Digital image processing solutions for spectral photon-counting CT with a CdTe detector

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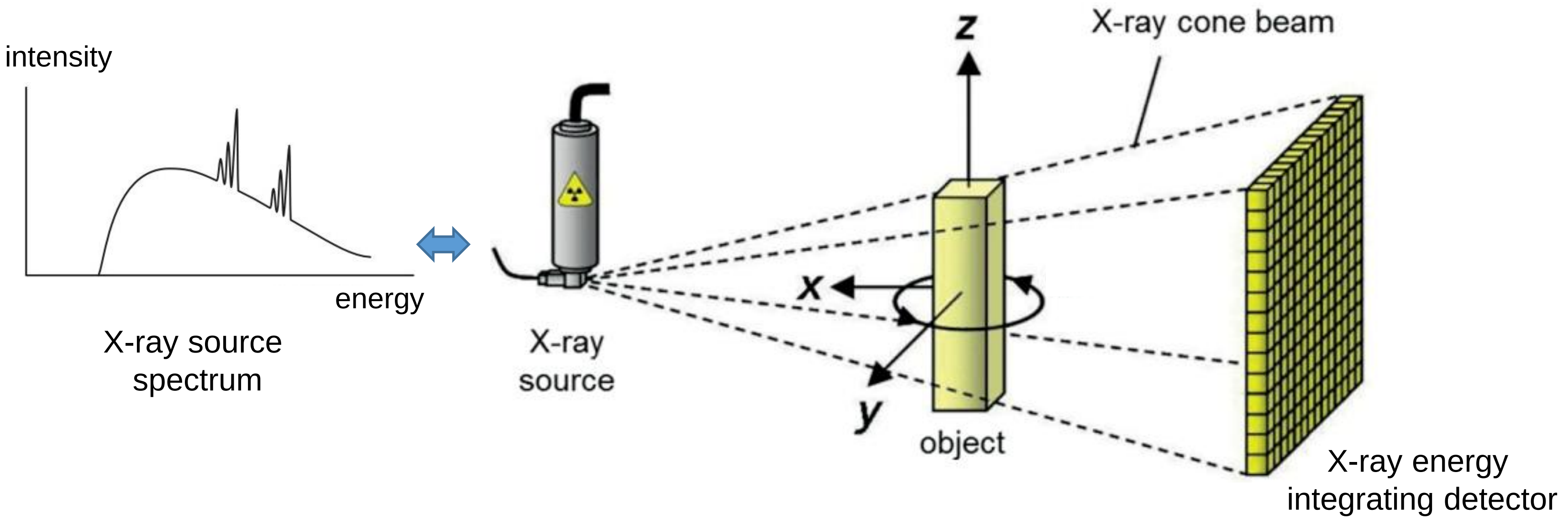
Conventional X-ray imaging

- Conventional (absorption) X-ray imaging is based on **energy-integrating** detectors



- A **polychromatic** X-ray beam is used and the absorption at all energies is recorded

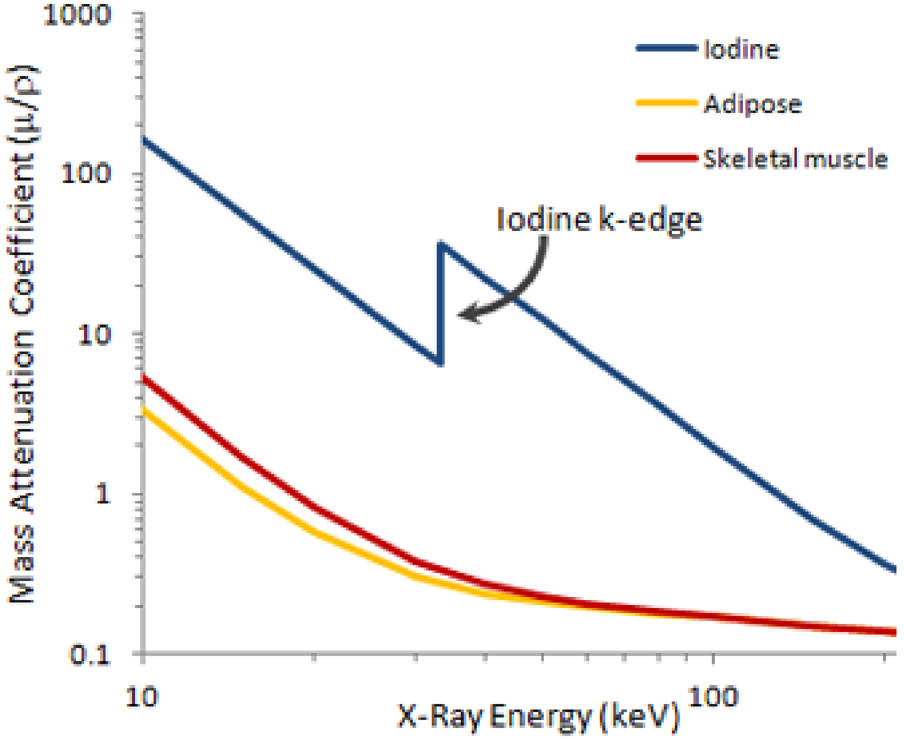
TO NOTE: the energy (or *spectral*) information is not discriminated

Contrast media

- Contrast media (e.g. Iodine or Barium) are used in X-ray imaging to:
  - provide contrast when the subject contrast is low
  - highlight where the substance accumulates

- An effective contrast medium must:
  - have **high attenuation**
  - have a suitable concentration
  - be biocompatible

- I and Ba have a strong discontinuity in the attenuation, known as **K-edge**, at suitable energies



Digital Subtraction Angiography

- An interesting example is Digital Subtraction Angiography where:
  - an image **before the injection** of the contrast agent is collected
  - an image **after the injection** of the contrast agent is collected
  - the *digital subtraction* of the two is performed

pre-contrast *post-contrast* *subtraction*

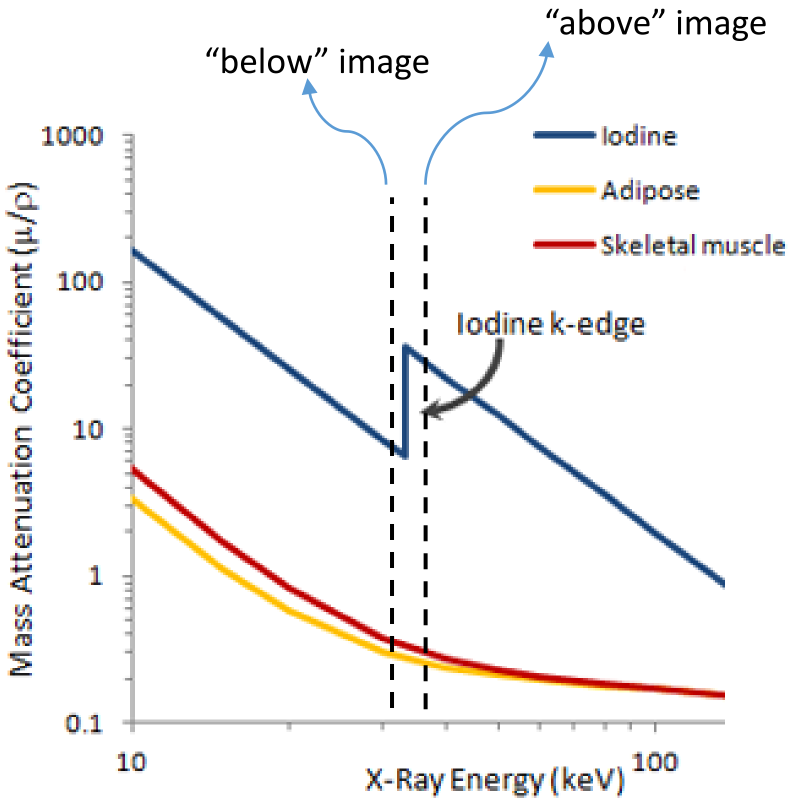
TO NOTE: **two shots** imaging technique (pre- and post- injection conditions)
image **co-registration** required and **motion artifacts** might occur

The K-Edge Subtraction principle

- Under the assumption of having a **monochromatic** incident beam
- **Two images** are required **after the injection** of the contrast agent:
  - the “below” image
  - the “above” image
- The differential digital image:

  `diff = above – below`

  is then computed #
- In this **K-Edge Subtracted (KES) image**:
  - the iodine contrast is **positive**
  - the contrast of bone, tissue, … is close to **zero (or negative)**



The acquired images are *flat-field* corrected and log transform is applied

Advantages of KES imaging

- Clinical advantages:

  - **only the post contrast** image is required
  - the radiation dose is reduced (if the images are collected in a *single-shot*)

  - lower concentrations of contrast media should be possible
  - new contrast media (better biocompatibility) can be conceived
  - L-Edge could be in principle considered

- Among the other advantages of KES imaging, an interesting one is:

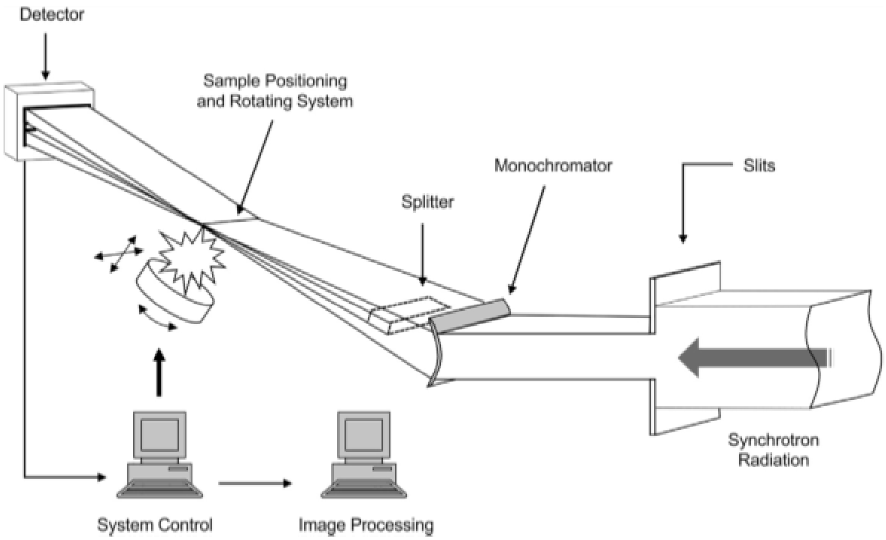
  - **easier** image **segmentation**
    (in principle *thresholding* with threshold slightly above background noise)

    ⇓

  - easier quantification

KES imaging at synchrotrons

- Monochromatic X-rays are easily available at synchrotron sources



- To have a *single-shot* technique (no motion artifacts) a beam splitter is used
- The two images are collected in different portions of the detector
- **TO NOTE**: a **synchrotron** is needed (monochromatic beam)
  simple **image registration** still required (different portions of the detector)

KES imaging with lab sources?

- The underlying question of our project is:

Since a conventional X-ray source outputs a polychromatic spectrum, is it possible to perform accurate *single-shot* KES imaging (both planar radiography and computed tomography) without a synchrotron source with potential small animals *in vivo* applications?

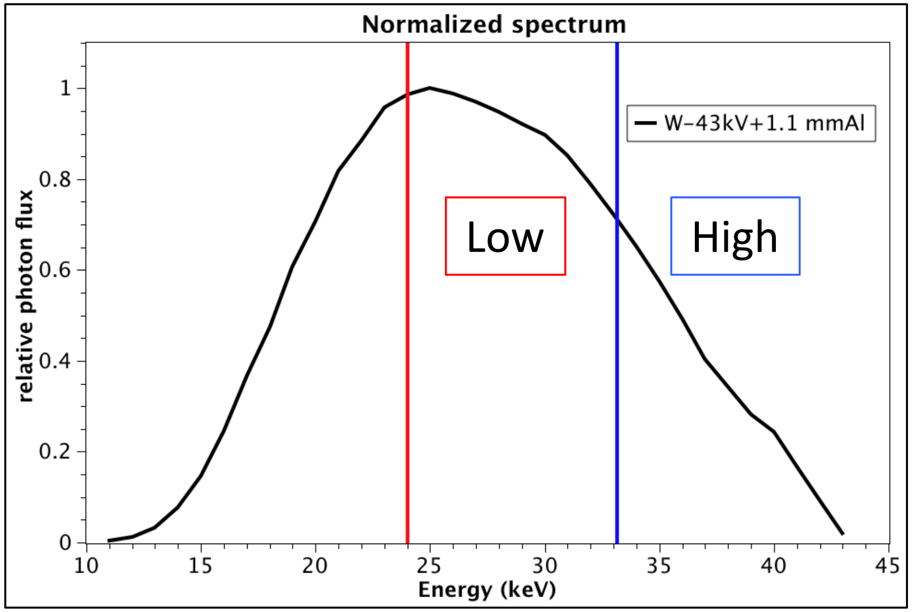
- The key point is a pixelated **energy-discriminating detector**

(This approach fall within the global name *spectral* or *color* imaging)

Photon-counting detectors

- Innovative X-ray **single photon-counting detectors** (XPCDs) are now available
- A XPCD has **programmable thresholds** to select photons according to their energy

- With **two counters** having independent thresholds:
  - two perfectly co-registered “low” and “high” images are acquired per shot (sometimes improperly called *virtually monochromatic* images)
  - single shot (only the post-injection condition is required)



Photon-counting detectors

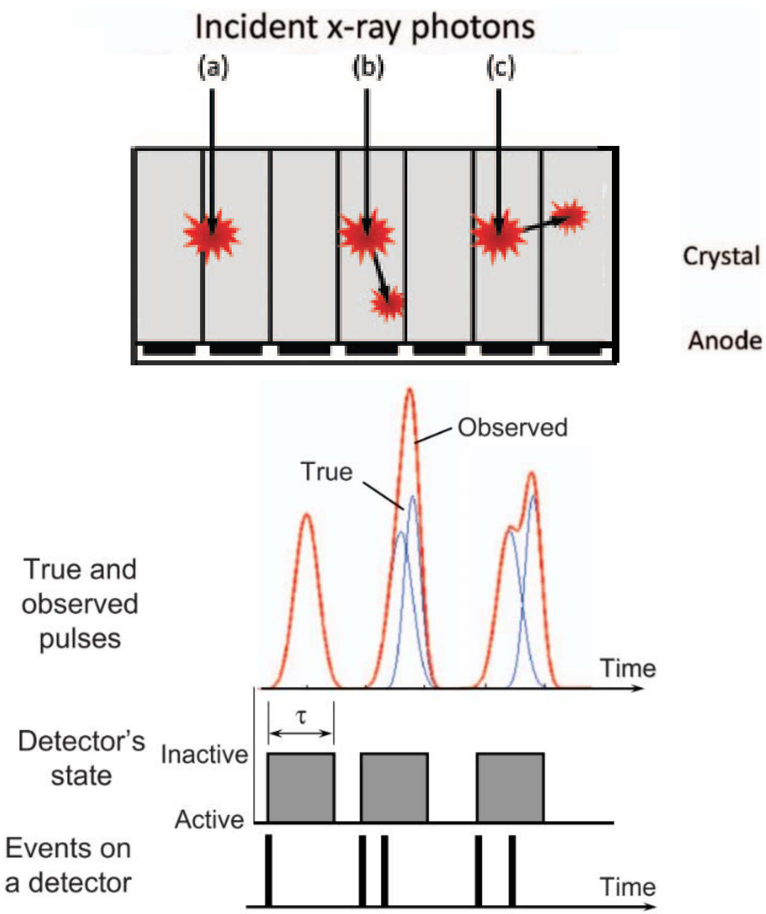
- The project exploits Pixirad-1/Pixie-III (originally designed at INFN – Pisa)

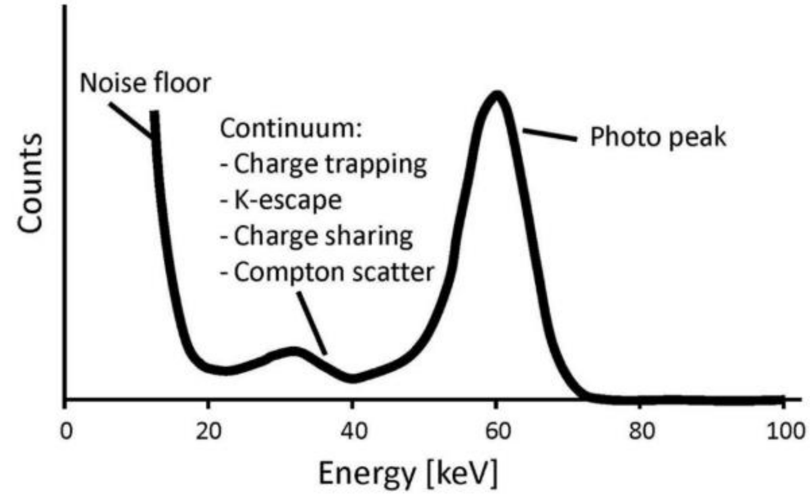
- **Characteristics**
  - Hybrid architecture: **CdTe** Schottky sensor and **PIXIE-III** readout system
  - **Two** independent acquisition **thresholds** and two counters per pixel **(2COL mode)**
  - Sensor: **650 µm** CdTe crystal
  - Pixel size**: 62 µm** pixel pitch
  - Detection Area: 512×402 elements
  - Resulting FOV: **31.7×25.0 mm^2**
  - Square pixels
  - **NPISUM mode**

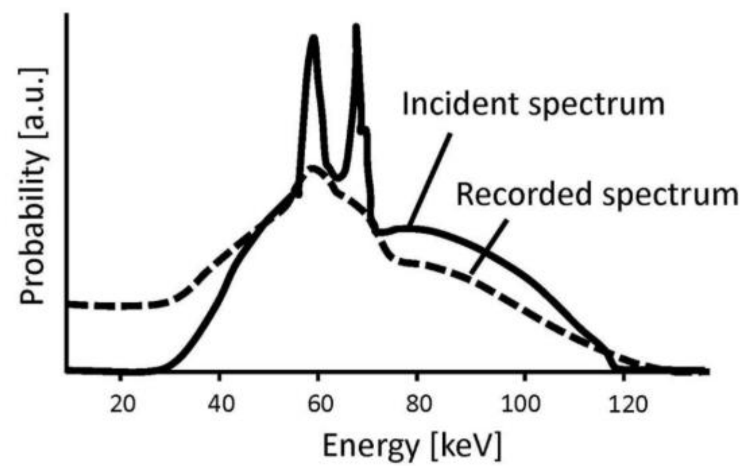
TO NOTE: "perfect" XPCDs do not exist (a **finite energy resolution** has to be considered)
many **technological issues** are still to be solved even with Pixie-III

XPCDs challenges

- The challenges of XPCDs are well known:





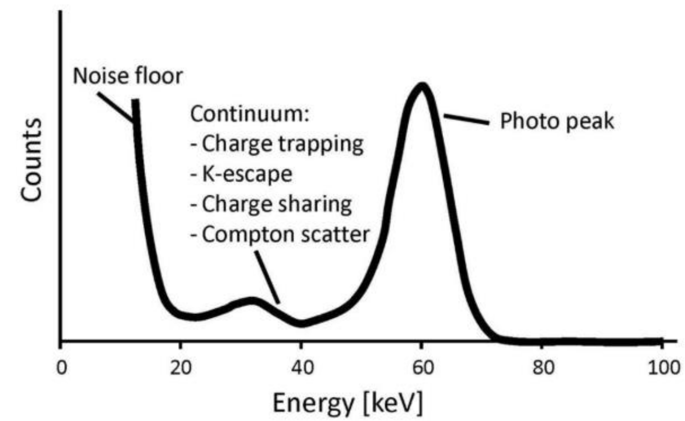


Source: Taguchi, K. and Iwanczyk, J.S. (2013) Medical Physics 40, 100901

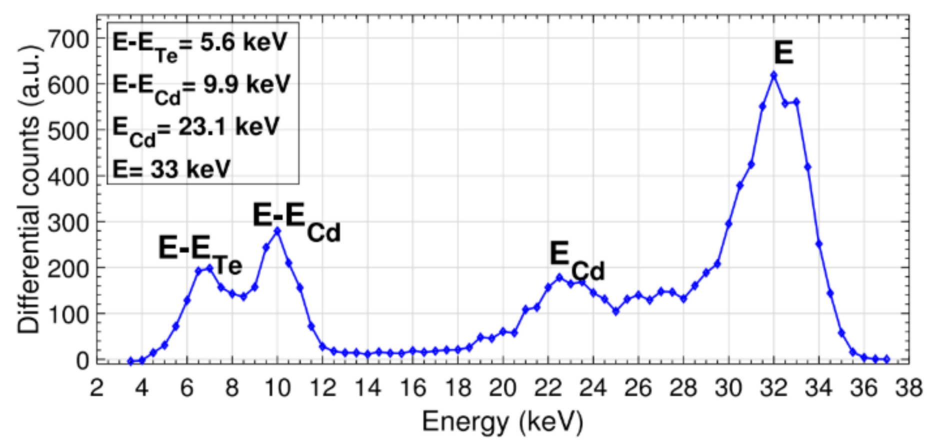
Characterization of Pixie-III

- Energy resolution of XPCDs is mainly affect by the charge sharing issue
- PIXIE-III has three different operating modes. The most interesting one:
  - Neighbor Pixel Inhibit and Pixel Summing Mode (**NPISUM**): the signals of 4 neighbor pixels are summed together to correctly evaluate the total energy of any event involving up to 4 pixels

E [keV]	FWHM [keV]	ΔE/E
26	3.4 ± 0.4	(13 ± 2)%
33	3.6 ± 0.4	(11 ± 1)%
37	3.7 ± 0.4	(10 ± 1)%
50	4.1 ± 0.4	(8.2 ± 0.8)%



Assessed differential spectrum at 33 keV

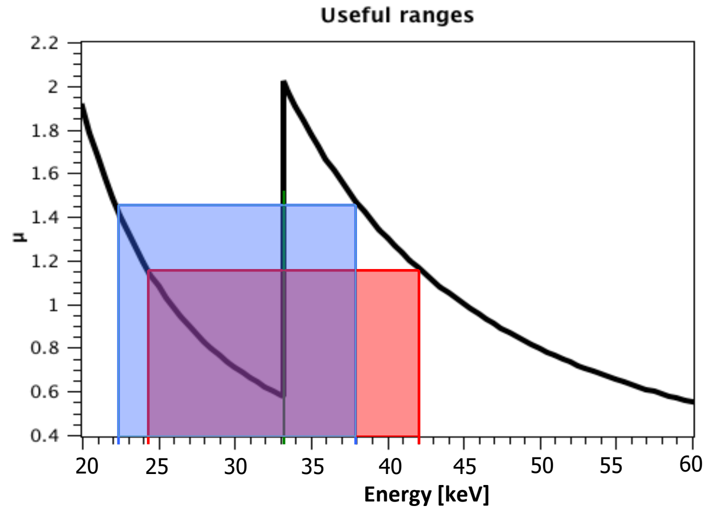


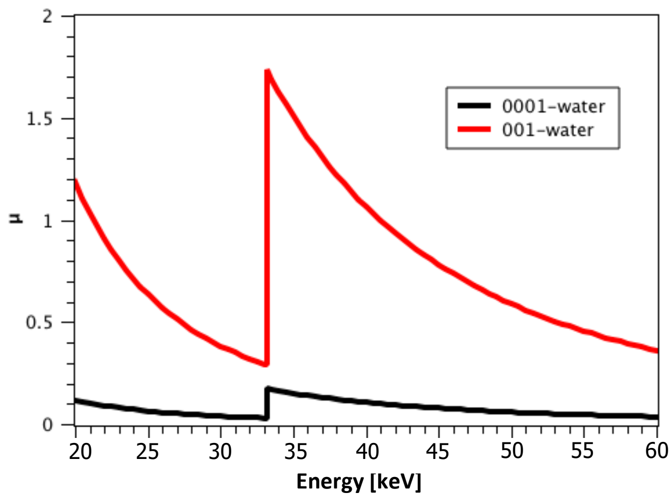
Threshold scan of flat images collected with mono SR at 33 keV

Optimization of KES acquisition

- A KES acquisition depends mainly on:

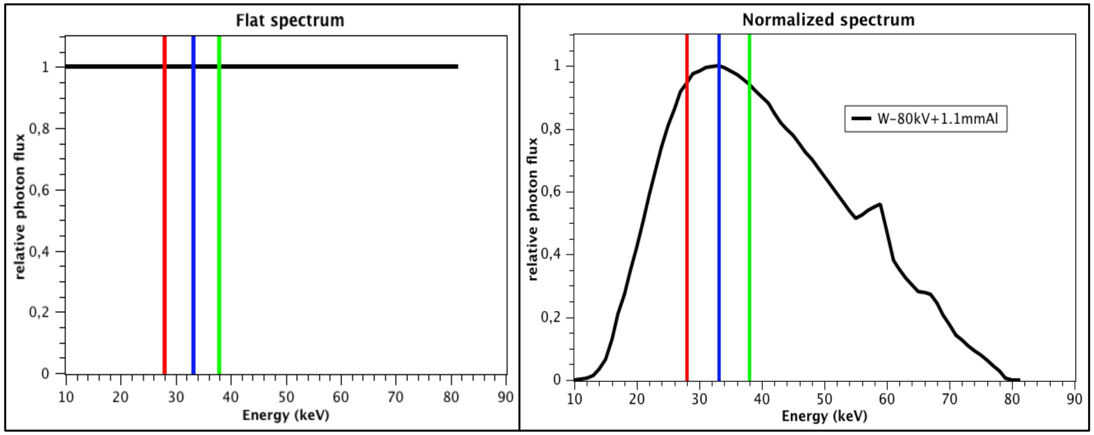
position of low and high detector thresholds





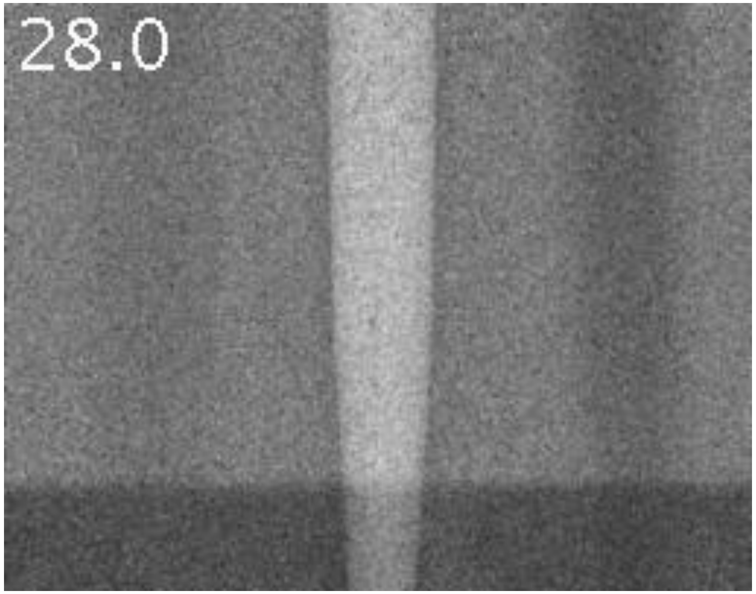
contrast media concentration

X-ray kV and filtration



Example with 2D planar imaging

KES with different HIGH image



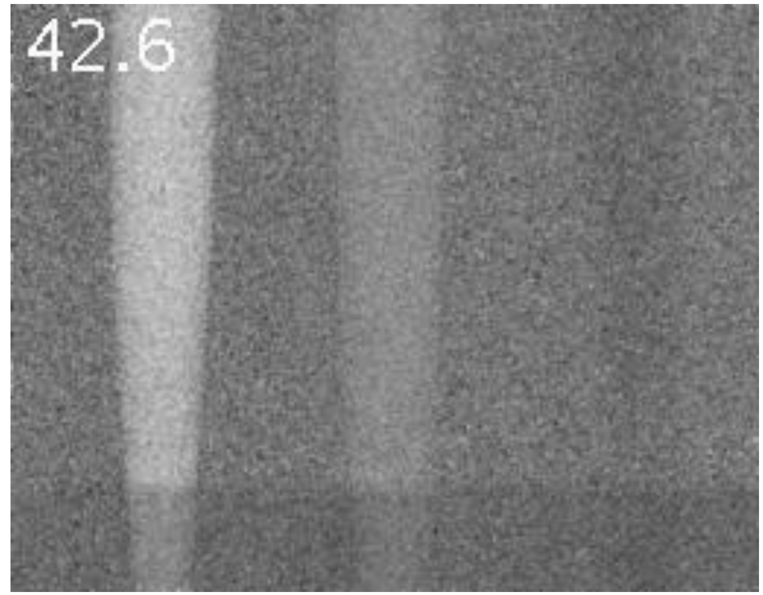
Settings:

- 45 kV + 1 mm of Al
- LOW threshold fixed at 26 keV
- HIGH scan 28-42.6 keV, steps = 0.2 keV

TO NOTE: the KES image is a simple **pixel-by-pixel subtraction** (no co-registration) segmentation of I or Ba becomes easy

Example with 2D planar imaging

KES with different HIGH image



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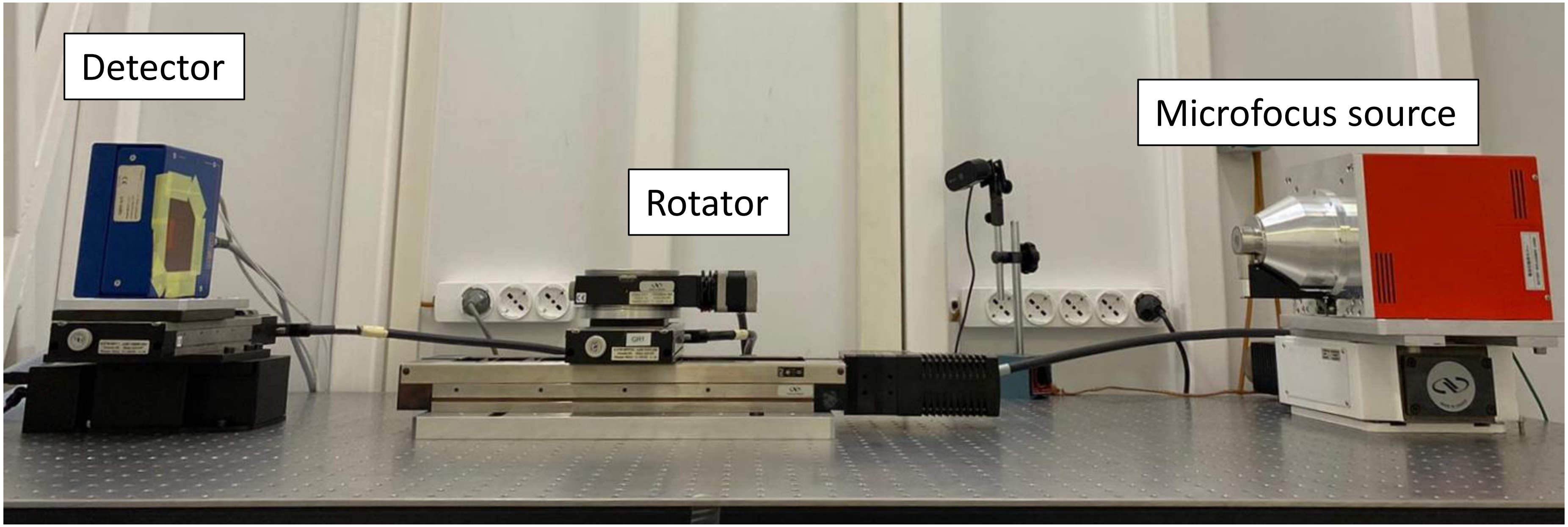
segmentation of I or Ba becomes easy

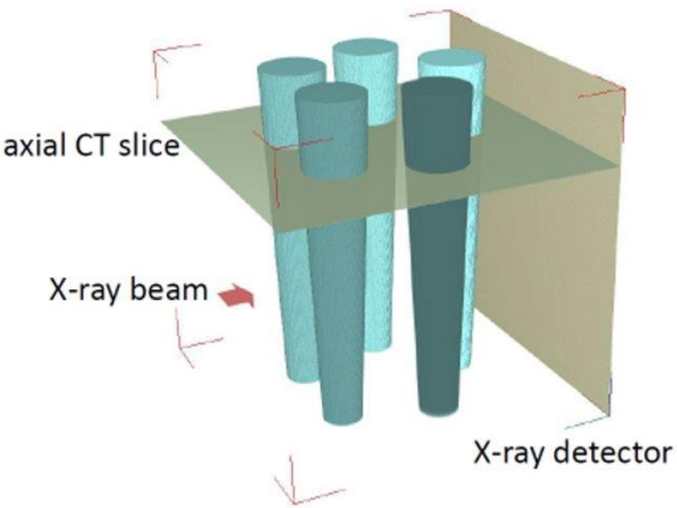
Spectral photon-counting CT

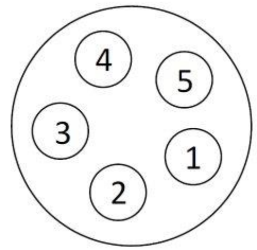
- Our focus is X-ray computed tomography (CT)
  (hereafter referred as *spectral photon-counting computed tomography*)



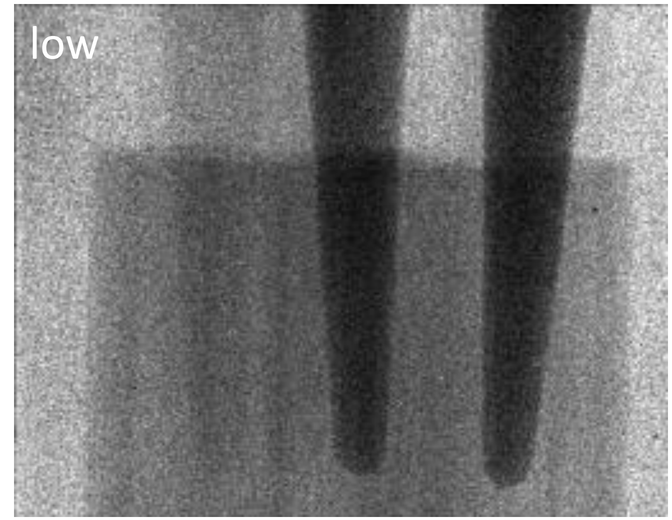
- Each element lays over translating stages
- **Flexible acquisition geometries** are therefore possible

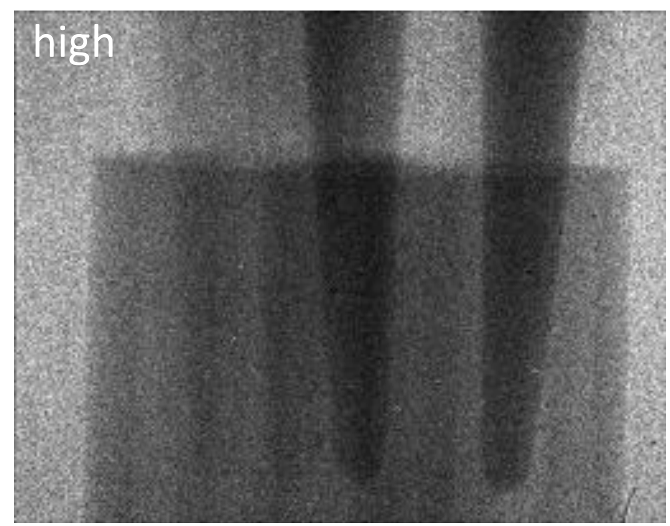
KES CT





1. Ultravist® 0.25M
2. Ultravist® 0.125M
3. $BaCl_2$ 0.25M
4. Multihance® 0.25M
5. H_2O





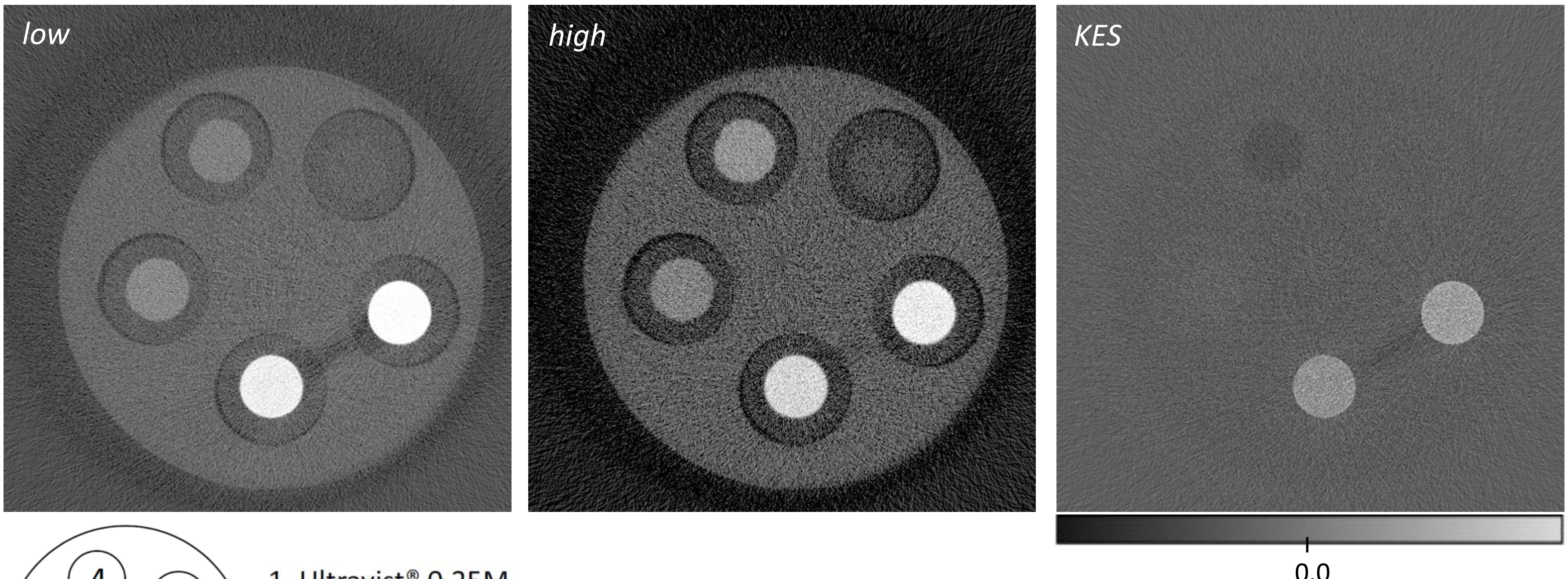
Settings for iodine detection:

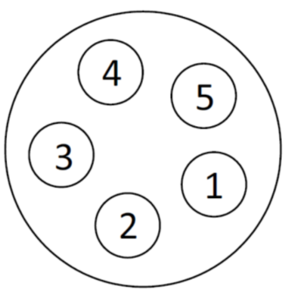
- X-ray with W anode at 45 kV
- filtration of 1 mm of Al
- LOW threshold = 26 keV
- HIGH threshold = 33.2 keV

The detector outputs two “raw” images per shot

KES CT

- Axial CT slice after FDK reconstruction (with pre- and post-processing):





1. Ultravist® 0.25M
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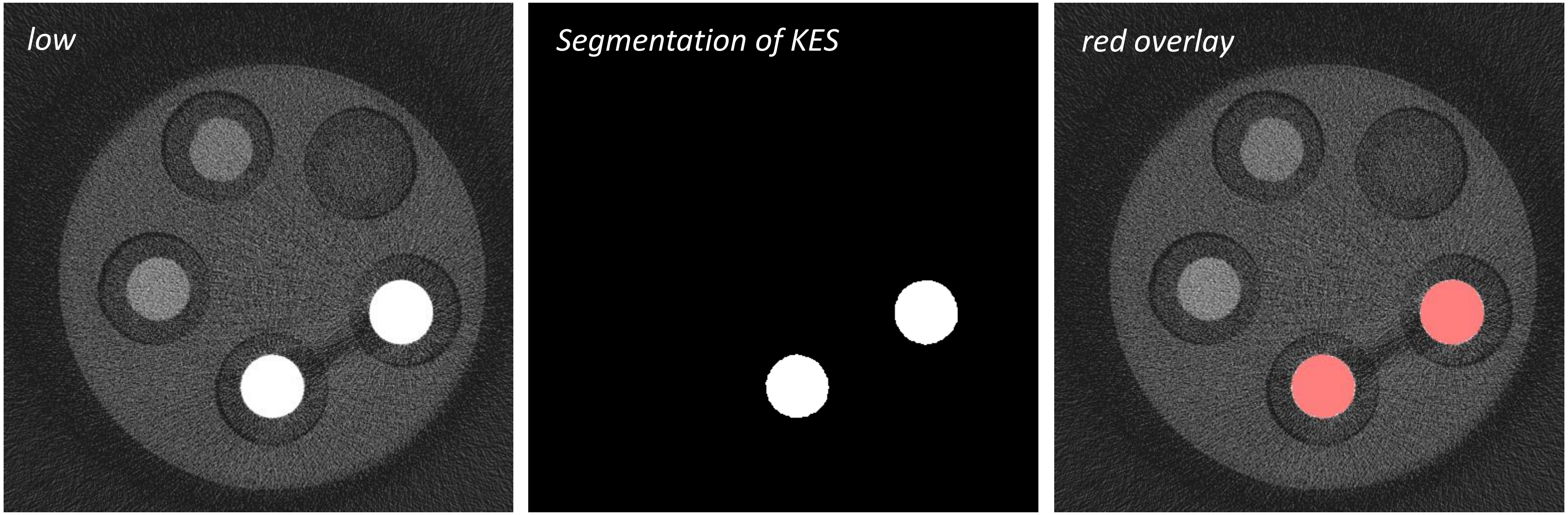
3. $BaCl_2$ 0.25M
4. Multihance® 0.25M
5. H_2O

TO NOTE: iodine is positive in the KES image
everything else is close to zero or negative

Color overlay

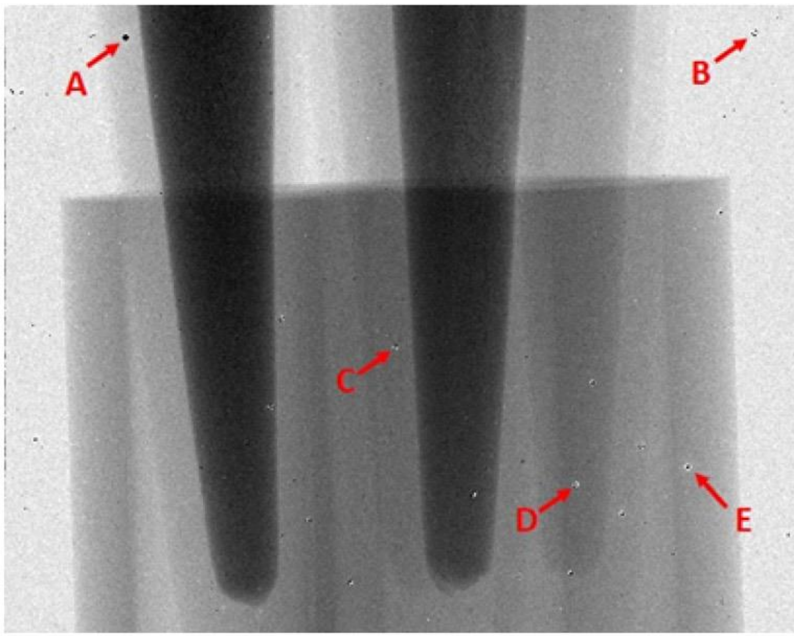
- Color overlay of the segmentation results might be interesting
- Segmentation can be done via simple thresholding (over background noise)

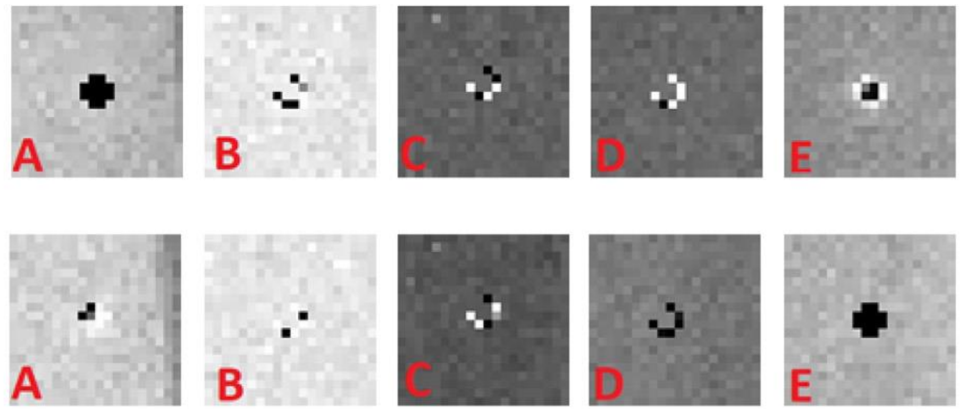


- Overlay over the “low”, the “high” or also the “sum” (low + high) image

Pre-processing

- The acquired raw images with the NPISUM mode present clusters of hot/dead pixels

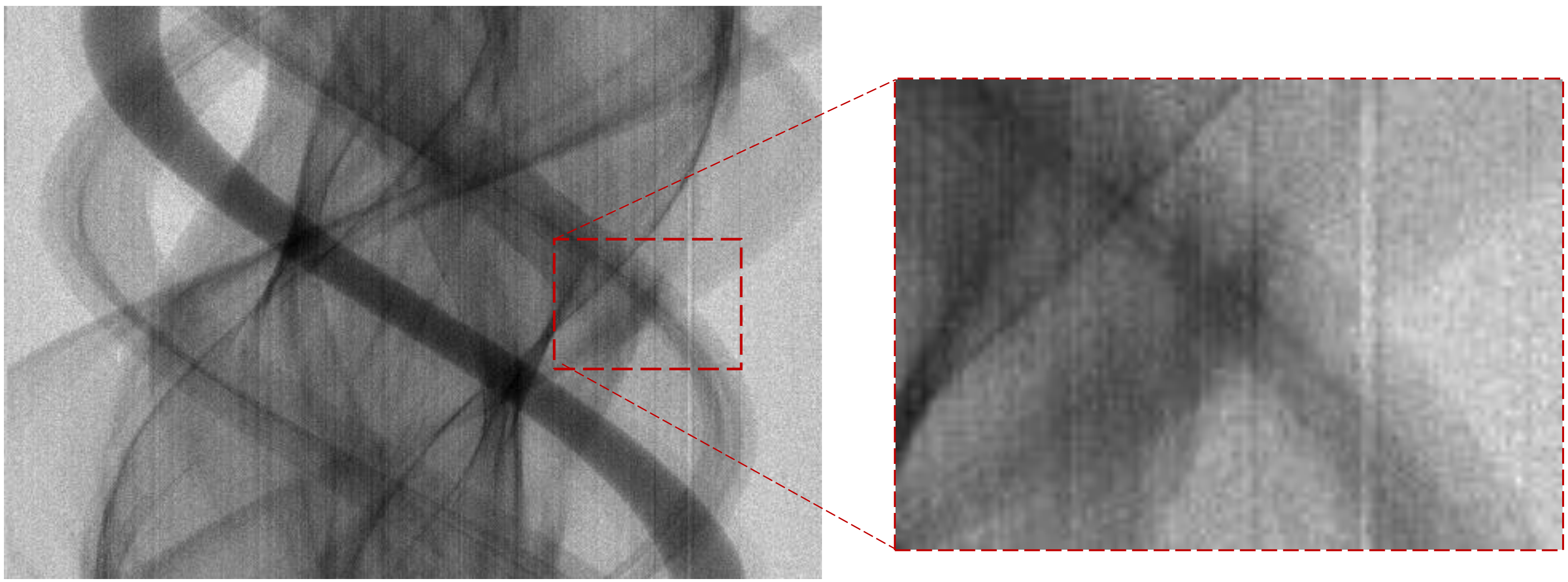




- A digital image processing solution has been studied to preserve spatial resolution
- The proposed solution is a custom adaptive 5×5 median filtering, which takes as input also the so-called “flat” image

Ring artifacts

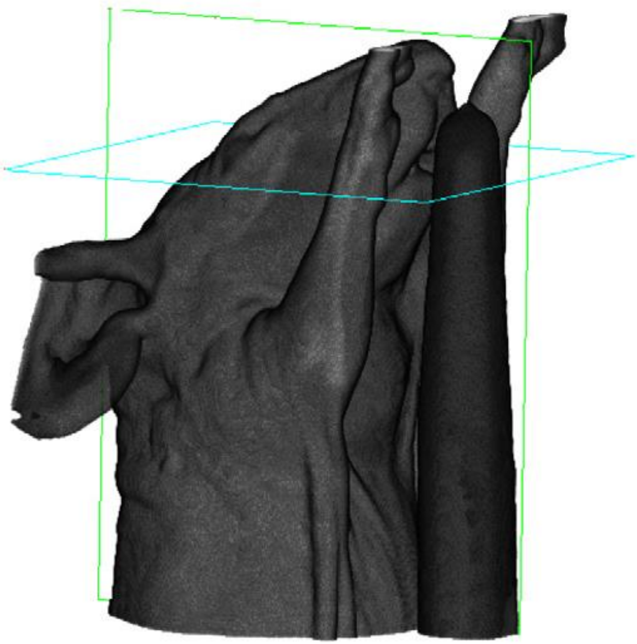
- Even with the clusters of hot/dead pixels correction, ring artifacts still appear
- The noise model is affected by the 2×2 pixel summing NPISUM mode



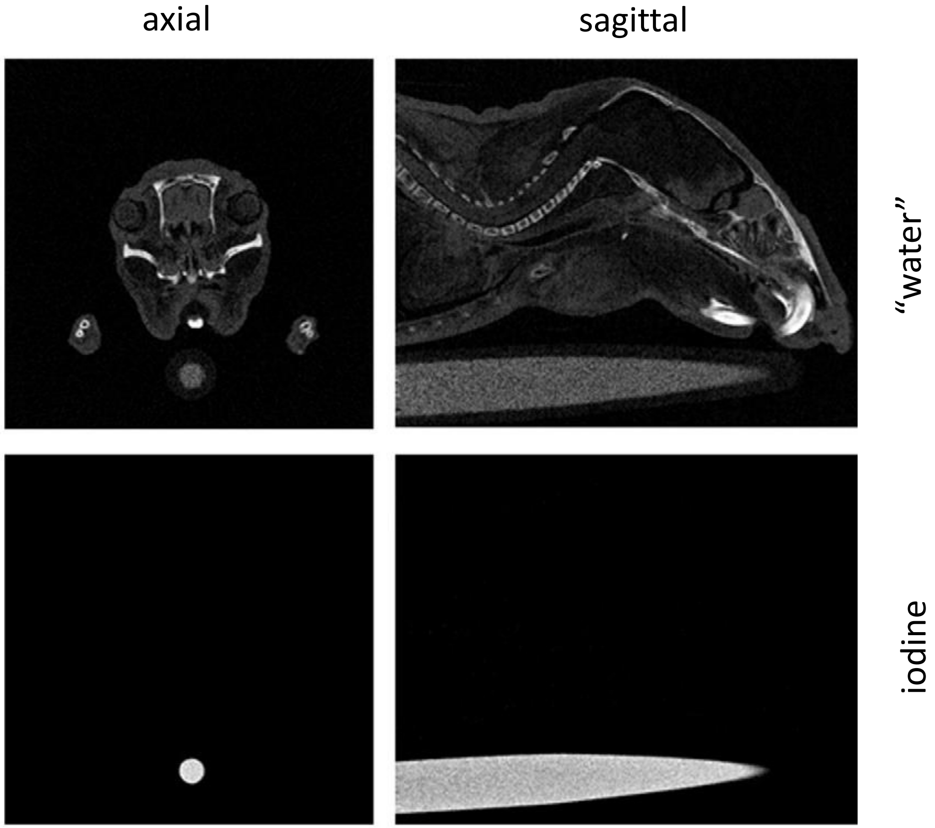
- A digital image processing solution has been studied to preserve spatial resolution
- The proposed solution is a custom combination of horizontal and vertical adaptive median filtering in the sinogram domain

Basis Material Decomposition

- Basis Material Decomposition (BMD) is also well known for spectral imaging
- Gray levels are forced to belong to e.g. iodine and "water" images

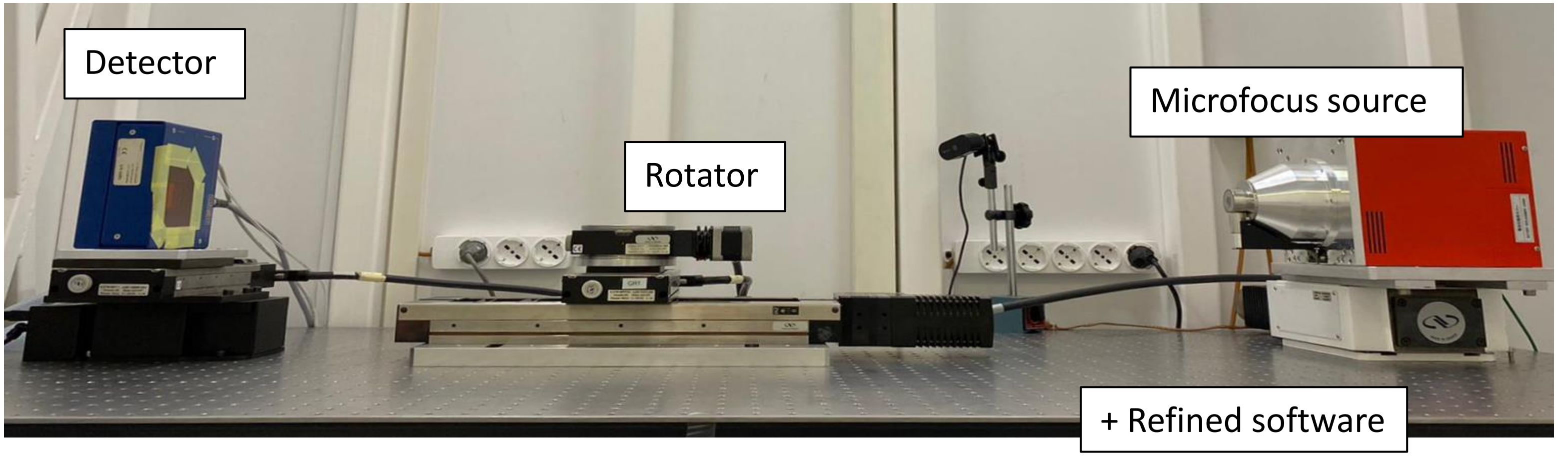


Plastinated mouse specimen with an iodine (diluted with water) pipette



Conclusion

- Polychromatic *single-shot* spectral µ-CT is possible
  - An operating setup + refined software is available in Trieste
    - Spatial resolution in the range 40-50 µm (depending on magnification)
    - FOV up to about 4 cm (in extended FOV CT mode)
    - Energy resolution in the range of 3-4 keV

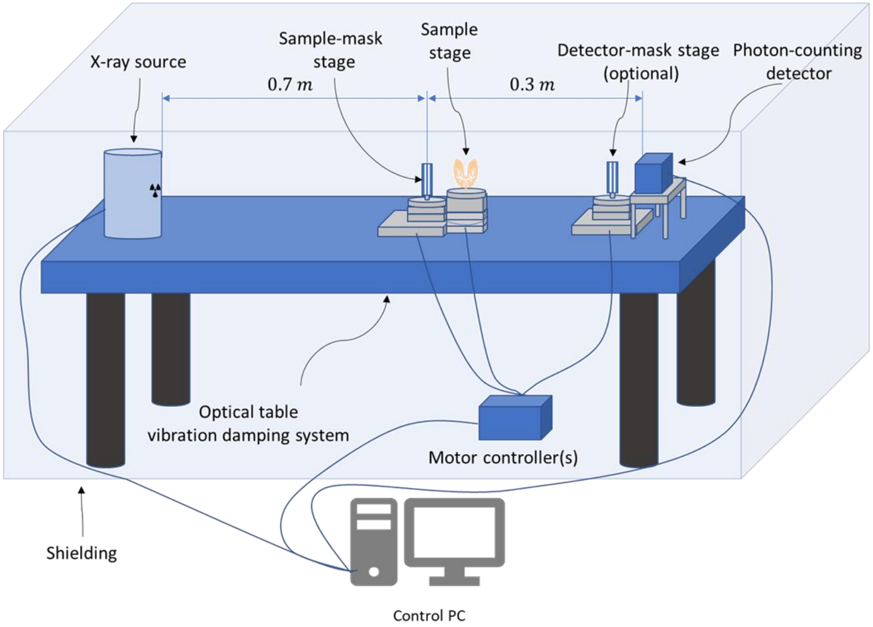


- **Applications**: small animals *ex vivo* elemental imaging
- Other applications in the field of e.g. material science can be considered

Current evolutions

- Integrating current setup with edge illumination phase-contrast

- Multi-modal scan of the very same sample (without repositioning):
  - conventional (absorption)
  - *single-shot* spectral (elemental)
  - phase contrast
- First setup of this kind in Italy



- Implementation of K-edge subtraction imaging at the Elettra synchrotron (Trieste) by exploiting the polychromatic white beam and innovative contrast agents

More information

- Publications list, how to contact us and more info can be found at:

k-edge
spectral
tomography

http://web.infn.it/kest

- Implementation of K-edge subtraction imaging at the Elettra synchrotron (Trieste) is currently part of the INFN **KISS** (**K**-Edge **I**maging with **S**ynchrotron **S**ources) project
- For information about spectral phase-contrast imaging (**PEPI** project):

P hoton-counting
E dge-illumination
P hase-contrast
I maging

http://web.infn.it/PEPI