energy-resolved approach,
    - Spectral detector for processing the energy of incident photons,
    - Outputs a 3D Matrix dataset including a profile in "Energy" (improving the sampling of the X-Ray spectrum in multiple energy bins).
  - Post-Processing & Thresholding Flexibility (Min/Max):
    - Scattering rejection: Effectively cuts off scattered radiation.
    - Contrast enhancement: Optimizes signal-to-noise ratio for specific materials,
    - Defect Analysis : spotting micro-cracks in dense materials
    - Material separation: Uses energy discrimination for advanced material characterization and sorting.
    - Advanced spectral analysis: Provides high-fidelity spectral radiography/CT.

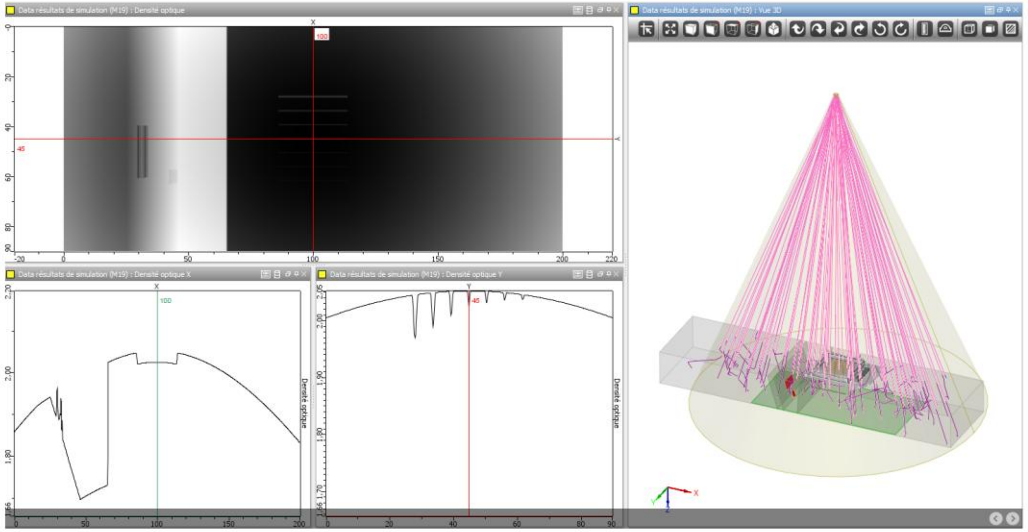
CIVA Modeling Platform

About CIVA software :

- Developed by CEA-LIST and distributed worldwide by EXTENDE
- Multi-technique:
  - Ultrasound Testing
  - Guided Waves Testing and SHM by guided waves
  - Radiography (X & Gamma) – Tomography
  - Eddy Current Testing
  - Thermographic Testing
- Advanced features
  - Parametric studies, Sensitivity and POD analysis
  - Data Science
    (to develop machine-learning based detection and classification tools)

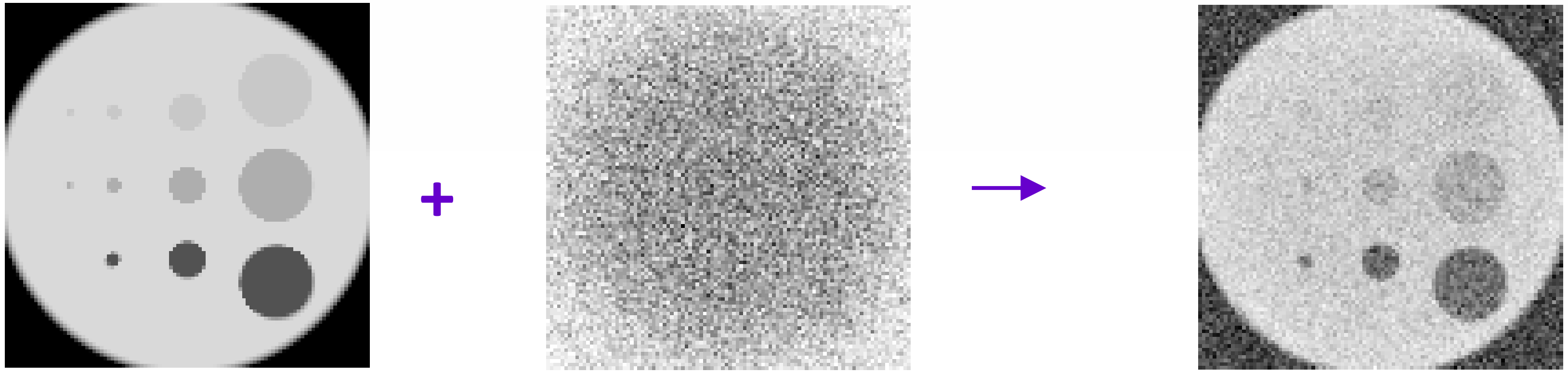






CIVA RT Simulation Framework

- Simulation of a global radiographic inspection,
- relies on a ray tracing engine to compute X-ray attenuation through meshed or parametric objects
- Relies on a Monte-Carlo method to account for scattering effects
- The primary photons can be generated either from an X-ray tube, a radionuclide source or a linear accelerator.



Direct radiation

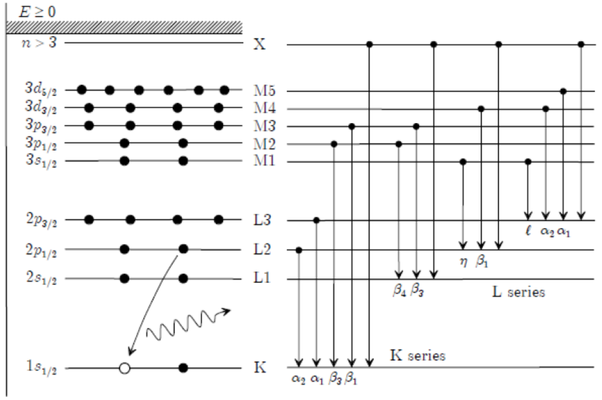
Scattered radiation

Final image

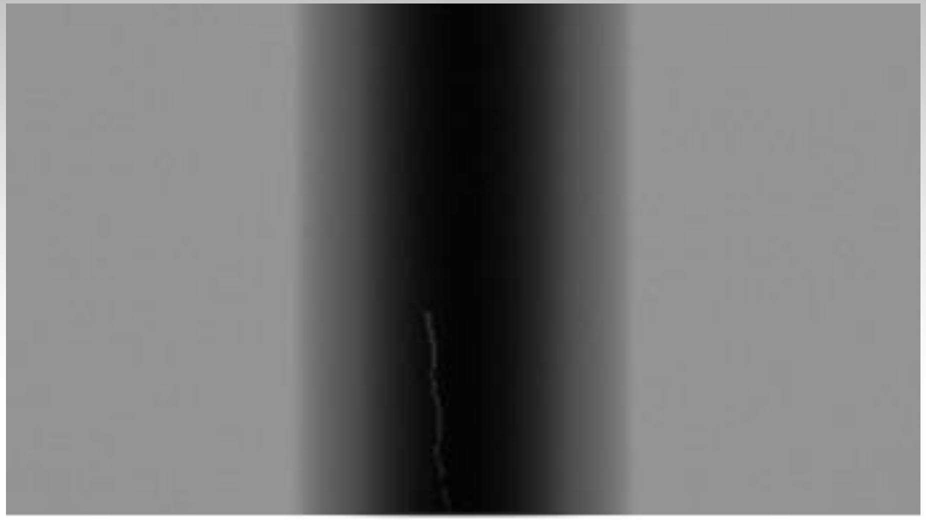
CIVA RT improvements

- Improvements of physical models
  - New cross sections material database from NIST and ENDF libraries
  - New RX generator spectrum (from SPEKPY) replacing the previous version
  - **Monte-Carlo calculation** (scattered radiation) **improved** including:
    - Bremsstrahlung interaction in the specimen (mainly for high energy sources and thick specimen),
    - X-ray Fluorescence interaction in the specimen (mainly for heavy materials)
    - Model optimization for faster convergence through variance reduction, thus reducing computing time

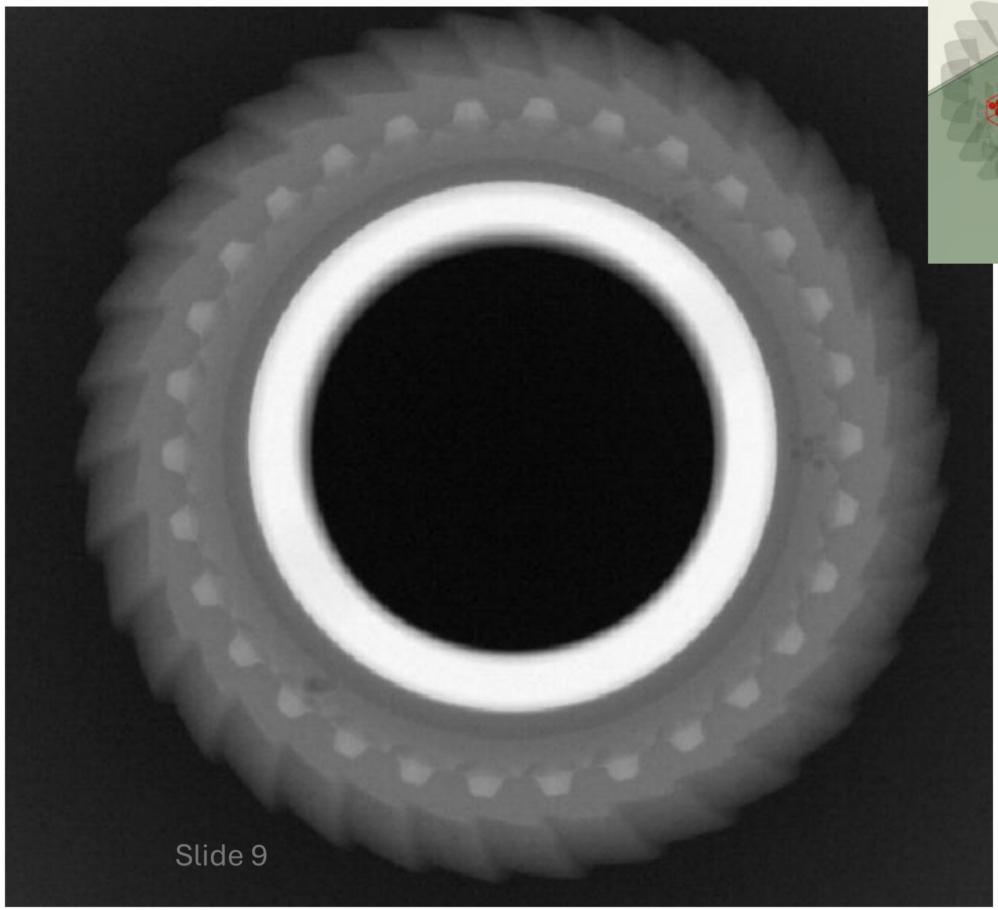
Case	Time calculation reduced by:
Weld / Ir192 / Silver film	2
Planar specimem / 450 keV / DR	3
Planar specimen / Co^{60} / DR	2
Planar specimen / betatron 2MeV / DR	4
Nozzle / 9 MeV / Silver film	4

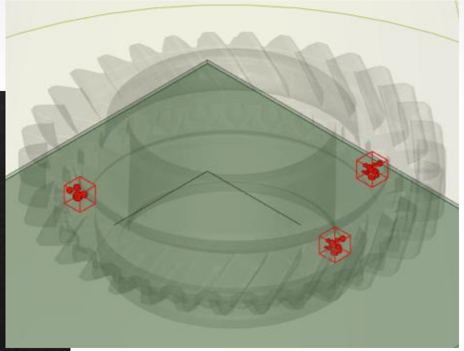


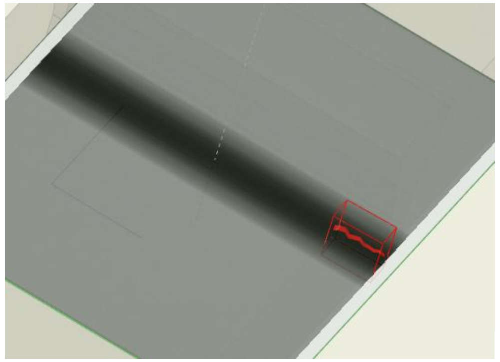
CIVA RT improvements

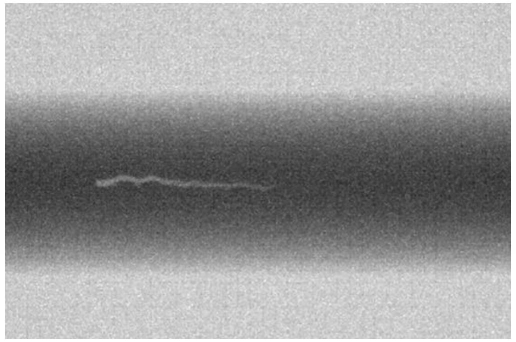


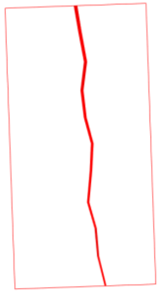
- New types of predefined defects
  - “Cluster of spherical porosities” and “parametric cracks”

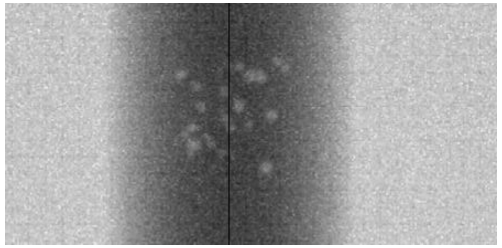


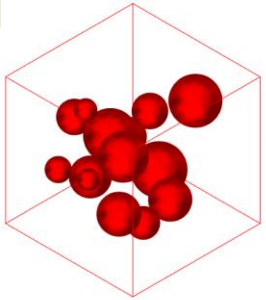






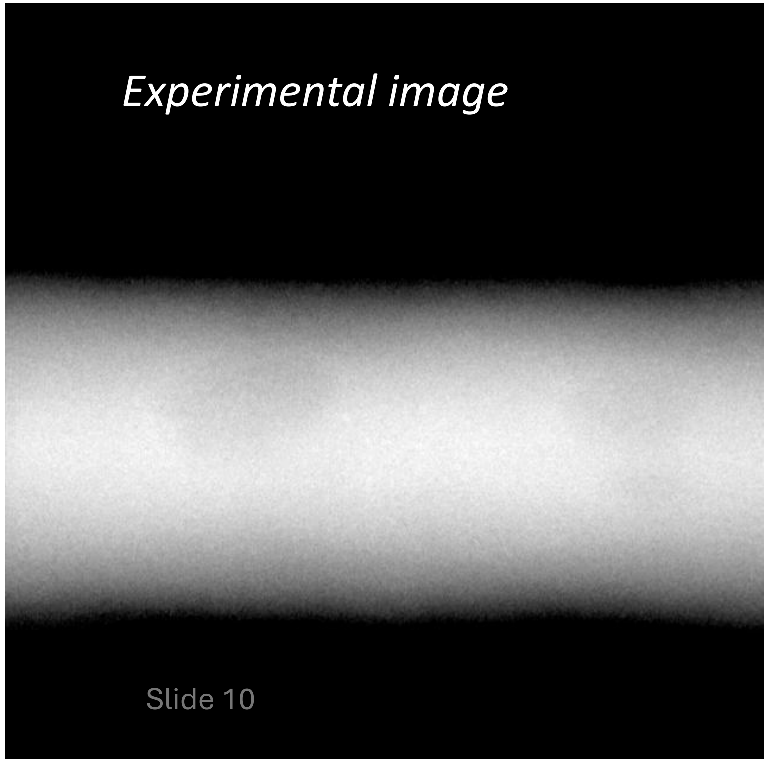


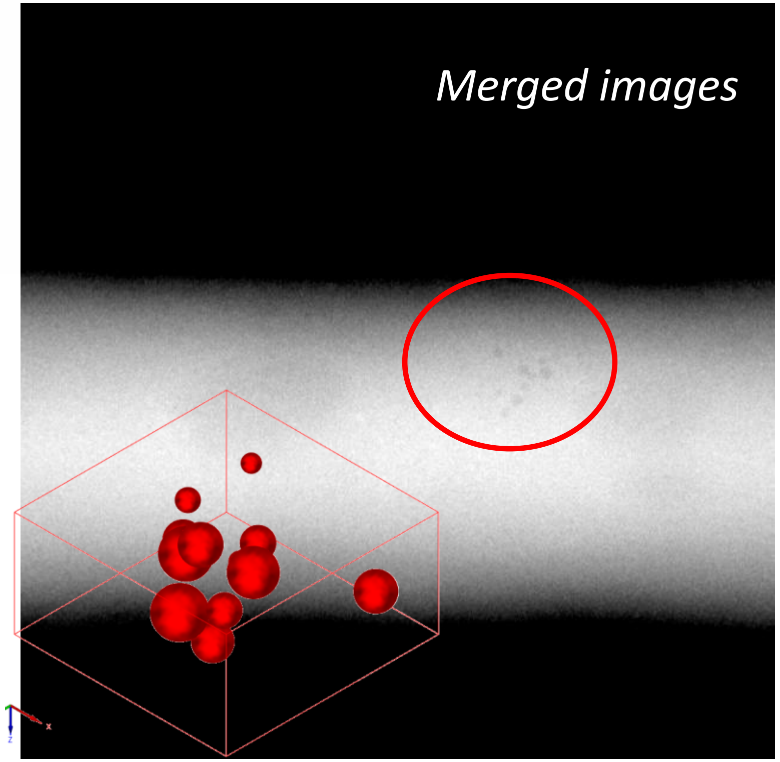


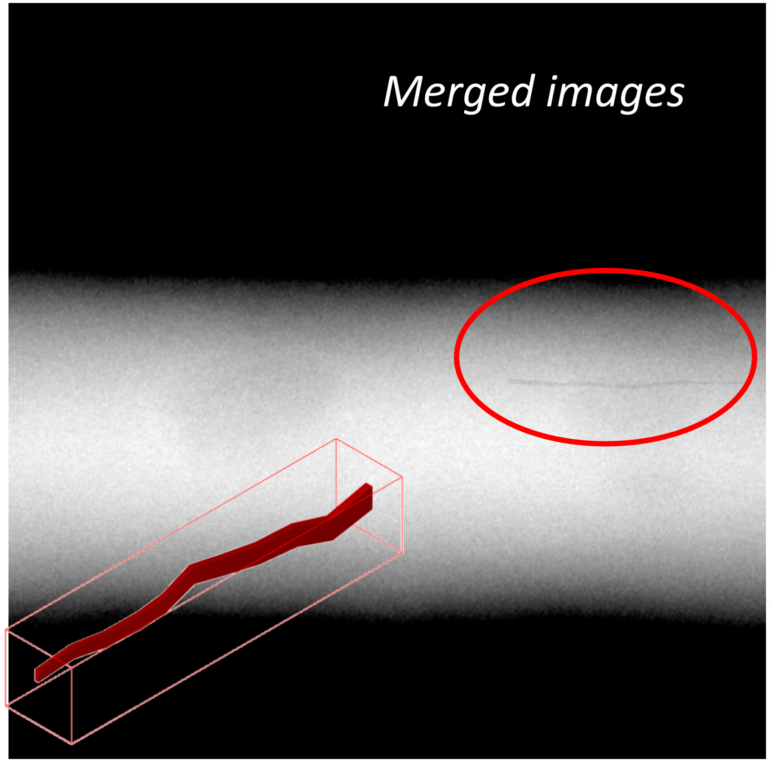


CIVA RT improvements

- Augmented imaging:
  - Specific merge to insert virtual defects into real images
    - Available for a « simple » RT simulation or using DS module (for machine learning, AI…)
  - For RT module, prepare a single CIVA configuration with defect and select an experimental image to import







PCD in CIVA

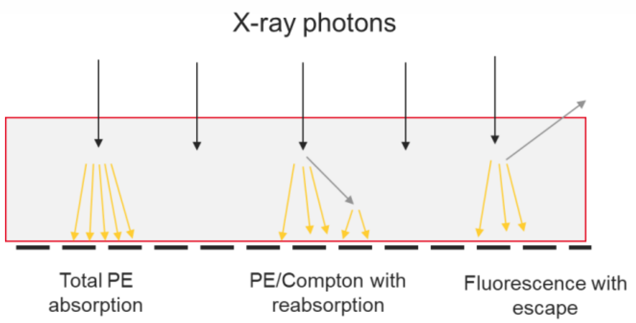
- The simulation accounts for the energy deposited in both energy-integrating detectors and photon-counting detectors,

- Energy resolution in PCD:
  - Realistic detector behaviour is captured via a user-defined response function accounting for noise in the signal chain

  - Customizable for various semiconductor materials and thicknesses

PCD in CIVA

- In the photon-counting mode, the output is a three-dimensional matrix that includes an energy dimension, corresponding to a deposited energy spectrum for each pixel,
- Detector Response Matrix (DRM):
  - When an X-ray photon interacts within the semiconductor, it deposits part of its energy. Tis complex mapping is computed using a DRM
  - Monte-Carlo based DRM for accurate energy deposition
  - Specific phenomena: Compton scattering, photoelectric absorption, fluorescence escape



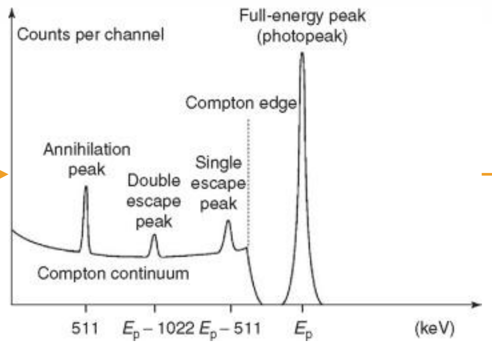
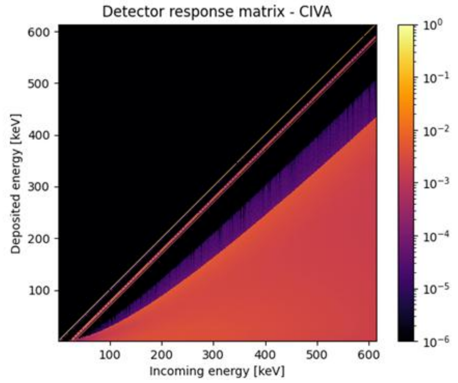


Illustration of a deposited energy spectrum

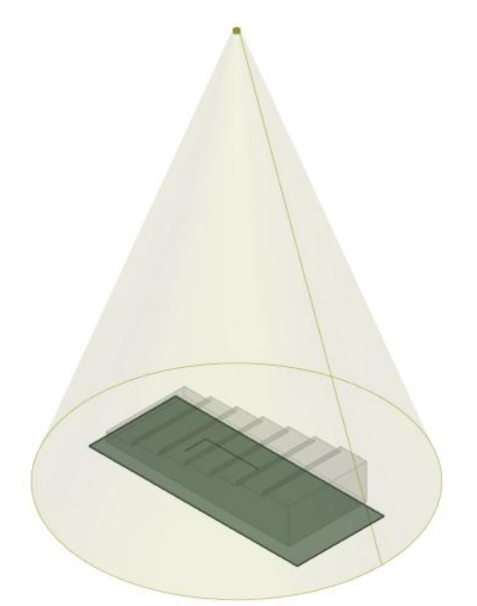


Pre-computed detector response matrix with CIVA

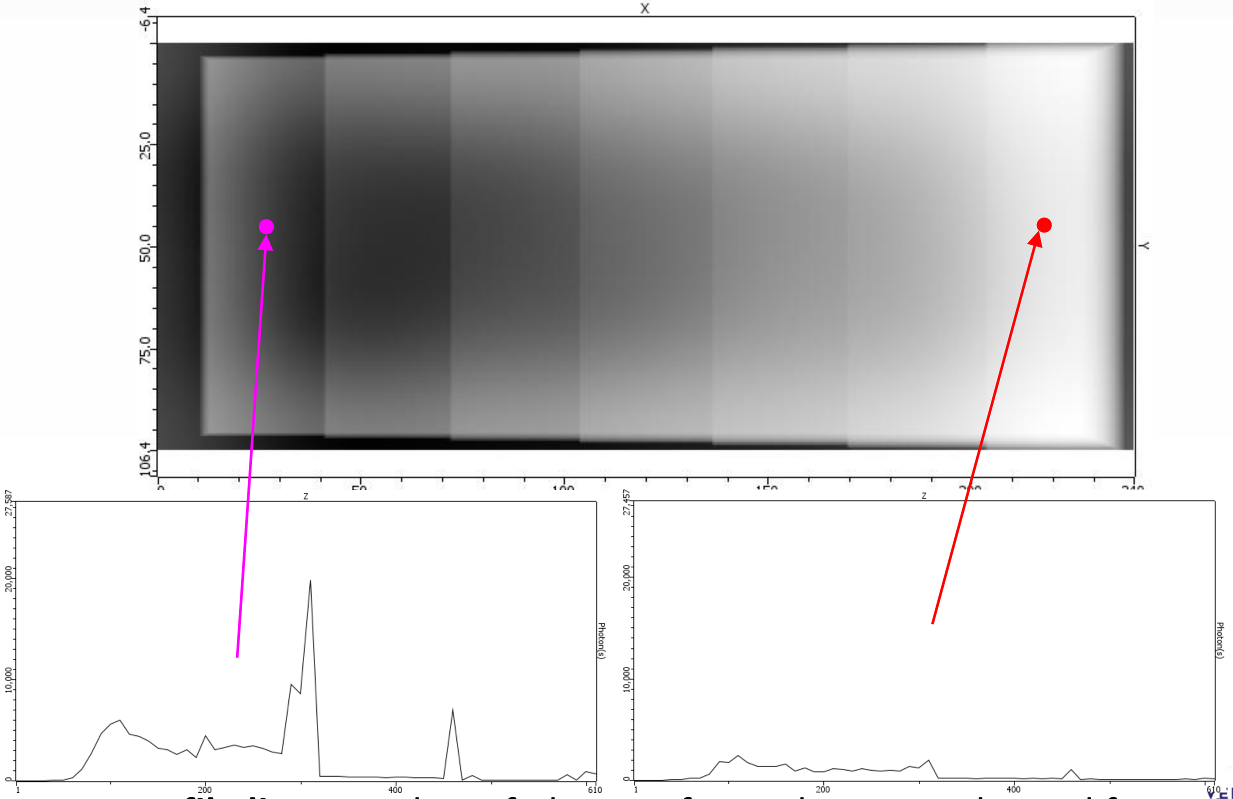
PCD in CIVA

- New type of detector: PCD
  - Illustration: <u>Cuts off scattered radiation</u>

Stainless Steel step wedge (10 to 40mm thickness)
Ir^{192} source (E_{max} = 612 keV)
Photon counting detector (Al and C front filter)



<u>**New image**: number of photons integrated for each pixel</u>

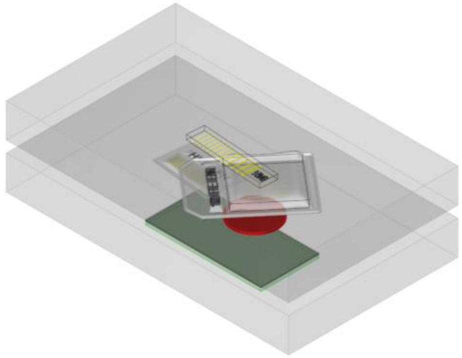


<u>**New profile line**: number of photons for each energy channel for a given pixel</u>

PCD in CIVA

Study conducted in collaboration with framatome Intercontrôle

- New type of detector: PCD
  - Illustration: <u>Cuts off scattered radiation</u> → Good agreement between simulation and experiment, in terms of CNR improvement



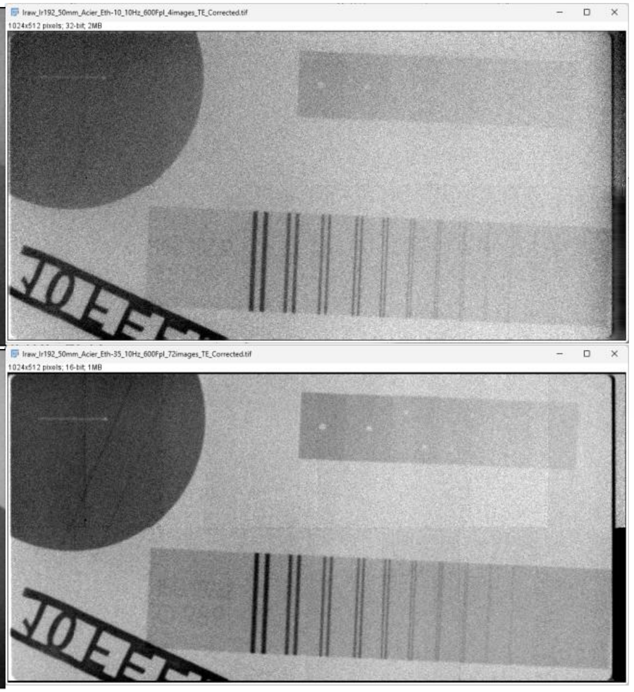
Stainless Steel plates (50 mm in total)
Ir^{192} source (E_{max} = 612 keV)
PCD (thickness of 3mm)

<u>Number of photons integrated for all energies</u>

<u>Number of photons integrated for energies upper to 450 keV</u>

Better discrimination of IQIs

<u>Simulation</u>

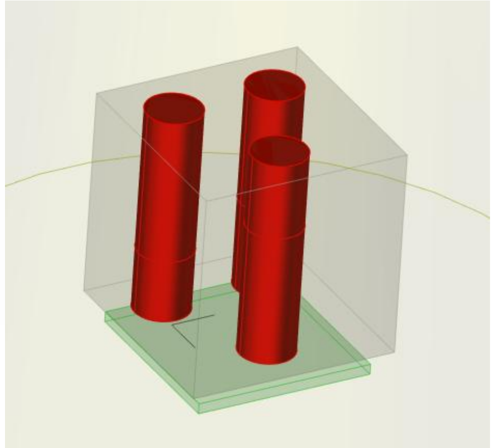


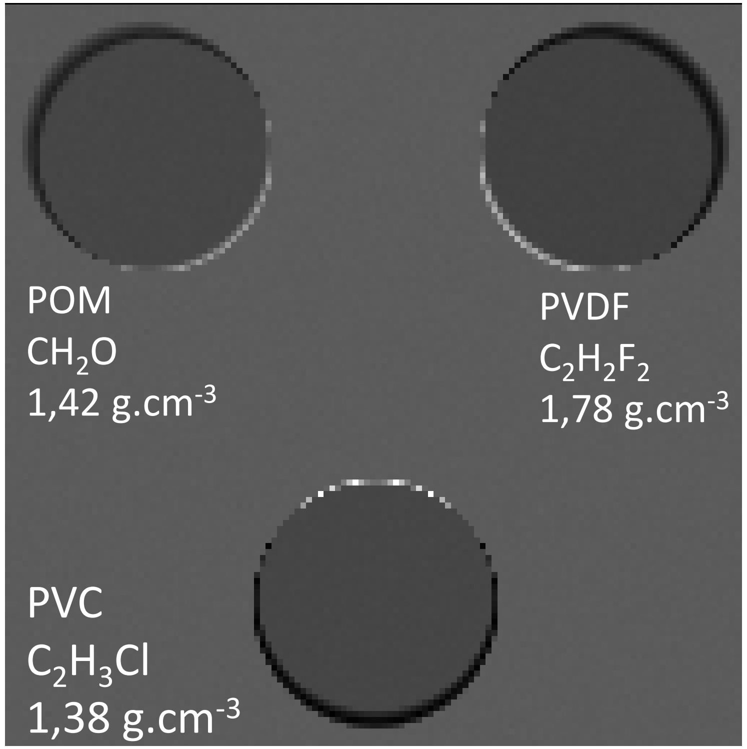
<u>Experiment</u>

PCD in CIVA

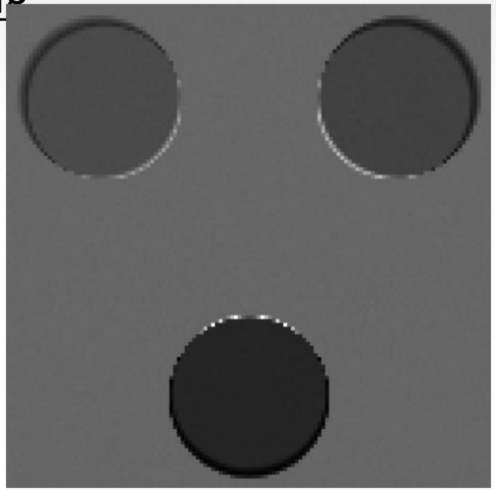
- New type of detector: PCD
  - Illustration: Material discrimination in spectral imaging

Cube with polymer inserts
X-ray source (E_{max} = 120 keV)
Photon counting detector (CdTe sensitive layer)

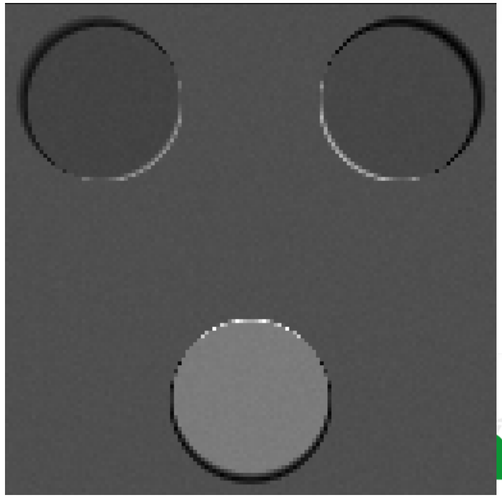




Number of photons integrated for each pixel for all energies



Number of photons integrated for each pixel for energies from 0 to 50 keV



Number of photons integrated for each pixel for from 50 to 120 keV

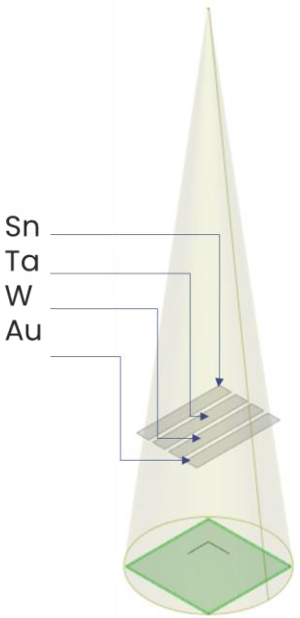
PCD in CIVA

Study conducted in collaboration with P.J. Benard and L. Admans from

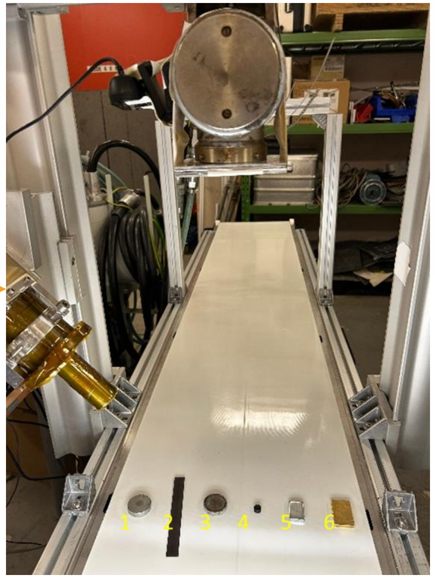
New type of detector: PCD

- Illustration: <u>Material discrimination in spectral imaging – **On-line sorting**</u>

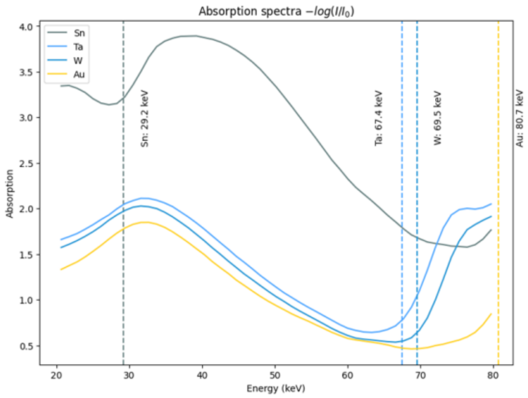
Pure materials ~75 µm thick, on conveyor
X-ray source (E_{max} = 80 keV)
Photon counting detector (CdTe sensitive layer)
1 keV resolution



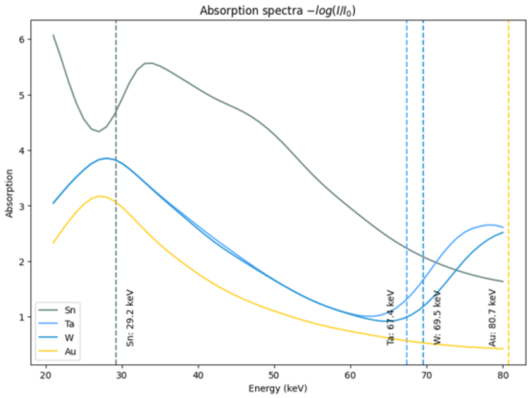
Towards unknow magnets



→ Good relation between Experiment and Simulated absorbance spectrum ($-\log\left(\frac{I}{I_0}\right)$)



Expérience



Simulation

Conclusion

- Interest of PCD:
  - Improvements in image quality with energy thresholds
  - Dual and multi energy imaging

- CIVA :
  - Well established solution for NDT simulations,
  - Recognized for its ability to simulate efficiently a large scope of NDT applications,
  - Good fidelity of the simulations for our PCD's optimization cases

  - Ongoing implementation of charge sharing effects to take into account the fact that the cloud of charge carriers may spread over multiple pixels and result in shared signals