Material Characterization using Spectral X-ray CT

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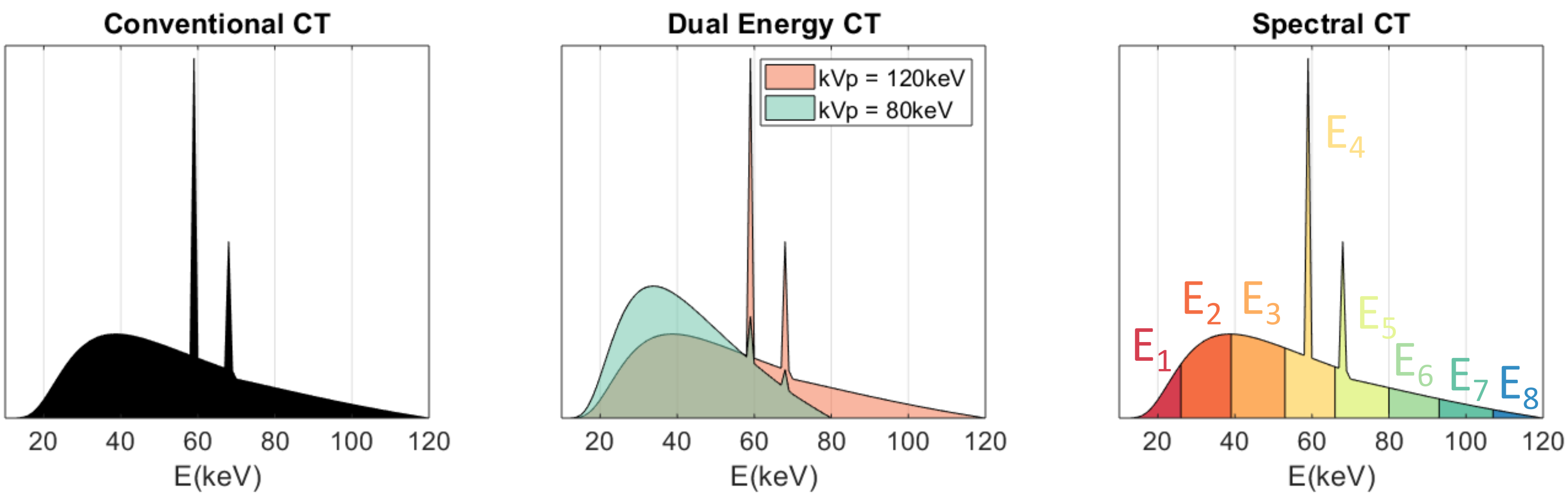
Introduction

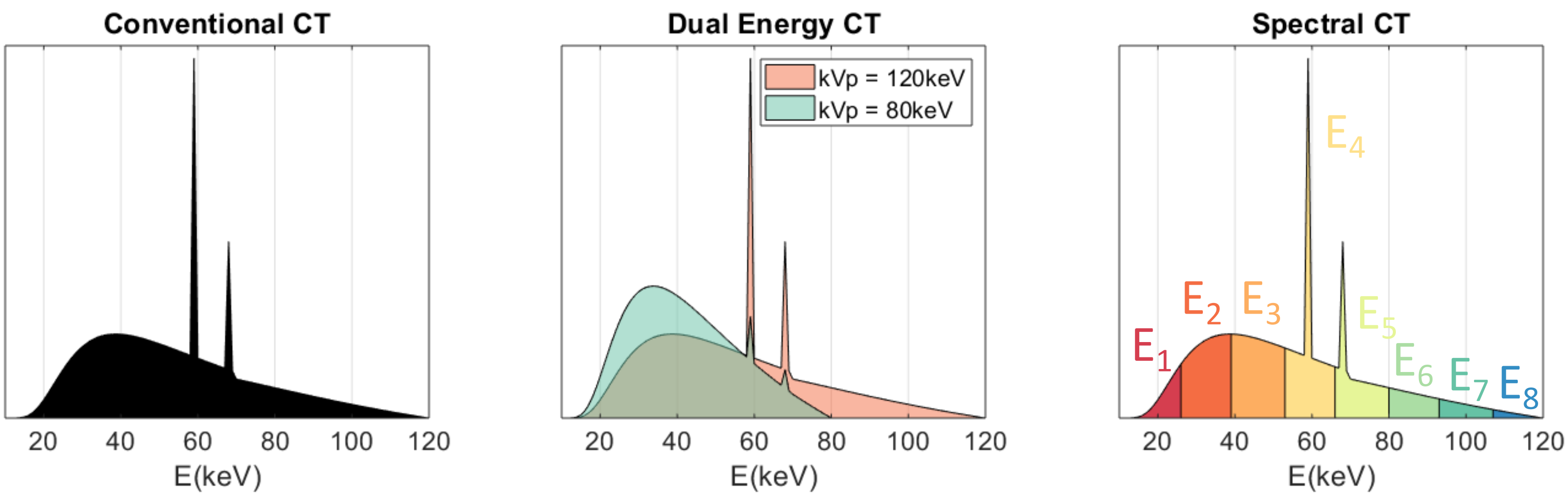
- PhD Project: Model-Optimized screening of Checked-in Luggage
- Goals:
  - ✓ Increase the threat detection accuracy
- How?
  - ✓ Spectral X-ray detectors
  - ✓ Physical-based models

Current Techniques



- Conventional and Dual Energy CT:
  Detectors integrate radiation over large energy range
  - Beam hardening and polychromatic effects induce non-linear artifacts
  - Highly attenuating materials (high-Z) completely attenuate low-energy photons

Current Techniques

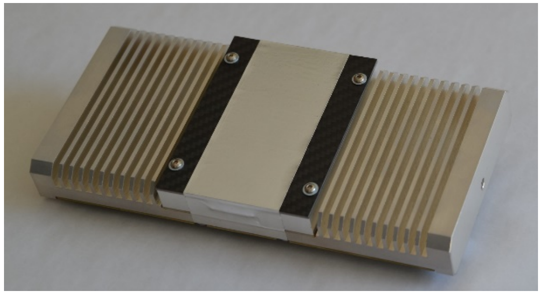


- Conventional and Dual Energy CT:
  Detectors integrate radiation over large energy range
  - Beam hardening and polychromatic effects induce non-linear artifacts
  - Highly attenuating materials (high-Z) completely attenuate low-energy photons

- Spectral CT:
  Detectors discriminate the energy of single photons into Energy bins
  - Spectral distortions (pile-up, charge sharing etc.) induce non-linear artifacts

Spectral detectors

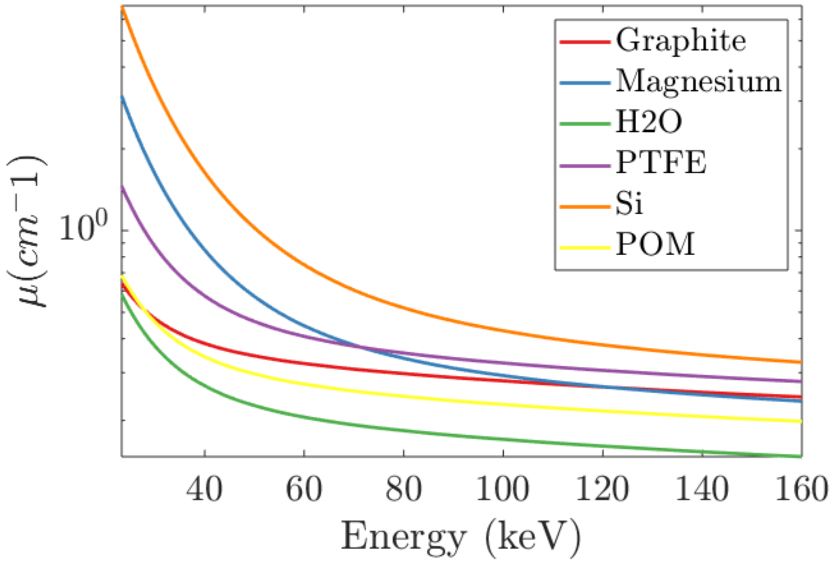
Multix ME-100



Specs	Multix ME-100
Pixel Pitch	800 μm (linear)
Pixel array	128
Sensor type	CdTe
Thickness	3 mm
Energy range	20-160 keV, 1.1 keV bins
Acquisition Time	1 ms - 100 ms
Count Rate	1,250,000 Photons/s/mm

Spectral X-ray Computed Tomography (SCT):

- Simultaneous energy resolved measurement of the Linear Attenuation Coefficient (LAC): $\mu(E)$



System-independent material features

SIRZ† and SIRZ-2‡ techiques introduced material characterization into system-independent features:

- Effective atomic number: Z_e
- Electron density: $\rho_e\ (\frac{e^{-1}mol}{cm})$

† S. G. Azevedo et al., **System-independent characterization of materials using dual-energy computed tomography**, IEEE Transactions on Nuclear Science 63 (1) (2016) 341–350.
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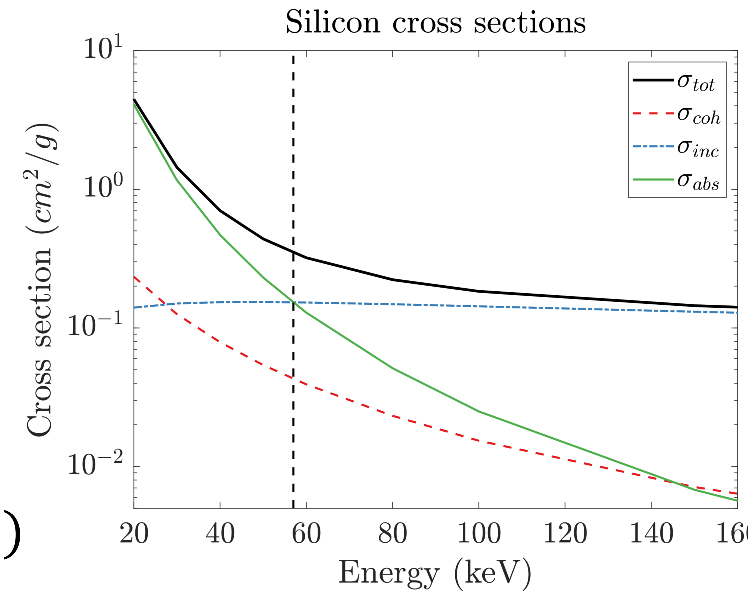
These are used to model the LAC:



$$\mu(E) = \rho_e \sigma_e(Z_e, E)$$

- $\sigma_e(Z_e, E)$: electronic cross sections (NIST standard tables)

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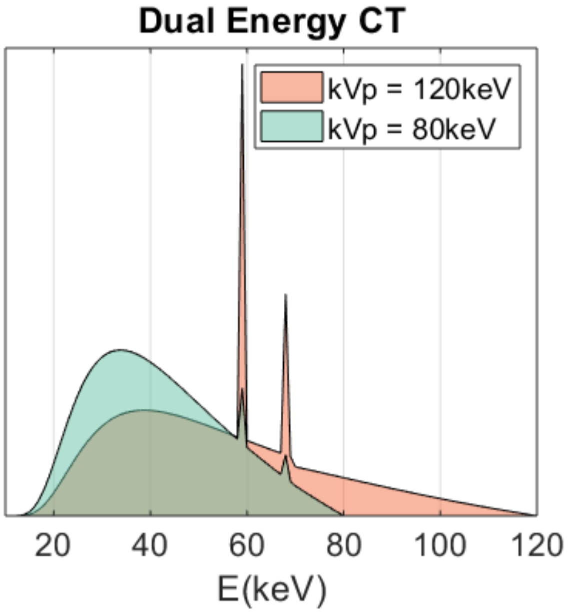
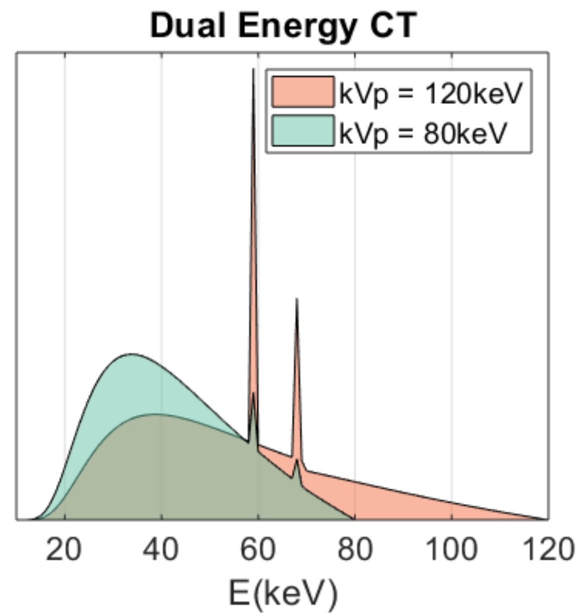
SIRZ-2 Briefed

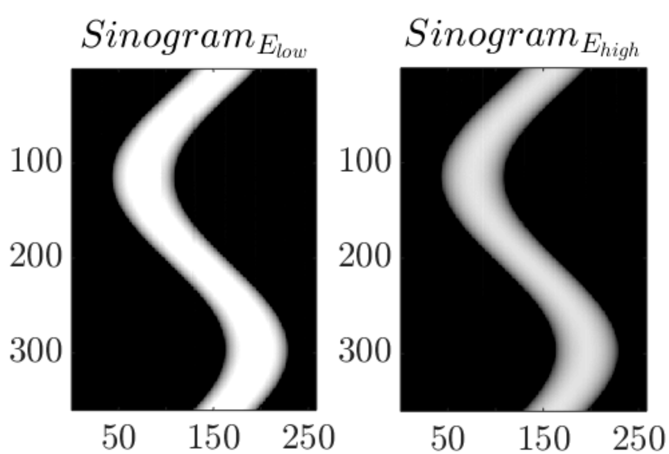
- The technique requires dual-energy CT acquisitions, and knowledge about the source and detectors
- Using calibrated Detectors Spectral Response, the low- and high-energy scans are transformed into synthetic monochromatic sinograms μ_{low}, μ_{high}



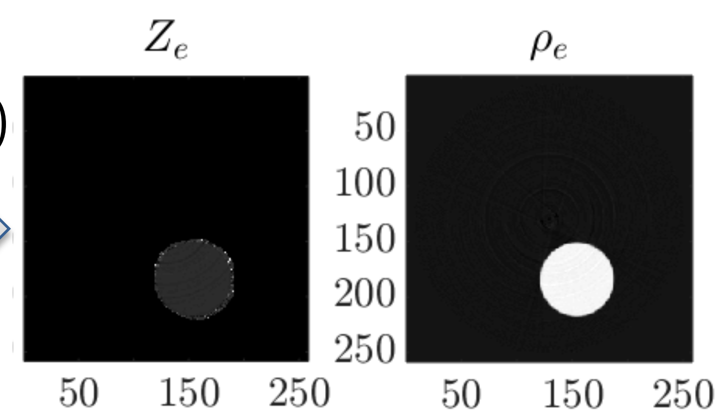
SIRZ-2 Briefed

- The technique requires dual-energy CT acquisitions, and knowledge about the source and detectors
- Using calibrated Detectors Spectral Response, the low- and high-energy scans are transformed into synthetic monochromatic sinograms μ_{low}, μ_{high}
- Volume Reconstruction and transformation into ρ_e, Z_e :



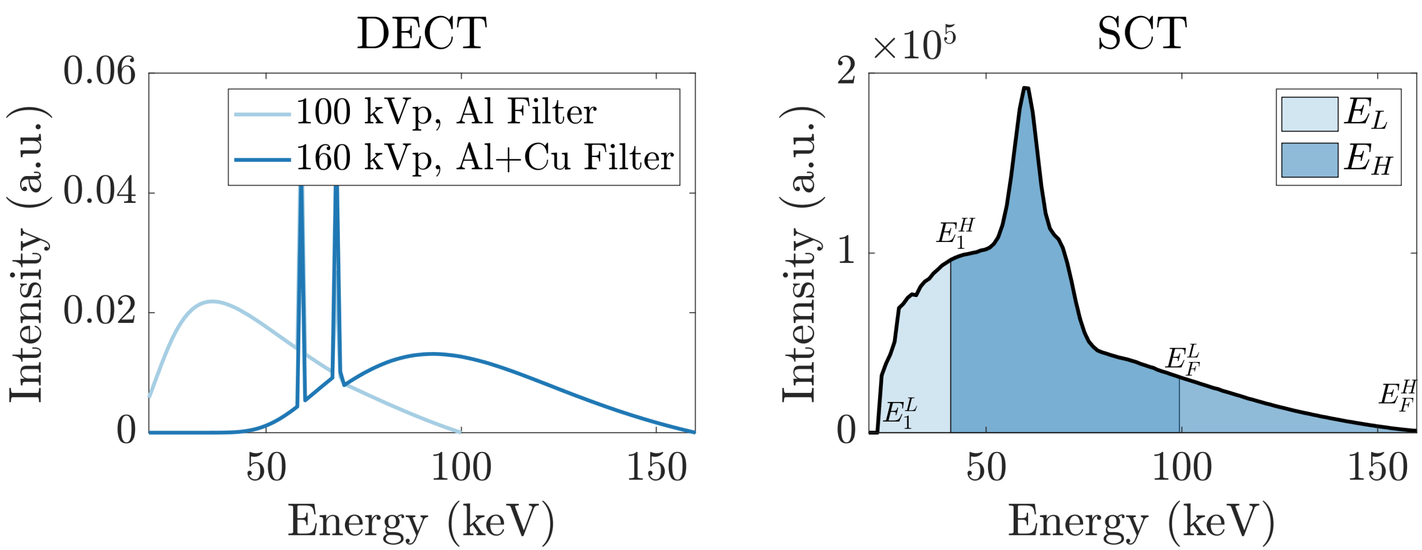


$$\mu_{low} = \rho_e \sigma_e (Z_e, E_{low})$$
$$\mu_{high} = \rho_e \sigma_e (Z_e, E_{high})$$



SIRZ-2 adaptation to SCT measurement

- Using the SCT the energy dependence is collected simultaneously



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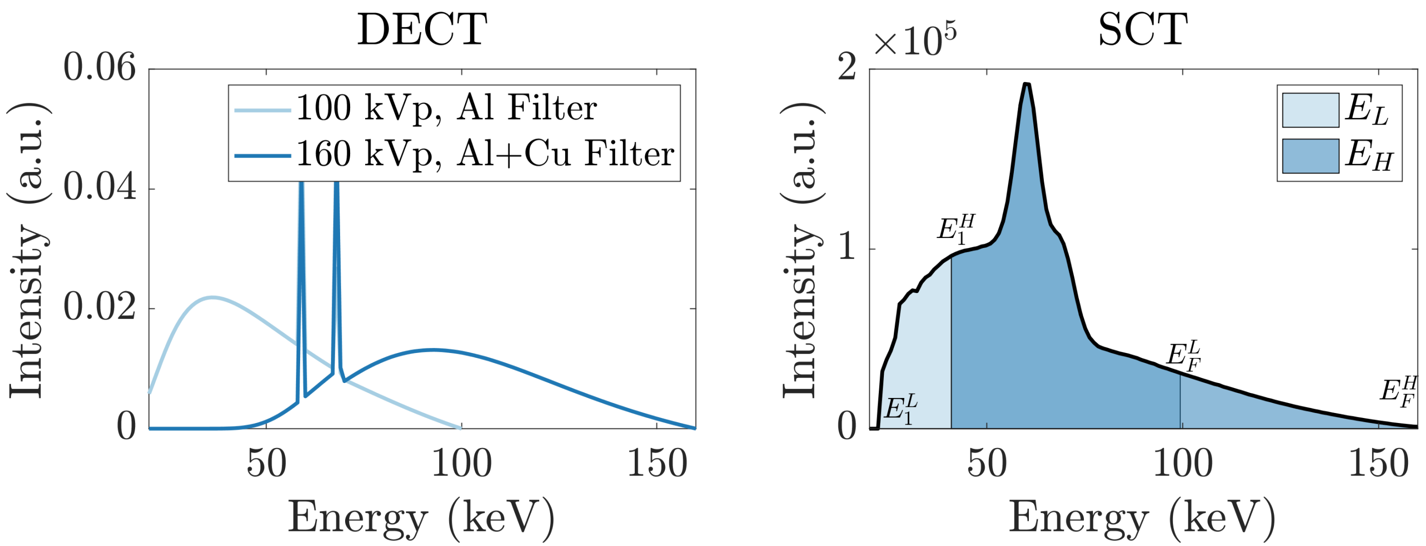

- The detector spectral responses are calculated directly from flat field (I_0) scans, by choosing the low- and high-energy intervals
- The acquisition is transformed into synthetic dual-energy data, integrating the energy bins within the two energy intervals

New Method: SRZE (Spectral ρ_e/Z_e Estimation)

Idea:

- SCT provides energy dependence of the measured LAC: $\mu(E)$
- Estimate ρ_e, Z_e from the LAC:

$$\mu(E) = \rho_e \sigma_e(Z_e, E)$$

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How:

- Solving

$$\underset{\{\rho_e, Z_e\}}{\operatorname{argmin}} \sum_{E=1}^{N_E} \lambda_E |\mu_E - \rho_e \sigma_e(Z_e, E)|^2$$

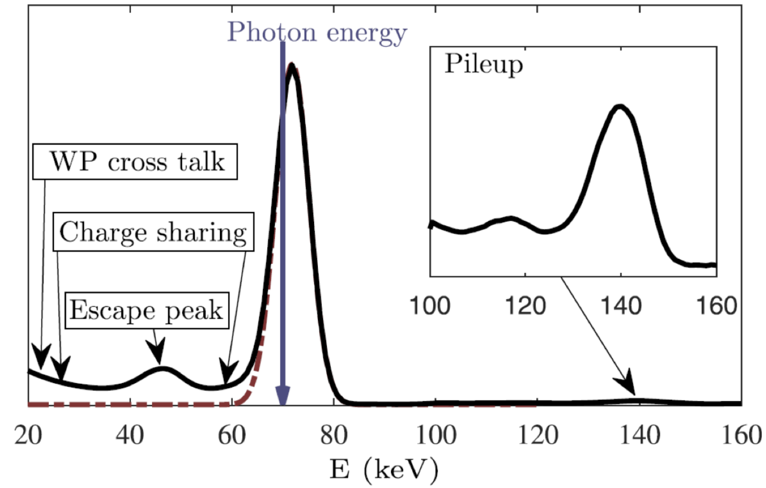
- λ_E: Energy weights; $\lambda_E = \frac{1}{s^2(\mu(E))}$; s^2: variance

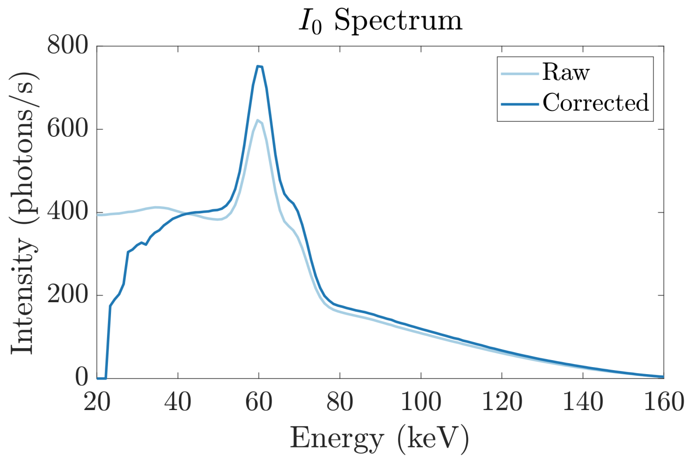
SRZE Routines

1. **Detector Spectral Correction**

A flux-dependent correction algorithm* was developed to correct detector spectral distortions:

- Charge-sharing
- Pile-up
- Escape Peaks
- Insufficient charge collection
- Weighting potential cross talk



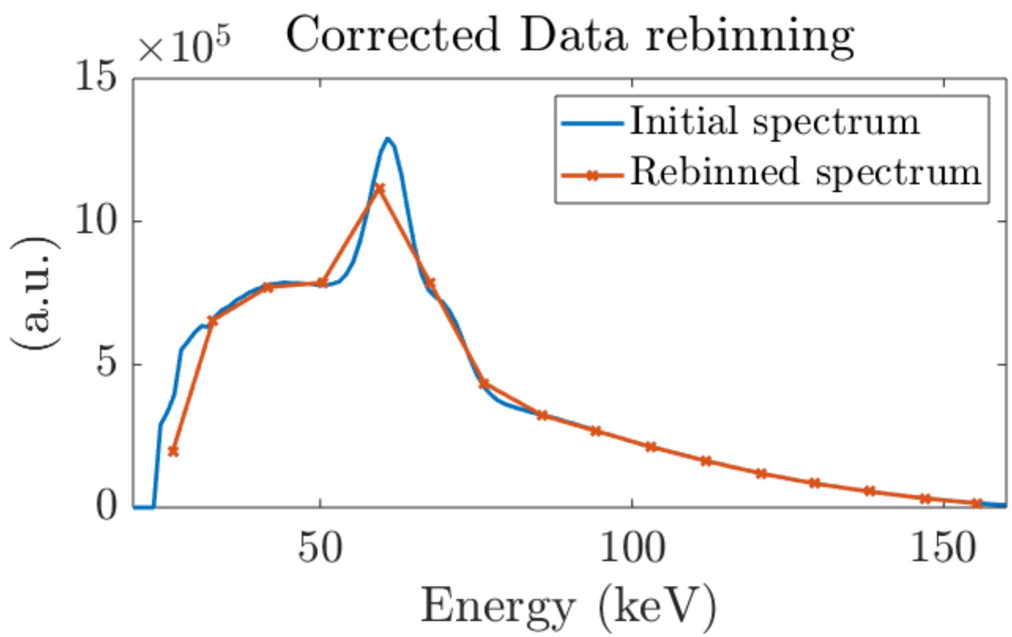


* E. S. Dreier et al., **Spectral correction algorithm for multispectral CdTe x-ray detectors**, Optical Engineering 57 (5) (2018) 054117.

SRZE Routines

1. Detector Spectral Correction

2. **Energy rebinning (optional)**

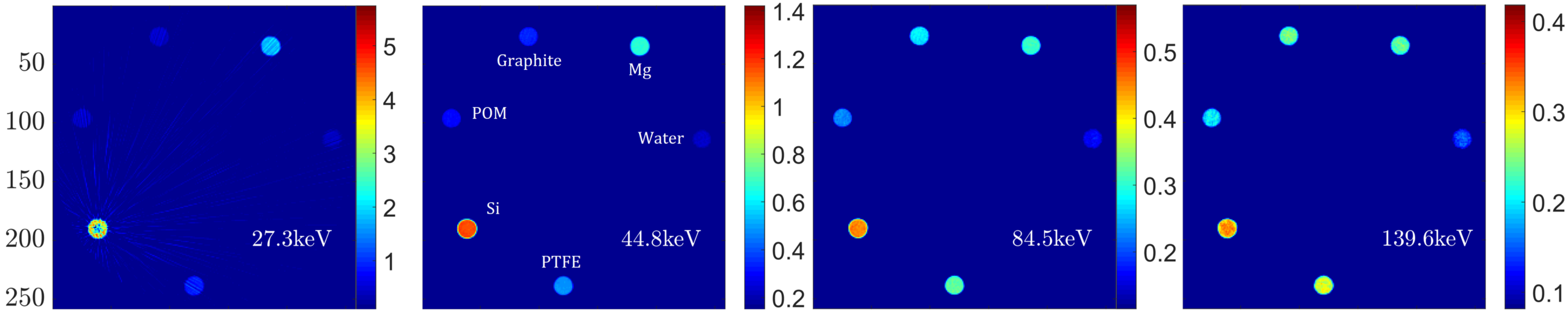


SRZE Routines

1. Detector Spectral Correction
2. Energy rebinning (optional)
3. **Conversion to attenuation and volume reconstruction**

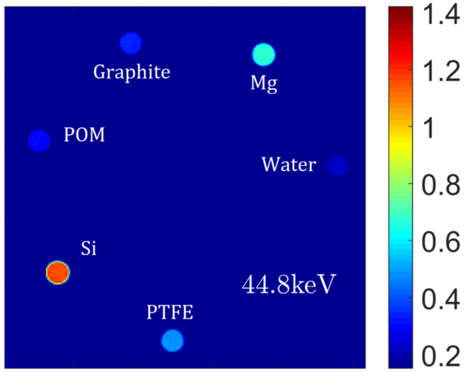
Using Lambert-Beer's law the projections are converted into energy resolved sinograms:

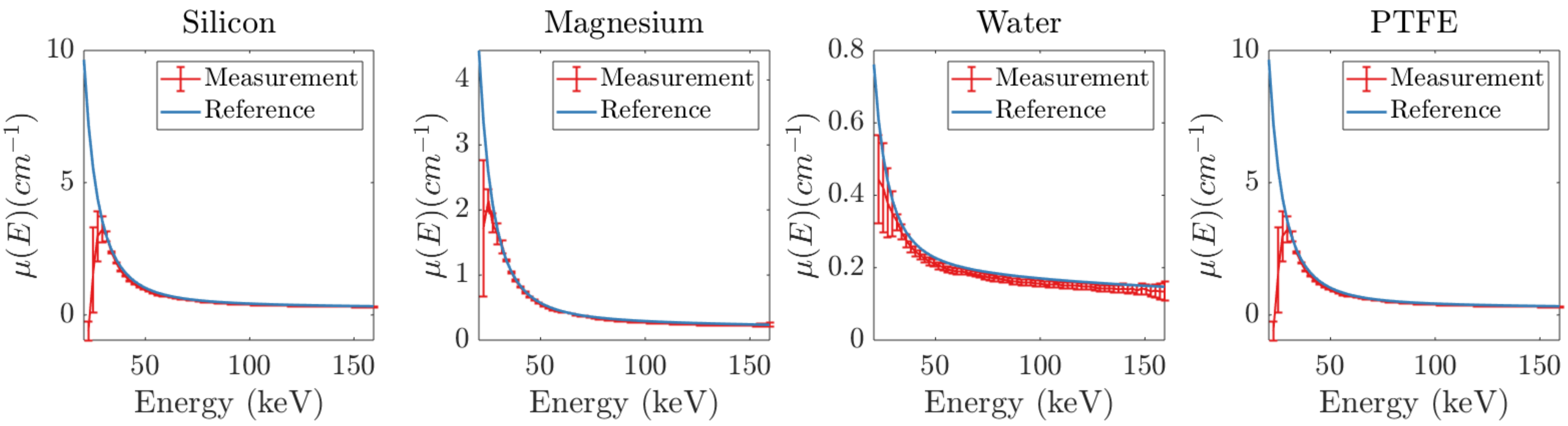
$$\mu(E_k) = -\frac{1}{l}\log\left(\frac{I(E_k)}{I_0(E_k)}\right), \qquad E_k = energy\ bin$$



SRZE Routines

1. Detector Spectral Correction
2. Energy rebinning (optional)
3. Conversion to attenuation and volume reconstruction
4. **Region of Interest (ROI) and $\mu(E)$ retrieval**





SRZE Routines

1. Detector Spectral Correction
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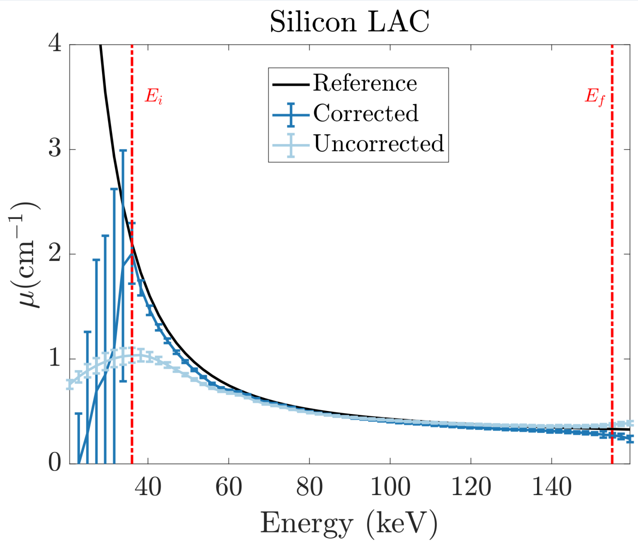
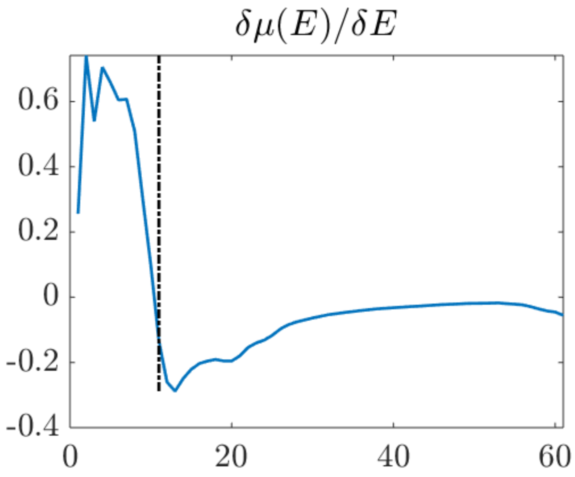
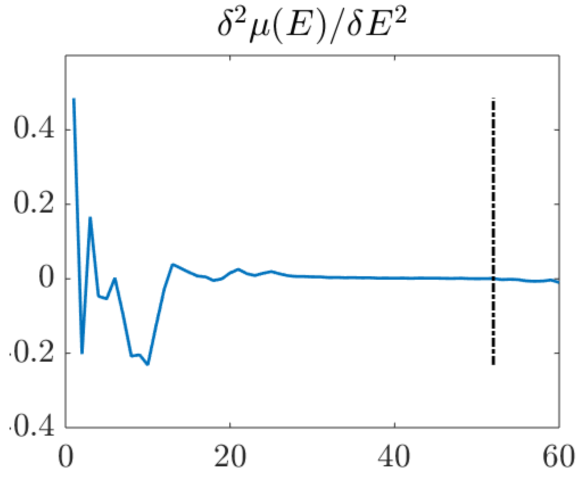
4. Region of Interest (ROI) and $\mu(E)$ retrieval
5. **Automated Energy thresholding**





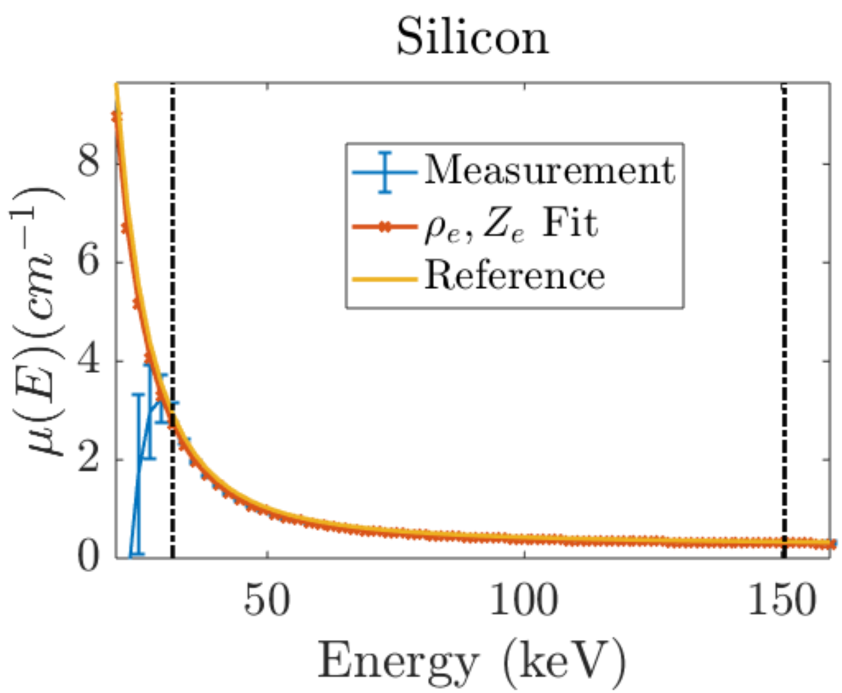


SRZE Routines

1. Detector Spectral Correction
2. Energy rebinning (optional)
3. Conversion to attenuation and volume reconstruction
4. Region of Interest (ROI) and $\mu(E)$ retrieval
5. Automated Energy thresholding
6. **Features Estimation**

$$\underset{\{\rho_e, Z_e\}}{\operatorname{argmin}} \sum_{E=1}^{N_E} \lambda_E |\mu_E - \rho_e \sigma_e(Z_e, E)|^2$$

- $\lambda_E = \frac{1}{s^2(\mu(E))}$; s^2: variance

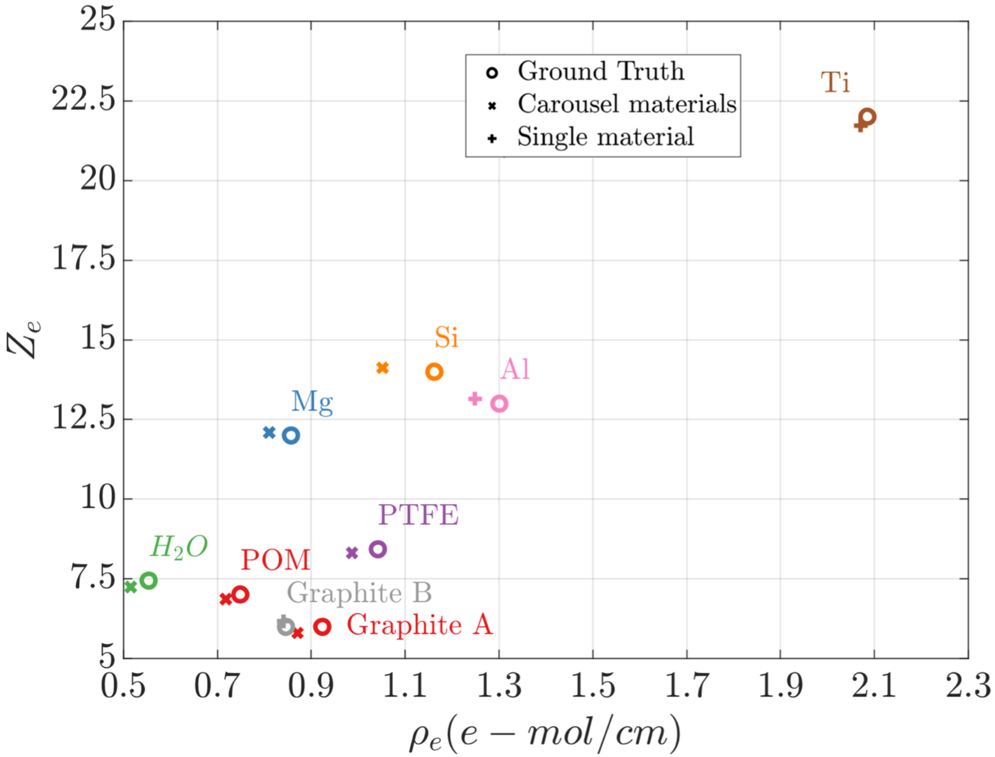


Experiments

- Samples
  1. Carousel with 6 samples
     - Silicon, Graphite B, Magnesium, Water, PTFE, POM
  2. Individual materials
     - Silicon, Titanium, Aluminum, Graphite A, Graphite A

- 360 Projections between 0° and 360°
- 100ms integration time, total exposure per projection: 5 s (average of 50 acquisitions)
- Filament current: 0.5 mA
- 2mm Al Filter
- Source-detector distance: 3000mm, sample-detector: 150mm

Results



	Z_e^{ref}	Z_e^{rel}	ρ_e^{ref}	ρ_e^{rel}
Graphite B*	6	2.95	0.846	-0.52
Graphite A	6	-3.18	0.924	-5.74
POM	7.01	-1.97	0.749	-4.17
H_2O	7.45	-2.68	0.554	-6.93
PTFE	8.43	-1.29	1.042	-5.31
Graphite B*	6	2.95	0.846	-0.52
Mg	12	0.81	0.857	-5.38
Al*	13	1.16	1.301	-4.03
Si	14	-0.52	1.162	-5.75
Ti*	22	-1.24	2.085	-0.68

Conclusions

- We have presented a novel method for ρ_e/Z_e characterization of material from Spectral X-ray CT acquisitions
- The method is free of calibration, and works with any type of spectral detector
- Promising results, specially for high ρ_e/Z_e materials.

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- The method is free of calibration, and works with any type of spectral detector
- Promising results, specially for high ρ_e/Z_e materials.

Future work:

- Test robustness of the method to different source condition (filters, source power)
- Test a broader range of Z_e materials, including K-edges materials

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